INFLUENCE OF POLYAMIDE-12 COMPOSITION ON THE MECHANICAL PROPERTIES AND DIMENSIONAL ACCURACY IN SELECTIVE LASER SINTERING

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MASTER OF SCIENCE IN MECHANICAL ENGINEERING

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DEDICATION

This thesis is dedicated to my beloved wife Rizwana Seeni and children, Rauf, Razeef and Raisha because knowledge is very important as a source of inspiration for them to succeed in life.

ABSTRACT

There are significant differences in surface morphology and physical characteristics between the various 3D printed objects that are being produced, which compromises the preciseness of the finished product. This study examines how several key parameters of the Selective Laser Sintering (SLS) 3D printer impact the material strength of Polyamide -12 (PA-12) using the Taguchi optimization method. The primary factorial parameter chosen is the material PA-12, which is a mixture of virgin, heated, and recycled materials. Additional parameters being studied include laser beam strength and layer thickness. Test specimens were fabricated using an SLS 3D printer following normal procedures to evaluate the physical qualities including tensile strength, roughness, impact resistance, and Rockwell hardness, as well as surface morphology and dimensional accuracy. Next, the surface morphology and dimension accuracy of the samples were assessed using a scanning electron microscope (SEM) and coordinate measuring machine (CMM). The optimal results were obtained with 100% virgin PA-12 material with a machine parameter of 60 watts of laser power and a layer thickness of 0.06 mm. This set of parameters achieved the best performance in terms of the mechanical qualities, dimensional accuracy, and part quality. Composition 1, produced completely of virgin material scored the highest in all tests, including tensile, impact, roughness, torsion, compression, and hardness tests. The two most important contributing factors for evaluating the mechanical qualities of PA-12 at a high-grade level are the laser's 60-watt output and the layer's 0.06 mm thickness. In addition, with a layer thickness of 0.06 mm and a laser power of 60 watts, the dimensional accuracy test revealed 100% pure material for the X, and Y, demonstrating high accuracy in this study. Dimensional accuracy of this research 0.14 mm on the X-axis and 0.11 mm on the Y-axis were all result within the acceptable ±0.1% tolerance limits, indicating that the selected material composition and process parameters significantly enhanced dimensional accuracy beyond the manufacturer's standards. The Hence, this study has proven that recognising how process parameters affect accuracy is essential to achieving high accuracy in the production of 3D printed objects.

PENGARUH KOMPOSISI POLYAMIDE-12 TERHADAP SIFAT-SIFAT MEKANIKAL DAN KETEPATAN DIMENSI DALAM PERSINTERAN LASER TERPILIH

ABSTRAK

Terdapat perbezaan signifikan ke atas sifat mekanikal dan morfologi permukaan setiap objek dicetak menggunakan 3D yang akan menjejaskan ketepatan produk. Kajian ini dijalankan bagi beberapa parameter utama pencetak 3D Pensintaran Laser Selektif(SLS) yang memberi kesan kepada kekuatan bahan Polyamide-12 menggunakan kaedah pengoptimuman Taguchi. Parameter faktorial utama yang dipilih ialah bahan PA-12, yang merupakan campuran bahan dara, dipanaskan, dan kitar semula. Parameter tambahan yang sedang dikaji termasuk kekuatan pancaran laser dan ketebalan lapisan. Spesimen ujian telah direka menggunakan pencetak SLS 3D mengikut prosedur biasa untuk menilai kualiti fizikal termasuk kekuatan tegangan, kekasaran, rintangan hentaman dan kekerasan rockwell, serta morfologi permukaan dan ketepatan dimensi. Seterusnya, morfologi permukaan dan ketepatan dimensi sampel dinilai menggunakan mikroskop elektron pengimbasan (SEM) dan mesin pengukur koordinat (CMM). Keputusan optimum diperolehi adalah bahan PA-12 dara 100% dengan parameter mesin 60 watt kuasa laser dan ketebalan lapisan 0.06 mm. Parameter ini mencapai prestasi terbaik dari segi kualiti mekanikal, ketepatan dimensi dan kualiti bahagian. Komposisi 1, dihasilkan sepenuhnya daripada bahan dara mendapat markah tertinggi dalam semua ujian, termasuk ujian tegangan, hentaman, kekasaran, kilasan, mampatan dan kekerasan. Dua faktor penyumbang terpenting untuk menilai kualiti mekanikal PA-12 pada tahap gred tinggi ialah output 60 watt laser dan ketebalan 0.06 mm lapisan. Di samping itu, dengan ketebalan lapisan 0.06 mm dan kuasa laser 60 watt, ujian ketepatan dimensi mendedahkan 100% bahan tulen untuk paksi X dan Y, menunjukkan ketepatan yang tinggi dalam kajian ini dengan pencapaian ketepatan dimensi adalah 0.14 mm bagi paksi-X and 0.11 mm, dan paksi-Y, kedua-dua berada dalam had toleransi ±0.1% yang boleh diterima, menunjukkan bahawa komposisi bahan dan parameter proses meningkat dengan baik. ketepatan dimensi ini lebih baik daripada piawaian pengilang. Oleh itu, kajian ini telah membuktikan bahawa mengenali bagaimana parameter proses mempengaruhi ketepatan adalah penting untuk mencapai ketepatan yang tinggi dalam penghasilan objek bercetak 3D.

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AM	-	Additive manufacturing
d	-	Laser beam diameter
ED	-	Energy density
h	-	Scan spacing, hatch distance
P	-	Laser power
PA-12	-	Polyamide-12
SLS	-	Selective Laser Sintering
υ	-	Laser beam speed
CP	-	Composition Material

LIST OF PUBLICATIONS

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2. Omar, M. R., Abdullah, M. I. H. C., Alkahari, M. R., Hussin, M. S.F., Abdullah, R., Abdollah, M. F., Subramaniam, M. and Ibramsa, R. S., 2022. Effects of Different Polyamide (PA-12) Composition on Dimensional Accuracy in Selective Laser Sintering. *Lecture Notes in Mechanical Engineering*, 4, pp. 31-36.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Many industries have recognized 3D printing as the production approach of the future. 3D printing is able to create a three-dimensional object of practically every shape from a digital model (Jamadi et al., 2023). Nowadays, 3D printing is becoming increasingly popular among manufacturers. The demand growth is due to the revolutionary benefits 3D printing is able to offer. 3D printing permits the conception and production of more unique details than conventional manufacturing techniques. In addition, the traditional methods impose design limitations that are no longer compatible to 3D printing. Furthermore, 3D printing manages to speed up the prototyping process by producing parts in hours, enabling quicker completion of each phase (Abdallah et al., 2023). One of the most prominent additive manufacturing techniques is selective laser sintering, which allows the fabrication of complex shapes from a variety of materials such as polymers, ceramics, and metals (Ngo et al., 2018).

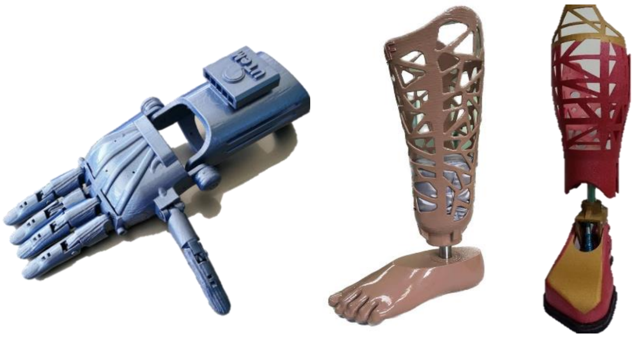

Figure 1.1: 3D Printing Biomechanical Hands and Prosthetic Legs

Figure 1.1 above demonstrates how 3D printing, particularly through Selective Laser Sintering (SLS) has revolutionized the production of biomechanical hands and prosthetic legs. This technology has replaced conventional methods by offering cost-effective, ultra-lightweight, and robust designs, making prosthetic devices more accessible, durable, and tailored to individual needs. One of the famous 3D printing approaches is SLS, an additive manufacturing process that allows the fabrication of three-dimensional structures by melting powdered material layer by layer using a laser according to the product's geometry. Selective laser sintering is a widely adopted additive manufacturing technique that utilizes laser energy to selectively fuse polymer powders layer-by-layer to create complex three-dimensional parts. The popularity of polyamide 12 as a material choice for SLS can be attributed to its desirable thermal characteristics, including a relatively low melting point, high thermal stability, and good mechanical properties (Yang et al., 2020). However, a key challenge associated with the repeated exposure of polyamide 12 powders to high temperatures during the SLS process is material degradation, which can negatively impact the mechanical performance of the final printed components. Recent studies have focused on investigating the influence of various SLS process parameters on the mechanical properties of polyamide 12 parts and dimensional accuracy (Schneider and Kumar, 2020).

The microstructure and mechanical properties of 3D-printed objects have been influenced by virgin and recycled PA-12 powders (Rosso et al., 2020). PA-12 commonly used in SLS, features particle sizes ranging between 40 and 70 micrometers in diameter (Su et al., 2022). Results from Brydson, (2021) showed that the powder forms well and conforms to the forming parameters of an SLS machine. PA-12 offers a unique balance of mechanical strength, flexibility, and chemical resistance, making it an ideal candidate for creating durable and functional parts in industries such as automotive, aerospace, and medical devices. PA-12 lower melting point compared to other polyamides like PA-6 and PA-66 allows for easier processing and better fusion of powder particles during the SLS process, resulting in parts with superior surface finish and dimensional accuracy (Sanders et al., 2024). Additionally, PA-12 also lowers moisture absorption rate is critical in maintaining the mechanical integrity of the final printed parts, preventing warping or dimensional changes over time. In comparison to other polyamide grades, PA-12 stands out for its specific advantages in 3D printing applications. Unlike PA-6 and PA-66, which have higher melting points and are more prone to brittleness, PA-12 lower melting point facilitates a more controlled sintering process, producing parts that are both flexible and strong. Its reduced moisture absorption also ensures better performance in humid environments, making it more reliable for use in various conditions. Furthermore, PA-12 superior chemical resistance compared to other polyamides makes it suitable for applications where exposure to corrosive substances is a concern, further highlighting its versatility in industrial applications.

Optimize the SLS process using PA-12, the Taguchi L9 orthogonal array was selected for this study. This statistical approach is particularly advantageous because it allows for the efficient exploration of multiple factors such as layer thickness and laser power while minimizing the number of experiments needed (Narayana and Venkatesh, 2019). The Taguchi method aims to identify the optimal combination of parameters that will yield the highest accuracy in the calibration blocks, while also minimizing variability. This approach not only saves time and resources but also ensures that the findings are robust and applicable to real world manufacturing scenarios.

This study focuses on the optimization of dimensional accuracy in calibration blocks produced via Selective Laser Sintering (SLS) using PA-12 material. It systematically examines the effects of varying layer thicknesses, laser power, and PA-12 composition on the accuracy of the fabricated components. The Taguchi L9 method systematically examines nine different combinations of these critical parameters, enabling a comprehensive understanding of their individual and combined impact on accuracy. Through detailed statistical analysis, including signal-to-noise ratio and analysis of variance ANOVA, the study aims to identify the optimal settings that maximize accuracy while minimizing variability.

1.2 Problem Statements

Additive manufacturing (AM) techniques, such as SLS have revolutionized the production of complex 3D structures by offering precise material deposition, faster production times, and cost-efficiency, while enabling the creation of intricate, high-quality parts (Ngo et al., 2018; Sinha et al., 2021; Yao et al., 2020). Despite these advancements, the use of recycled PA-12 materials in SLS presents challenges, particularly in high-performance applications where mechanical strength is important. Recycled PA-12 often shows lower tensile strength compared to virgin materials due to the breakdown of polymer chains during the recycling and reheating processes, which undermines the materials structural integrity (Frölich et al., 2024). This degradation highlights the need to investigate the impact of different PA-12 material compositions virgin, recycled, and reheated on mechanical properties to determine their suitability for various applications.

Moreover, while SLS is a versatile AM method capable of producing complex, support-free structures, it is also prone to challenges such as material shrinkage, dimensional inaccuracies, and poor surface finishes, which often necessitate post-processing to achieve higher quality (Yao et al., 2020). The use of recycled or reheated PA-12 materials exacerbates these issues due to the degradation caused by repeated thermal cycles, leading to reduced mechanical properties and dimensional accuracy (Vendittoli et al., 2023). Therefore, balancing cost-efficiency and performance requirements through material optimization is critical. This research will systematically explore these concerns by analyzing the effects of material composition on the SLS process.

This study aims to investigate the effect of PA-12 material composition on the dimensional accuracy of products fabricated through the SLS process. Using the Taguchi L9 Design of Experiment (DOE) approach, key processing parameters such as laser beam power and layer thickness will be optimized to improve both mechanical properties and dimensional accuracy (Frölich et al., 2024). By evaluating the use of virgin, recycled, and reheated PA-12 powders, the study will further explore the relationship between material composition and dimensional accuracy, while also conducting a cost analysis to assess the economic viability of different material compositions (Hofland et al., 2017). The goal is to enhance overall production efficiency, minimize material waste, and improve cost-effectiveness in the SLS process.

1.3 Research Objectives

i. To investigate the effects of PA-12 material composition by comparing virgin, recycled, and reheated material on the mechanical properties using the Selective Laser Sintering method.

ii. To optimize the mechanical properties of PA-12 materials by applying the Taguchi L9 Design of Experiment (DOE) approach.

iii. To investigate the effect of PA-12 material composition on the dimensional accuracy of products fabricated through the SLS process.

1.4 Research Scopes

The scope of this study is limited to the following:

i. Investigate the effects of PA-12 material composition comparing virgin, recycled, and reheated states on the mechanical properties using the Selective Laser Sintering (SLS) method, including analyzing ultimate tensile strength, torsion test, compression test, impact test, rockwell harness, roughness and surface morphology.

ii. Optimize the mechanical properties and dimensional accuracy of PA-12 materials by applying the Taguchi L9 Design of Experiment (DOE) approach, considering parameters such as laser beam power, material composition, and layer thickness.

iii. Examine effect of PA-12 material composition on the dimensional accuracy of products fabricated through the SLS process, focusing on variations in material composition.

1.5 Hypothesis

The Hypothesis of this study is limited to the following:

i. PA-12 materials in virgin, recycled, and reheated states will exhibit significant differences in mechanical properties, such as tensile strength and yield strength, when processed using the SLS method. Specifically, recycled and reheated PA-12 may show altered mechanical performance compared to virgin PA-12.

ii. The application of the Taguchi L9 Design of Experiment (DOE) approach will enable the optimization of both mechanical properties and dimensional accuracy of PA-12 materials. Key parameters such as laser beam power, material composition, and layer thickness will interact to influence the performance and accuracy of the SLS process, with optimal settings yielding improved results.

iii. The dimensional accuracy of products fabricated through the SLS process will vary depending on the PA-12 material composition virgin, recycled, and reheated. Differences in composition will affect the precision of the final dimensions of the products.