THE ENHANCEMENT OF PROCESS PARAMETERS TO IMPROVE MICROSTRUCTURES AND MECHANICAL PROPERTIES OF TI-6AL-4V ALLOY PRODUCED BY SELECTIVE LASER MELTING

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DEDICATION

My sincere thanks to Allah SWT and to my family especially my loving parents, Sadali Bin Wahab and Sartina Binti Serus, who taught me that the best kind of knowledge to have is what is learned for its own sake. I also dedicated to my family members, who always gives me motivation and inspired me to be better when I am at my lowest. Last but not least, I am dedicating this to my friends who have supported and encouraged me throughout the process.

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ABSTRACT

Additive manufacturing (AM) is a powder bed process for the build-up of parts by the distribution of material in which laser power melts the powder layer by layer as generated from a three-dimensional (3D) model design. Selective laser melting (SLM) is an AM method that enables the manufacture of complex geometries, lighter and stronger parts. In this research, the SLM parameters like scanning speed, laser power, and hatching distance were studied using Ti6Al4V powder. The influence of parameters on the surface morphology, surface roughness, and hardness of Ti6Al4V parts was characterised using field emission scanning electron microscope (FESEM), hardness tests, and 3D profiler analysis. In addition, the surface morphology was studied to prove its significance in terms of micropores, balling, and splashing effects. Results showed that the quality of produced parts from SLM was significantly affected by various manufacturing parameters. Hence, the orthogonal array design of experiment was conducted, and statistical analysis with signal-to-noise response was used to obtain the optimal SLM parameters. The experimental outcomes showed that laser power had a high impact on density. Besides, a confirmation experiment was carried out by using optimal parameters (P = 175W, v = 852.5mm/s, and h = 0.13mm) and it was proven that the density increased to 99.933%. The optimal parameter was then implemented to produce body cubic centric (BCC), body cubic centric in Z direction (BCCZ), body cubic centric Z direction in centre (BCCZC), face cubic centric (FCC), and face body cubic centric (FBCC) Ti6Al4V lattice structures. The mathematical modelling, finite element analysis, and experimental studies were conducted to predict and compare the quality of the SLM product. It was discovered that the BCCZ had the highest strength at 5000 MPa. Moreover, the strut and fractured struts were examined to carry out the microcrack and void effect on the strut. The Ashby graph was deployed and the lattice structure was in the range of Ti6 strength. Based on this, the optimal SLM parameters were observed to produce a Ti6Al4V part which had the potential for aerospace, automotive, and biomedical industries. It can be highlighted that this study approached the national policy on Industrial Revolution 4.0 (4IR) through future technologies.

ABSTRAK

Pembuatan tambahan (AM) ialah proses membina produk melalui penambahan serbuk bahan di mana kuasa laser mencairkan serbuk lapisan demi lapisan yang dihasilkan daripada reka bentuk model tiga dimensi (3D). Pemilihan laser pencairan (SLM) ialah kaedah pembuatan tambahan yang menghasilkan geometri yang kompleks, ringan dan lebih kuat. Dalam penyelidikan ini, parameter SLM seperti kelajuan imbasan, kuasa laser, dan jarak penetasan dikaji menggunakan serbuk Ti6Al4V. Pengaruh parameter pada morfologi permukaan, kekasaran permukaan, dan kekerasan bahagian Ti6Al4V telah dicirikan menggunakan mikroskop pengimbas pelepasan medan elektron (FESEM), ujian kekerasan, dan analisis pemprofilan 3D. Selain itu, morfologi permukaan dikaji untuk membuktikan kepentingannya dari segi mikropori, pembebolaan, dan kesan percikan. Keputusan mendapati bahawa kualiti bahagian yang dihasilkan daripada SLM banyak dipengaruhi oleh pelbagai parameter pembuatan. Oleh itu, kaedah reka bentuk eksperimen tatasusun ortogon telah dijalankan, dan analisis statistik dengan tindak balas isyarat-ke-bunyi telah digunakan untuk mendapatkan parameter SLM yang optimum. Keputusan eksperimen menunjukkan bahawa kuasa laser mempunyai kesan yang tinggi ke atas ketumpatan. Tambahan pula, eksperimen mengesahkan dengan menggunakan parameter optimum (P = 175W, v = 852.5mm/s, dan h = 0.13mm) dan membuktikan bahawa ketumpatan meningkat kepada 99.933%. Parameter optimum kemudiannya digunakan untuk menghasilkan struktur kekisi kiub berpusat (BCC), kekisi kiub berpusat arah tegak (BCCZ), kekisi kiub berpusat arah tegak jasad (BCCZC), kekisi kubus berpusat muka (FCC), dan kekisi kubus berpusat kiub (FBCC) Ti6Al4V. Pemodelan matematik, analisis unsur terhingga dan kajian eksperimen telah dijalankan untuk meramal dan membandingkan kualiti produk SLM. Berdasarkan keputusan, BCCZ telah direkodkan sebagai mempunyai kekuatan tertinggi pada 5000 MPa. Tambahan pula, struktur tupang dan struktur tupang yang patah telah diperiksa untuk menjalankan kesan retak mikro dan lompang pada tupang. Graf Ashby telah digunakan dan mendapati bahawa struktur kekisi berada dalam julat kekuatan Ti6. Berdasarkan keputusan itu, parameter SLM yang optimum telah diamati untuk menghasilkan produk dari Ti6Al4V yang mempunyai potensi untuk industri aeroangkasa, automotif dan bioperubatan. Dalam kajian ini, dapat diketengahkan bahawa topik ini mendekati dasar revolusi industri keempat (4IR) negara melalui teknologi masa depan.

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LIST OF ABBREVIATIONS

AM	-	Additive Manufacturing
BCC	-	Body Cubic Centric
BCCZ	-	Body Cubic Centric with Z-struts
BCCZC	-	Body Cubic Centric with Z-struts in Centre
CAD	-	Computer Aided Design
DMLS	-	Direct Metal Laser Sintering
FDM	-	Fused Depositing Material
FEA	-	Finite Element Analysis
FCC	-	Face Cubic Centric
FBCC	-	Face Body Cubic Centric
FGL	-	Functional Graded Lattice
FESEM	-	Field Emission Scanning Electron Microscope
IGES	-	Initial Graphics Exchange Specification
LENS	-	Laser Net Shaping
RSM	-	Response Surface Methodology
SEM	-	Scanning Electron Microscope
SLM	-	Selective Laser Melting
STL	-	Stereolithography
TM	-	Taguchi Method
VED	-	Volumetric Energy Density

LIST OF SYMBOLS

ρ	-	Density
$\Delta\rho$	-	Density error
ρ_w	-	Density water
$\rho_{titanium}$	-	Density Titanium
ω	-	Angle of struts
A	-	Absorption Coefficient
D	-	Distance
E_0*	-	Normalized equivalent energy density
E_c	-	Young modulus
h	-	Hatching distance
l	-	Length of struts
M	-	Maxwell number
N	-	Noise
n	-	Nodes
p	-	Pressure
r	-	Diameter of struts
S_E	-	Error sum of the square
S_m	-	Mean sum of the square
S_T	-	Total sum of the square
s	-	Struts
S	-	Signal
t	-	Thickness
T_o	-	Solidified Temperature
T_m	-	Melting Temperature
v	-	Velocity
W	-	Watt
W_1	-	Weight initial
W_2	-	Weight final

CHAPTER 1

INTRODUCTION

1.1 Research Background

Additive manufacturing (AM) is defined by the French Standard NF E 67-001 AFNOR (2011) as the method of creating three-dimensional objects by slicing material onto a CAD model and saving the file in Standard Tessellation Language (.STL) format. Figure 1.1 shows the AM process, where the STL (Figure 1.1(a)) represents the actual design that dictates the size and shape of the component. As a result of the exquisite triangulation, a high-quality product can be produced. The programme combines the file into layers (Figure 1.1(b)), which are sent to the AM device (Figure 1.1(c)) as instructions for constructing the components (Figure 1.1 (d)) (Kusuma, 2016). In general, the AM method requires the material to be metal powder. However, fused deposition modelling (FDM) uses material in wire form. This tool less process may manufacture excellent metallic parts precisely and reduce the finishing procedures like polishing, sanding, curing, or filing. Also, programmed tool paths such as undercuts and draught angles are not required for this technique.

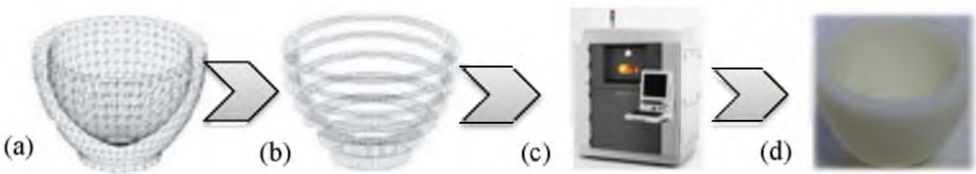

Figure 1.1 The Process of AM Method (a) Creation of Electronic Design File (.STL) using CAD, (b) Modelling of Software Slices into Cross-Sectional Layers, (c) AM Machines Following the Design, (d) Production of Final Object.

Popular additive manufacturing processes are photopolymerization, material jetting, material extrusion, powder bed fusion, binder jetting, sheet lamination, and directed energy deposition, as shown in Figure 1.2. Photopolymerization uses the stereolithography and digital light processing (DLP) methods, where cross-section of a part of the liquid resin's surface is traced by a laser beam. The resin is inserted and immersed in a chemical bath. The cross-section of the part is swept across with a blade and re-coated with new material. The material jetting uses the drop-on technique similar to multi-jet modelling (MJM). The material is deposited via a nozzle that moves horizontally across the build platform, with the print head above it. Then, the material layer is hardened or cured using ultraviolet (UV) light. In contrast, binder jetting is a printing technique that uses glue or binder to be jetted from an inkjet print head using the powder bed inkjet 3D printing (PBIH) method. On top of the previous layer, a new layer of powder is distributed with the roller. The jetted binder is then printed on the next layer and bonded to the previous one. Material extrusion is a fuse deposition modelling (FDM) technique. The material is drawn through a heated nozzle and then deposited layer-by-layer. The layers fuse upon deposition as the material is in a melted state. Powder bed fusion is the typical technique used for selective laser sintering (SLS), selective laser melting (SLM), and electron beam melting (EBM). The material powder layer is spread over the build platform, and the laser fuses the layer powder. The new layer of powder is applied by roller or blade. Furthermore, the next layer is then mixed and applied (B. K. Gu et al., 2016). The technique is repeated until the model is complete. However, the aggregate powder in the powder bed is preheated by the SLS machine. Sheet lamination uses a metal sheet positioned on the cutting bed, referred to as laminated object manufacturing (LOM). The laser beam cuts the contours of each layer. Then, the material is bonded with the previous layer using adhesive or glue activated by hot rollers. Directed energy deposition (DED) consists of laser metal deposition with the nozzle mounted on a multi-axis arm moveable in multiple directions. The material is melted when the material is deposited using a laser, electron beam, or plasma arc. In addition, the material is applied in layers and solidified to manufacture or repair an existing object.

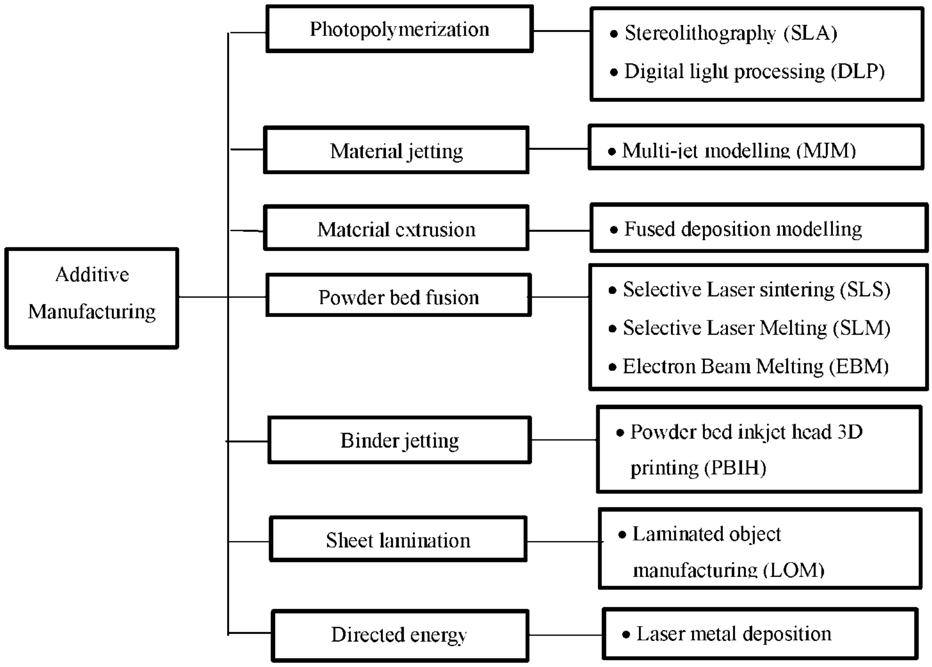

Figure 1.2 AM Technologies with Different Methods and Techniques (Cotteleer et al., 2014).

SLM (selective laser melting) is a revolutionary additive manufacturing (AM) process that first appeared in the late 1980s (Nolan, 2014). This procedure begins with slicing the STL-formatted 3D CAD file data and creating a 2D image of each layer. Then, the data file is transferred to a pre-processing software application. The software provides settings, physical supports, and values to the file, allowing the object to be created by many types of additive manufacturing machines. Following the design, the SLM emerges the raw materials until the final object is produced.

In SLM, the part is constructed on top of a base plate or substrate in the build cylinder. A feed container is located next to the build cylinder (also called powder depositor). By lowering the build cylinder and elevating the feed container, the powder depositor evenly deposits a thin layer of powder metal on top of the metal substrate plate. Following layer deposition, a cross-section of the object to be constructed is scanned with a laser emitting hundreds of watts of power, such as an Nd: YAG or ytterbium fibre laser (Seok et al., 2020). These cross-sections are generated using the CAD model preparation tools. Heat is applied to the material via scanning the powder layer's surface, which absorbs the energy. The layer powder melts, and the molten pool immediately solidifies. The material that has consolidated begins to form the product. Then, the build platform is lowered by the thickness of the layer, and a powder depositor is used to deposit a fresh layer on top of the previous one (Wits et al., 2021). The technique continues layering until the part is finished, as shown in Figure 1.3. The whole printing process is carried out in a chamber with nitrogen or argon-based inert gas environment. SLM techniques were selected for this study since the SLM methods are suitable to produce a high-quality, dense pack, and surface finish, particularly for metal alloys such as Ti6Al4V.

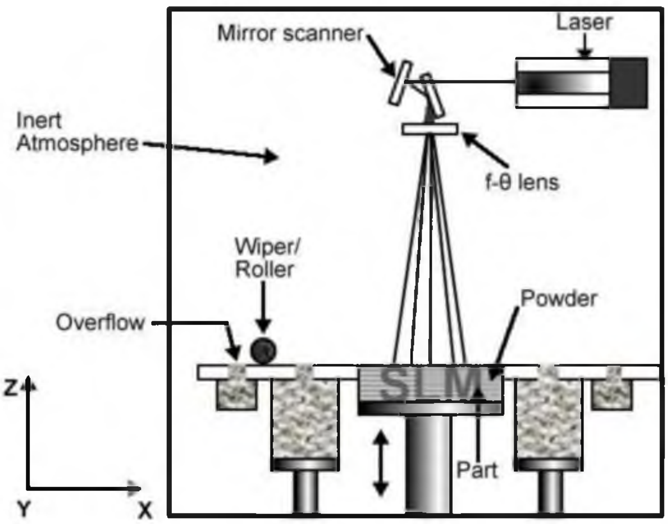

Figure 1.3 Process of SLM (Sidambe, 2014).

Powder metals and wire that AM use must fulfil two requirements, such as excellent weldability to prevent cracks during solidification and spherical particles with a size of a few microns to ensure adequate packing density, and uniformity of the powder deposition. The most frequent and mature metallic alloys produced by AM are

Ni-based superalloys (Inconel 625, 718 and Hastelloy X), tool steels (H13 and maraging 300), Co-Cr alloys (Co28Cr6Mo), Al-based alloys (AlSi12, AlSi10Mg, 5083, 6061, 7050), and Ti-based alloys (commercial purity grade 1, grade 2, Ti6Al4V).

Ti6Al4V powder alloy is most widely utilised for SLM techniques to produce medical devices and parts. It has a high-temperature stability, excellent specific strength, attractive mechanical properties, corrosion resistance, high strength, lightweight, and low density to make a high-performance part. It is considered more substantial than some other titanium compounds (Kadirgama et al., 2018).

Today, Ti6Al4V powder is mainly used in the SLM method and considered more robust than some other titanium compounds. It has been widely used in biomedical, space, military, aerospace, and automotive industries (ISO 1997). According to Luo et al. (2020), SLM is used to construct scaffold materials with diamond cellular structures to meet the load-bearing function of bone tissues (Luo et al., 2020). Fiocchi et al. (2020) revealed that the Ti6Al4V trabecular structure produced by SLM decreases vibration as in the application of dampers on aerospace parts.

1.2 Problem Statement

The quality of produced parts from SLM is significantly affected by various manufacturing parameters of the machine. The denser titanium alloy resulted in an increase in energy density, where scan speed majorly contributed to optimum condition. C. Han et al. (2018) revealed that the micropores were presented from 0.01% to 3.18% on the titanium alloys cube produced by SLM. Seifi et al. (2016) reported that Ti6Al4V produced by SLM contained defects such as voids and lack of fusion, which ultimately affected their mechanical properties. A study by Galarraga et al. (2016) suggested an average of 0.09% porosity on Ti6Al4V samples fabricated from the SLM method and these samples obtained irregular shape and spherical shape on the surface (balling effect). An experiment by M. Tang et al. (2021) found that the highest percentage of density was higher than 98.7% for Ti6Al4V samples and observed that the powder was not sufficiently melted. It was confirmed that insufficient energy density caused inappropriate scanning parameters during the fabrication process, which resulted in a defect of the product. Hence, optimisation of SLM process parameters is necessary to improve the quality of the final product. The contribution of this research is to enhance the density up to 98.7% of the Ti6Al4V samples. Therefore, this work explores the effects of SLM parameters including laser power, scanning speed, and hatching distance to reduce the defects and increase the density.

In this study, the influence of laser power, scanning speed, and hatching distance was examined to enhance the quality of the samples, particularly related to the balling effect in the creation of microcracks and micropores. Besides, improving the parameters showed an increase in the quality of products with regards to surface morphology related to the balling effect at their peak value. The balling and microcrack effect were obtained the major defects on this research. However, the hardness of the Ti6Al4V parts needs to study for prove that the fabricated part has appropriated quality. An experimental study was initially conducted to characterise the nature of the SLM-processed titanium compound, especially the impact of SLM parameters. Here, the optimum parameter to manufacture Ti6Al4V parts was found and should be utilised with the optimum value of the SLM parameter to produce bones and dental devices.

1.3 Aims and Research Objectives

This research aims to conduct an experimental study of enhancing manufacturing parameters with Ti6Al4V alloy using an SLM machine. The research objectives for this study are as below:

(a) To characterise the surface morphology, balling effects, hardness, and porosity of the Ti6Al4V fabricates using SLM at different parameters.

(b) To enhance the SLM parameters for improving the packing density of Ti6Al4V using the orthogonal experimental design (OED).

(c) To propose the lightweight lattice structure by comparing the compression strength and energy absorption of mechanical properties using the optimum conditions of the SLM parameters.

1.4 The Significance of the Research

SLM technology has the potential to increase innovation, minimise materials, compress the supply chain, and reduce waste. SLM allows manufacturing prototypes and parts on-demand, while saving time during development, design, and manufacturing processes without using any tooling. SLM technique is able to fabricate complex parts without additional cost compared to conventional manufacturing. This research has contributed to the enhancement of SLM parameters such as laser power, scanning speed, and hatching distance to reduce the defects and improve the packing density, focusing on medical and aerospace devices. Moreover, the global AM market in 2020 was estimated at 12.6 billion USD on average. Over the next three years, it is expected to grow by 17% and continue to reach 37.2 billion USD in the year 2026 (Roberts, 2021). The prediction on the AM market is shown in Figure 1.4.

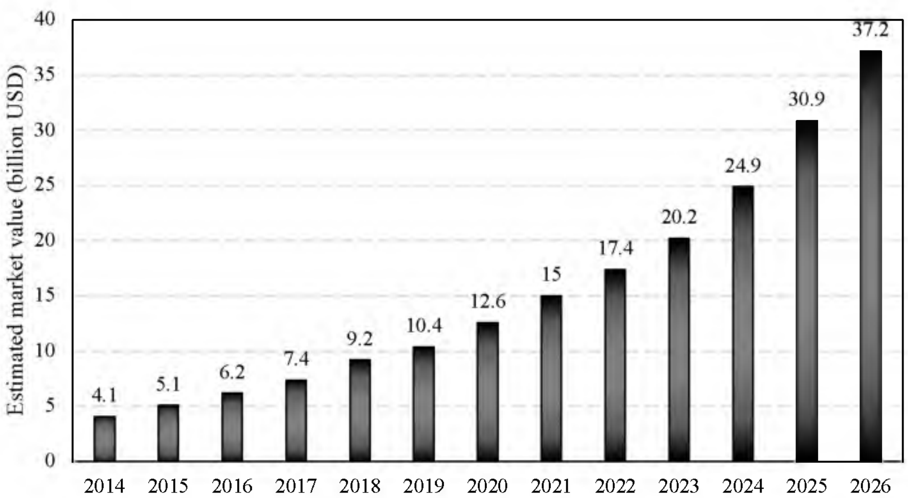

Figure 1.4 Estimated Market Growth for AM (Roberts, 2021).

Besides, additive manufacturing is one of the pillars of the Industry Revolution 4.0 (IR4.0), which is related to the latest manufacturing technology. AM technology is ready to be implemented together with internet of things (IoT) and connected to other machines through big data, which will create more intelligent machines. This technology gives an entirely automated process to a factory for production and transforms it into smart manufacturing (Idris, 2019). Nowadays, with the capabilities to manufacture and directly use parts as a functional component, the development of 4D and 5D printing is introduced as the upcoming technology for AM research.

During the COVID-19 pandemic, the AM business market has been affected due to supply chain disruption, social distancing and remote working. However, according to the survey from Hubs conducted in February 2021, the overall AM market experienced unexpected growth. The results were evaluated that 83% of AM businesses maintained and increased their AM usage, as shown in Figure 1.5. The significant factors of the growing usage of AM have been due to filling up demands of personal protective equipment (PPE) in producing masks and face shields (Roberts, 2021).

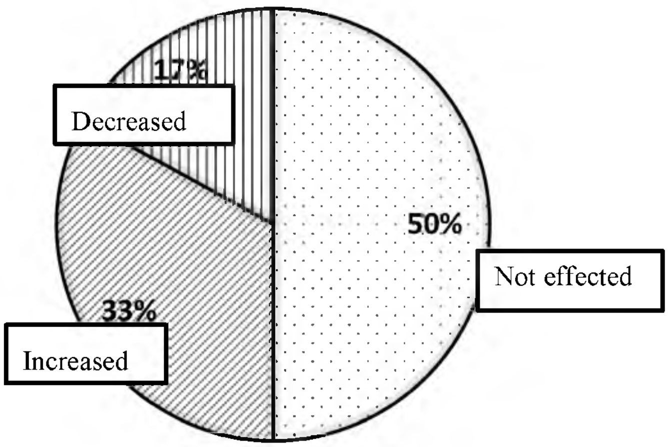

Figure 1.5 Effect of COVID-19 on AM Usage (Roberts, 2021).

1.5 Scope and Limitation of the Research

This study focused on the optimisation of SLM parameters. The parameters of manufacturing were limited to laser power, scanning speed, and hatching distance. However, the laser beam diameter, layer thickness, and machine build size were not covered in this research.

The titanium alloy grade 5 or Ti6Al4V was employed in this experiment. The material was supplied by SLM Solutions Group AG, which was suggested by the machine fabricator and prohibited to be mixed with other materials with the reason of protecting the environment and maintenance of the machine. Additionally, the grain size for Ti6AL4V powder was fixed at 30 μm due to the quality of the product fabrication.

The lattice structure has been designed based on the BCC structure and compared. The diameter of struts has been limited to 1 mm to calculate the shrinkage of the lattice structure parts. Additionally, this study compared and investigated the energy absorption capability and mechanical properties of lattice structures made of Ti6Al4V and fabricated by the enhancement SLM process.

The SLM machine was utilised as the AM technique in this research. The capabilities and accuracy of the SLM technique were outstanding for Ti6Al4V fabrications. Moreover, the ability to fine-tune the parameters has great significance in fabricating the sample. Notably, the only AM machine available in Malaysia is at KKTM Kuantan, Pahang.

1.6 Thesis Outline

For this work, five chapters are presented. In Chapter 1, the research objective, aims, and limitations of this work are discussed. In Chapter 2, the literature review is elaborated, whereby, the differences between advanced additive manufacturing and traditional methods are presented, and the types of technology, and parametrics (including powder technology) are revealed. In Chapter 3, the material and processes that were used in this study are disclosed, followed by flowcharts, sample characteristics, optimisation technique, and including mechanical properties. In Chapter 4, the resulting interpretation is scrutinised whereby, all results from the energy density, morphology, and mechanical analysis are shown. Furthermore, the results from the experiment and the field emission scanning electron microscopy (FESEM) are illustrated and described in detail pertaining to surface morphology, micropores, and microcracks. In Chapter 5, the conclusion for all the research findings is discussed. The main findings of this thesis regarding improvement of the new parameter by using the Taguchi method and reduction of the porosity on the process parameter of SLM are explained.

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1. **MF Sadali,** MZ Hassan, F Ahmad, H Yahaya, ZA Rasid. Influence of selective laser melting scanning speed parameter on the surface morphology, surface roughness, and micropores for manufactured Ti6Al4V parts. *Journal of Materials Research, 35 (15),* 2025-2035. https://doi.org/10.1557/jmr.2020.84 **(Q3, IF: 3.089)**

Indexed Journal

1. **Sadali, M.F.,** Hassan, M.Z., Ahmad, N.H., Yahya, H., Nor, A.F.M. Effect of hatching distance on surface morphology and surface roughness of the TI6AL4V for biomedical implant using SLM process. *Malaysian Journal of Microscopy, 15(1),* 72-82. **(Indexed by SCOPUS)**

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2. M Subramaniam, M Z Hassan, **M F Sadali**, I Ibrahim, Y Daud, S A Aziz and S Sarip (2018). Evaluation and Analysis of Noise Pollution in the Manufacturing Industry. *9th International Conference on Mechanical and Manufacturing (ICME' 2018)* doi:10.1088/1742-6596/1150/1/012019 **(Indexed by SCOPUS)**

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1. **M F Sadali.,** M Z Hassan. Tensile Behaviour of Polylactide Acid Strut for 3D Filament Printing. *7th International Graduate Conference on Engineering, Science and Humanities (IGCESH 2018),* 508–510. **(Indexed by SCOPUS)**