MECHANICAL PERFORMANCE OF 3D- PRINTED TI-6AL-4V

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STATEMENT OF CANDIDATE

I, Yuefeng Yu, declare that this report, submitted as part of the requirement for the award of Bachelor of Engineering in the Department of Mechanical Engineering, Macquarie University, is entirely my own work unless otherwise referenced or acknowledged. This document has not been submitted for qualification or assessment an any academic institution.

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Date: November 1, 2017

Abstract

Titanium alloys has a wide range of applications in the industry especially in aerospace industry and biomechanical applications. The Ti-6Al-4V is a α- β phase titanium alloy with high strength, low weight ratio and high corrosive resistance. The traditional manufacturing such alloy takes plenty of time and money to achieve required features when compared to 3D-printed method. 3D printing is famous for the efficiency as well as the geometry shape it can create but there are lots of settings when manufacturing it such as the thickness of the layer and the moving speed of the nozzle. In this paper, samples with 60μm layer thickness and 1029mm/s scanning speed using selective laser melting(SLM) method will be studied, and focus on the harness mapping along the building direction before and after heat treatment as well as the microstructure. The connection between the dimensions of the samples and its related mechanical features will be discussed as well.

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Chapter 1

Introduction

Titanium is an important structural metal developed in 1950s. It is characterized by small density, high mechanical strength and easy processing. The plasticity of titanium mainly depends on its purity. The purer the titanium is, the greater the plasticity is. The density of titanium is higher than that of aluminium, but lower than that of iron, copper and nickel, but the specific strength is at the head of the metal.[1] Titanium alloy has high strength, good corrosion resistance and high heat resistance. The working temperature range of titanium alloy is wide, low temperature titanium alloy keeps good plasticity in -253°C, and the working temperature of heat resistant titanium alloy is about 550°C, the heat resistance was significantly higher than that of aluminium Alloy and magnesium alloy. [2][3]

Also, Titanium and titanium alloy has excellent corrosion resistance, especially high corrosion resistance in seawater and marine atmospheric environment, which has great advantage in the application in the ship and water on the plane. The application of this material is limited by its manufacturing technique, since titanium alloys are hard to machine. Raw material is not the main problem, the issue is the chemical activity of titanium is very high, very susceptible to hydrogen, oxygen, nitrogen pollution. As mentioned, the more impurities existed the harder for smelting and processing. In addition, titanium alloy process better mechanical performance than pure titanium which leads to high production cost.

Titanium alloys are applied in many areas such as aerospace and biomedical aspects. Total aerospace raw material demand through the year 2020 is projected to grow at an annual rate of 0.9 percent, with titanium alloys occupying a healthy 13 percent of a 1.6-billion pound market (compared with aluminium alloys at 44 percent, composites at 6 percent, and superalloys at 10 percent).[4] The efficiency of the traditional manufacturing method is low and now there is a new method to manufacture titanium product with high efficiency and lower production cost, 3D printing technology. This new technology reduces time in shaping the material and unlike factories it safes space and minimise the waste during the manufacturing process. However, this technology is not yet suitable for large scale manufacturing, only capable for small components. The overall mechanical properties cannot fulfil most the real-life situations when compare to the product from industrial manufacturing.

Improving the mechanical performances of the 3D printed product is the key to develop this new manufacturing technology. This paper will focus on 3D printed Ti-6Al-4V created by selective laser melting method and investigate the hardness along the building direction. During the 3D printing process, the raw material will be melt with high temperature. The finished product contains lots of residual stress and affect the mechanical performance. Proper heat treatment can improve this situation and the samples after heat treatment will be compared with the original samples which not going through heat treatment to find out their connections.

1.1 project goals

The goal of the project is to investigate the mechanical performance of the 3D printed Ti-6Al-4V before and after heat treatment. The printed sample will be divided into serval parts for different types of heat treatment to study how the heat treatment is related to their mechanical properties. The two types of the heat treatment are called stress relief and performance enhancing. Certain results will be acquired in this project, such as:

- All samples will go through the scanning electronic microscopy (SEM) to obtain the microstructure.
- Hardness mapping will be proceeded on the surface that can indicate the characteristics on both building direction and along the layer.
- Samples will be divided into parts to go through different heat treatments.

Analysis on the results will be discussed. Different methods will be applied to study the relationship among the data, including:

- Finding the average, maximum, minimum and the standard deviation of the hardness value from the sample.
- Compare the results between the original and the sample after different heat treatment, and find out the relationship among them.
- Compare the microstructure of the all samples and see if there are any significant changes appears.
- Using statistic method to analyse the data obtain from the sample to observe the difference
- Find out the relationship among hardness along the building direction and within the same building layer.
- Compare the results with the hypothesis
- Recommendations for the future work on this project.

1.2 Motivation for thesis

The applications and demand of titanium alloys are increasing dramatically, especially on aerospace and medical aspect. [5] 3D printed titanium alloy is proved to be stronger than those manufacture by traditional means. However, unexpected facture occurs and leads to catastrophic failure quite often. The main reason of such accidents is that the microstructure of this alloys cannot process high damage tolerance. This project aims to enhance its mechanical properties by starting to examine the relationship between the microstructure and the hardness, which provides a direction for how to improve this product and creates ideas about how to tailor microstructures for the achievement of a great combination of strength and fracture toughness. The outcomes are expected to address knowledge gaps in 3D printing of high-performance titanium alloys.

The industrial manufacturing method is the main stream even the cost is much higher the new technique, since there are still lots of limitations. This project will focus on one of them and try to minimize the gap. The results of the project provide information about how to improve current titanium 3D printing technology, and enhance the quality of the product.

1.3 project plan

Project pan is a schedule about the time allocation of the project and it is essential part to make sure the whole project will finish in time and deliver expected results. The original plan is created at the beginning of the project, but due to unexpected issues such as equipment breakdown, material delivery time behind schedule; the original plan needs to be modified to adapt the situation. Both original plan and the actual timeline are shown below in table 1.1 and 1.2.

The initial plan gives lots of time for all the steps related to the project by considering some issues might happen and affects the whole schedule. Before making the plan, certain factors that might cause negative impacts are already been considered. This whole project includes sample preparation, machining, hardness testing, scanning and heat treatment. All steps can be done in labs which means booking appointments for accessing related instrument will be a problem. The original plan based on ideal condition, and cannot ensure the actual time when the experiments starts. In addition, the experiments are unable to proceed until the test samples are arrived, also there is orders among experiments and in different. The coordination of appointments is another key to keep the whole project running smoothly. Space is already created in the plan for unexpected issues, and meanwhile the plan will be simplified and updated when those happens.

The actual schedule shows all the activities and when they are. The main issues happened during the project are booking appointment for sample preparation and machining, sample surface scanning and the biggest problem is that the furnace for heat treatment is broken and everything else needs to put behind for 2 weeks. After all, the whole project accomplished on time and deliver useful information for further research and analysis on enhancing the mechanical properties of 3D printed Ti-6Al-4V.

	Weeks												
Tasks	1	2	3	4	5	6	7	8	9	10	11	12	13
Research on 3d printed Ti-6Al-4V													
Research mechanical properties of Ti-6Al-4V													
Hardness test and SEM													
Prepare progress report													
Research on heat treatment													
Heat treatment on samples													
Hardness test and SEM on heat treated samples													
Data analysis													
Write thesis report													

Table 1.1 Gantt chat for initial thesis plan

Tasks	Weeks												
	1	2	3	4	5	6	7	8	9	10	11	12	13
Research on 3d printed Ti-6Al-4V													
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Table 1.2 Table 1.1 Gantt chat for actural thesis plan

Chapter 2

Background and related work

2.1 Titanium alloy

The density of titanium alloy is about 4.5g/cm3, only 60% of that of steel. The strength of pure titanium is close to the strength of ordinary steel. Some high-strength titanium alloys exceed the strength of many alloy structural steels. Therefore, the specific strength (strength / density) of titanium alloy is much larger than that of other metal structural materials. It is a suitable material for parts with high unit strength, good rigidity and light quality. Titanium alloys are currently used for aircraft engine components, frames, diaphragms, fasteners and landing gear.

The industrial production of titanium began in 1948. The development of the aviation industry makes the titanium industry develop at an average annual rate of about 8%. The annual output of titanium processing materials in the world has reached 450 kilotons [6]

Titanium is an important structural metal developed in 1950s. Titanium alloy has been widely used in various fields because of its high strength, good corrosion resistance and high heat resistance. Many countries in the world have recognized the importance of titanium alloy materials, and have carried on the research and development of them, and have been applied in practice.

2.1.1 Ti-6Al-4V

The first practical titanium alloy Ti-6Al-4V alloy is successfully developed in the United States in 1954, because of its heat resistance, strength, toughness, ductility, formability, weldability, corrosion resistance and biocompatibility are better, and become the ace titanium alloy industry, the alloy consumption has accounted for titanium alloy from 75% to 85%. Many other titanium alloys can be regarded as the modification of Ti-6Al-4V alloy also known as grade 5 titanium. It has a chemical composition of 6% aluminium, 4% vanadium, 0.25% (maximum) iron, 0.2% (maximum) oxygen, and the remainder titanium[7]

The working temperature is a few hundred-degree Celsius higher aluminium alloy, also can maintain the required strength at moderate temperatures at 450 ~ 500°C under long service time. The working temperature of titanium alloy can reach 500 degrees, while that of aluminium alloy is below 200 since the specific strength of it decrease significantly when it is heated up 150°C.

Ti-6Al-4V is available to work in humid atmosphere and seawater medium, its corrosion resistance is much better than that of stainless steel. Besides, its resistance to pitting corrosion, acid corrosion and stress corrosion is especially strong, also has excellent corrosion resistance against organic matter, nitric acid and alkali, chloride and chlorine, nitric acid, sulfuric acid and so on. [8]

After all the strength when compared with popular alloys in real life situation, the limitations of its development are outstanding as well. It has poor thermal conductivity, large friction coefficient and poor wear resistance, so in the cutting process, it is easy to make the workpiece and tool temperature rise, causing sticky knife, reduce tool life. Pure titanium has high chemical activity and is easy to be polluted by hydrogen, oxygen and nitrogen. It is difficult to smelt and process, which makes the production cost higher.

2.1.2 Raw material

Titanium is abundant in the earth, the crust abundance is 0.61%, and seawater contains titanium 1 x 10^{-7}%, and its content is higher than that of common copper, nickel, tin, lead and zinc.[9] There are about 140 kinds of titanium minerals known, but the industrial applications are mainly ilmenite ($FeTiO_3$) and rutile (TiO_2)

According to United States Geological Surve (USGS) report on titanium ore across the globe in 2015, the overall reservation is around 2 billion tonnes. The identified reserves of both ilmenite and rutile is 750 million tonnes. The report also presents the reserves of both mineral in different countries, and from the table below, China process most of the ilmenite reserves in the world and Australia is the country that owns most of rutile reserve. It is obvious that the world total reserves on ilmenite and rutile is around 750 million tonnes. [10]

2.1.3 Application

In the 32nd annual conference and exhibition produced by the International Titanium Association (ITA), guest speakers from Russia and Europe Union (EU) presents their titanium market demand by application. Figure 2.1 below shows almost two thirds of the titanium demand are from aerospace area in EU, and the estimation of EU aerospace titanium demand (Figure 2.2) will reach 25,000 metric tonnes by 2020 while in 2014 the actual demand is around 10,000 metric tonnes.[3]

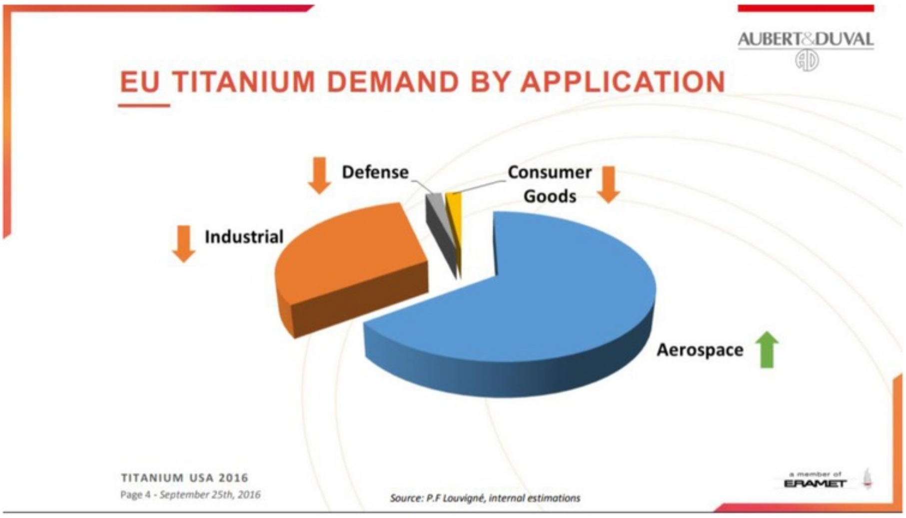

Figure 2.1 EU titanium demand by application[3]

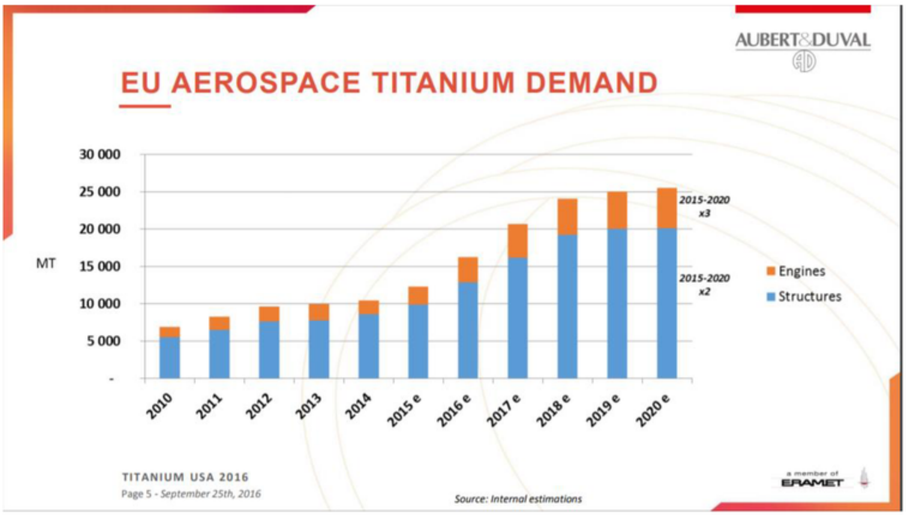

Figure 2.2 EU aerospace titanium demand[3]

The application of titanium in aircraft mainly has the following places. First is the engine. The titanium content of each engine is 20 to 30% of the total weight of the engine. Most of them are components of the compressor, including the blade, hub, inlet guide valve and shell. Second, is the plane frame, with the amount of titanium in this part also great. Because of the its high strength, titanium alloy is considered to be one of the best choice for framework, especially the middle and back section of the frame. The middle section is the wing and fuselage connection section, which experiencing the biggest force among the whole frame. The latter section is the engine installation place, also an important force bearing part. Third, is landing gear. Many aircraft crashes are on the rise and fall, because the aircraft landing load and impact force is very large, so the requirements for landing gear is extremely high. The selection of titanium alloy not only ensures the performance of high strength and impact resistance, but also is lighter than the choice of high quality steel. [11]

Another main application of Ti-6Al-4V is in biomedical aspect. Artificial joints and artificial bone substitute materials should have the following properties: lightweight and high strength material, good biocompatibility, corrosion resistance, deterioration of tissue response to implants, fatigue damage and repeated stress. The most important performance of the metal implant is forming, Additivity and polishability. It must maintain the function in the expected lifetime, and will not deteriorate under fatigue, abrasion, corrosion and impact load, titanium and titanium alloy meet all the above requirements. [9][12]

The titanium alloy is the metal materials used for the repair of human hard tissues. the elastic modulus of titanium is closest to that of human tissue, which can reduce the mechanical inadaptability between metal implants and bone tissue. The thermal conductivity of titanium is the lowest in all dental metallic materials, low thermal conductivity can reduce the thermal stimulation to the dental pulp with a crown, which is very important for dental restoration. Titanium inlay, full crown and so on, have the function of protecting dental pulp, avoiding cold and hot stimulation.

2.1.4 Current shaping technique and limitations

Machining of titanium alloy includes turning, drilling, milling, tapping and grinding. It is expensive for titanium to be machined since the components are craved out of the material, and makes the leftovers become wastes. The thermal conductivity of titanium is poor, so the heat generated by machining will be absorbed by the cutting tool, which often causes premature tool failure. During the machining process, plenty of sparkles will be generate and poses potential safety risk. Therefore, in order to reduce such hazards as well as prolong the service life of the tools, machining tools always runs at low RPMs.[13][15]

To obtain desired shapes of titanium products, lots of machining methods needs to be applied, and all the parameters using in each step are different. For example, the common lathe. In the process of machining, the cutting tool material, cutting conditions and cutting time will affect the efficiency of titanium alloy cutting, there are some machining conditions need to be thought of [14][15]

- Choose reasonable tool materials

  Based on the different types of the machining titanium alloys, the material of the cutting tool is necessary to increase the efficiency and minimize the possibility of hazardous risks.

- Improve cutting conditions

  The position of the machine tool, clamps and cutting tool required to be tuned before cutting process. Before starting the operation, check if the cutting sample and cutting tool are well fixed.

- Reasonable tool geometric parameters

  Frequently check the wear down of the cutting tool is important, since the change of the geometric shape of the blade will affect the whole cutting process. When the wear down at certain critical point, it should be replaced.

- Selecting reasonable cutting parameters

Cutting force and cutting feed are the most important parameters in the cutting process. When the cutting force or cutting feed is too high, the blade will suffer overrated load, and it is not good for the whole operation.

- Proper heat treatment of the material to be processed

Proper heat treatment applied to finished product help to reduce the residual stress accumulate during machining process and enhance the mechanical properties.

- Chip control

Chips are involved during the cutting process, it will obstruct the cutting process in some way, so eliminate the chips from the sample also an important factor.

2.2 3D printing

With the rapid progress of science and technology, the machining industry continues to develop. The rapid prototyping technology, especially 3D laser printing technology plays a more and more important role in the manufacturing industry, and gradually in the manufacturing industry has been widely applied and become an integral part of the mechanical manufacturing industry. 3D printing technology is rapidly changing our traditional way of production and lifestyle.

3D printing is a metal or plastic binder as a printing material, based on digital models for printing layer by layer technology. By connecting the computer with the 3D printer, the drawing can be printed as a means of the model. Nowadays, this technology has been applied in many fields, and people use it to make clothing, building models and automobiles

In short, 3D printing is based on the common two-dimensional printing plus one-dimensional. The printer first prints a layer of powder like plastic, metal and other powder on a plane like ordinary printing, and then glue them together one by one. Through the accumulation of different layers of graphics, a three-dimensional object is finally formed.

3D printing is very different from the traditional mould production, the biggest advantage is without any moulding or mechanical processing, and it can be directly generated from the computer graphics data in any shape parts, thus greatly shorten the product development cycle, improve productivity and reduce production costs. At the same time, 3D printing can also print some complex geometry that the traditional production technology cannot create, at the same time, 3D printing technology can also simplify the entire production process, with fast and effective characteristics.

2.2.1 Different methods

As the most advanced and potential technology in the whole 3D printing system, 3D printing technology of metal parts is an important development direction of advanced manufacturing technology. According to the way of adding metal powder, the 3D printing technology is divided into three categories: [16]

- Using laser to irradiate the metal powder that spread in advance, which means the metal parts will be completely covered by powder after forming. This method is currently widely used by equipment manufacturers and scientific research institutes, including direct metal laser sintering (DMLS), selective laser melting (SLM) and laser cussing (LC);

- Using a laser irradiation nozzle conveying powder flow, and laser and powder conveying work at the same time laser engineered net shaping, (LENS).
- Electron beam melting, (EBM) The metal powder is pre-melted by electron beam melting. This method is similar to the first principles, but only with different heat sources.

2.2.2 Selective Laser Melting

Selective laser melting technology is an important part of metal 3D printing field, with its fine focal spot rapid melting 500 objective pre-set powder material, almost arbitrary shape can be obtained directly and has the function of metallurgical bonding parts completely. The density can reach nearly 100%, size precision of 20-50 microns, and the surface roughness of 20-30 microns. This is a kind of rapid prototyping technology development prospects, and its application has been extended to aerospace, medical, automotive, moulding and other fields. At present, the research and development of SLM equipment has become a hot spot in the field of rapid prototyping. [16]

SLM equipment is generally composed of optical unit, mechanical unit, control unit, process software and protective gas sealing unit. The optical units mainly include fibre laser, beam expander, mirror, scanning galvanometer and F- focus lens. Laser is the core component of SLM equipment, which directly determines the moulding quality of the whole equipment.

The following figure shows the composition of a SLM 3D printing machine. First, use 3D modelling software to create the 3D model of the designed parts, then the software will slice the model into certain layers. The number of layers generated from the software depends on the layer thickness settings. Next step for the software is to contour data for each section, and filling the scanning path based on the contour data. Then, the device will follow the generated path and manipulate the laser beams to melt metal powder material in each layer.

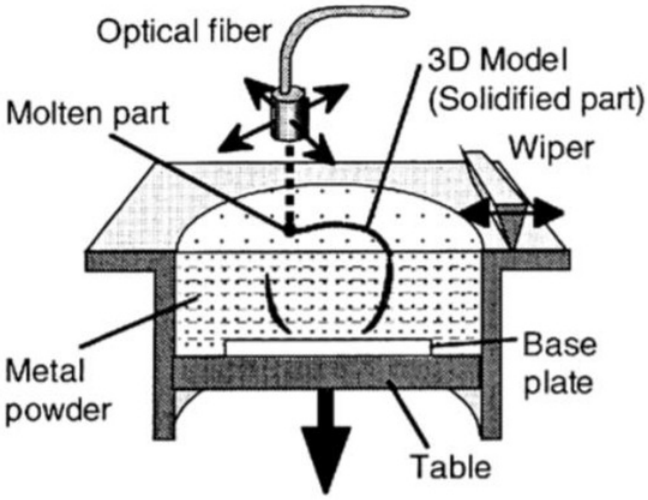

Figure 2.3. Selective melting laser system[[17]

Before the laser beam starts scanning, powder spreading device will put metal powder onto the flat substrate, then the laser beam will melt the powder on the current layer followed the designed path. After the laser beam finished the path, the flat substrate will lower certain designed depth while the powder cylinder increase certain thickness and get ready for the next layer printing. New contour data for next layer printing is transferred to the equipment and starts printing , so layer by layer processing until the whole part processing is completed. The processing chamber in the protection of inert gas with the whole process, in order to avoid the metal reacts with other gases at high temperature.[13] Figure 2.4 shows the SLM operating process.

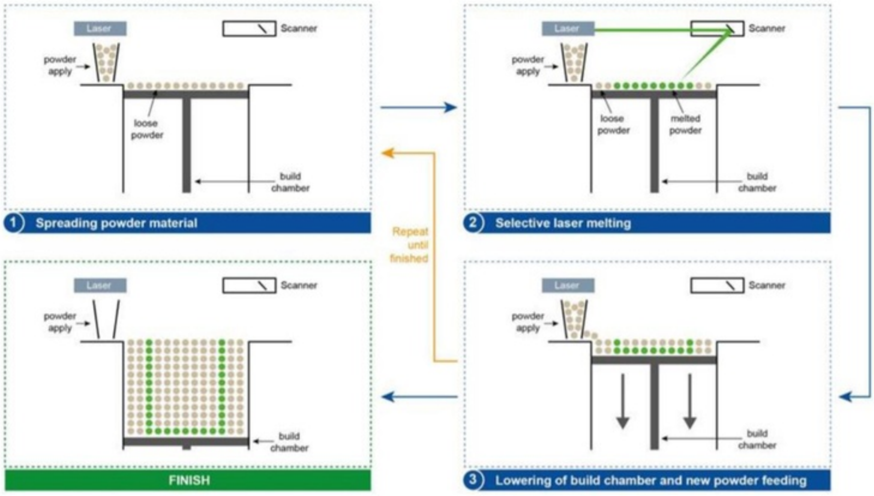

Figure 2.4 SLM operating process [18]

SLM250HL

The 3D printing machine using in this project is SLM250HL. This 3D printing machine using fine metal powders to deliver metal parts with homogeneity. The product density is up to 99.9% of the material density. Serval types of metal can be produced such as steel, aluminium, titanium and super alloys. System parameters of this machine is shown in Figure 2.5.

Anlagenparameter System Parameters	
Bauraum in mm (x/y/z) Build Chamber in mm (x/y/z)	248 x248 x 250 (350)
Laserleistung Laser Power	200/400 W, YLR-Faser-Laser
Baugeschwindigkeitsrate* Build Speed Rate*	20 ccm/h
Prakt. Schichtdicke Pract. Layer thickness	20 µm - 75 µm (100 µm)
Min. Spurbreite / Wandstärke Min. Scan Line / Wall Thickness	150 µm
Operativer Strahlfocus frei wählbar Operational Beam Fokus variable	60 µm -100 µm (85 µm -130 µm)
Belichtungsgeschwindigkeit Scan Speed	20 m/s
Schutzgasverbrauch im Prozess Inert Gas Consumption in Operation	Ar/N_2, 1,5 l/min
Schutzgasverbrauch Fluten Inert Gas Consumption Venting	Ar/N_2, 1500 l @ 100l/min.
Druckluftanforderung Compressed Air Requirement	ISO 8573-1, 15 l/min. @ 1,5 bar
Abmessungen in mm (B x H x T) Dimensions in mm (B x H x D)	1650 x 1900 (2400) x 1000
Gewicht Weight	ca. 850 kg
E-Anschluß / Verbrauch E-Connection / Consumption	400 Volt 3NPE, 32 A, 50/60 Hz, 5 KW/h

Table 2.1 System parameters of SLM 250 HL [19]

2.3 Residual stress and heat treatment

The residual stress is when no external force is exerted on objects, objects are kept stress self-balanced system. A variety of mechanical processes such as casting, cutting, welding, heat treatment, assembly and so on, will produce different degrees of residual stress. Local plastic deformation occurs while the object experiencing external forces, but when the external force is removed, the local plastic deformation restricts the recovery of the whole section deformation, so the residual stress is generated. This residual stress caused by local plastic deformation can occur in many processing processes, such as forging, cutting, cold drawing, cold bending and so on. This residual stress is often very large. The presence of residual stresses is not immediately manifested as defects, cracks and breaks occur when the part is overloaded by the working stress and the residual stress in the work, so that the total stress exceeds the strength limit. [19][20]

The residual stress produced mainly has the following two reasons: the first is due to the non-uniform temperature caused by plastic deformation of local heat; second is due to phase change caused by volume expansion caused by uneven local plastic deformation. When metal material under high temperature condition; its performance will change a lot, such as yield strength, elastic modulus decrease with increasing temperature. The temperature field of the metal differs in , then the distribution of yield limit and elastic modulus is not uniform, resulting in high temperature thermoplasticity under high temperature is not uniform.

Metal components (casting, welding, forging), in the manufacturing process, the highest residual stress produced will be around high yield limit. The residual stress in the component mostly show great harmful effect; such as reducing the intensity of the component, reducing the fatigue limit, caused by stress corrosion and brittle fracture. Due to the relaxation of residual stress, the component deforms and influence the size precision of the component. Therefore, reducing and eliminating the residual stress from the component become necessary.

The formation of the Ti-6Al-4V using SLM printing method will cause residual stress as there are lots of heating and cooling operations. [21] The powder will be heat up and melt into solid form, then it will be cool down to create a layer on the top surface. The layer thickness is tiny so numerous layers will be formed to produce an actual product. The cumulating residual stress will have problems sometime, so the it is better to eliminated. Heat treatment is considered to be one of the effective method to reduce the residual stresses.

In addition, heat treatment not only can eliminate the residual stress but also improve the mechanical performance of the material,[22] so another objective is to investigate the physical properties before and after the heat treatment.[18] The enhancement is based on the improving its microstructure by transforming different phases existing in the sample to more strong structure.

2.4 Microstructure

Titanium consists of 3 main different types of the microstructure which are α phase, β phase and α+β structure. The mechanical properties are based on the microstructures, so different compositions in the microstructure will directly affect its physical characteristics.

Based on different phases of titanium structures within the titanium alloy, such alloys are categorised as α alloys, β alloy and α+β alloy.

α titanium alloy is a single-phase alloy consisting of α stabilizer. No matter at normal temperature or high temperature, the α phase remains, so the microstructure is stable. The wear resistance is higher than that of pure titanium, and the oxidation resistance is strong. [23]

β titanium alloy is also a single-phase alloy consisting of β stabilizer which has a higher strength without heat treatment. After quenching and aging, the alloy is further strengthened, the room temperature strength can reach 1372~1666 MPa, but the thermal stability is poor, thus it should not be used at high temperature.

α+β titanium alloy is a dual phase alloy with good comprehensive properties, such as good microstructure stability, good toughness and plasticity as well as deformability under high temperature. good thermal pressure processing, hardening and aging, and strengthening of the alloy. It can be heat treated to obtain around 50-100% strength enhancement. The thermal stability is next to α alloy and combined with the high strength under high temperature, this alloy can sustain under long-term, high temperature working environment.

The most commonly used titanium alloys are α titanium alloy and α+β titanium alloy. the α titanium alloy has the best machinability, followed by the α+β titanium alloy, and the β titanium alloy in the last place. [23]

Ti–6Al–4V is an which means the microstructure consists of both α and β phase. Through surface imaging by scanning electronic microscopy (SEM), these two different phases can be identified.[19] The Ti–6Al–4V created by SLM always contains columnar prior-β grains filled with acicular α martensite, which enables it to achieve wide range of properties. The mechanical property is acceptable since it has high yield strength, but limited ductility. [23] From research, it shows that the laminar (α+β) structure has better mechanical performance than the α martensite structure. [23]

2.5 Hypothesis of the project

Based on the information in section 2.3, heat treatment is a kind of hot working process that heats the metal to a predetermined temperature and stays at this temperature for a period of time and then cools down at a certain speed. By using proper heat treatment can improve the mechanical properties of titanium alloy, and prolong the service life of machine parts. Heat treatment process can not only strengthen the metal material fully tap the material performance potential, reduce the structural weight, save materials and energy, but also can improve the quality of mechanical products, greatly extend the service life of machine parts.

650°C heat treatment is also considered as stress relieving process. Samples after such heat treatment will increase the uniformity on mechanical performances. In this project, the measuring parameter is the hardness of the sample. The heat contains both 650°C and 850°C will cause lot of influences on its mechanical properties, since the residual stress is already being taken off. Further impacts on the object will be structure related.

Chapter 3

Experiment procedure

3.1 Sample preparation

There are 4 samples to be tested in this project which are all created by SLM method. All of them are using Ti-6Al-4V powder as raw material. The six Ti-6Al-4V samples are producing with same parameters but different dimension, and they can be separated into two groups based on different height. 2 samples in group 1 has 6mm height and 4mm width, along with different length: 2mm and 10mm. The rest 2 samples in group 2 has 11mm height and 9mm width, also has length 2mm, 10mm respectively. The front view in the following diagram are bounded with length and height. All the following tests are focus on this cross-section, and the long beam below is the supporting base for the samples and they are not to be thought of. The figures below shows the front view and top view of the samples.

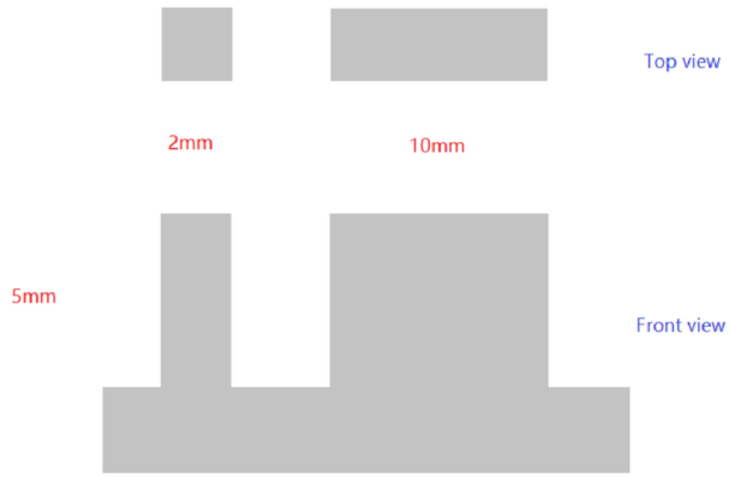

Figure 3.1 Views of the samples with 5mm height

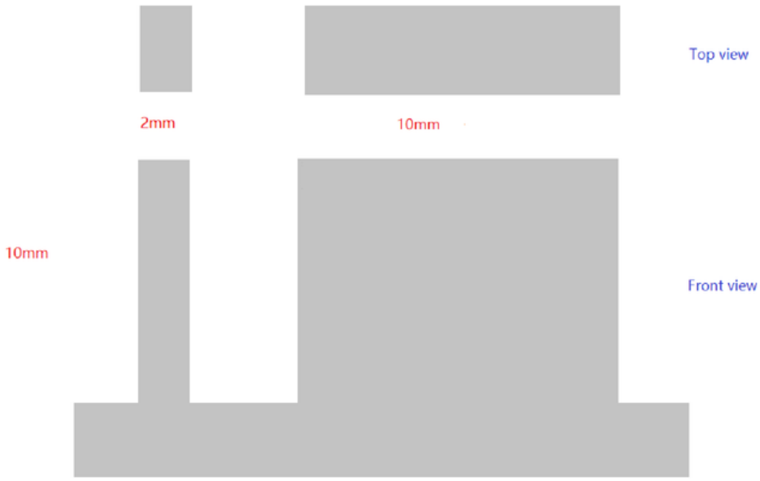

Figure 3.2 Views of the samples with 510mm height

These four samples can form many different control groups to study the parameters that will affect the mechanical performances. The settings for them are shown in the following table.

Table.3.1 Printing parameters for Ti-6Al-4V

Parameters	Values
Layer thickness (μm)	60
Laser power (W)	375
Scanning speed (mm/s)	1029
Hatch spacing (mm)	0.12
Energy density (ED) (J/mm^2)	50.62
Focal offset distance (FOD) (mm)	2

The purpose of the project is to study how to improve the mechanical properties of 3D printed Ti-6Al-4V, in other words, finding out the parameters that will affect such properties. To achieve the goal, each sample need to be cut into several parts to compare the changes before and after heat treatment. Using same sample to compare the results is more convincing. The cutting will proceed on the top view of the sample bounded by length and width as shown in figure 3.2. Each sample need to cut into three pieces for all the tests, but for the sample with 4mm width it can only capable to provide two pieces. Expect the hardness test, SEM is required to monitor the microstructure, so grinding and polishing process is necessary on the surface.

Totally, all group 1 samples are cut into 2 parts, half of them will go straight for moulding, the rest of them will be sent to furnace for 2-hour 650°C heat treatment. All group 2 samples are cut into three parts and identify them as set 1, set 2 and set 3. No heat treatment will be done on set 1 samples. Set 2 samples are doing 2-hour 650°C heat treatment, and set 3 samples are having 2-hour 650°C heat treatment and 2-hour 850°C heat treatment. There is no time gap between the two heat treatment, once the 650°C heat treatment is done, the furnace will heat up to 850°C immediately.

Finally, sample preparation required cutting, moulding, grinding and polishing process. Some samples need to go through heat treatment should heat treated first then the machining. All samples are relabelled for the convenience of data collection and analysis, and their new allocated names are shown below.

Table 3.2 Sample description

	Height (mm)	Lehgth (mm)	Desceiption
Sample 1	5	2	no heat treatment
Sample 2	5	10	no heat treatment
Sample 3	5	2	650˚C heat treatment
Sample 4	5	10	650˚C heat treatment
Sample 5	10	2	no heat treatment
Sample 6	10	10	no heat treatment
Sample 7	10	2	650˚C heat treatment
Sample 8	10	10	650˚C heat treatment
Sample 9	10	2	both 650˚C and 850˚C heat treatment
Sample 10	10	10	both 650˚C and 850˚C heat treatment

3.2 Testing

When the sample preparation is done, next step is to get imaging of the microstructure by SEM. The SEM process launch electron beam to the tested surface and according the reflected feedback to provide images. Since the samples are homogenous, the microstructure should be the same across the whole surface. The hardest part is to get the microscopy focus, reference point near the imaging spot is necessary. Once the focus is complete, go back to the designated point to obtain images.

When the SEM is finished, the samples will continue for hardness test. The working theory of the hardness test is to apply certain force on the indenter and make contact with the surface for certain time, the software will automatically measure the dimension of the mark and apply algorithm to get the hardness value.

The force setting on this hardness test is 2kg (HV 2), the time of contact is 10s. Since the samples have been though huge temperature change during manufacturing, the residual stress will affect the mechanical properties somehow. Hardness mapping will help to investigate the hardness distribution all over the surface.

When the sample are set into the hardness tester, a small microscope provides the image of the area that the indenter will it. First of all, use the microscope to identify the effective tested area which means within the area no edges of the sample in the image, since the edge will be contaminate by the mould material. Once the tested area is set, start to choose points for testing. In this area, distance between adjacent point in both horizontal and vertical direction is 0.5mm. The figure below shows the first two row of the pin points.

The above SEM and hardness test will apply to those sample with heat treatment as well.

Chapter 4

Results and analysis

The hardness test results show the hardness on different spot are not the same. The unit for all hardness is HV, serval samples will be combine together to investigate the relationships among dimension of the printed object, heat treatment influences. All the results include the average value, standard deviation of the hardness. Also, maximum, minimum values and the distribution diagram will be applied to find out the if there exist any connections.

4.1 Geometrical comparation

In this section, samples with same condition but with different dimension. For example, samples without heat or different heat treatment will not be put together to compare in this section.

Both sample 1 and sample 2 has same height and width but different length, as well as sample 3 and 4, 5 and 6, 7 and 8, 9 and 10. According to a series of data below, length will not affect much on the hardness.

Although samples with different height has different width, the comparation between 1 and 5, as well as 2 and 6 almost has same data on average, maximum and minimum values.

Therefore, there is no connection appears between the geometry and the mechanical properties.

Table 4.1 Sample 1 hardness result summary

Mean	399.2
Deviation	8.6
Max	420.0
Min	373.0
Range= MAX-MIN	47.0
No. of groups	8.0
Distance between groups = Range/No. of groups	5.9

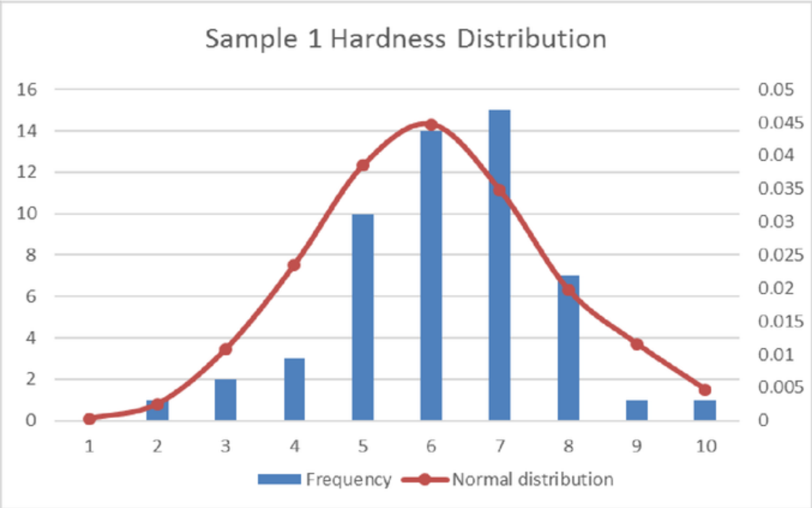

Figure 4.1 Sample 1 hardness distribution

Table 4.2 Sample 2 hardness result summary

Mean	400.4
Deviation	8.9
Max	436.0
Min	353.0
Range= MAX-MIN	83.0
No. of groups	13.0
Distance between groups = Range/No. of groups	6.4

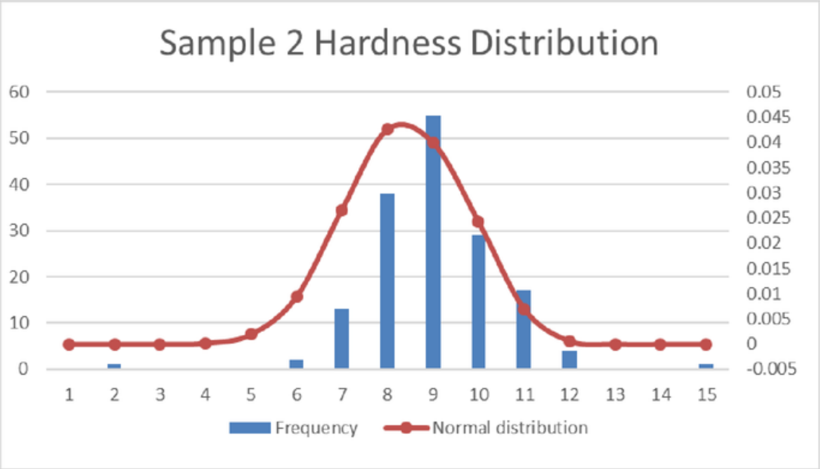

Figure 4.2 Sample 2 hardness distribution

Table 4.3 Sample 3 hardness result summary

Mean	392.3
Deviation	7.5
Max	411.0
Min	366.0
Range= MAX-MIN	45.0
No. of groups	8.0
Distance between groups = Range/No. of groups	5.6

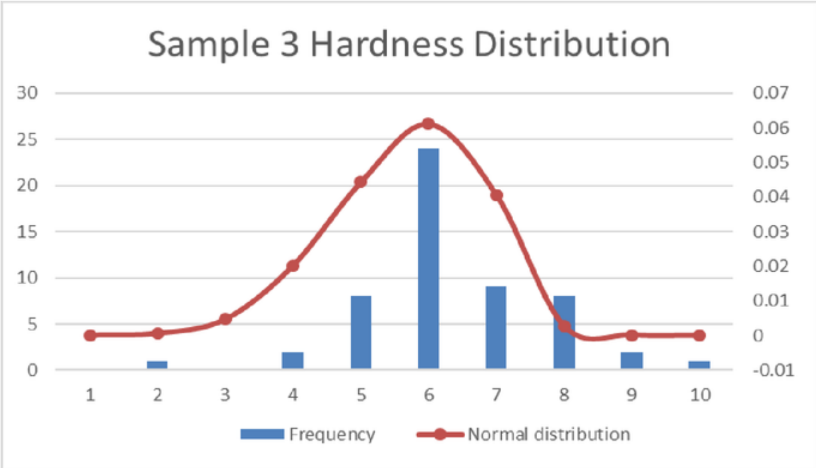

Figure 4.3 Sample 3 hardness distribution

Table 4.4 Sample 4 hardness result summary

Mean	395.7
Deviation	7.8
Max	417.0
Min	373.0
Range= MAX-MIN	44.0
No. of groups	12.0
Distance between groups = Range/No. of groups	3.7

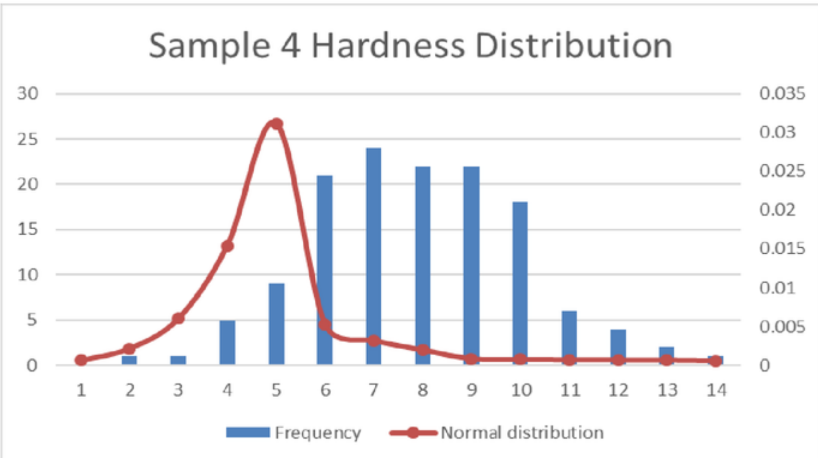

Figure 4.4 Sample 4 hardness distribution

Table 4.5 Sample 5 hardness result summary

Mean	396.7
Deviation	8.6
Max	417.0
Min	372.0
Range= MAX-MIN	45.0
No. of groups	11.0
Distance between groups = Range/No. of groups	4.1

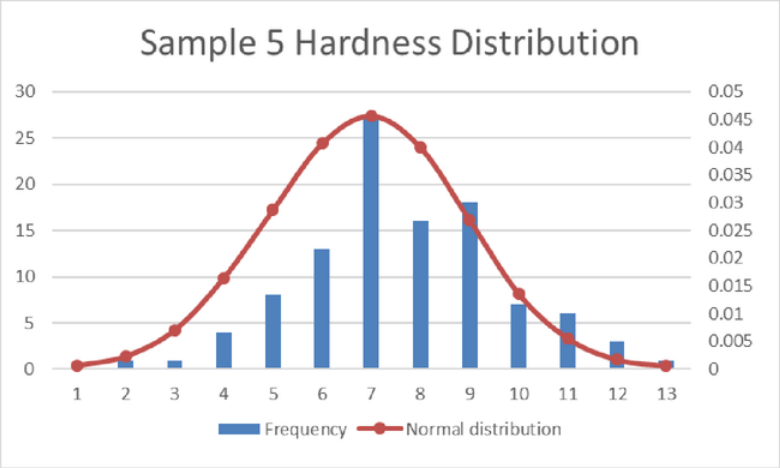

Figure 4.5 Sample 5 hardness distribution

Table 4.6 Sample 6 hardness result summary

Mean	402.2
Deviation	13.3
Max	441.0
Min	280.0
Range= MAX-MIN	161.0
No. of groups	19.0
Distance between groups = Range/No. of groups	8.5

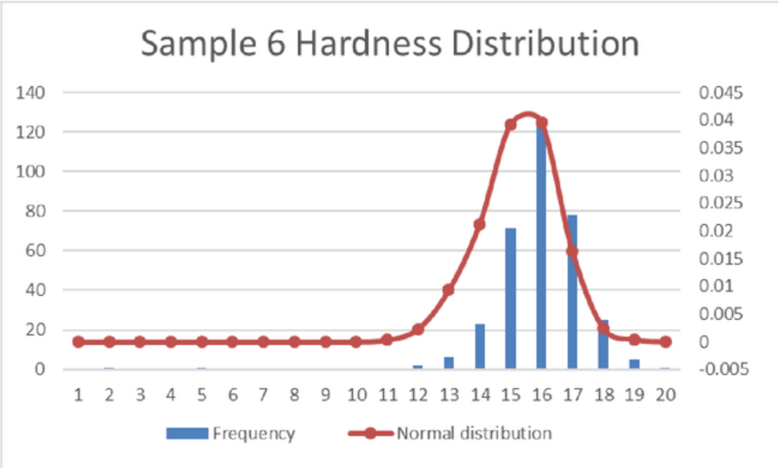

Figure 4.6 Sample 6 hardness distribution

Table 4.7 Sample 7 hardness result summary

Mean	397.2
Deviation	9.0
Max	415.0
Min	338.0
Range= MAX-MIN	77.0
No. of groups	11.0
Distance between groups = Range/No. of groups	7.0

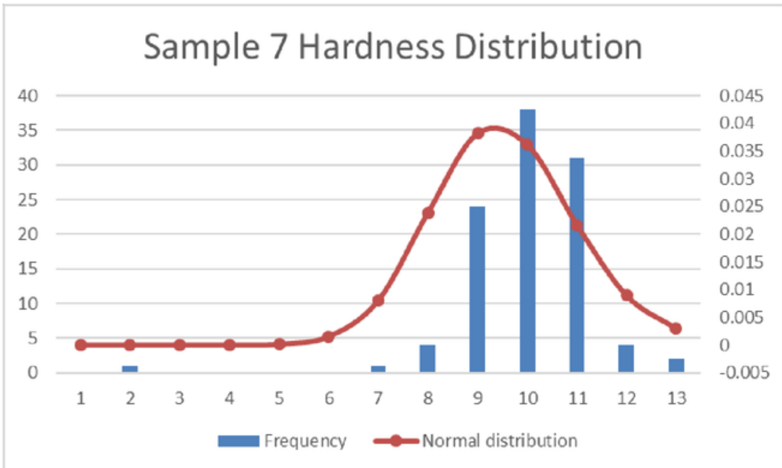

Figure 4.7 Sample 7 hardness distribution

Table 4.8 Sample 8 hardness result summary

Mean	398.5
Deviation	13.3
Max	437.0
Min	229.0
Range= MAX-MIN	208.0
No. of groups	19.0
Distance between groups = Range/No. of groups	10.9

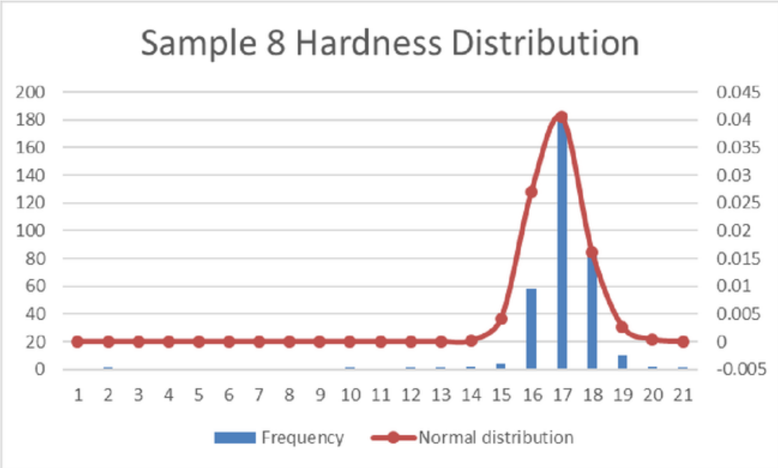

Figure 4.8 Sample 8 hardness distribution

Table 4.9 Sample 9 hardness result summary

Mean	358.8
Deviation	10.3
Max	380.0
Min	312.0
Range= MAX-MIN	68.0
No. of groups	7.0
Distance between groups = Range/No. of groups	9.7

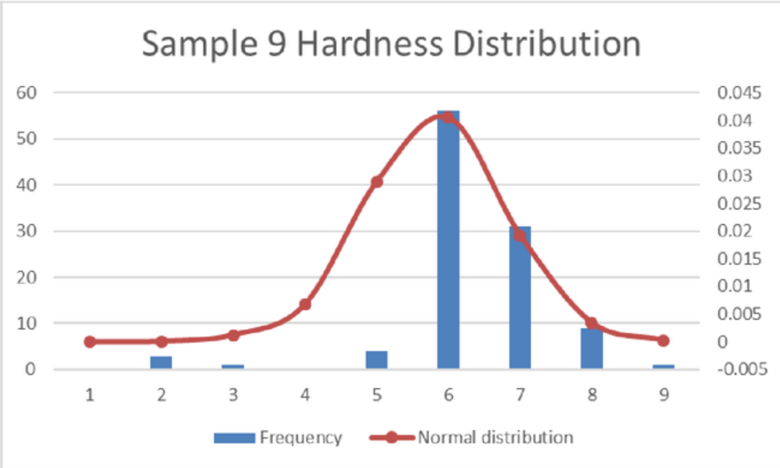

Figure 4.9 Sample 9 hardness distribution

Table 4.10 Sample 10 hardness result summary

Mean	365.6
Deviation	7.4
Max	391.0
Min	345.0
Range= MAX-MIN	46.0
No. of groups	18.0
Distance between groups = Range/No. of groups	2.6

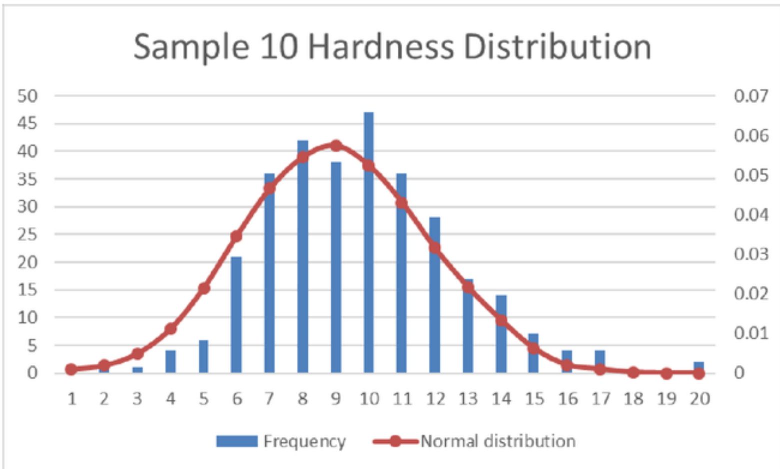

Figure 4.10 Sample 10 hardness distribution

4.2 Comparation before and after heat treatment.

In this section, samples with same geometry will be put together to compare the difference. There four different groups in this section:

4.2.1 Sample 1 and sample 3

From table 4.1 and 4.3, there is almost no difference, but when it goes to the hardness distribution histogram, it is obvious that the majority of the hardness reading are very close to the average value after heat treatment, which also indicates that the structure variation might be minimized.

4.2.2 Sample 2 and sample 4

Sample 2 and sample 4 results are quite different. The results seem to be more chaotic than before the treatment. The range of the hardness result in sample 2 is almost twice as sample 4, when referring to the histogram, there are separate value far away from the range that almost all value falls in. the isolated case might be caused by error.

4.2.3 Sample 5, sample 7 and sample 9

This set of samples shows strong relationship after going through different heat treatment. Table 4.5, 4.7 and 4.9 are not useful to find out their relationships, but figure 4.5, 4.7, and 4.9 illustrate that the difference among those three sample is quite obvious. Similar results from section 4.2.1 obtained when compare the harness data between sample 5 and 7. The hardness along the surface are tending to become stable, a tip appears in the histogram which means the homogeneity increasing dramatically.

The shape of the diagram from figure 7 and figure 9 are very similar, when checking the number of values falls into the range includes the average, the uniformity strength after 850°C heat treatment.

The biggest changes exist between two different types of heat treatment. The overall hardness decreased, not only the maximum and minimum value but also the average value. This presents that the entire mechanical structure has changed.

4.2.4 Sample 6, sample 8 and sample 10

The relationship between samples in this section is similar to section 4.2.3, 650°C heat treatment helps to improve uniformity, combining heat treatment of 650°C and 850°C alter the mechanical properties and weakening the hardness. However, the homogeneity between sample 8 and 10 are different from the previous group. Such ability seems to be weaken significantly even worse than the original sample.

4.3 Comparation in microstructure

The SEM machine takes pictures of the surface of the samples, from sample 1 to 8 different structures are obtain but all looks similar, and cannot observe any remarkable changes within the structure. Results are shown below:

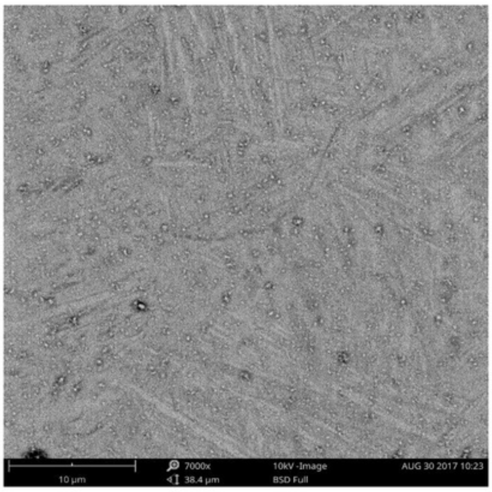

Figure. 4.11 Sample 1 scanning results

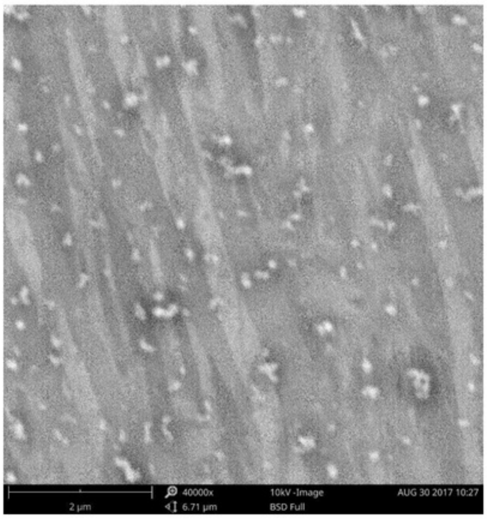

Figure. 4.12 Sample 2 scanning results

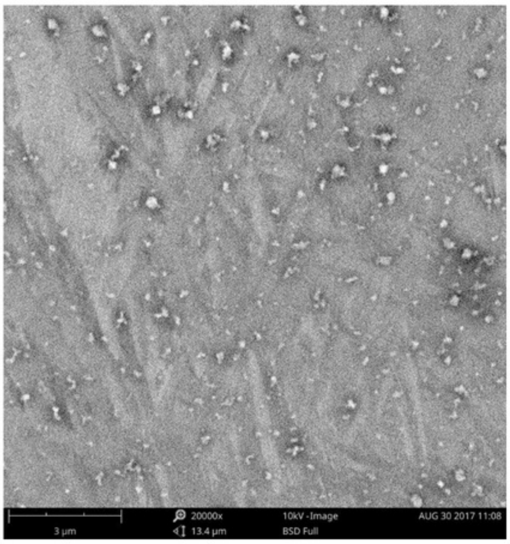

Figure. 4.13 Sample 3 scanning results

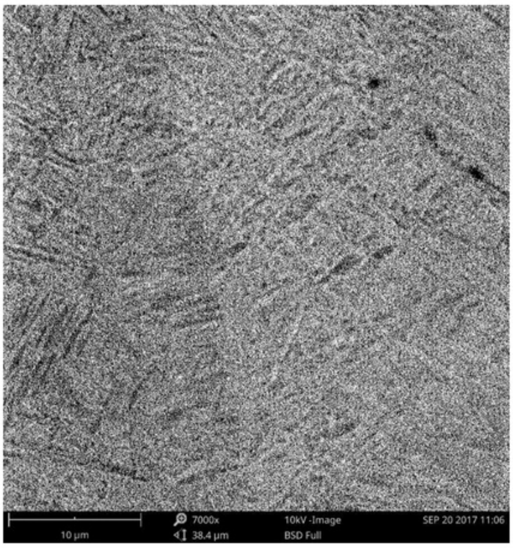

Figure. 4.14 Sample 4 scanning results

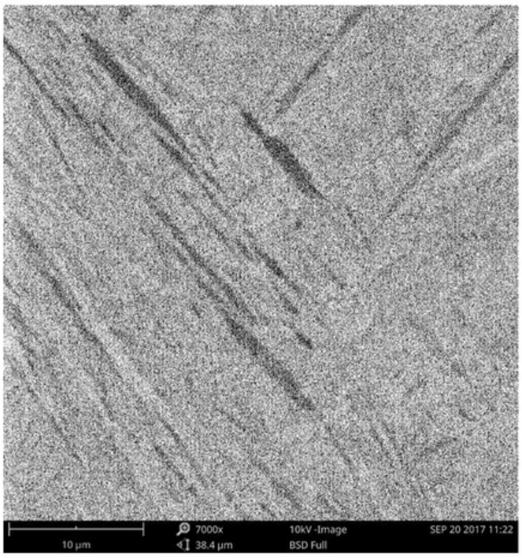

Figure. 4.15 Sample 5 scanning results

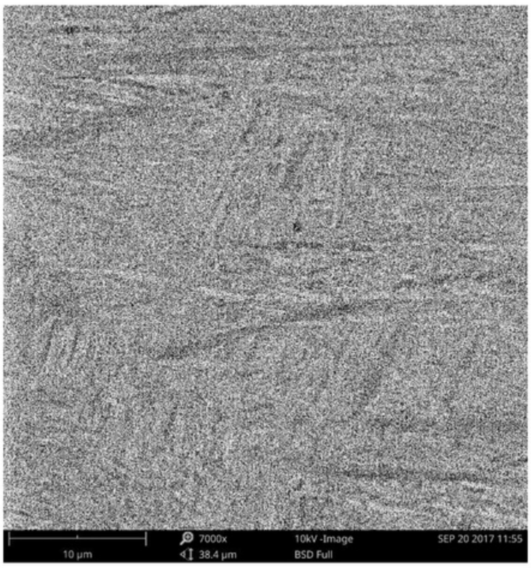

Figure. 4.16 Sample 6 scanning results

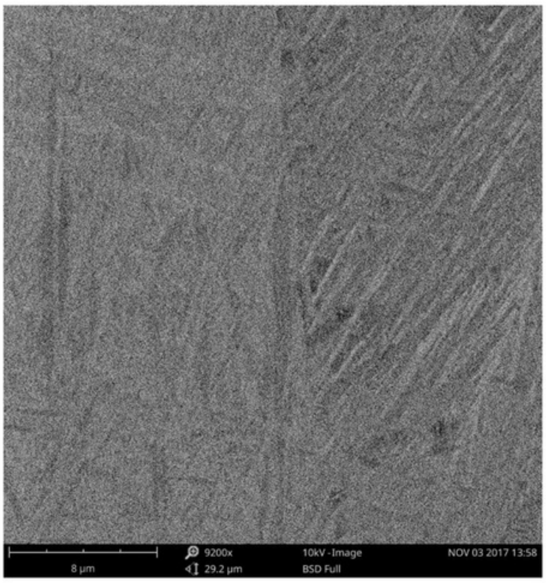

Figure. 4.17 Sample 7 scanning results

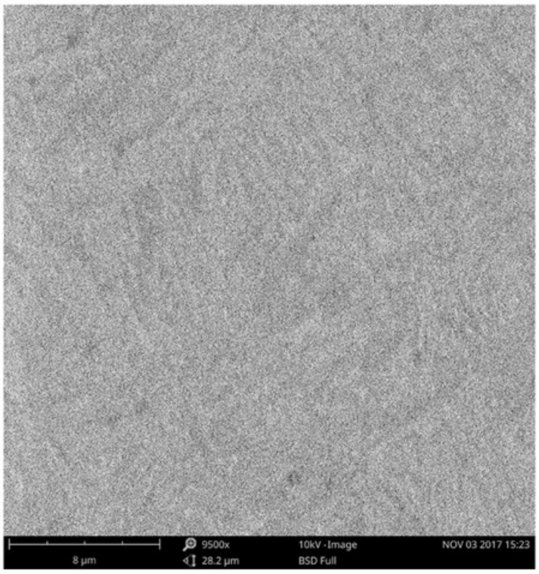

Figure. 4.18 Sample 8 scanning results

The above microstructures is not clear enough to identify the changes in microstructure, but when those samples are compared with the sample 9 and 10, huge changes happens. Unlike the tiny grains in the previous 8 samples, these two samples have much larger grain structure. Figure 9 and 10 shows the difference.

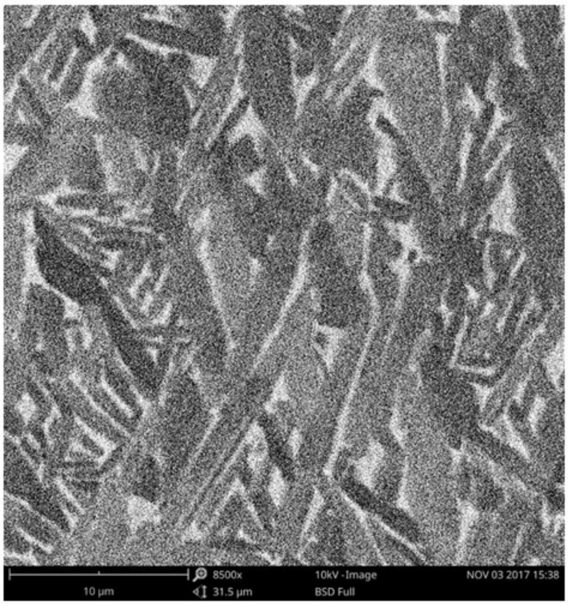

Figure. 4.19 Sample 9 scanning results

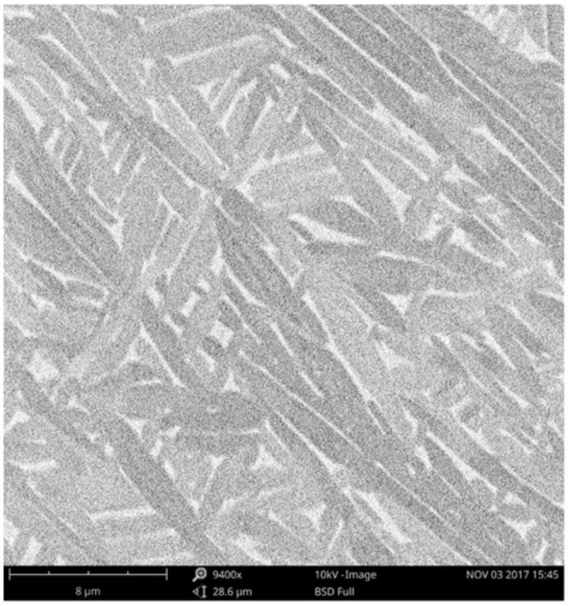

Figure. 4.20 Sample 10 scanning results

Chapter 5

Discussion

5.1 Mechanical properties

The properties of metal materials are generally divided into two categories: process performance and usability. The so-called process performance refers to the mechanical parts in the process of manufacturing, the performance of metal materials under the specified cold and hot processing. The quality of the metal material determines the adaptability of the forming process in the manufacturing process. Due to the different processing conditions, the required process performance is also different, such as casting performance, weldability, malleability, heat treatment performance, machinability and so on. The usability refers to the performance of metal parts in the operating conditions, the performance of metal materials, including mechanical properties, physical properties, chemical properties. The service performance of metal materials decides its application range and service life. In the machinery manufacturing industry, the general mechanical parts are used in the normal temperature, atmospheric pressure and non-strong corrosive medium. During the process of use, all the mechanical parts will bear different loads. The mechanical properties of metal materials under the external load are called resistance to failure. The mechanical properties of metal materials are the main basis for the design and material selection for parts. The commonly used mechanical properties include strength, plasticity, hardness, impact toughness, multiple impact resistance and fatigue limit.

In this project, only hardness is measured, and it cannot represent the overall mechanical properties of the material. Yet the result in this project means all other related mechanical properties will be affected as well. Based on the data and diagram, the only conclusion can be made is that the stress relief heat treatment at 650°C help to develop the uniformity, and the heat treatment involving 650°C and 850°C weakens the hardness of Ti-6Al-4V.

5.2 Residual stress

3D printing process cause accumulation of residual stress. First, the powder will be melted to form the layer, then it will be cooled down quick to allow the start for next layers printed. [21]When an object is under cooling condition, the surface reacts immediately, since the outside surface will conduct heat exchange with outside first, while the core is still surrounded by heat. Such phenomenon obstructs the cooling rate especially for the material with poor thermal conductivity. Due to the time inconsistency of cooling rate between the surface and the core, it will lead to volume expansion and shrinkage uneven stress, which is thermal stress. Under the action of thermal stress, because the surface temperature is lower than the core, the contraction is greater than the core and experiencing the pulling from the core. [24][25][26] When at the end of the cooling, the core volume shrinkage cannot proceed normally because there is a pull from the surface as well.[27]

The temperature of the heat treatment and the operation time are the key to reduce or even eliminate the residual stress. The temperature using in the project is 650°C and proved to be helpful in reducing residual stress.

5.3 Phase transformation of Ti-6Al-4V

Other than reduce residual stress, certain heat treatment can also strengthen the mechanical properties. In the project, sample 9 and 10 experience an extra heat treatment at 850°C right after the stress relief process finished. Apparently, the new temperature is above the upper critical temperature, because at this point, metal experiences a period of hysteresis and all of the heat energy is used to cause the crystal change. [28][29]

5.4 Limitation of the project

The results from the project shows connections among heat treatment, mechanical properties and microstructure. Hardness as the parameter to measure the changes in mechanical properties. Some results are not reliable that affects the overall result such as sample 6 and sample 8. An extremely low hardness appears on both samples. Also, the heat treatment is not satisfied since there is leakage on the furnace and it turns out the sample are covered black crust. The effect of this situation cannot be quantified as no comparable samples draws comparation.

The SEM machine using in the project is Phenom XL, it appears that the imaging quality is not good enough for the project. Scanning results for sample 1 to 8 is not clear enough to identify the phases exists within, but the imaging for sample 9 and 10 is good. It is possible that the settings for the scanning is not so appropriate for Ti-6Al-4V or it is the best work this machine can do.

Unexpected results may cause by the cutting, moulding, polishing and grinding process, since when the sample goes under the microscope certain black spots are detected on the surface and after the repolishing step some of the contamination are gone but there still residuals. Another detected problem in the machining process is that no matter how many times going through the polishing and grinding process, there is always contamination on the edge and nearby area, some false reading may come from this.

The hardness test also has space to improve. There is no fixing device to stabilise its position and no reference point to put it in the right place. The indenter can only move manually and in order to save time the chosen area for testing is a rectangle that picked when the edge is not showing in the screen. The y-axis of the rectangle may not exactly the actual vertical building direction. Both boundaries of the area are not parallel to the edge of the sample. The hardness around the edge cannot be obtained.

Chapter 6

Conclusion

This project has delivered some expected outcome and provide evidence that proper heat treatment has the ability to enhance the mechanical properties in some way. The 650°C heat treatment presents that it can reduce the residual stress accumulate within. The hardness of the Ti-6Al-4V remains the at the same level without any big changes. Referring to the heat treatment involving both 650°C and 850°C, remarkable changes appeared, not only the overall hardness decreased but also the microstructure changes as well. The result proves that heat treatment can improve the mechanical properties of Ti-6Al-4V, and affect the microstructure.

Chapter 7

Future work

The project is not finished yet, there still remains lots technology gaps to fill in. First of all, the rest of the mechanical properties such as ultimate strength and ductility. Hardness is just one aspect of the overall mechanical properties. Heat treatment in high temperature reduce the hardness and alter the microstructure, other physical property might not be stay the same, because the mechanical properties are based on the structure of the material. One direction of the future study is to investigate other related parameters and find out the bonds among them.

Second direction of the study can focus on residual stress, once the product is generated, residual stress will come along. There may some relationship between the 3D printed product and the settings of the printing machine. Perhaps scanning speed is accountable for most of the accumulated residual stress.

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