STUDY THE EFFECT OF MECHANICAL PROPERTIES ON THE IMMERSED EXTREMELY AGED FS3300PA PA- 12 POWDER IN SEA WATER ON XYY 0 DEGREE ORIENTATION

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Faculty of Mechanical Technology and Engineering

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A thesis submitted in fulfillment of the requirements for the degree of Bachelor of Mechanical Engineering Technology (MaintenanceTechnology) with Honours

Faculty of Mechanical Technology and Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2024

DECLARATION

I declare that this choose an item entitled "Study the Effect of Mechanical Properties on The Immersed Extremely Aged FS3300PA-12 Powders in Sea Water on XYY 0 Degree" is the result of my own research except as cited in the references. The Choose an item. has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : ______________________________

Name : Muhammad Al-Hadi Nashrullah bin Mustapha Kamal

Date : _______________11/1/2025_______________

APPROVAL

I hereby declare that I have checked this thesis and, in my opinion, this thesis is adequate in terms of scope and quality for the award of the Bachelor of Mechanical Engineering Technology Maintenance Technology (specialisation) with Honours.

Signature : ______________________________

Supervisor Name : Ts Ahmad Nizam Bin Jamaludin

Date : _________10/1/2025_____________________

DEDICATION

My road to finish my degree has been filled with progress, obstacles, and priceless support. My loving parents and siblings, your unfailing encouragement and sacrifices have been the foundation of my success. I want to express my gratitude to my mother Zaitun binti Manan for her unwavering love and support, which have kept me going even when things were very difficult. I am very grateful to my father, Mustapha Kamal bin Abdullah, for his knowledge and advice that have defined my path and given me the perseverance to conquer challenges. They both deserve my thanks for all of their efforts for me when I was a student at this university, as well as the help, financing, and encouragement they offered as I worked on my report. Next, I would like to thank everyone who assisted me with my final year project, specially Ts. Ahmad Nizam bin Jamaludin, my supervisor, Ts. Mohd Idain Fahmy Bin Rosley, and my friends.

ABSTRACT

This research investigates the influence of layer thickness, laser power, and sintering orientation on the mechanical properties of virgin and extremely aged FS3300PA Polyamide-12 (PA-12) powder using the Selective Laser Sintering (SLS) 3D printing method. The study also explores the effects of prolonged seawater immersion on the material's dimensional stability, water absorption, and mechanical performance. A comprehensive literature review highlights the potential of PA-12 in demanding marine environments, focusing on its abrasion resistance, chemical stability, and mechanical strength, while emphasizing the impact of processing parameters on its performance. Methodologies involved preparing standard test specimens, sintering them with varying parameters (laser power: 65 W, 70 W, 75 W; layer thickness: 0.09 mm, 0.12 mm, 0.15 mm; orientations: XYY 0°, YZY 0°, YZY 90°), and immersing them in seawater for 1,000 hours to simulate aging. Mechanical properties were assessed through tensile tests to measure tensile strength, Young's modulus, and elongation at break. Results indicate that samples processed with 75 W laser power and 0.09 mm layer thickness demonstrated superior mechanical performance, achieving a tensile strength of 36.37 MPa, Young's modulus of 0.48 GPa, and elongation at break of 20.74%, even after seawater exposure. Orientation played a critical role, with XYY 0° exhibiting the highest mechanical integrity due to optimal interlayer bonding, while YZY 90° showed the lowest performance. The study underscores the importance of optimizing sintering parameters and build orientation to enhance durability and mitigate aging effects, providing valuable insights for the development of cost-effective, high-performance materials for industrial and marine applications.

ABSTRAK

Kajian ini menyelidik pengaruh ketebalan lapisan, kuasa laser, dan orientasi pensinteran terhadap sifat mekanikal serbuk FS3300PA Polyamide-12 (PA-12) dara dan yang telah lama digunakan, menggunakan kaedah percetakan 3D Selective Laser Sintering (SLS). Kajian ini juga meneliti kesan perendaman air laut yang berpanjangan terhadap kestabilan dimensi, penyerapan air, dan prestasi mekanikal bahan tersebut. Tinjauan literatur yang komprehensif menekankan potensi PA-12 dalam persekitaran marin yang mencabar, dengan fokus pada ketahanan lelasan, kestabilan kimia, dan kekuatan mekanikalnya, serta memberi penekanan kepada kesan parameter pemprosesan terhadap prestasinya. Metodologi kajian melibatkan penyediaan spesimen ujian standard yang disinter menggunakan pelbagai parameter (kuasa laser: 65 W, 70 W, 75 W; ketebalan lapisan: 0.09 mm, 0.12 mm, 0.15 mm; orientasi: XYY 0°, YZY 0°, YZY 90°), dan spesimen ini direndam dalam air laut selama 1,000 jam untuk mensimulasikan proses penuaan. Ujian mekanikal dilakukan untuk menilai kekuatan tegangan, modulus Young, dan pemanjangan pada takat putus. Hasil kajian menunjukkan bahawa sampel yang disinter dengan kuasa laser 75 W dan ketebalan lapisan 0.09 mm mempamerkan prestasi mekanikal terbaik, mencapai kekuatan tegangan 36.37 MPa, modulus Young 0.48 GPa, dan pemanjangan pada takat putus sebanyak 20.74%, walaupun selepas pendedahan kepada air laut. Orientasi memainkan peranan penting, dengan XYY 0° menunjukkan integriti mekanikal tertinggi hasil ikatan antara lapisan yang optimum, manakala YZY 90° mempamerkan prestasi paling rendah. Kajian ini menekankan kepentingan pengoptimuman parameter pensinteran dan orientasi binaan untuk meningkatkan ketahanan serta mengurangkan kesan penuaan, memberikan pandangan yang bernilai untuk pembangunan bahan kos efektif dan berprestasi tinggi bagi aplikasi industri dan marin.

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LIST OF SYMBOLS AND ABBREVIATION

AM	-	Additive manufacturing
BT	-	Bed temperature
BO	-	Build orientation
BMKM	-	Bachelor of Mechanical Engineering Technology
EaB	-	Elongation at break
ET	-	Extrusion temperature
FA	-	Fill angle
FFF	-	Fused filament fabrication
GFRP	-	Glass Fiber Reinforced Polymer
ID	-	Infill density
ISO	-	International Organization for Standardization
LCD	-	Liquid Crystal Display
LT	-	Layer thickness
MPa	-	Mega Pascal
Mm	-	millimeter
MOE	-	Modulus of elasticity
MOHE	-	Malaysian Ministry of Higher Education
NC	-	Number of contours/perimeters
PS	-	Printing speed
PBF	-	Powder bed fusion
PA12	-	Polyamide 12 (Nylon 12)
SLS	-	Selective Laser Sintering
SEM	-	Scanning Electron Microscopes

UTS	-	Ultimate tensile strength
UTEM	-	Universiti Teknikal Malaysia Malaysia
UTM	-	Universal Testing Machine
3D	-	3 Dimension
%	-	Percent
°C	-	Degree Celsius
G	-	Gram
KJ/m3	-	Kilojoule per meter cube
°	-	Degree

LIST OF APPENDICIES

Chapter 1

INTRODUCTION

1.1 Background

FS3300 PA-12 powder is high-performance polyamide 12 (PA-12) material specifically designed for powder bed fusion (PBF) additive manufacturing processes. Known for its versatility and reliability, FS3300 PA-12 powder has become preferred choice across various industries due to it exceptional mechanical properties and ease of processing. Its particle size distribution is optimized for uniform laser sintering, enabling the detailed production, dimensionally accurate components with an excellent surface finish.

One of the key advantages of FS3300 PA-12 powder is its wide range applications. It is used in industries such as consumer goods, healthcare, automotive, and aerospace for creating a functional prototypes, final parts, and tooling. Its high strength, durability, and precision make it ideal for manufacturing components that must deal with difficult condition operating and feature complex geometries.

For demanding engineering applications, FS3300 PA-12 powder's outstanding mechanical properties make it an excellent choice. Its high tensile strength, flexural modulus, and impact resistance ensure the production of solid parts capable of withstanding environmental stresses and mechanical loads. Additionally, its thermal stability and chemical resistance enhance its utility, allowing for reliable performance in corrosive environments and at high temperatures. Overall, FS3300 PA-12 powder stands out as a versatile and dependable material, empowering manufacturers to innovate and produce high-quality components with confidence.

1.2 Problem statement

The FS3300PA PA-12 powder, well-known for its strong mechanical strength, surface quality, and chemical resistance, is important in industrial applications, especially additive manufacturing. However, the high cost of virgin powder (RM500 per kilogramme) and the huge quantity needed by machines such as the Farsoon SS402P, which requires 60 kilogrammes of powder to run at full capacity, present major challenges for budgets. This cost part requires the investigation of cost-effective alternatives, such as recycling old powder, in order to guarantee long-term industrial sustainability. Although using recycled powder might save money, it complicates the material setup process and may have an impact on the end product consistency and quality.

The study will investigate the mechanical properties of virgin and extremely aged FS3300PA PA-12 powder components after 1000 hours of seawater immersion to solve these issues. The research will focus on tensile strength, flexural modulus, and impact resistance to see how prolonged seawater exposure affects the material. The research on additive printing's XYY 0-degree orientation is important for designing Hydro Quality Survey System housings. The mechanical behaviour of this orientation in seawater will affect design, material selection, and performance expectations, which are important for HydroQS product manufacture.

According to initial data, laser power settings (65-watt, 70-watt, and 75-watt) and layer thicknesses (0.09mm, 0.12mm, and 0.15mm) have significant effects on dimensional stability, and water absorption. By comparing these elements before and after seawater immersion, the team hopes to get a better understanding of how mechanical properties change with longevity and environmental exposure. This study has importance for ensuring the reliability and longevity of FS3300PA PA-12 components in unwelcome maritime environments, eventually contributing to the development of cost-effective, high-performance materials for industrial applications.

1.3 Research Objective

The main objective of this study is to investigate the effect of mechanical characteristics on severely old FS3300PA PA-12 powder submerged in sea water at XYY 0° orientation. Specifically, the aims are as follows:

a) To study the dimensional stability and water absorption of the virgin and extremely aging powder PA-12 based on XYY 0-degree orientation, different laser power and layer thickness before and after soak in seawater.
b) To study the mechanical properties of the virgin and extremely aging powder PA-12 based on XYY 0-degree orientation, different laser power and layer thickness before and after soak seawater.
c) To study the comparison mechanical properties of virgin and extremely aged PA-12 powder based on XYY 0-degree between YZY 0-degree, and YZY 90-degree orientations, using different laser powers and layer thicknesses before and after soaking in seawater.

1.4 Scope of Research

The scope of this research are as follows:

1. Examine how aging and seawater immersion affect the physical characteristics (e.g., weight, dimensions, water absorption) of PA-12, specifically in relation to the impact of processing parameters like laser power and layer thickness.
2. Assess the variations in the mechanical performance of PA-12, including tensile strength, young modulus and elongation at break under different conditions of aging, laser power, and layer thickness, as well as after exposure to seawater.
3. Examines the mechanical properties of virgin and extremely aged PA-12 powder across XYY 0-degree, YZY 0-degree, and YZY 90-degree orientations, assessing the effects of different laser powers and layer thicknesses before and after seawater exposure.

Chapter 2

Literature Review

2.1 Introduction

The study of polymer materials, particularly polyamide 12 (PA-12), in seawater environments is of significant interest due to the increasing use of these materials in underwater applications. The FS3300PA PA-12 powder is a widely use material known for its excellent mechanical properties and resistance to chemicals and abrasion. However, its long-term performance in harsh environments, such as seawater, requires thorough investigation. This literature review examines the mechanical properties of extremely aged FS3300PA PA-12 powder when immersed in seawater, specifically at the XYY 0-degree orientation. This orientation refers to the alignment of the polymer samples during testing, which can influence the mechanical behaviour under stress. The review will provide insights into the aging mechanisms, the impact of seawater on mechanical properties, and the relevance of studying the XYY 0-degree orientation.

2.2 Selective Laser Sintering (SLS) Technology

Selective laser sintering (SLS) is an additive manufacturing technique that uses a laser beam to melt polymer powder and build products layer by layer. In recent years, laser sintering of polymers has evolved into a viable prototyping tool and production method for customised, noncritical products. The industry is exploring the potential of selective laser sintering (SLS) to create fully functional products with consistent mechanical properties. SLS has the potential to be the top choice for small series production of high-strength polymer parts. Figures 2.1 and 2.2 provide a schematic visualisation of the SLS fabrication process and an overview of production. Laser power is a key factor in determining energy input during sintering and its impact on part properties. Scan rate, scan spacing, layer thickness, and preheating temperature. Part build orientation has a significant impact on product quality, beyond energy-related parameters.

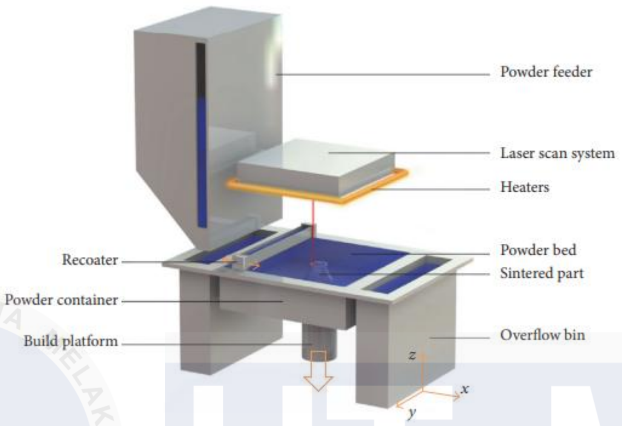


FIGURE 1: Visualization of the SLS fabrication process.

Figure 2.1 Visualization of the SLS fabrication process. (Hofland et al., 2017)

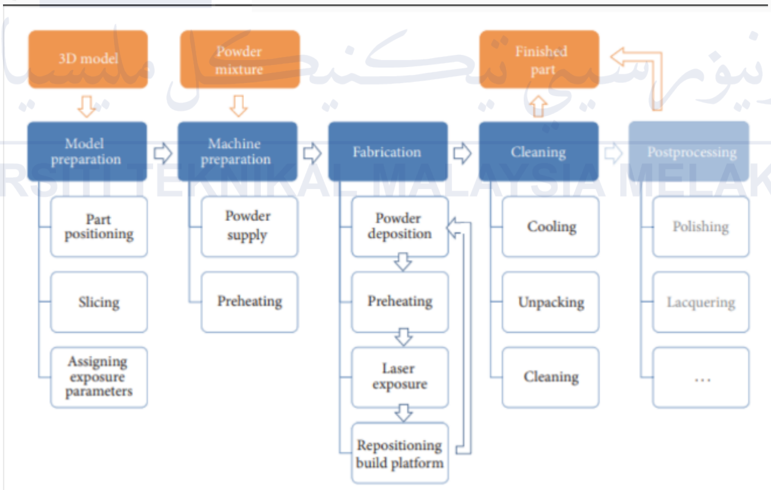


Figure 2. 2 Schematic overview of the complete SLS production process. (Hofland et al., 2017)

2.3 Farsoon SS402P SLS Machine

The Farsoon SS402P is a high-performance selective laser sintering (SLS) system with advanced features designed for demanding additive manufacturing applications. It has a powerful build, with external dimensions of 2660x1540x2150 mm and a weight of 3000 kg, indicating a durable and industrial-grade design. The SS402P has a maximum build size of 400x400x450 mm, which is enough space for large-scale prototyping and production tasks. It can produce layer thicknesses ranging from 0.06 to 0.3 mm, ensuring precision and flexibility when creating detailed and complex parts. The machine has a volume build rate of 3.0 l/hr and a scanning speed of 12.7 m/s, making it an excellent choice for rapid manufacturing. The CO_2 100W laser and dynamic-focusing, high-accuracy galvo scanning system improve performance by providing precise and powerful laser control. The machine also features advanced thermal management, including an eight-zone heater and real-time build surface temperature monitoring, to ensure optimal printing conditions and consistent quality.

Figure 2. 3 Farsoon SS402P SLS Machine

SPECIFICATIONS	FS402P	HS402P	SS402P
External Dimensions	2660x1540x2150 mm (104.8 x 60.7 x 84.7 in)		
Weight	3000 kg (6613 lb)		
Effective Build Size*	350x350x430 mm (13.78 x 13.78 x 16.93 in)		
Max Build Size*	400x400x450 mm (15.75 x 15.75 x 17.72 in)		
Layer Thickness (Typical)	0.06-0.3 mm (0.1 mm) / 0.002-0.011 in (0.004 in)		
Volume Build Rate	0.7 l/hr (43 in^3/h)	1.5 l/hr (92 in^3/h)	3.0 l/hr (183 in^3/h)
Scanning Speed	7.6 m/s (300 in/s)	7.6 m/s (300 in/s)	12.7 m/s (500 in/s)
Scan Spacing	0.15 mm (0.006 in)	0.30 mm (0.012 in)	0.30 mm (0.012 in)
Scanner	Dynamic-focusing, high-accuracy galvo scanning system		
Laser Type	CO_2 30W	CO_2 60W	CO_2 100W
Laser Power Control System	High-precision, digital signal		
Laser Window	Removable, easy to clean		
Power Requirements	2.5 kW (15 kW Max)	2.5 kW (15 kW Max)	3.0 kW (15 kW Max)
Powder Feed Mode	Bi-Directional powder feed system with single feed cylinder		
Powder Deliver	Precision counter-rotating roller		
Max. Chamber Temperature	190°C (374°F)		
Heating Element	Shortwave gold-plated twin tube (Fast-heating and easily accessible)		
Thermal Field Control	Eight-zone heater & intelligent temperature control systems		
Temperature Regulation	Real-time build surface temperature monitoring & optimization		
Operating System	Windows XP / Windows 7 (Coming soon)		
System Control Software	Farsoon AllStar™ open platform control interface		
Data File Format	.STL		
Key SoftwareFeatures	Manual and automatic control modes, real-time build parameter modification, three-dimensional visualization, diagnostic functions		
System Warranty	One-year parts and labor warranty		

Figure 2. 4 Specification of Farsoon SS402P

In terms of material flexibility, the Farsoon SS402P is highly adaptable, allowing users to work with any open platform application. This means that users are not limited to proprietary materials and can select the best materials for their specific production or prototyping needs. The machine features a bi-directional powder feed system with a precision counter-rotating roller, which improves material handling efficiency and consistency. Farsoon's commitment to freedom and innovation allows users to use both Farsoon and third-party materials without restriction, providing a broader range of material options for achieving desired mechanical properties and performance characteristics. The SS402P's high thermal stability, efficient material use, and ability to fine-tune machine parameters ensure that it can handle a diverse range of materials, making it a flexible and valuable tool for a variety of industrial applications.

2.4 Advances in Additive Manufacturing of PA-12

PA-12 is a common engineering thermoplastic that has made tremendous developments in additive manufacturing (AM) recently due to its advantageous qualities, including strong mechanical strength and chemical resistance. A thorough review of recent advancements in this sector is given by (Picard, Mohanty, and Misra et., al 2020), who emphasise the opportunities and difficulties brought about by novel AM approaches. The improvement of process parameters that boost the mechanical characteristics and surface finish of PA-12 parts is one of the notable advances that have been highlighted. Through the optimisation of variables including temperature, layer thickness, and build orientation, researchers have created PA-12 components that exhibit better performance characteristics than those manufactured with more conventional techniques.

Another significant area of progress highlighted by (Picard, Mohanty, and Misra et., al 2020) is the development of novel PA-12 powder formulations that enhance the printability and final properties of AM parts. Additives that increase flowability and reduce the possibility of flaws like warping or incomplete fusion are frequently used in these formulations. For instance, it has been demonstrated that adding particles greatly improves PA-12's mechanical and thermal characteristics, creating new uses in sectors that require high-performance materials. This material science breakthrough is significant because it directly affects PA-12's adaptability and dependability in AM.

In spite of these developments, (Picard, Mohanty, and Misra et., al 2020) nevertheless identify a number of obstacles that must be overcome in order to properly utilise AM with PA-12. Significant obstacles still exist, such as the high cost of raw materials and the requirement for post-processing to provide desirable surface finishes. Moreover, there are still unresolved economic and environmental issues with the recycling and reuse of PA-12 powders in the AM process. However, these challenges may be overcome with continued study and development in this field, increasing PA-12's usefulness and effectiveness in additive manufacturing.

In summary, the latest developments in PA-12 additive manufacturing demonstrate the hurdles still present as well as the progress that has been made. While research is being conducted to solve the current constraints, the capabilities of PA-12 in many applications are being enhanced by constant improvement of process parameters and material formulations. PA-12 is going to become more and more important in the industrial industry as long as these efforts are sustained.

2.5 Virgin FS3300PA PA12

Virgin FS3300PA PA12, also known as polyamide 12, is a high-performance thermoplastic valued for its strength, stiffness, toughness, and resistance to chemicals, abrasion, and fatigue. Its molecular structure, which is made up of repeating units of 12-amino lauric acid, adds to its durability and flexibility. Being a virgin material ensures a consistent and predictable composition, which is important for maintaining uniform properties throughout manufacturing processes. (Damanhuri et al., 2021) highlighted its importance in selective laser sintering (SLS), where consistent material properties have an important for achieving optimal results in powder-based additive manufacturing. This emphasises the important function of virgin PA12 in achieving success in additive manufacturing applications such as SLS.

2.5.1 Material Composition, and Effects on Properties

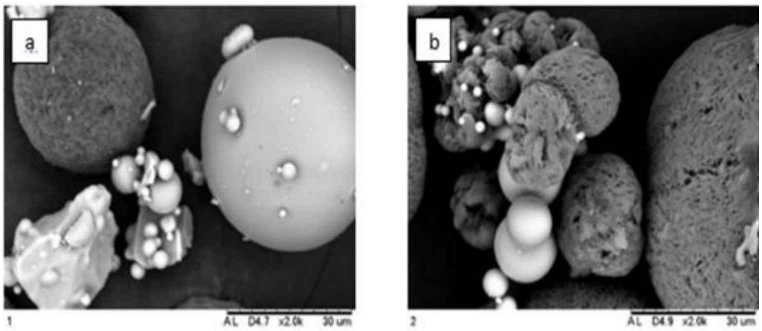


Figure 2. 5 Scanning electron micrographs of the (a) virgin PA12 powder and (b) recycled PA12 powder at magnification of 2000×. (Damanhuri et al., 2021)

The composition of virgin FS3300PA PA12 is affected by manufacturing processes and the addition of additives to improve properties such as fire protection or heat resistance. Changing the composition of a material can have an impact on its performance, including physical and mechanical properties. For example, adding fillers may increase stiffness while decreasing ductility. (Damanhuri et al., 2021) demonstrated how material changes can influence in the air particle release during SLS processes, thereby affecting occupational exposures. Virgin FS3300PA PA12 has a wide range of physical and mechanical properties, including high tensile strength, flexural modulus, and impact resistance, making it suitable for a variety of applications. Its exceptional chemical resistance and low water absorption make it ideal for harsh environments. These properties are derived from its molecular structure and manufacturing process. (Damanhuri et al., 2021) study investigates how both virgin and recycled PA12 powders affect occupational exposures in SLS processes, focusing on the potential impact of particle size and distribution on final product performance.

2.5.2 Advantages and Disadvantages of Virgin FS3300PA PA12

Virgin FS3300PA PA12 has numerous advantages, including consistent composition, predictable performance, and a high strength-to-weight ratio, making it a popular choice in industries that require durable and lightweight materials, such as automotive and aerospace. Its resistance to wear, tear, and chemicals makes it ideal for demanding environments. However, these advantages come with drawbacks, most notably its relatively high cost and the requirement for specialised equipment due to its high melting point. Furthermore, its use of virgin material raises environmental concerns, prompting the search for more sustainable alternatives to reduce its ecological impact, as highlighted in studies such as (Damanhuri et al., 2021). Thus, while the Virgin FS3300PA PA12 delivers exceptional performance, its drawbacks necessitate careful material selection and utilisation to balance cost, performance, and sustainability.

2.6 Extremely Ageing FS3300PA PA12

The term "extremely ageing" refers to the long-term exposure of PA12 powder to environmental factors such as humidity, temperature, and oxygen. This process can cause significant changes in the chemical and physical properties of the powder, affecting its suitability for SLS printing. (Yang et al., 2023) present a thorough examination of the ageing, degradation, and reusability of PA12 powders in SLS, shedding light on the complex interplay of these factors.

2.6.1 Material Composition, and Effects on Properties

They discovered that exposure to moisture can cause hydrolysis of the PA12 polymer chains, resulting in a reduction in molecular weight and a decrease in overall strength and toughness. Furthermore, oxygen exposure can promote oxidation reactions, which degrade the polymer and change its chemical composition. These changes are manifested in a variety of observable effects, including decreased powder flowability, increased particle size, and altered surface structure.

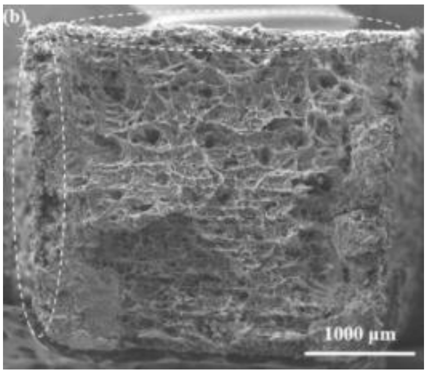


Figure 2. 6 Cross-section of SLS printed parts using 3-time reused powders. (Yang et al., 2023)

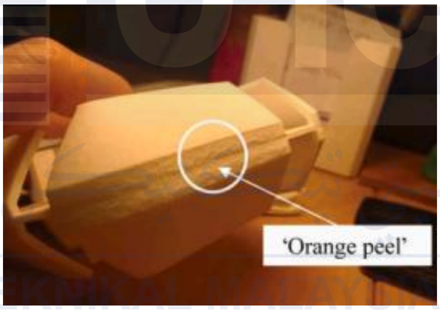


Figure 2. 7 SLS printed parts with “Orange peel” using aged powders. (Yang et al., 2023)

These changes have a significant impact on the printed parts' physical and mechanical properties. As the material ages, it becomes more brittle, with decreased tensile strength, elongation at break, and impact resistance. This deterioration in mechanical properties has a direct impact on the performance of the final product, making it unsuitable for applications that require high strength or durability. The aged powder's reduced flowability can also cause printing defects, making it more difficult to produce reliable and high-quality parts.

2.6.2 Advantages and disadvantages of Extremely Ageing FS3300PA PA12

Despite the significant disadvantages of extremely ageing FS3300PA PA12, there are a few circumstances in which its use may be considered. For example, in applications where the mechanical properties of the finished product are not important and the cost of using freshly manufactured powder is prohibitively expensive, aged PA12 may be a viable option.

However, it is important to note that using extremely aged PA12 carries certain risks. The unpredictable and inconsistent nature of the aged material makes it difficult to control the final product's properties, and unexpected failures cannot be ruled out. Furthermore, the risk of environmental contamination and the difficulty in predicting the extent of degradation in aged powder make it unsuitable for most applications. As a result, the use of extremely aged FS3300PA PA12 should be carefully considered and used only in specific cases after a thorough analysis of the potential risks and benefits.

2.7 Effect of layer thickness on the mechanical properties on PA-12 SLS

Selective laser sintering (SLS) is an additive manufacturing technique that is widely used to create polymer parts, particularly those made of polyamide 12 (PA-12). The layer thickness is an important factor that influences the mechanical properties of PA-12 components manufactured using SLS. According to research (Malashin et al., 2024), varying layer thickness has a significant impact on the tensile strength, elasticity, and surface finish of printed parts. Thinner layers improve tensile strength and elongation at break due to improved interlayer bonding and reduced voids, whereas thicker layers may speed up the manufacturing process but often compromise mechanical integrity and surface quality.

(Malashin et al., 2024) investigate the mechanical testing of selective laser-sintered polyamide PA2200 details using the Finite Element Method (FEM) and machine learning approaches to analyse tensile properties. Although their research focuses on PA2200, the findings can be applied to PA-12 as well, given the similarities in material behaviour under SLS. Their findings highlight the importance of optimising SLS parameters, such as layer thickness, in order to achieve desirable mechanical properties. They show how to use advanced simulation and predictive modelling to systematically study variations in processing parameters and predict the resulting material performance.

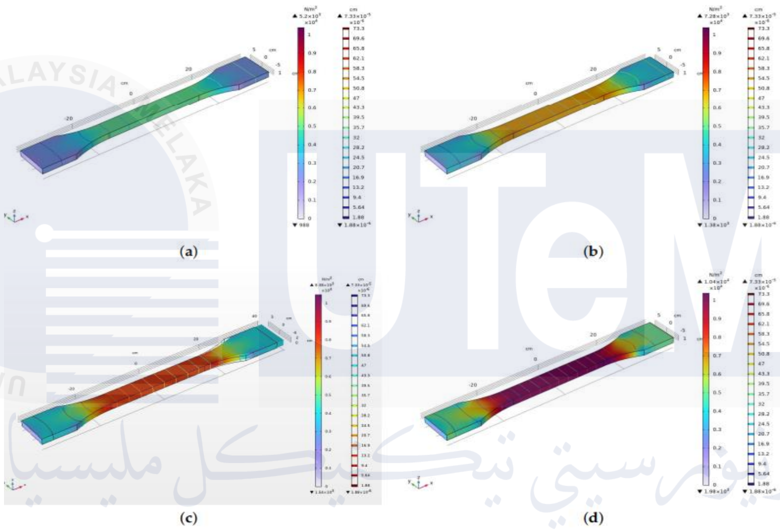


Figure 2. 8 FEM modelling outcomes depicting stress distribution and deformation characteristics of the polyamide 2200 component under tensile loading conditions. (Malashin et al., 2024)

This study contributes to the overall understanding of how layer thickness affects the mechanical properties of SLS-manufactured parts. It highlights that, while advanced modelling techniques can provide valuable insights, validation by evidence remains important. (Malashin et al., 2024) argue that a thorough understanding of the relationship between SLS parameters and material properties is very important for improving the reliability and performance of PA-12 parts in practical applications. As a result, ongoing research and technological advancements in SLS will continue to refine these relationships, ensuring that layer thickness is optimised for both mechanical performance and manufacturing efficiency.

2.8 Effect of orientation and laser power on the mechanical properties on PA-12 SLS

Selective laser sintering (SLS) has become a popular technique in additive manufacturing, especially for producing polymer parts. Polyamide 12 (PA-12) is a popular material in SLS due to its excellent mechanical properties and flexibility. Recent studies have delved into the intricate parameters of the SLS process that influence the final properties of PA-12 parts, with a particular emphasis on the effects of laser power and hatch orientation.

(El Magri et al., 2022) investigated how variations in laser power and hatch orientation influence the final properties of PA-12 parts. Their findings, published in the journal "Polymers," emphasise the importance of laser power in determining part density and mechanical strength. Higher laser power generally increases energy input, resulting in better sintering of powder particles and improved mechanical properties such as tensile strength and modulus. However, excessive laser power can degrade the material, reducing its properties. Hatch orientation, or the pattern in which the laser moves to sinter the material layer by layer, is also important. Different orientations can cause variations in internal stresses and anisotropy within the parts, influencing their mechanical performance.

As an addition to this study, (Razaviye et al., 2022) published an experimental analysis of the mechanical properties of PA-12 parts produced by SLS in the "CIRP Journal of Manufacturing Science and Technology." They investigated a variety of laser powers and orientations, concluding that both parameters are important in determining the mechanical behaviour of the parts. Their findings indicate that optimising laser power and hatch orientation is important for achieving desired properties, especially in applications that require specific strength and durability. For example, their findings suggested that lower laser power could lead to insufficient sintering, resulting in porous structures with poor mechanical properties. In contrast, an optimal balance of laser power and orientation can result in parts with greater uniformity and mechanical integrity.

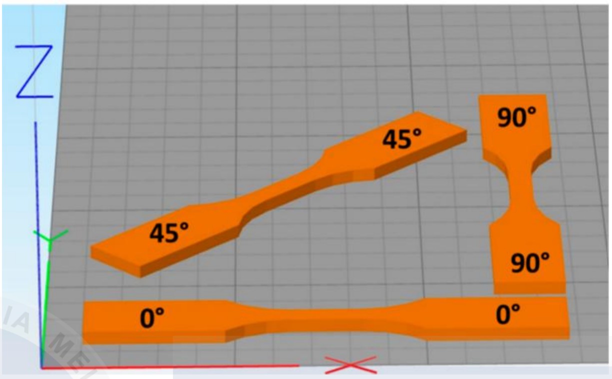


Figure 2. 9 Illustration of different specimen orientation. (El Magri et al., 2022)

Both studies emphasise the complex relationship between laser power and hatch orientation in SLS. (El Magri et al., 2022). focused on the theoretical implications and modelling of these parameters, offering a thorough examination of how energy input and sintering dynamics influence part quality. (Razaviye et al., 2022) on the other hand, provided practical insights using experimental data to demonstrate real-world applications and the tangible effects of parameter changes on PA-12 parts. Together, these studies contribute to a comprehensive understanding of the SLS process, which will guide future research and industrial practices aimed at optimising SLS for PA12.

In summary, laser power and hatch orientation have a significant impact on the mechanical properties of SLS-produced PA-12 parts. As demonstrated by the studies of (El Magri et al., 2022) and (Razaviye et al., 2022) precise calibration of these parameters is important for improving the quality and performance of manufactured parts. Continued research in this area is critical for improving SLS capabilities, particularly in modifying mechanical properties to meet specific application requirements. These findings not only set the way for better manufacturing techniques but also expand the potential applications of SLS in a variety of industries.

2.9 Evaluating the Impact of Short- and Long-Term Water Immersion on the Mechanical Properties of FS3300PA PA-12 Powder

The effect of water immersion on the mechanical properties of polyamide 12 (PA-12) powder, particularly the FS3300PA grade, is an important factor to consider for long-term performance in a variety of applications. While extensive research has been conducted on the effect of ageing on the mechanical properties of PA-12, investigations into the specific effects of water immersion are limited. Notably, (Goodridge et al., 2010) investigated the effect of long-term ageing on the tensile properties of PA-12 laser sintering material. Their findings revealed a significant decrease in tensile strength and elongation at break after long-term exposure to ambient conditions. This suggests that water absorption, which is a key factor in ageing, can have a negative impact on the mechanical properties of PA12.

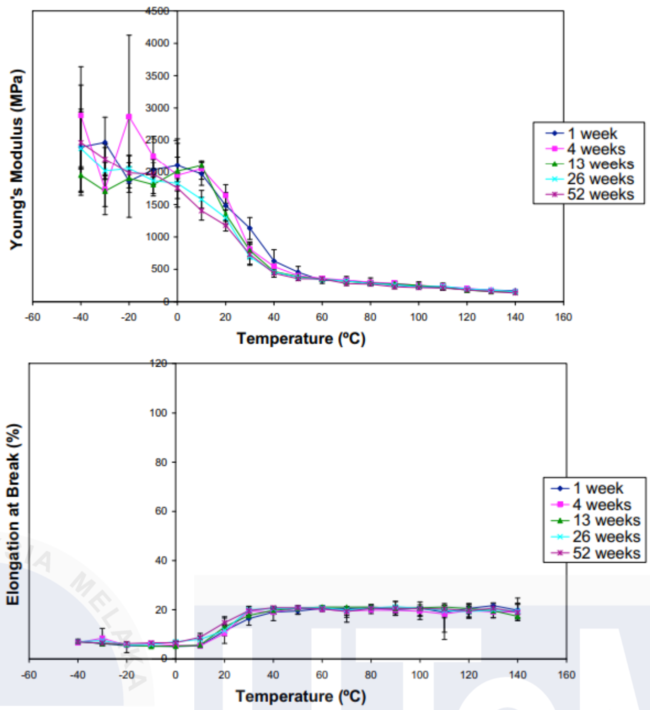


Figure 2. 10 Effect of storage time and testing temperature on the tensile properties of IM-PA12 samples. (Goodridge et al., 2010)

Extrapolating from (Goodridge et al., 2010) findings, it can speculate that short-term water immersion may have a less significant impact on the mechanical properties of FS3300PA PA-12 powder than long-term exposure. This is because the rate of water absorption and subsequent degradation is expected to be slower in the early stages of immersion. However, dedicated studies into the effects of both short- and long-term water immersion on FS3300PA are required to determine the exact impact on tensile strength, elongation at break, and other relevant mechanical properties. By comparing the results of these studies, we can determine how short-term versus long-term water exposure affects the material's performance. This information will be extremely useful in optimising the design and application of PA-12 components, particularly in environments that contain moisture.

In decision, while existing ageing literature provides valuable insights, more research is needed to determine the specific impact of short- and long-term water immersion on the mechanical properties of FS3300PA PA-12 powder. These studies will provide a comprehensive understanding of the material's behaviour under various environmental conditions, assisting in the development of more reliable and durable PA-12 components.

2.10 Material Properties of PA-12 (Polyamide 12) and FS3300PA Powder

Polyamide 12, often known as PA-12, is a thermoplastic semi-crystalline polymer known for its low water absorption, chemical resistance, and exceptional mechanical property balancing. Chemically, PA-12 is a member of the nylon family; its strength and durability are attributed to the amide groups (-CONH-) that are present in its backbone. Because of its strong resistance to oils, fuels, and solvents, the polymer finds use in a wide range of industrial settings. Furthermore, PA-12 may be processed and shaped more easily because of its comparatively low melting point (178–180 °C) in comparison to other polyamides. Because of its semi-crystalline structure, which offers an excellent balance between toughness and stiffness, components that can sustain high mechanical stress without deforming may be produced.

(Rafi Omar et al., 2022) Farsoon Technologies have developed a thermoplastic semi-crystalline polymer material based on PA-12 and SLS FS3300PA part, which have good mechanical properties and is manufactured to high quality standards. This material is perfect for precise applications since it is made to have excellent mechanical qualities and high production standards. The chemical resistance and low water absorption of PA-12 are retained by FS3300PA, guaranteeing its effectiveness in challenging conditions. It produces products with better surface quality and dimensional correctness by providing increased strength and durability, better layer adhesion, and less porosity. The material is appropriate for high-performance functional components because of its semi-crystalline structure, which keeps it stable under thermal stress.

2.10.1 The mechanical properties of PA-12 such as tensile strength, elasticity, and impact resistance.

The adaptable polymer known as Polyamide 12 (PA-12) is well-suited for a variety of applications, including those in the automotive, aerospace, and industrial sectors due to its exceptional mechanical property balancing. The improvement of PA-12's mechanical qualities by adding different reinforcements has been one of the main focuses of study in recent years. The study by (Nakonieczny et al. 2022) contributes significantly to this field by investigating the effects of cenosphere reinforcement on PA-12 composites, focusing on their preparation, physicochemical properties, and soaking tests.

2.10.2 Elasticity

The elasticity of PA-12, often quantified by its elastic modulus, determines its ability to return to its original shape after deformation. This property is crucial for applications requiring flexibility and durability. According to (Nakonieczny et al., 2022), the inclusion of cenospheres in PA-12 composites results in a noticeable increase in the elastic modulus. This enhancement is due to the rigid nature of the cenospheres, which restricts the polymer chains' mobility, thereby increasing the composite's stiffness. This finding is consistent with previous studies that have shown how rigid fillers can improve the elasticity of polymer composites by reinforcing the polymer matrix and reducing its deformability.

2.10.3 Impact Resistance

Impact resistance is another important mechanical property for materials subjected to sudden or shock loads. PA-12 is generally appreciated for its good impact resistance, which can be further optimized through composite formulation. The research by (Nakonieczny et al., 2022) indicates that the cenosphere-reinforced PA-12 composites exhibit improved impact resistance compared to neat PA-12. The enhancement in impact resistance can be attributed to the energy absorption capabilities of the cenospheres, which help dissipate the energy from impacts more effectively. This result supports the broader literature that suggests incorporating hollow or lightweight fillers can improve the impact resistance of polymer composites by creating energy-absorbing microstructures within the material.

2.10.4 Comprehensive Mechanical Performance

The study by (Nakonieczny et al., 2022) provides a holistic view of how cenosphere reinforcement can enhance the overall mechanical performance of PA-12. By improving tensile strength, elasticity, and impact resistance, cenosphere-reinforced PA-12 composites offer a balanced combination of properties that can be tailored for specific applications. This comprehensive enhancement is essential for developing advanced materials that meet stringent performance requirements in various industries. The findings of this study complement the existing body of research on polymer composites, highlighting the potential of cenospheres as effective reinforcement agents for enhancing the mechanical properties of PA-12.

In summary, the addition of cenospheres may greatly enhance the mechanical qualities of PA-12, such as its tensile strength, flexibility, and impact resistance. (Nakonieczny et al., 2022) offers insightful information about the creation and characteristics of these composites, highlighting their potential for high-performance uses. The significance of ongoing research into innovative reinforcing materials and their incorporation into polymer matrix is highlighted by these developments in PA-12 composite technology.

2.10.5 Orientation Effects on Mechanical Properties

A lot of interest has been shown in the investigation of orientation effects on the mechanical characteristics of polyamide-12 (PA-12) in additive manufacturing, especially in light of developments in methods like multi-jet fusion (MJF). According to (Lee, Pandelidi, and Kajtaz et., al 2020), construction orientation has a significant impact on the mechanical characteristics and porosity of polyamide-11 (PA-11), which is identical to PA-12 in terms of their chemical structures and production methods. According to their research, the construction orientation of printed PA materials can significantly change their tensile strength, elongation at break, and modulus of elasticity. This knowledge is crucial for maximising PA-12's mechanical performance in a variety of settings, such as the automotive and aerospace sectors, where material performance and dependability are critical.

The impact of various build orientations (such as horizontal, vertical, and angled) on the mechanical properties of PA-11 were investigated by (Lee, Pandelidi, and Kajtaz et., al 2020) study, and their findings are extremely relevant to PA-12 as well. They found that samples printed horizontally had lower porosity and higher tensile strength than samples printed vertically. This is explained by the layer-by-layer bonding mechanism used in additive manufacturing, which results in less inter-layer delamination and more uniform fusion of horizontal layers. Given the identical processing conditions and material behaviours, it is reasonable to apply these findings to PA-12 and detect similar tendencies. The study emphasises how crucial it is to optimise build orientation in order to improve PA-12 parts' mechanical performance and structural integrity.

In summary, the study conducted by (Lee, Pandelidi, and Kajtaz et., al 2020) on PA-11 provides a significant understanding of the orientation-dependent mechanical characteristics of polyamide materials, and this understanding can be extended to PA-12. Understanding how construction orientation affects tensile strength, elasticity, and porosity is essential to producing durable and dependable components. Subsequent investigations ought to carry out a deeper examination of these correlations in PA-12, utilising the discoveries from PA-11 to enhance additive manufacturing procedures and material compositions. This ongoing study will contribute to raising performance benchmarks and broadening PA-12's application scope across a number of high-demand industries.

2.11 Effects of Seawater Exposure on Polymer Materials

The exposure of polymeric materials to seawater is a critical area of study, given the extensive use of these materials in marine environments. Seawater, with its unique composition of salts, organic compounds, and microorganisms, can profoundly affect the durability and performance of polymers. Among the polymers commonly exposed to such conditions is polyamide 12 (PA-12), which is widely used in underwater pipelines, cables, and structural components. Research, such as that conducted by (Cavasin et al., 2019), has highlighted the importance of understanding these impacts to ensure the longevity and reliability of polymer-based marine infrastructure. The study by (Cavasin et al., 2019) provides a comprehensive examination of how glass fiber reinforced polymer composites (GFRP), similar to PA-12, are affected by prolonged seawater exposure.

2.11.1 Chemical Changes Induced by Seawater Exposure

Extended contact to seawater causes polymeric materials go through a number of chemical transformations that profoundly alter their characteristics. The crystallisation of salts inside the polymer matrix is one significant alteration that can cause microcracks and enhanced brittleness. Furthermore, hydrolysis is a typical breakdown process in which polymer chains are broken down by water molecules, resulting in a decrease in mechanical strength and molecular weight. According to (Cavasin et al., 2019)'s study, GFRP composites exposed to seawater had significant chemical deterioration, which showed up as decreased mechanical performance. Further study into improving the seawater resistance of PA-12 and related polymers used in marine applications is important due to this critical chemical modification.

2.11.2 Physical Degradation Due to Seawater Immersion

The changes in structure brought about by immersion in seawater play an important part in determining the durability of polymer materials. Surface erosion, plasticization, and swelling are examples of physical degradation. For example, a saltwater's osmotic pressure differential might allow water to seep into the polymer matrix, causing swelling and plasticization that weaken the material's strength and stiffness. (Cavasin et al., 2019)'s research showed that exposure to saltwater caused GFRP composites to physically deteriorate noticeably, showing signs of increased surface roughness and fiber-matrix debonding. These results imply that comparable impacts on the structural integrity of PA-12 and other polymers exposed to maritime environments should be expected.

2.12 Summary

The study of polymer materials, particularly polyamide 12 (PA-12), in industrial environments has received a lot of attention as they become more common in underwater applications. The outstanding mechanical qualities, abrasion resistance, and chemical resistance of FS3300PA PA-12 powder are well known. It is imperative to comprehend its long-term performance in challenging conditions such as seawater. This review of literature focuses on the mechanical properties of FS3300PA PA-12 powder that is extremely aged and submerged in seawater, specifically at the XYY 0° orientation. The alignment of polymer samples during testing is referred to as orientation, and it can have a big impact on how they behave mechanically under stress. The ageing mechanisms, the effect of seawater on mechanical properties, and the importance of the XYY 0° orientation in testing are all covered in this review.

Selective laser sintering (SLS) is a popular additive manufacturing method for processing PA-12 because of its precision and design flexibility. Studies show that the mechanical properties of PA-12 parts can be improved by adjusting laser parameters such as power and scanning speed, resulting in parts with higher tensile strength and durability. Furthermore, to improve surface finish and mechanical properties, improved packing density and lower porosity have been attained by creating complex powder compositions using SLS technology. The potential of SLS to change manufacturing is highlighted by its ability to produce functional and high-quality parts directly from digital designs. This is especially true for complex geometries that are difficult to achieve with traditional methods.

The effects of seawater exposure on polymer materials, including PA-12, are a critical area of study due to the unique composition of seawater, which can significantly impact the durability and performance of polymers. Extended exposure to seawater can induce chemical changes such as salt crystallization and hydrolysis, leading to microcracks and reduced mechanical strength. Physical degradation, including surface erosion and plasticization, and microbial attack, which can further deteriorate mechanical integrity, are also significant concerns. According to research, comprehensive investigations are required to fully understand these degradation mechanisms and to develop materials with increased resistance to environmental stressors. In order to protect the functionality and safety of underwater infrastructure, it is imperative that this understanding be had in order to ensure the longevity and reliability of PA-12 components in marine applications.

Chapter 3

Methodology

3.1 Introduction

Understanding impact of environmental factors on mechanical properties of advanced materials is critical for their application in harsh conditions. This study focuses on examining the mechanical properties of FS3300PA PA-12 powder, a type of polyamide commonly used in additive manufacturing, after being immersed in seawater for an extended period. By specifically analysing samples oriented at 0 degree (XYY orientation), it aims to elucidate how prolonged exposure to a marine environment influences the material's durability and performance. This research addresses a significant gap in current knowledge regarding the long-term stability of 3D-printed polyamide components in underwater settings, which is crucial for applications ranging from marine engineering to underwater robotics.

The methodology of this study involves a comprehensive series of tests to evaluate changes in mechanical properties such as tensile strength, elongation at break, and young's modulus of the FS3300PA PA-12 powder after aging in seawater. The process begins with the preparation of standard test specimens oriented at 0°, followed by controlled immersion in seawater under specific conditions designed to simulate extreme aging. The samples will go through extensive mechanical testing utilising standardised procedures after immersion. Subsequently, a statistical analysis will be conducted to detect significant changes and connections, offering valuable perspectives on the mechanisms underlying the material's performance deterioration and possible ways to improve it. The study aims to provide important information to the field of materials science and engineering, particularly in the context of marine applications, using this thorough methodological approach.

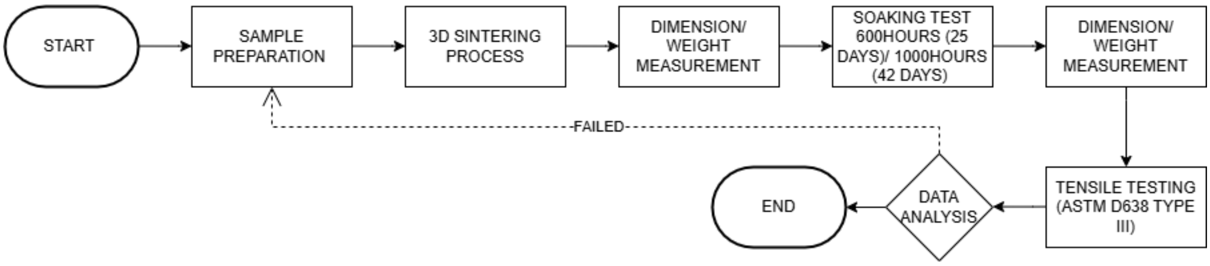


Figure 3. 1 Flowchart Complete for PSM 1

The flowchart methodology describes a systematic process for preparing and testing these materials, with particular focus on the performance of 3D-printed samples after immersion in seawater. The process starts with sample preparation, and then the sample is designed with a XYY 0° orientation. In this section, the process of setting parameters such as laser power and layer thickness will be implemented. Before beginning the sintering process, both virgin and recycle Then, a 3D sintering process will be used to produce measurable test specimens that meet the requirements. After measuring all of the specimens with a CMM and a Vernier Calliper for dimension stability, the samples are immersed in seawater for 1000 hours to simulate environmental conditions that may affect their mechanical properties. d powders will be prepared. The samples will then be designed with SolidWorks.

After being immersed in seawater, the samples are subjected to three different tensile tests per ASTM D638 Type III: elongation, tensile, and flexural strength tests. These tests assess several aspects of the material's mechanical performance: Ductility is determined by tensile strength and flexural strength tests, as well as elongation tests. The data analysis stage is important for determining whether the tests produce definitive insights into the material's performance. If the analysis produces acceptable outcomes, the process is complete. If not, it may return to sample preparation for any required rewrites or evaluations.

3.2 Research Design

The research aimed to evaluate the influence of dog-bone-shaped specimen geometry on the tensile properties of Nylon 12 (PA-12) fabricated through fused filament fabrication (FFF), particularly focusing on specimens subjected to extreme ageing in seawater. The dog-bone shape was selected based on its established efficacy in standard tensile testing, as cited in (Baba & Itu, 2023). Their study demonstrated that the geometry significantly affects the mechanical properties observed in tensile tests, providing a consistent and comparable basis for assessing material performance. This choice ensures that the results are reliable and align with the broader scientific consensus on tensile testing methodologies.

In this study, PA-12 specimens were fabricated using the FFF process, with careful control of printing parameters to ensure consistency. The specimens were then immersed in seawater for an extended period of time to simulate extreme ageing conditions. The tensile tests were performed on specimens oriented at an XYY 0-degree configuration, which is critical for understanding the anisotropic properties of FFF-fabricated materials. This specific orientation was chosen to isolate and examine the mechanical behaviour of the material when the tensile force is applied along the layer lines, which is known to be a critical factor influencing the strength and failure modes of additively manufactured components.

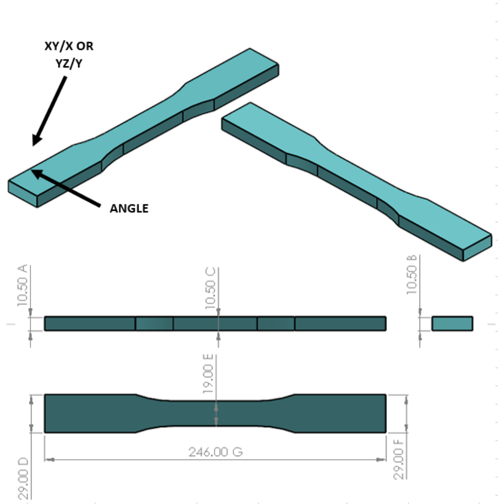


Figure 3. 2 The sintered sample in XYY plane orientation

The dog-bone geometry facilitated a clear and standardised comparison of tensile properties before and after seawater immersion. This shape minimises stress concentration at the grips and ensures a uniform distribution of stress along the gauge length, leading to more accurate and reproducible results. By leveraging the insights from (Baba & Itu, 2023), this research design not only adheres to established testing protocols but also allows for a nuanced understanding of how extreme environmental exposure affects the mechanical integrity of PA-12. This methodology provides a robust framework for evaluating the durability and reliability of 3D-printed materials in harsh

3.3 Methodology

The primary aim of this study is to find out how mechanical characteristics affect the extremely aged FS3300PA PA-12 powder that is submerged in seawater with an XYY 0° orientation. The goal of the study is to comprehend the effects of extended exposure to seawater on the material characteristics of FS3300PA PA-12, a polymer that is frequently used in marine applications. This will be accomplished by using a variety of quantitative techniques to carefully evaluate changes in mechanical performance, yielding accurate and trustworthy data that supports the research's objectives.

Given the specific focus on mechanical properties, this study will utilise tensile and compression testing methods to measure changes in strength, elasticity, and durability of the PA-12 powder after immersion. These methods are chosen for their accuracy and ability to provide detailed insights into the material's behaviour under stress. Furthermore, the XYY 0° orientation is important because it represents the usual alignment in real-world applications, ensuring that the outcomes are directly applicable to actual situations. The selected techniques enable a thorough evaluation of the ways in which exposure to seawater changes the material's mechanical integrity over time.

Given the availability of resources and equipment for mechanical testing, the possibility and practicality of these methods align well with the limitations of the study. Since the study uses non-living materials, there are not many ethical issues. Any potential limitations, like variations in the composition of seawater and ageing conditions, will be handled in carefully monitored lab environments. This methodological approach guarantees a solid and comprehensive study, offering insightful information about the durability and functionality of FS3300PA PA-12 in marine environments.

3.3.1 Experimental Setup

An organised experimental setup is required to thoroughly examine the impact of mechanical properties on extremely aged FS3300PA PA-12 powder immersed in seawater in the XYY 0° orientation. First, the powder known as FS3300PA PA-12 was chosen for the study due to its widely used industrial use and risk of environmental deterioration. Testing methods, including tensile testing (ASTM D638), impact testing, and hardness testing, will be employed to ensure consistency and reliability. The ASTM D638 standard will specifically guide the tensile testing process, where dog-bone-shaped specimens will be subjected to controlled tensile loads to measure properties such as tensile strength, elongation at break, and modulus of elasticity. These methods will help characterise the material’s mechanical performance under various stress conditions. In order to replicate real-world conditions, the immersion procedure in seawater will also be closely monitored and controlled, with variables like temperature, salinity, and exposure time being closely watched and adjusted.

The experimental setup will then concentrate on conducting a number of methodical tests to characterise the mechanical behaviour of the immersed FS3300PA PA-12 powder. In order to monitor the specimens' response in terms of tensile strength, impact resistance, and hardness, this will entail exposing them to various mechanical stress levels. In order to facilitate understanding of directional variations in mechanical properties and to be in line with common industrial applications, the XYY 0° orientation has been specifically selected. Data will be gathered and statistically analysed during the experimentation process in order to determine any correlations between mechanical properties and immersion conditions as well as to quantify the degree of degradation. By adhering to a rigorous experimental methodology, this study aims to provide valuable insights into the behaviour of FS3300PA PA-12 powder under extreme environmental conditions, thereby facilitating informed decision-making in industrial applications.

3.3.2 Test setup

In order to verify the mechanical characteristics and fracture behaviour of the virgin and severely aged powder PA-12, two major tests were carried out for this study. Tensile strength and material elongation tests were conducted using the universal testing machine. As per the ASTM D638 standard (Rafi Omar et al., 2022), these data proved to be beneficial in qualitatively characterising a stiffer CP material (Rafi Omar et al., 2022). Afterwards, the surface roughness values were acquired straight from the LCD display of the machine. The device had a probe travelling length and was used as a table surface tester. To ensure data precision, the point measurement was done three times.

3.3.3 Parameters

This research focuses on investigating the impact of mechanical properties on the degradation of FS3300PA PA-12 powder when immersed in seawater, specifically at an XYY 0-degree orientation. To conduct this study, a systematic approach involving controlled aging and mechanical testing is employed. The specimens were fabricated using a Selective Laser Sintering (SLS) 3D printer, a technology known for its ability to produce complex geometries and high-performance parts. The SLS process parameters, as outlined in Table 1, were carefully selected to ensure consistent part quality and minimize variability in mechanical properties. These parameters include laser power, layer thickness, and orientation, which directly influence the microstructure and integrity of the printed material. Specifically, the laser power ensures proper sintering of the powder particles, leading to well-fused layers, while the layer thickness impacts the resolution and surface finish. By employing these carefully controlled parameters, the study aims to isolate the effects of seawater immersion and aging on the material's mechanical properties, contributing to a comprehensive understanding of the material's long-term durability and performance in marine environments.

Table 1 SLS 3D Printer Settings Parameter

Properties	Value
Orientation	XYY 0 degree
Laser Power	65-Watt, 70-Watt, 75-Watt
Layer Thickness	0.09mm, 0.12mm, 0.15mm
Immersion Medium	Seawater

The table 1 shows the settings parameters for the SLS 3D Printer used in the specimen printing process. The settings parameters in Selective Laser Sintering (SLS) have importance for producing high-quality products. These parameters have a significant impact on the mechanical properties, dimensional accuracy, surface finish, and overall performance of printed parts. Adequate laser power ensures proper sintering of the powder particles, which results in well-fused layers. Using thinner layers improves the resolution and surface finish of the components. Because each layer is sintered more precisely, this fine resolution enables greater detail and more precise mechanical properties.

3.3.4 Equipment

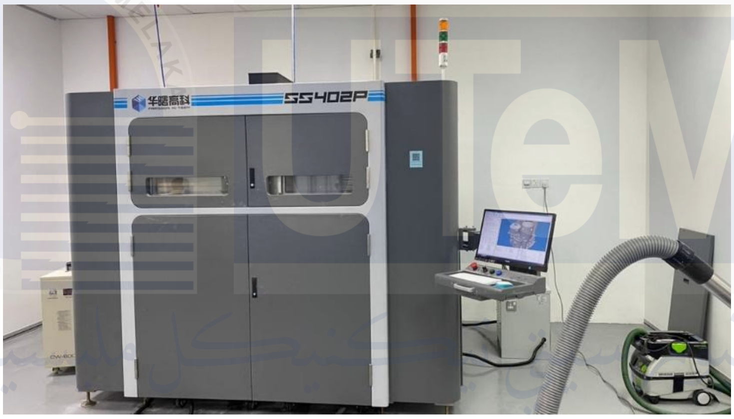


Figure 3. 3 Farsoon SS402P SLS Machine

The Farsoon SS402P Selective Laser Sintering (SLS) machine was a key tool in this study, this machine was used to manufacture test specimens from FS3300PA PA-12 powder through a layer-by-layer sintering process, where a high-powered laser selectively fused powdered material according to a digital design. The Farsoon SS402P allowed precise control over important parameters, including laser power, scanning speed, and layer thickness, ensuring consistent fabrication of samples with high dimensional accuracy and uniform density. These specimens were subsequently evaluated to investigate the influence of long-term seawater immersion and material aging on mechanical properties such as tensile strength and fracture behavior, providing valuable insights into the material's performance under extreme conditions.

3.3.4.1The process of SLS

Figure 3.4 illustrates a typical system scheme for 3D printing parts using SLS technology. For a detailed description of this system, the SLS process, and the impact of the various process parameters on the formation of porosity in the particles produced, please refer to

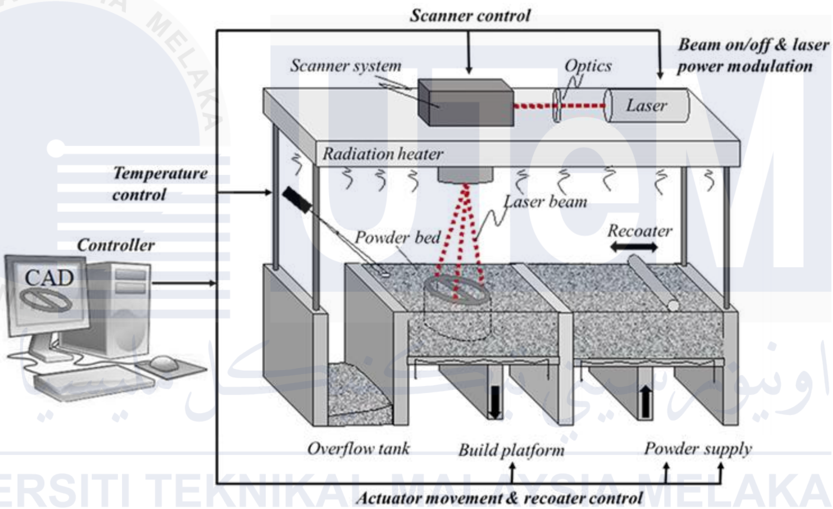


Figure 3. 4 SLS Process. (Morano & Pagnotta, 2023)

In short, the manufacturing process consists of three stages:

I. Preheating phase: The powder bed is heated to a specific temperature (bed temperature, Tb) that remains constant throughout the part-building process. The Tb is kept just below the polymer's softening temperature to reduce laser energy and eliminate distortion during cooling.

II. Building phase: This is the main phase of the fabrication process, which includes a variety of operations. First, the platform is lowered to collect powder particles dragged by the roller or spreading blade. Following that, the laser beam melts the layer of particles on the computerized trajectory. Finally, the piece is gradually cooled until it reaches the Tb value and solidifies.

III. Cooling phase: During this phase, the heat source is turned off, and the powder bed gradually cools until it reaches the extraction temperature of the piece.

3.3.4.2 Universal Testing Machine (UTM)

Figure 3. 5 Universal Testing Machine (UTM)

The Universal Testing Machine (UTM) was a important tool employed in the study that highly versatile machine is designed to perform a variety of mechanical tests, including tensile, compression, and flexural testing, on materials and components. Equipped with precise load cells and extensometers, the UTM allowed for accurate measurement of forces, displacements, and deformation, enabling the detailed characterisation of material behaviour under controlled conditions. Its robust construction and adaptability made it ideal for evaluating the mechanical properties of the sintered FS3300PA PA-12 specimens.

In this study, the UTM was utilised specifically to determine the tensile properties of the samples, including tensile strength, modulus of elasticity, and elongation at break. By applying a controlled uniaxial tensile load to the specimens, the machine facilitated the collection of stress-strain data, which was essential for understanding how prolonged seawater immersion and ageing affected the material's performance. The UTM's precise and reliable testing capabilities played a important role in assessing the durability and mechanical integrity of the PA-12 powder, providing critical insights into its behaviour in extreme environmental conditions.

3.3.5 Specimen preparation

As indicated in table 3.2 by (Rafi Omar et al., 2022), three distinct composition percentages of PA-12 material were used to prepare the specimens. The mechanical properties of virgin PA-12 material as confirmed by the manufacturer are displayed in figure 3.3 By (Rafi Omar et al., 2022). Next, a comparison was made between virgin and recycled powders for the PA-12 material. The findings demonstrated that compared to the adhered powder samples, the scratched samples sintered with virgin powder were more fractured and had smaller, smoother spheres.

Table 2 Table PA-12 Composition Percentage (Rafi Omar et al., 2022)

Composition (CP)	(%) Virgin	(%) Reheat	(%) Recycled
1	100	0	0
2	40	20	40
3	0	0	100

Table 3 PA-12 Mechanical Properties Based on Manufacture Data (Rafi Omar et al., 2022)

Properties	Value
Density	0.95 g/cm^3
Tensile Strength	48.1MPa
Impact Strength	3.6KJ/m^2

In the study conducted by (Razaviye et al., 2022) the specimen preparation for SLS (Selective Laser Sintering) involved careful consideration of various parameters to examine their impact on the mechanical properties of printed parts. The researchers used polyamide-12 (PA12) materials, to observe the mechanical behavior, noting that PA12 parts exhibited ductility. To further understand the influence of orientation, parts were printed in four different orientations (0°, 30°, 45°, and 90°) in the XY plane figure 3.4, revealing that parts oriented at 0° and 90° had higher Young's modulus compared to those at 30° and 45°. The relationship between laser energy density and dimensional accuracy was also explored, with the lowest laser energy density resulting in the highest dimensional errors. Moreover, the maximum laser energy density yielded the highest tensile properties at a 45° orientation. According to (Rafi Omar et al., 2022), orientation is also an influencing factor to increase the printed part tensile strength.

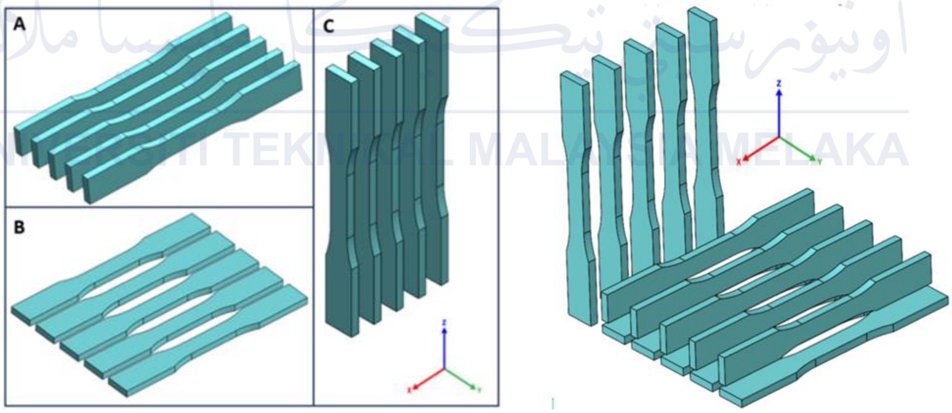


Figure 3. 6 Sintering parts in different orientations in(A)XYY0°,(B)YZY0°and(C)YZY90°plane.

3.3.6 3D printing process

The parts were designed according to the ISO standard in order to test their tensile properties. One significant factor influencing the mechanical characteristics of SLS-printed parts is part orientation. A part can be printed in three different orientations: inclined, horizontal, and vertical. A previous study by (Razaviye et al., 2022) found that the ultimate strength of a part is higher when the scan direction is aligned with the part than when the directions are perpendicular to the part length.

(a) **(b)**

Figure 3. 7 (a) and (b) Specimen and calibration block sample that will be printed

Three primary stages made up the operation setup: (i) the pre-process stage (figure A–B), (ii) the 3D printing process stage (figure C–F), and (iii) the post-process stage (figure G–I). The feeder chamber, building chamber, collector chamber, and powder overflow chamber with roller for figure levelling are the four main chambers of the SLS 3D printer. First, Materialise Magics software was used to calculate the material weight and volume based on the quantity of the component that needed to be printed. The main constant parameters for the SLS 3D printer were configured at the beginning of the 3D printing process.

Afterwards, as illustrated in figure 3.7 (G-I), the material block was taken out of the SLS machine building chamber and moved to the sieve machine during the post-processing stage. Figure 3.7 (J) displays every completed specimen that was prepared for examination. The Farsoon model FS4092P SLS 3D printer, depicted in figure 3.8, was utilised to fabricate every specimen, with a maximum usable area measuring 350x350x400mm.

Figure 3. 8 The process of 3D Printing Process

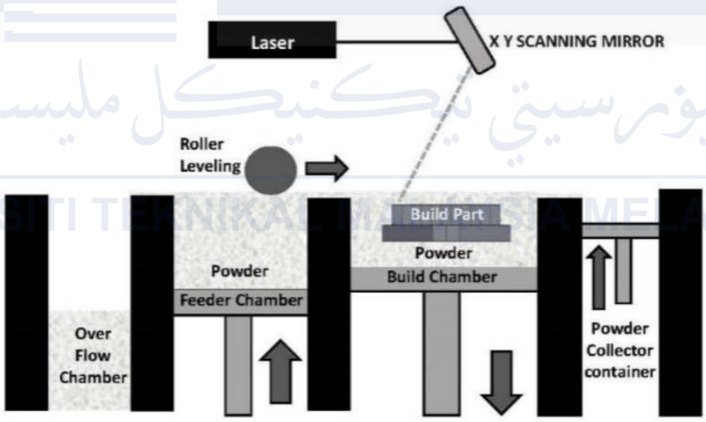


Figure 3. 9 SLS process for Farsoon FS402P (Rafi Omar et al., 2022)

Layer thickness (LT), number of contours/perimeters (NC), infill density (ID), fill angle (FA), printing speed (PS), nozzle/extrusion temperature (ET), bed temperature (BT), and build orientation (BO) are the printing process factors taken into consideration in this study. According to (Almuflih et al., 2024), each of these factors is crucial in defining the printed object's accuracy, robustness, and quality. The number of contours or perimeters impacts the print's structural integrity, while layer thickness affects resolution and surface polish. Fill angle maximises strength in particular directions, whereas infill density establishes the object's weight and internal strength. Print quality can be impacted by printing speed, particularly for intricate designs, which therefore directly affects production time.

3.3.7 Immersion Process

The immersion process is an essential aspect of determining the behaviour of sintered samples of PA-12 polymer under marine environments. This method mimics natural exposure to seawater and can affect the dimensional stability, water-absorbing capacity, mechanical properties, and fracture characteristics of the material. The convenience of the samples is used in seawater to determine degradation of the samples and how well the material will perform over a certain period of time in a marine application.

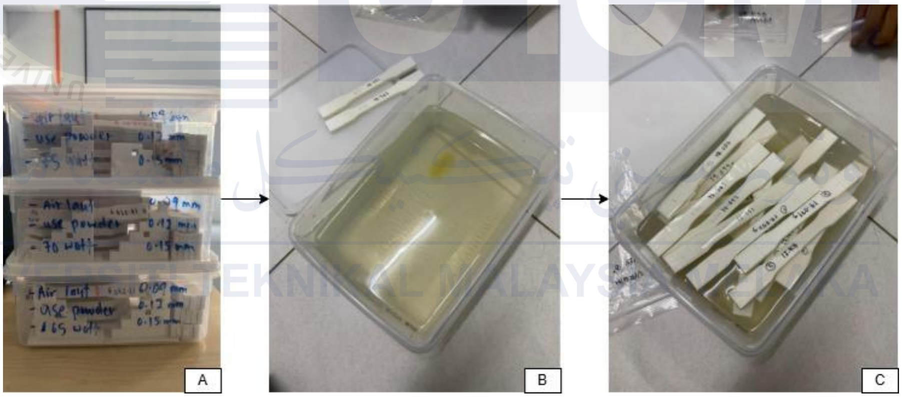


Figure 3. 10 The Immersion of Seawater Process

Figure 3.9 showed the immersion process was carried out systematically to ensure accurate and reliable results. Initially, as shown in **Picture A**, the PA-12 samples were prepared and labelled according to specific parameters, including laser power, layer thickness, and other experimental variables. Each sample was carefully stored in separate airtight containers to maintain its integrity and prevent contamination prior to immersion. Following this, as depicted in **Picture B**, seawater was collected from Pantai Klebang Melaka and transferred into a clean plastic container, ensuring sufficient volume to completely submerge all the samples. Finally, as shown in **Picture C**, the labelled PA-12 samples were immersed in the seawater, ensuring full submersion and proper arrangement to avoid overlapping. The setup was maintained under controlled conditions to simulate the intended marine environment during the immersion period.

3.3.8 Measurement Process

This measurement process is useful in assessing the impact of seawater exposure on the dimensional stability and weight of the sintered PA-12 samples. One of the most important factors that are required to be measured in this study is the pre- and post-marine condition of the samples; this can only be achieved by using accurate and precise measurement methods. With a vernier calliper and analytical/scientific balance, this study provides credible data for assessing the effects of immersion on the dog bone and block calibration samples. All such measurements are important in order to know about the overall performance and characteristics of the material, like swelling, shrinking, or water-absorbing capacity, and therefore play an important role in deciding the suitability of the material for marine use.

(a) **(b)**

Figure 3. 11 (a) and (b) The measurement process for both the dog bone and block calibration samples using an analytical/scientific balance and vernier calliper

The measurement process for both the dog bone and block calibration samples was conducted systematically before and after the immersion process to assess any changes in dimensions and weight. Initially, the dimensions of the samples were measured using a vernier caliper with a precision of 0.01 mm. For the dog bone samples, measurements included the length, width, and thickness at specific regions, while for the block calibration samples, all edges and surfaces were measured to capture any dimensional variations accurately. The caliper was handled carefully to ensure consistent pressure and avoid deformation of the samples during measurement. After recording the dimensions, the samples were weighed using an analytical/scientific balance with a precision of 0.0001 g. Each sample was placed gently on the balance to ensure accurate weight readings, and the measurements were repeated three times to minimize errors and ensure reliability. This process was repeated after the immersion process, where the samples were first rinsed with distilled water to remove any residual seawater and dried at ambient temperature before measurement. The pre- and post-immersion data were recorded and compared to evaluate the dimensional stability and weight changes of the PA-12 samples.

3.3.9 Tensile Test Process

Tensile testing represents one of the most elementary means of characterising materials for their strength and stiffness as well as ductility. This is done through applying an axial load on a specimen until it fails, and through this, the stress-strain curves are generated, giving an indication of how the material responds in tension. Sample handling and setup of the machine, as well as the parameter configurations of the actual tests performed, are key elements that must be done correctly to get good results. In the present investigation, a tensile test was performed as per ASTM guidelines on a tensile testing machine with hydraulic grips and an extensometer to evaluate the mechanical behaviour of sintered PA-12 samples. This approach helped to achieve a certain level of stability and accuracy of the data, which is important to determine the usefulness of the material in different fields.

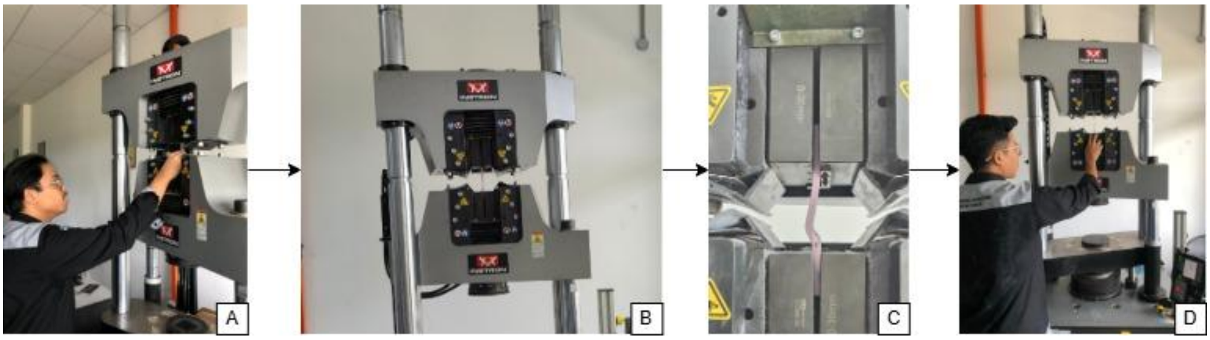


Figure 3. 12 The Tensile Test Process

Based on the provided images and accompanying instructions, the tensile testing procedure was conducted as follows. Initially, as shown in **Picture A**, the tensile testing machine was prepared, and the appropriate grips for the test, such as hydraulic grips, were installed. The grips were properly tightened and aligned to ensure secure placement of the test specimen. Next, as depicted in **Picture B**, the specimen was carefully mounted between the upper and lower grips of the machine. The grips were adjusted to securely hold the specimen, ensuring no slippage occurred during the test while avoiding over-tightening that could damage the sample. Following this, as shown in **Picture C**, the specimen was positioned correctly within the grips, and an extensometer was attached to the gauge length of the specimen to accurately measure strain, ensuring it was aligned and securely attached. Finally, as depicted in **Picture D**, the testing parameters were configured in the machine's software, including the crosshead speed, gauge length, and maximum load or displacement limits. The appropriate testing standard was selected for calculations, and the machine was set to initiate the tensile test under controlled conditions.

3.4 Limitation of Proposed Methodology

It is important to recognise the following related limitations of the proposed methodology for investigating the impact of mechanical properties on the immersed, extremely aged FS3300PA PA-12 powder in seawater, specifically in the XYY 0° orientation. First of all, the results' comprehensiveness is constrained by their exclusive focus on one orientation (XYY 0°). Because of their anisotropic behaviour, the mechanical properties of materials like PA-12 can change significantly with different orientations. The study may not fully capture the range of mechanical property variations by focusing only on the XYY 0° orientation, thus missing important information that might arise from other orientations like XYY 45° or 90°.

Second, there may be some variability introduced by the ageing process of the FS3300PA PA-12 powder in seawater that cannot be fully controlled or replicated. Geographical location, depth, and environmental factors can all affect the composition of seawater, which can cause variations in the ageing process. The results' ability to be applied broadly may be impacted by this variability. Moreover, the term "extremely aged" is not precisely defined in the methodology, which complicates the process of standardising the conditions and duration of ageing for various samples. In the absence of a well-defined and uniform ageing protocol, the study's findings may not be repeatable, which could lead to issues when comparing the results to those of other studies.

Finally, the immersion setting in seawater adds more outside variables that might affect PA-12 powder's mechanical characteristics. The characteristics of the material can change significantly over time due to a variety of factors, including biological growth, temperature changes, and chemical interactions with pollutants or marine life. It is possible that the study's methodology did not fully take into account these detailed interactions, which could have resulted in inaccurate assessments of the true effect of seawater immersion on the powder's mechanical properties. Future studies could benefit from a multi-orientation approach, standardised ageing protocols, and controlled environmental conditions to improve the reliability and applicability of the findings in order to mitigate these limitations.

3.5 Summary

FS3300PA PA-12 powder's mechanical properties are examined in this study in relation to environmental factors, with a particular focus on samples oriented at 0 degrees (XYY orientation). This is especially important after a prolonged immersion in seawater. Standard test specimens are prepared, immersed in seawater under controlled conditions to simulate extreme ageing, and then subjected to a battery of mechanical tests to measure variations in Young's modulus, elongation at break, and tensile strength. The purpose of this research is to provide precise and trustworthy information about the material's performance and durability in marine environments through the use of tensile and compression testing methods. The goal of the project is to close a big knowledge gap regarding the long-term stability of polyamide components made with 3D printing for use in underwater robotics and marine engineering.

For accuracy and consistency in the results, the experimental setup makes use of Universal Testing Machine, and SLS 3D printers. The specimens are put through a rigorous testing process to assess their mechanical behaviour at different stress levels. Correlations between mechanical properties and immersion conditions are then found through statistical analysis. Although the study only considers one orientation (XYY 0°), which might restrict how thorough the findings are, it does highlight how crucial it is to comprehend how exposure to seawater impacts the mechanical integrity of the material. This study offers important insights into the longevity and functionality of FS3300PA PA-12 in marine applications, addressing potential drawbacks like variability in seawater composition and the ill-defined "extremely aged" condition. These insights will help shape future advancements and applications in materials science and engineering.

Chapter 4

Result and Discussion

4.1 Introduction

This chapter presents the results and analysis from the study of the mechanical properties of FS3300PA PA-12 powder immersed in seawater, with a focus on the effects observed in the XYY 0-degree orientation. The research aims to gain a thorough understanding of how extreme ageing in a marine environment affects the mechanical behaviour of this material. Case studies are carried out to demonstrate the practical applications of these findings. The case studies use real-world samples that have been immersed in seawater for an extended period of time to highlight the differences in mechanical properties caused by ageing. The case study includes two distinct scenarios: (i) exposure under controlled laboratory conditions, and (ii) exposure in the natural marine environment. It is important to note that these case studies are intended to demonstrate the proposed methodology, regardless of the specific conditions of exposure.

The mechanical properties of the samples are evaluated over a 25-day (600-hour) period using the proposed method. The results are validated through rigorous mechanical testing and analysis, ensuring their reliability and accuracy. Key properties analyzed include the maximum tensile strength in the XYY 0-degree orientation, elongation to break in the XYY 0-degree orientation, and Young's modulus in the XYY 0-degree orientation. Stability is assessed by measuring the weight of the samples before and after immersion in seawater. These parameters provide important insights into the material's performance and its capacity to withstand marine ageing.

By integrating these mechanical properties and stability assessments, the study offers a comprehensive evaluation of FS3300PA PA-12's suitability for applications requiring long-term marine exposure. The findings not only enhance the understanding of the material's behaviour under such conditions but also serve as a foundation for developing improved materials and methodologies for marine applications.

To further illustrate the findings, Table 5 summarizes the mechanical properties of FS3300PA PA-12 samples, including tensile strength, elongation at break, and Young's modulus, for various laser power and layer thickness combinations in the XYY 0-degree orientation. The table highlights the differences between virgin and aged samples after seawater immersion, providing a comprehensive view of how extreme marine ageing affects the material. The inclusion of visual evidence from post-testing samples further emphasizes the impact of seawater immersion on the mechanical integrity of the material.

Table 4-7 Mechanical Properties (Tensile Strength, Elongation at Break, and Young's Modulus) of FS3300PA PA-12 Samples Before and After Seawater Immersion at XYY 0° Orientation

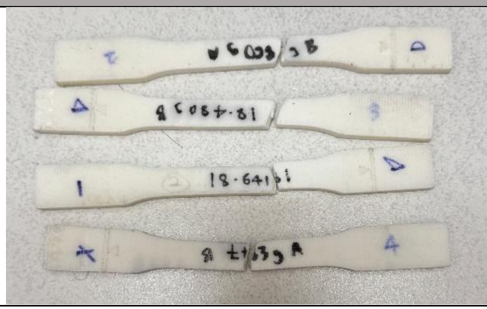
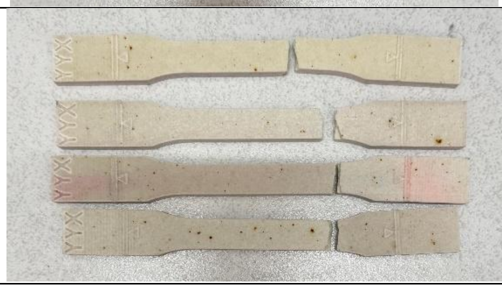
Parts Name	No	Max tensile strength XYY 0 Degree	Average	Elongation to break XYY 0 Degree	Average	Young's Modulus XYY 0 Degree	Average	Part After Testing
65 WATT 0.15MM (VIRGIN)	1	25.83786	18.40	17.7344	16.21	0.263117	0.191593	
	2	20.22896		16.3235		0.121733		
	3	16.13899		15.9593		0.079001		
	4	11.39361		14.8408		0.30252		

Table 4

Parts Name	No	Max tensile strength XYY 0 Degree	Average	Elongation to break XYY 0 Degree	Average	Young's Modulus XYY 0 Degree	Average	Part After Testing
75 WATT 0.15MM	1	30.62333	30.3484	12.3657	12.0035	0.487768	0.4835	
	2	30.57252		12.1944		0.485121		
	3	30.39943		12.1567		0.484467		
	4	29.7983		11.297		0.476675		
75 WATT 0.12MM	1	34.16337	33.2129	16.259	15.5958	0.478442	0.4579	
	2	33.74129		15.8568		0.473457		
	3	33.18904		15.5557		0.446654		
	4	31.75797		14.7116		0.432927		
75 WATT 0.09MM	1	36.64246	36.3733	21.5634	20.2429	0.484822	0.4796	
	2	36.36875		20.4184		0.481752		
	3	36.27249		19.7572		0.476182		
	4	36.20963		19.2326		0.475604		

Table 5

Parts Name	No	Max tensile strength XYY 0 Degree	Average	Elongation to break XYY 0 Degree	Average	Young's Modulus XYY 0 Degree	Average	Part After Testing
70 WATT 0.15MM	1	30.18705	29.2702	9.5594	8.7302	0.491331	0.4823	
	2	29.85591		8.7152		0.480105		
	3	28.72043		8.5203		0.479897		
	4	28.31757		8.1258		0.47769		
70 WATT 0.12MM	1	34.34491	33.4663	13.4188	11.9083	0.582328	0.5707	
	2	33.91688		12.0651		0.581593		
	3	33.63913		11.1944		0.580088		
	4	31.96445		10.9547		0.538944		

70 WATT 0.09MM	1	36.73969	36.3025	18.4484	17.5436	0.514407	0.5000	
	2	36.66507		17.3864		0.504035		
	3	36.02058		17.1944		0.498475		
	4	35.78476		17.145		0.483119		

Table 6

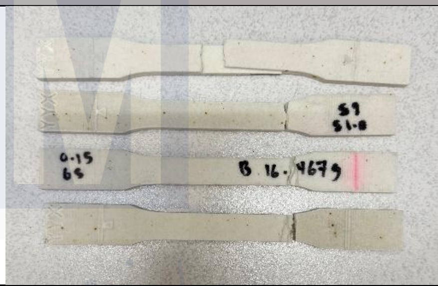
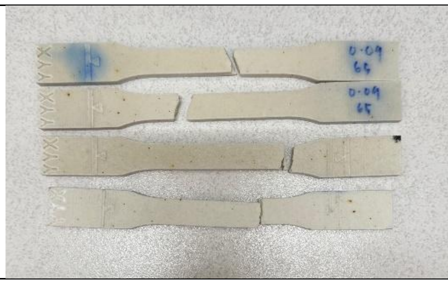
Parts Name	No	Max tensile strength XYY 0 Degree	Average	Elongation to break XYY 0 Degree	Average	Young's Modulus XYY 0 Degree	Average	Part After Testing
65 WATT 0.15MM	1	24.26279	21.7925	9.583	7.2722	0.409826	0.3659	
	2	22.81053		7.02		0.3739		
	3	21.96619		6.3273		0.344424		
	4	18.13065		6.1583		0.335556		
65 WATT 0.12MM	1	32.19994	31.1659	13.3992	12.3102	0.484184	0.4771	
	2	31.92125		12.1639		0.480081		
	3	31.19011		12.0878		0.477945		
	4	29.35238		11.5899		0.466242		
65 WATT 0.09MM	1	37.14439	36.6480	19.6319	18.7337	0.569065	0.5461	
	2	36.70579		19.0653		0.548742		
	3	36.66131		18.7499		0.535921		
	4	36.08062		17.4875		0.53086		

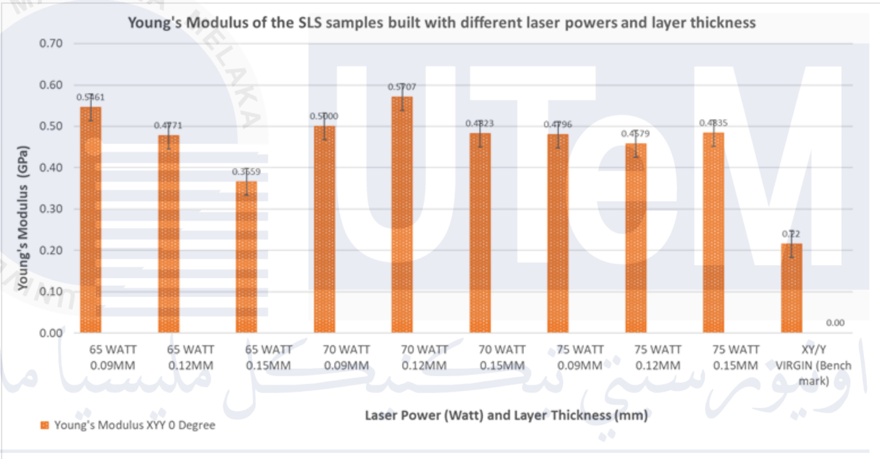
Table 7

4.2 Effect of Laser Power, Layer Thickness, Aging, and Seawater Immersion on the Mechanical Properties of PA12

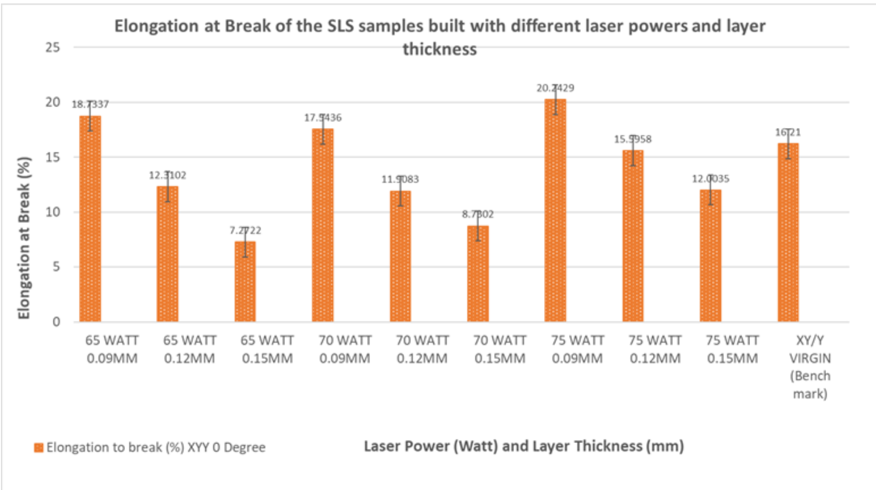
In this study, the mechanical properties of PA-12, including tensile strength, elongation at break, and Young's modulus, were evaluated under varying laser power, layer thickness, aging, and seawater immersion conditions, with a focus on the XYY 0° orientation. Laser power plays a important role in determining the energy density during the sintering process, directly influencing the bonding between powder particles and, consequently, the mechanical performance of the sintered material. Higher laser power typically enhances particle fusion but may lead to over-sintering or thermal degradation, while lower power may result in insufficient bonding and reduced strength. (El Magri et al. 2022) found that "the significant impact of the laser power while hatching is almost unnoticeable when using a high laser power," emphasizing the importance of optimizing laser settings to achieve desired material properties.

Layer thickness, on the other hand, governs the material's resolution and uniformity during additive manufacturing, with thinner layers promoting better bonding and smoother surfaces at the cost of longer production times. In this experiment, these parameters were systematically varied to investigate their combined impact on the mechanical behavior of both virgin and extremely aged FS3300PA PA-12 powder, including its performance after prolonged seawater exposure. The results provide valuable insights into optimizing processing parameters to improve the durability and stability of PA-12 under challenging environmental conditions.

(a)



(b)



(c)

Figure 4.1 Tensile properties as a function of XYY 0 degree orientation, layer thickness and laser power: (a) Tensile Strength; (b) Young's Modulus; (c) Elongation at break.

Figure 4.1 (a, b, and c) shows the tensile properties of the extremely aged FS3300PA PA-12 powder immersed in seawater, evaluated at the XYY 0-degree orientation, showed significant variation with changes in laser power and layer thickness. The maximum tensile strength of (36.6480 MPa) was recorded for the laminates with 65 Watts and 0.09mm thickness because of proper energy input resulted in proper layer adhesion and efficient polymerization. Conversely, the lowest tensile strength (21.7925 MPa) occurred at 65 W and 0.15 mm, likely due to insufficient energy density leading to weaker bonding and void formation in thicker layers. For Young's modulus, the maximum value (0.5707 GPa) was recorded at 70 W and 0.12 mm, where balanced energy input promoted higher stiffness, while the lowest modulus (0.3659 GPa) at 65 W and 0.15 mm reflected the adverse effects of reduced cohesion in thicker layers.

Elongation at break peaked at 75 W and 0.09 mm (20.2429%), indicating ductility and robust interlayer adhesion under optimized conditions, while the lowest elongation (7.2722%) at 65 W and 0.15 mm was due to insufficient energy distribution in thicker layers, reducing flexibility. These findings align with (El Magri et al. 2022), who stated that "laser power and layer thickness significantly influence tensile properties due to their effects on energy density and material consolidation," and (Goodridge et al. 2010), who noted that "reduced energy input and thicker layers often lead to voids and weakened interlayer cohesion in aged materials." Among the aged samples, 75 W and 0.09 mm exhibited the best overall tensile performance, highlighting its suitability for maintaining mechanical integrity in aged PA-12 materials.

When comparing the best tensile performance of the aged FS3300PA PA-12 powder (75 W and 0.09 mm) to the virgin benchmark, the aged sample exhibited significantly higher tensile strength (36.3733 MPa vs. 18.40 MPa), Young’s modulus (0.4796 GPa vs. 0.072 GPa), and elongation at break (20.7429% vs. 16.721%). This improvement highlights the effectiveness of optimized laser power and layer thickness in restoring mechanical properties by ensuring thorough melting, strong interlayer bonding, and minimized void formation. The

75 W and 0.09 mm combination exhibited the best overall tensile performance due to the optimal balance of energy density and layer thickness. The high laser power (75 W) ensured thorough melting and strong interlayer bonding, while the thinner layer thickness (0.09 mm) improved heat distribution and reduced void formation. As (El Magri et al. 2022) stated, "optimal energy density promotes effective polymer consolidation, enhancing mechanical properties." Additionally, thinner layers improved interlayer interaction, minimizing defects, as supported by (Goodridge et al. 2010), who noted that "voids and weak interlayer adhesion reduce mechanical performance." This combination resulted in superior tensile properties, even in aged and seawater-immersed PA-12 samples.

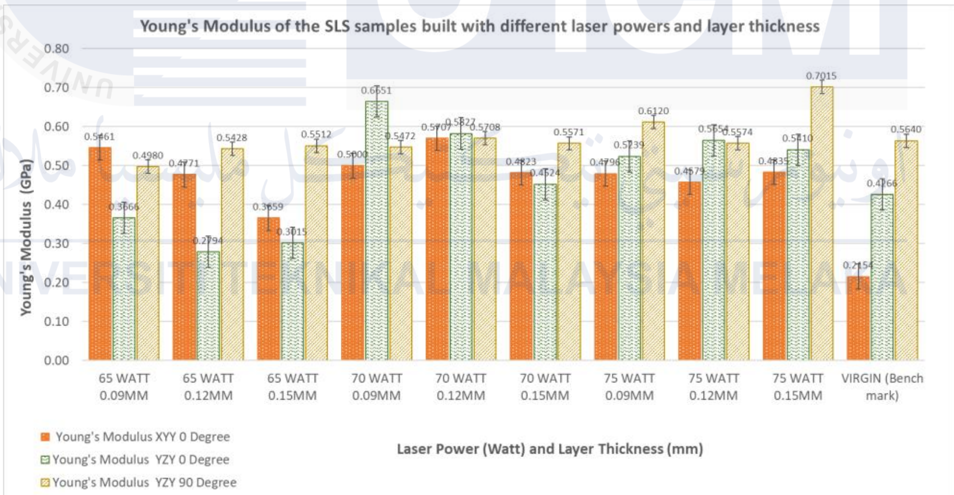
Aged powder tends to have a higher melting point because it has been sintered over an extended period and gone through numerous, often untraceable, cycles. As a result, melting the powder effectively requires increasing the laser's strength. The tensile strength of parts is directly linked to laser power, as higher laser power melts the polymer at elevated temperatures, enhancing material coalescence. Laser power plays a crucial role in sintering by determining the amount of energy absorbed by the PA-12 powder. This effect is especially pronounced for aged powder. When laser power is too low, the sintered parts are less compact, looser, and have reduced mechanical properties due to insufficient energy. Lower laser power can also lead to microstructural defects like un-melted powder particles and porous structures. On the other hand, increasing laser power improves the compactness of the parts because of the greater energy input. This leads to better tensile strength, elongation at break, and Young’s modulus. Research by Caulfield supports this, showing that higher energy density from increased laser power results in stronger parts. Similarly, Hofland found that mechanical properties improve when more particles are fully melted in SLS specimens. However, excessive laser power can cause issues, such as yellowing, hardening of the material, and higher processing costs. Interestingly, while higher laser power contributes to improved mechanical properties, the results also suggest that layer thickness plays an even more significant role in this improvement.

Layer thickness refers to the thickness of each layer being sintered during the sintering process, which is primarily influenced by the laser beam's penetration depth into the powder. This depth is closely tied to factors such as compaction, thermal conductivity, powder density, particle size, energy density, and the material's specific heat. Smaller layer thickness generally leads to higher tensile properties. This trend is evident across all three laser power settings tested, where tensile strength, elongation at break, and Young's modulus values decreased significantly as layer thickness increased—particularly at 65 W and 70 W laser powers. One reason thinner layers improve tensile strength is the reduced gap between layers, which minimizes porosity in the specimen's cross-section. As Ayrilmis's research highlights, lower porosity often results in better mechanical properties.

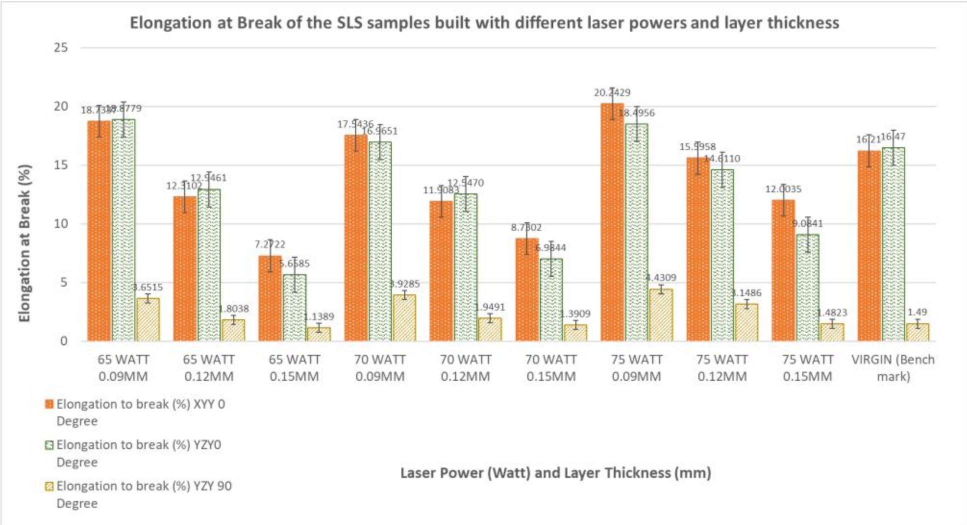
4.3 Impact of Orientation (XYY 0°, YZY 0°, YZY 90°) on the Tensile Properties of PA12

The impact of build orientation on the tensile properties including tensile strength, elongation at break, and Young's modulus, of PA-12 was evaluated in this study, focusing on XYY 0°, YZY 0°, and YZY 90°. Build orientation played an important role in determining the mechanical performance of the material by influencing the alignment and bonding of layers and the resulting anisotropy in the sintered parts during the sintering process. Orientations parallel to the loading direction typically demonstrated higher strength and stiffness due to enhanced layer bonding, whereas perpendicular orientations often exhibited reduced mechanical performance due to weaker interlayer adhesion. (Lee et al. 2020) emphasized that "build orientation significantly affected the mechanical properties and porosity of polymeric parts," underscoring its importance in tailoring the strength, ductility, and overall performance of additively manufactured components. In this experiment, the tensile properties of PA-12 in different orientations were systematically analyzed to understand the effects of build orientation on its anisotropic behavior. The findings provided valuable insights into the selection of optimal build orientations to enhance the performance of PA-12 components in engineering.

(a)



(b)



(c)

Figure 4. 2 Comparison of Tensile Properties (Tensile Strength (a), Young's Modulus (b) and Elongation at Break) of PA-12 at Different Build Orientations (XYY 0°, YZY 0°, and YZY 90°)

From the data presented in the three graphs, the tensile properties of the aged FS3300PA PA-12 samples immersed in seawater were evaluated based on tensile strength, Young's modulus, and elongation at break across different orientations (XYY 0°, YZY 0°, and YZY 90°). For tensile strength, the highest value (40.4488 MPa) was observed in the YZY 0° orientation at 70 W and 0.09 mm thickness. This can be attributed to the optimal energy density at this configuration, leading to improved layer bonding and reduced porosity, as noted in (Lee, K. P. M., Pandelidi, C., & Kajtaz, M. 2020), where the authors state, "the alignment of build layers significantly influences interlayer strength and porosity." Conversely, the lowest tensile strength (7.1901 MPa) in the YZY 90° orientation indicates weak interlayer bonding due to the orientation, where the tensile forces are perpendicular to the layers.

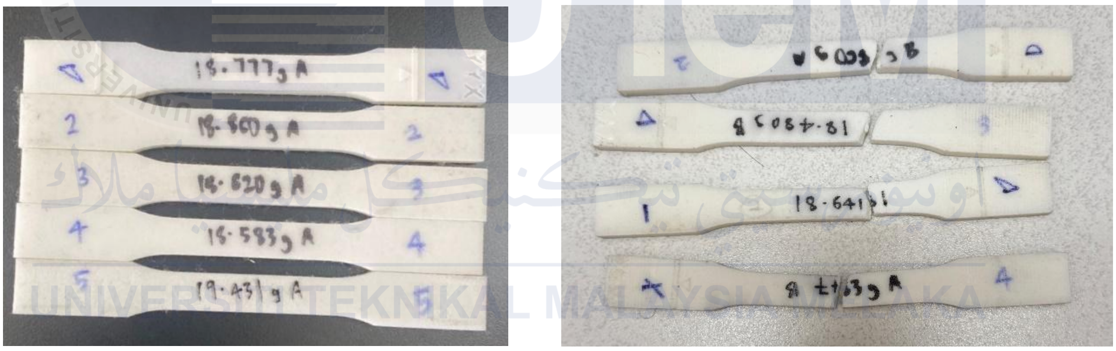
For Young's modulus, the highest value (0.7015 GPa) was also recorded in the YZY 90° orientation at 75 W and 0.15 mm thickness, indicating superior stiffness due to enhanced molecular alignment along the load direction. The lowest value (0.2794 GPa) was seen in the YZY 0° orientation aligning with findings that layer orientation has a profound effect on stiffness, as mentioned in the cited study. Regarding elongation at break, the highest value

(20.2429%) was observed in the XYY 0° orientation at 75 W and 0.09 mm thickness, likely due to better ductility and energy absorption from improved bonding. The lowest elongation (1.1389%) occurred in the YZY 90° which shows the poor toughness caused by the brittle failure at perpendicular orientations. The XYY 0° orientation consistently demonstrated the best performance across all metrics due to superior layer alignment and reduced porosity, as supported by the citation. In contrast, the YZY 90° orientation was the weakest, illustrating the challenges of load-bearing across perpendicular layers.

The comparison between the aged FS3300PA PA-12 samples and the virgin benchmark reveals significant variations in tensile properties, demonstrating the effects of seawater immersion on mechanical performance. For tensile strength, the highest value in the aged samples was 40.4488 MPa (YZY 0° at 70 W, 0.09 mm), which is more than double the virgin benchmark's 18.40 MPa, highlighting the role of optimized energy density in improving interlayer bonding and reducing porosity. In terms of young's modulus, the aged samples peaked at 0.7015 GPa (YZY 90° at 75 W, 0.15 mm), exceeding the virgin benchmark's 0.5640 GPa, demonstrating superior stiffness likely due to enhanced molecular alignment from the laser sintering process. For elongation at break, the aged samples achieved a maximum of 20.2429% (XYY 0° at 75 W, 0.09 mm), outperforming the virgin benchmark's 16.21%, indicating improved ductility and toughness. The enhanced properties of the aged samples, compared to the virgin benchmark, emphasize the importance of optimized processing parameters in maintaining mechanical performance even after seawater immersion.

The orientation of sintering planes plays a crucial role in determining tensile mechanical properties, particularly for the YZY 90° sintering orientation, as shown in previous studies. The tensile strength along the construction direction of sintered specimens is influenced by the bonding strength between adjacent layers, which are built layer by layer during the process. Results indicate that in both XYY 0° and YZY 0° sintering orientations, molecules tend to align parallel to the stress axis, optimizing the direction of the layers. However, in the YZY 90° orientation, tensile loading occurs parallel to the layer deposition direction, causing inter-layer fusion bond failure when the load is applied perpendicular to the layers. The fracture path in tensile specimens is strongly influenced by layer orientation. Delamination along the layer interfaces often occurs due to weak interlayer bonding and the presence of interlayer porosity, a challenge that is particularly pronounced when using aged (non-virgin) powder. In summary, significant differences were observed in tensile strength, elongation at break, and Young's modulus values across the XYY 0°, YZY 0°, and YZY 90° orientations in all nine experimental groups.

4.4 Stability Assessment and Weight Analysis of Samples Before and After Immersion



(a) **(b)**

Figure 4. 3 (a) and (b) Weight Analysis of FS3300PA PA-12 Samples Before and After Immersion

The stability of FS3300PA PA-12 samples was evaluated through weight analysis conducted before and after seawater immersion to determine the effects of extreme marine ageing on the material. This assessment focused on identifying changes in weight that could indicate water absorption, swelling, or degradation. The analysis provided key insights into the material's resistance to environmental exposure. Chaudhary et al. (2023) highlighted that "prolonged exposure to seawater can lead to mechanical weakening and dimensional instability in 3D printed thermoplastics due to water ingress and hydrolysis.” Similarly, (Oluwoye et al. 2023) noted that “marine environments accelerate polymer degradation through mechanisms such as hydrolysis, oxidation, and microbial activity, impacting long-term stability and performance.” These findings underscore the importance of weight analysis in evaluating the material's stability under marine conditions. The results of the analysis revealed notable differences in the weight of the samples before and after immersion, offering critical data on the material's susceptibility to seawater exposure and its implications for long-term applications.The table below presents the weight measurements of each sample, including the percentage difference and average percentage difference, highlighting the extent of water absorption or potential material degradation caused by immersion. These results provide valuable insights into the environmental durability of the material.

Table 8 Weight Analysis of FS3300PA PA-12 Samples Before and After Seawater Immersion

Parts Name	No	Weight before immersed (g)	Weight after immersed (g)	Difference (%)	Average difference (%)
65 WATT 0.15MM (VIRGIN)	1	19.099	19.431	1.74	1.04
	2	18.688	18.86	0.92	
	3	18.641	18.777	0.73	
	4	18.48	18.62	0.76	
75 WATT 0.15MM	1	17.343	17.535	1.11	1.10
	2	17.442	17.64	1.14	
	3	17.546	17.727	1.03	
	4	17.365	17.558	1.11	
75 WATT 0.12MM	1	18.24	18.527	1.57	1.48
	2	17.891	18.043	0.85	
	3	18.285	18.645	1.97	
	4	17.91	18.185	1.54	
75 WATT 0.09MM	1	18.278	19.104	4.52	2.51
	2	18.778	19.12	1.82	
	3	18.689	19.031	1.83	
	4	18.75	19.1	1.87	
70 WATT 0.15MM	1	16.624	16.92	1.78	1.57
	2	16.813	17.14	1.94	
	3	17.293	17.518	1.30	
	4	16.571	16.778	1.25	
70 WATT 0.12MM	1	17.658	17.942	1.61	1.78
	2	17.81	18.111	1.69	
	3	17.723	18.032	1.74	
	4	17.861	18.229	2.06	
70 WATT 0.09MM	1	18.713	19.041	1.75	1.77
	2	18.364	18.659	1.61	
	3	18.563	18.904	1.84	
	4	18.77	19.12	1.86	
65 WATT 0.15MM	1	16.835	17.104	1.60	1.56
	2	16.467	16.732	1.61	
	3	15.814	16.053	1.51	
	4	16.323	16.569	1.51	
65 WATT 0.12MM	1	17.185	17.484	1.74	1.72
	2	17.634	17.931	1.68	
	3	17.794	18.062	1.51	
	4	17.64	17.987	1.97	
65 WATT 0.09MM	1	18.492	18.773	1.52	1.50
	2	18.707	18.97	1.41	
	3	18.848	19.108	1.38	
	4	18.453	18.765	1.69	

The stability assessment and weight analysis of the aged FS3300PA PA-12 samples showed significant differences in weight before and after seawater immersion, with percentage differences highlighting the effects of marine aging. The highest average percentage difference was observed in the 75 WATT 0.09 MM sample at 2.51%, indicating the highest susceptibility to water absorption or degradation due to its specific processing parameters, which might have increased porosity. (Chaudhary et al. 2023) noted that "the susceptibility of thermoplastics to water uptake is influenced by the material's porosity and exposure conditions." Conversely, the lowest average percentage difference was observed in the 75 WATT 0.15 MM sample at 1.10%, indicating superior stability and reduced water absorption, aligning with (Oluwoye et al. 2023), who stated that "optimized material processing enhances resistance to degradation in marine environments." When compared to the virgin benchmark, which showed minimal weight differences, the aged samples exhibited differences ranging from 1.10% to 2.51%, illustrating the impact of aging on the material. Among the aged samples, the 75 WATT 0.09 MM sample demonstrated the best stability, while the 75 WATT 0.15 MM sample showed the least stability, emphasizing the importance of optimizing processing parameters to enhance material durability under marine exposure.

The comparison between the aged and virgin FS3300PA PA-12 samples highlights the distinct effects of seawater immersion on the material's stability. The virgin sample, used as a benchmark, showed a minimal average percentage difference of 1.04%, reflecting its relatively unaffected state, as it had not undergone prolonged exposure to seawater or extreme aging. In contrast, the aged samples exhibited significantly higher percentage differences, ranging from 1.10% (75 WATT 0.15 MM) to 2.51% (75 WATT 0.09 MM), indicating a clear impact of aging on their ability to resist water absorption and maintain weight stability. The virgin sample's low difference underscores its preserved microstructure and lack of prior degradation, while the aged samples experienced microstructural changes and increased porosity due to marine aging, as supported by Chaudhary et al. (2023), who explained that "prolonged exposure to seawater can alter the polymer matrix and increase water uptake."

The stark contrast between the virgin and aged samples demonstrates how aging influences mechanical and stability performance. While the virgin sample consistently outperformed the aged samples in terms of weight stability, among the aged samples, the 75 WATT 0.15 MM demonstrated the smallest deviation from the virgin benchmark, showcasing better resistance to water absorption. This suggests that higher energy density during processing (as seen in the 75 WATT 0.15 MM) contributed to denser bonding and reduced susceptibility to degradation, aligning with the findings of Oluwoye et al. (2023), who noted that "materials processed with optimized energy inputs exhibit improved long-term resistance to environmental factors." Conversely, the 75 WATT 0.09 MM sample, with the highest average percentage difference of 2.51%, deviated the most from the virgin sample, reflecting its higher vulnerability to marine aging. This comparison emphasizes the importance of processing parameters in influencing both the initial and long-term stability of the material under seawater exposure.

4.5 Summary

The results and discussion focusing a comprehensive analysis of the mechanical properties and stability of FS3300PA PA-12 powder, with a focus on the effects of prolonged seawater immersion and the impact of laser power, layer thickness, and build orientation. The study highlights the importance of optimizing laser sintering parameters to enhance mechanical performance, even in extreme marine environments. The results reveal that samples processed with 75 W laser power and a 0.09 mm layer thickness demonstrated the best overall tensile performance among aged samples, achieving a maximum tensile strength of 36.3733 MPa, Young’s modulus of 0.4796 GPa, and elongation at break of 20.7429%. These findings emphasize the significance of balanced energy density and layer thickness for improving interlayer bonding, ductility, and stiffness, even after seawater exposure. In contrast, samples with thicker layers (0.15 mm) exhibited reduced mechanical properties, primarily due to insufficient bonding and void formation. Additionally, the study underscores the influence of build orientation, with the XYY 0° orientation consistently delivering superior mechanical properties compared to YZY 90°, which showed weaker interlayer adhesion and lower tensile strength.

The chapter also highlights the stability of FS3300PA PA-12 by evaluating weight differences before and after seawater immersion. Virgin samples showed minimal weight changes (average 1.04%), demonstrating their resistance to water absorption. However, aged samples exhibited higher percentage differences, with the highest at 2.51% for the 75 W, 0.09 mm configuration, indicating increased susceptibility to water ingress due to potential microstructural changes and porosity caused by aging. The 75 W, 0.15 mm sample showed the lowest percentage difference (1.10%), reflecting superior stability due to reduced porosity from optimized processing. These findings underscore the importance of laser power and layer thickness optimization in maintaining both mechanical integrity and stability under marine conditions. The results of this chapter are crucial for understanding the behavior of PA-12 in challenging environments, offering valuable insights for the development of more durable materials and methodologies for long-term marine applications.

Chapter 5

Conclusion and Recommendation

5.1 Conclusion

In conclusion, this study successfully investigated the mechanical properties of extremely aged FS3300PA PA-12 powder immersed in seawater, focusing on the effects of laser power, layer thickness, and sintering orientation. The findings revealed that mechanical properties such as tensile strength, elongation at break, and Young's modulus were significantly influenced by these parameters. Higher laser power enhanced material consolidation and interlayer bonding, while thinner layer thickness reduced porosity, leading to improved mechanical performance. Among the aged samples, the combination of 75 W laser power and 0.09 mm layer thickness exhibited the best tensile properties, aligning with prior studies emphasizing the importance of energy density and layer thickness in optimizing material performance.

Sintering orientation also played a critical role, particularly for the YZY 90° orientation, which demonstrated significantly lower mechanical properties compared to XYY 0° and YZY 0° orientations. Weak interlayer bonding and increased porosity, especially in aged powder samples, contributed to the reduced performance in the YZY 90° orientation when subjected to tensile loading perpendicular to the layer deposition direction. Conversely, XYY 0° and YZY 0° orientations showed comparable tensile properties, highlighting the influence of layer alignment on mechanical integrity.

The study further demonstrated that optimized sintering parameters could restore and even enhance the mechanical properties of aged powders compared to virgin powder benchmarks. The aged samples sintered at 75 W and 0.09 mm layer thickness achieved superior tensile strength (36.3733 MPa vs. 18.40 MPa), Young’s modulus (0.4796 GPa vs. 0.072 GPa), and elongation at break (20.7429% vs. 16.721%). These results underscore the potential for process optimization to mitigate the effects of aging and environmental exposure, ensuring the viability of aged PA-12 materials for demanding applications in marine environments.

While the study successfully achieved its objectives, certain limitations were acknowledged, such as constraints on time and resources that restricted the exploration of additional environmental conditions or materials. Nonetheless, the findings provide valuable insights into the behavior of FS3300PA PA-12 powder under seawater immersion, offering practical implications for industries operating in marine environments. This research lays a solid foundation for future studies, enabling further exploration of material performance optimization under various conditions.

5.2 Recommendation

The recommendations section follows from the conclusions drawn in the previous chapter. Based on the research findings, this section provides suggestions for future studies and improvements to the methodologies used in this project. It also offers practical advice on how the results can be applied in real-world scenarios, particularly in the selection and development of materials for marine applications. These recommendations aim to guide further research in the field and contribute to the continued advancement of material science, particularly concerning the performance of materials in harsh environments such as seawater exposure.

Future research should expand the scope of this study to include a broader range of environmental conditions and orientations, such as the addition of tests for XYY 45 and XYY 90 orientations of the FS3300PA PA-12 powder. By examining these different orientations, along with varying seawater immersion times, researchers can gain a more comprehensive understanding of how the material performs under different stress conditions. This would enhance the knowledge of material behavior and help optimize material selection for marine applications where orientations play a critical role in performance.

It is also recommended to explore the long-term effects of seawater immersion on other materials similar to FS3300PA PA-12, such as PA11(Polyamide), PA6/12 materials, to compare their performance in marine environments. By including additional polymers or composite materials in the study, a more holistic understanding of material durability can be achieved, helping to identify the most suitable materials for specific marine applications. This comparative analysis would allow for the selection of materials that provide better resistance to seawater exposure, offering more reliable and long-lasting solutions.

Additionally, future studies should focus on utilizing scanning electron microscopy (SEM) to analyze the fracture behavior of the FS3300PA PA-12 powder. SEM would provide detailed images of the fracture surfaces, helping to understand the material's failure mechanisms and the impact of seawater immersion on its microstructure. Investigating the fracture behavior under various conditions will offer crucial insights into the material's performance, guiding improvements in its mechanical properties for use in challenging marine environments.

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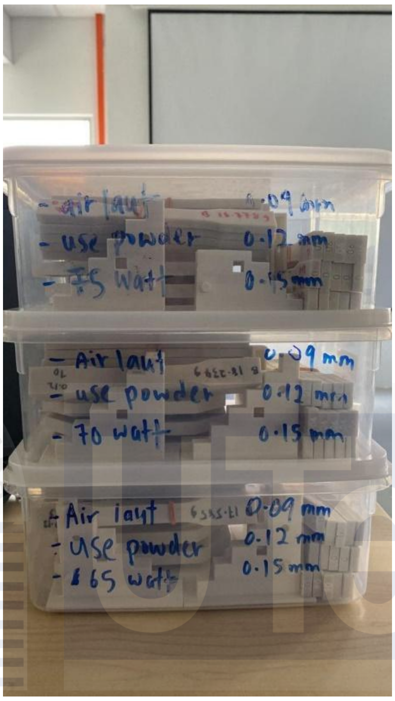
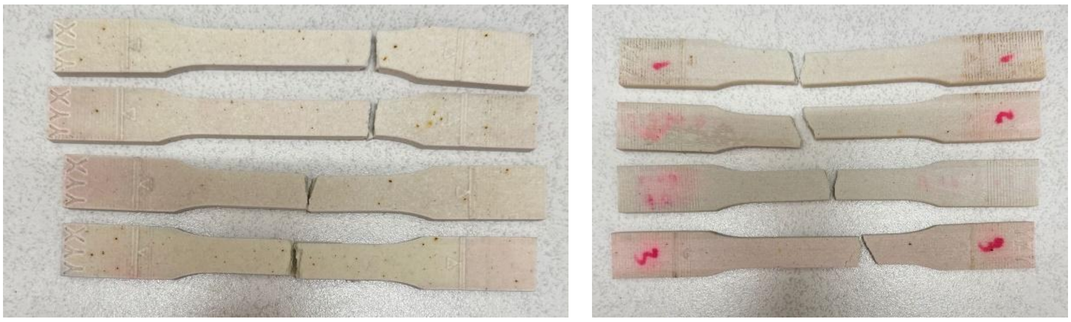
APPENDICIES

Appendix A Sorting and labelling the aging samples before immersion



Appendix B Processes undertaken during the project

Appendix C aging sample after immerse and tensile test



Appendix D table of data mechanical properties aging sample xyy 0 degree orientation

Parts Name	No	Max tensile strength XYY 0 Degree	Average	Elongation to break XYY 0 Degree	Average	Young's Modulus XYY 0 Degree	Average
65 WATT 0.15MM (VIRGIN)	1	25.83786	18.40	17.7344	16.21	0.263117	0.191593
	2	20.22896		16.3235		0.121733	
	3	16.13899		15.9593		0.079001	
	4	11.39361		14.8408		0.30252	
75 WATT 0.15MM	1	30.62333	30.3484	12.3657	12.0035	0.487768	0.4835
	2	30.57252		12.1944		0.485121	
	3	30.39943		12.1567		0.484467	
	4	29.7983		11.297		0.476675	
75 WATT 0.12MM	1	34.16337	33.2129	16.259	15.5958	0.478442	0.4579
	2	33.74129		15.8568		0.473457	
	3	33.18904		15.5557		0.446654	
	4	31.75797		14.7116		0.432927	
75 WATT 0.09MM	1	36.64246	36.3733	21.5634	20.2429	0.484822	0.4796
	2	36.36875		20.4184		0.481752	
	3	36.27249		19.7572		0.476182	
	4	36.20963		19.2326		0.475604	
70 WATT 0.15MM	1	30.18705	29.2702	9.5594	8.7302	0.491331	0.4823
	2	29.85591		8.7152		0.480105	
	3	28.72043		8.5203		0.479897	
	4	28.31757		8.1258		0.47769	
70 WATT 0.12MM	1	34.34491	33.4663	13.4188	11.9083	0.582328	0.5707
	2	33.91688		12.0651		0.581593	
	3	33.63913		11.1944		0.580088	
	4	31.96445		10.9547		0.538944	
70 WATT 0.09MM	1	36.73969	36.3025	18.4484	17.5436	0.514407	0.5000
	2	36.66507		17.3864		0.504035	
	3	36.02058		17.1944		0.498475	
	4	35.78476		17.145		0.483119	
65 WATT 0.15MM	1	24.26279	21.7925	9.583	7.2722	0.409826	0.3659
	2	22.81053		7.02		0.3739	
	3	21.96619		6.3273		0.344424	
	4	18.13065		6.1583		0.335556	
65 WATT 0.12MM	1	32.19994	31.1659	13.3992	12.3102	0.484184	0.4771
	2	31.92125		12.1639		0.480081	
	3	31.19011		12.0878		0.477945	
	4	29.35238		11.5899		0.466242	
65 WATT 0.09MM	1	37.14439	36.6480	19.6319	18.7337	0.569065	0.5461
	2	36.70579		19.0653		0.548742	
	3	36.66131		18.7499		0.535921	
	4	36.08062		17.4875		0.53086	

Appendix E: Gant Chart

No.	Task	Implementation	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W14
1	PSM 2 briefing	Plan														
		Actual														
2	Meeting with supervisor	Plan														
		Actual														
3	Run Tensile Test (75-watt aging)	Plan														
		Actual														
4	Run Tensile Test (70-watt aging)	Plan														
		Actual														
5	Run Tensile Test (65-watt aging)	Plan														
		Actual														
6	Chapter 3 writing	Plan														
		Actual														
7	Dimensional stability and water absorption measurement	Plan														
		Actual														
8	Chapter 4 writing	Plan														
		Actual														
9	Chapter 5 writing	Plan														
		Actual														
10	Technical Report writing	Plan														
		Actual														
11	Poster presentation preparation	Plan														
		Actual														
12	Presentation	Plan														
		Actual														

Plan (P)	
Actual (A)	