SELECTIVE LASER MELTING OF COBALT CHROMIUM MOLYBDENUM FOR 3D IMPLANT COMPONENT

MOHD HAZLEN BIN RAMLI

A project report submitted in partial
fulfillment of the requirement for the award of the
Master of Mechanical Engineering

Faculty of Mechanical and Manufacturing Engineering
Universiti Tun Hussein Onn Malaysia

January 2015

ABSTRACT

The recent introduction of selective laser melting (SLM) for the processing of medical grade cobalt chromium (Co-Cr) alloy has led to a complex shape fabrication of porous custom Co-Cr alloy implants with controlled porosity to meet the requirements of the anatomy and functions at the region of implantation. Metal additive manufacturing (MAM) technique such as selective laser melting (SLM) process is progressively being utilized for new biomaterials such as cobalt-chrome-molybdenum (Co-Cr-Mo). The objective of this study is to analyze the effect of different structural design porosity of Cobalt-Chromium Molybdenum (Co-Cr-Mo) sample produced by laser sintering process. The second objective is to evaluate the mechanical and physical properties of open cellular structure Co-Cr-Mo samples fabricated by SLM with designed volume based porosity ranging between 0 % (full dense) to 80 %. A maximum 2.10 % shrinkage was successfully obtained by 80 % designed porosity sample. Samples with higher volume-to-surface area (full dense) demonstrated low total amount of shrinkage as compared to lower volume-to-surface area (80 % designed porosity). This paper also discusses mechanical characterization of porous medical grade Co-Cr alloy in cubical structures with volume based porosity ranging between 60% and 80% produced using SLM rapid manufacturing process. For compression test, 60% designed porosity exhibit higher elastic modulus compared to 70% and 80% designed porosity. Samples which undergo stress relief process behave more ductile and having higher strength compared to samples without stress relief. Which is samples which undergo 8 hour of stress relief process having higher compressive strength and elastic modulus compared to samples of 20 hour stress relief.

ABSTRAK

Pengenalan kepada proses pensinteran laser (SLM) telah digunakan di dalam kajian untuk memproses Kobalt Kromiun aloi gred perubatan dengan rekabentuk yang kompleks dimana ciri – ciri keliangan dikawal untuk memenuhi keperluan tubuh dan fungsi bagi tujuan implantasi. Teknik proses pensinteran laser (SLM) telah digunakan secara beransur-ansur untuk bahan bio baru seperti kobalt-chrome-molibdenum (Co-Cr-Mo). Objektif kajian ini adalah untuk menganalisis kesan keliangan yang berbeza terhadap reka bentuk struktur Kobalt-Kromium Molybdenum (Co-Cr-Mo) yang dihasilkan oleh proses pensinteran laser. Objektif kedua adalah untuk menilai sifat-sifat mekanikal dan fizikal terbuka struktur sel Co-Cr-Mo sampel dipalsukan oleh SLM dengan jumlah keliangan direka berasaskan antara 0% (penuh padat) kepada 80%. Daripada ujikaji yang dijalankan mendapati pengecutan maksimum sebanyak 2.10% daripada sampel yang mempunyai keliangan 80% yang direkabentuk. Sampel yang direkabentuk dengan tidak keliangan 0% menunjukan jumlah pengecutan yang sedikit iaitu 0.35% berbanding sampel yang mempunyai keliangan 80% yang direkabentuk. Kajian ini juga membincangkan sifat mekanikal bagi Kobalt Kromium Aloy yang mempunyai gred perubatan dalam bentuk struktur kubik dengan jumlah keliangan berasaskan di antara 60% dan 80% yang dihasilkan dengan menggunakan proses proses pensinteran laser. Daripada ujian mampatan, nilai modulus elastic bagi sampel yang mempunyai 60% keliangan adalah lebih tinggi berbanding dengan sampel 0% dan 80%. Sampel yang menjalani proses pengurangan tegasan adalah lebih mulur dan mempunyai kekuatan yang lebih tinggi berbanding dengan sampel yang tidak menjalani proses tersebut. Daripada ujian tersebut juga mendapati sampel yang menjalani 8 jam proses melegakan tekanan mempunyai kekuatan mampatan yang lebih tinggi dan modulus elastik berbanding sampel melegakan tegasan 20 jam.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

4.1 Background of study

There have been many cases of road accidents patients with knees that no longer functioning properly. Knee replacement that involves implants has shorter life expectancy and causes the knee not able to be fully functional. Nevertheless knee replacement therapy is a procedure that all patients will have to go through regardless of the age. Knee replacement therapy is seen as the best alternative to minimize the unbearable pain of a patient that may affect their quality of life such as mobility, to rectify previously ineffective treatment and to doctor the occurrence of knee damage, especially for those who are active in sports.

Knee replacement therapy is more popular among older patients due to osteoarthritis that affects the elderly. However, with the latest implant technology , it is also highly recommended for young patients who are active in sports. An implant is a medical device manufactured to replace a missing biological structure, support a damaged biological structure, or enhance an existing biological structure. Medical implants are man-made devices, in contrast to a transplant, which is a transplanted biomedical tissue.

Each artificial implant had its own unique size and shape, which are highly dependent on the patient’s body structure, thus there are many different manufacturing techniques had been applied in implant manufacturing sector in order to fabricate the artificial implant. Among the manufacturing techniques ,rapid prototyping is the one of the famous techniques used in implant manufacturing. [1]

The application of rapid prototyping had grown significantly and grow rapidly since two decades ago. This technology is commonly used to physically fabricate the 3-D model directly from the CAD file or another modeling sketching software. Because of the technical improvements of layer manufacturing (LM) processes and due to the possibility to process all kind of metals, Rapid Prototyping evolved to rapid manufacturing (RM) in recent years [2].

Selective Laser Melting (SLM) is one of the leading commercial rapid prototyping processes which allow fabrication of a fully functional model or component by using the laser on layer by layer process. SLM is a layer-wise material addition technique that allows generating complex 3D parts by selectively melting successive layers of metal powder on top of each other, using the thermal energy supplied by a focused and computer controlled laser beam. SLM technique is highly recommended for medical and dental applications due to their complex geometry, strong individualization and high aggregate price. [2]

This technique can be used in different material system such as metal, ceramic, and polymer as well as composite material. The production cost and processing time of the laser sintering process are much lower and faster compared with other manufacturing techniques. Nowadays, there are around 25 rapid prototyping technique had been develop by human for different field of manufacturing. [3]

The application of LM techniques in medical and dental applications are not only meant for plastic devices such as visual anatomical models or one-time surgical guides, but also for functional implants or prostheses with long-term consistency made from a biocompatible metal. Since the introduction of artificial implant, there have been many different materials used to manufacture the implant in order to get the most suitable material with good mechanical properties, in which it would not be rejected and harmful to human body. The most common material applied are the titanium and cobalt chromium, in which this study will focus on the Cobalt Chromium material.

Cobalt Chromium alloys are metal alloys of cobalt, chromium and other alloys material mixture. Cobalt Chromium was first introduced in the year 1907 by Elwood Haynes, the establisher of the Haynes International, Inc. Subsequent work, Haynes identified tungsten and molybdenum as powerful strengthening agents within the cobalt-chromium system and the patent of these alloys was granted in late 1912. Haynes had name these alloys as Stellite alloys because of their star-like luster [4]. Cobalt alloys were originally proposed for surgical implants 70 years ago. There are basically two types of Co alloys for medical application; the alloy Co-Cr-Mo for coating and the worked alloys Co-Ni-Cr-Mo. These alloys are highly resistant to corrosion in physiological environments and stainless steel materials. Moreover, its superior resistance limit and fatigue resistance enable its application where long service life without the occurrence of fractures or fatigue.

For a long time, cobalt chromium alloys have been the key materials for dentistry, and now they are also used for high-strength hip replacements because of their high corrosion and fatigue resistance. Presently, Cobalt Chromium alloy had become the commonly used material in biomedical application such as the dental implant and orthopaedic implant. Besides that, the Cobalt Chromium alloys is the most useful and balanced biomedical materials in terms of strength, fatigue and weariness as well as the resistance to corrosion [5]. Hence, this research is to study the laser sintering of cobalt chromium for artificial implant component.

1.2 Problem statement

Many of the manufacturing technology used nowadays demands long cycle of time and high cost to manufacture artificial components such as the artificial knee. This is because every implant component had its own lifespan based on certain specific criteria including the patient body structure and bone density. Therefore, most of the implant component can only being manufacture when needed and normally not in a long production.

Injection molding, one example of manufacturing technology, is found not suitable for artificial implant component fabrication due to the high cost of the manufacturing process and not cost-effective for low volume production. Thus, for this study, the researcher chose laser sintering technology to manufacture the artificial implant by using the Co-Cr-Mo material.

1.3 Objective

1. To analyze the effect of different structural design porosity of Cobalt-Chromium Molybdenum (Co-Cr-Mo) sample produced by laser sintering process.

2. To evaluate the mechanical and physical properties of open cellular structure CoCrMo samples fabricated by SLM with designed volume based porosity ranging between 0 % (full dense) to 80 %.

1.4 Scope

1. Commercial medical grade of Cobalt Chromium Molybdenum powder will be used as the sample material.
2. Manufacture a part of Cobalt Chromium Molybdenum material by using Eosint M280 laser machine.
3. Characterize evaluation of the Cobalt Chromium Molybdenum sample by using SEM, profile projector and surface roughness machine.

1.5 Significant of study

This research aims to provide the most suitable laser parameter needed in laser sintering process for the Co-Cr-Mo material to get the best dimensional accuracy, density and surface roughness of artificial implant. Hence, this research will provide a good understanding of the laser sintering and the effect of laser parameter on the dimensional accuracy, density, and surface roughness for the Co-Cr-Mo sample.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Rapid prototyping is the techniques that can let the designer directly produced the tangible prototype of their design, better that just in two-dimensional picture. Moreover, these prototype can be used as the visual aid for communicating ideas with co-worker or customer in order to test various aspect of their design such as dimensional checks. Beside the rapid prototyping technique also had been use to fabricate the mold or rapid tooling as well as the fully functional end-use part [6].

The term “rapid” in the rapid prototyping not really describe the speed of the technique but its more narrate to the automated step from CAD data to machine. The production time of the rapid prototyping technique is depending on the dimensional and complexity of the object, sometime its need few day to complete an object. However this may seem slow but if compared with other traditional techniques, its production time still much more shorter than the traditional technique production time needed. The resulting cost also had been reduced due to the relative fast production had allow analyzing part in a very early stage of designing. Beside, the cost can also be reduced due to the rapid prototyping process is fully automated and the product from the rapid prototyping process is nearly in net shape thus no other finishing process needed [6].

2.2 Rapid Prototyping

2.2.1 Basic rapid prototyping process

Rapid prototyping technique is undergo the following process steps:

1. First creating a CAD model either designing a new model by using some computer software like solid work or scanning and existing object.
2. Second converting the format of CAD model to STL format.STL format (Standard Triangulation Language) is the standard language for the rapid prototyping industry to establish consistency. The STL file is a concrete visualization of the product geometry, built up from triangle. In the rapid prototyping manufacture its better using the triangle to describe the surface than using the CAD data which using different type of algorithms to represent the solid object.
3. Then sized and oriented the STL file ,after that it is slice into thin cross sectional layers.
4. Next generate a base and support structure.
5. Then fabricated the object layer by layer.
6. Last post processing. Cleaning and finishing the object and removing the support structure [10].

2.2.2 Rapid prototyping technique

2.2.2.1 Selective laser sintering

Selective laser sintering (SLS) process was first introduced by Carl Deckard, University of Texas at 1989. Selective laser sintering is the RP technique that fabricate the object by bonded the powdered particle layer by layer from bottom to top by using the laser [3, 10]. The figure 2.1 had shown the schematics diagram of the SLS process. As shown in the figure 2.1, a layer of powdered particle was spread over the powder bed by the roller. Then a heat generating laser beam scan on the layer of powder to melt the powdered particle to form a layer according to the model in the computer aided design (CAD) file. The laser beam sintered the powder particle at the temperature that slightly higher than the material melting point. After the first layer had done, the powder bed move down according to the thickness of the first layer that being set, which approximate at 0.10-0.15mm and the new powder will spread over again at the surface of the first layer. Then, the laser will exposed the new layer to melt and bond with the previous layer. The process will repeated until the whole object had been complete fabricated. The unsintered powder particle around the object acts as the natural support material for the object. After the object had completed it has to cool down to room temperature and then removed out from the powdered bed. The object has to clean by brushing away all the excess powdered and the excess powdered can be reuse again for the next fabrication [3,10-12].

There are two types of lasers normally used in the SLS machine, which are CO_2 lasers and Nd: YAG lasers. The main requirement of the laser used in the SLS machine is their radiant energy can be readily absorbed by the powder. The wavelength of the CO_2 laser beam is 10.6pm while the wavelength of the Nd:YAG laser is 1064nm [13].

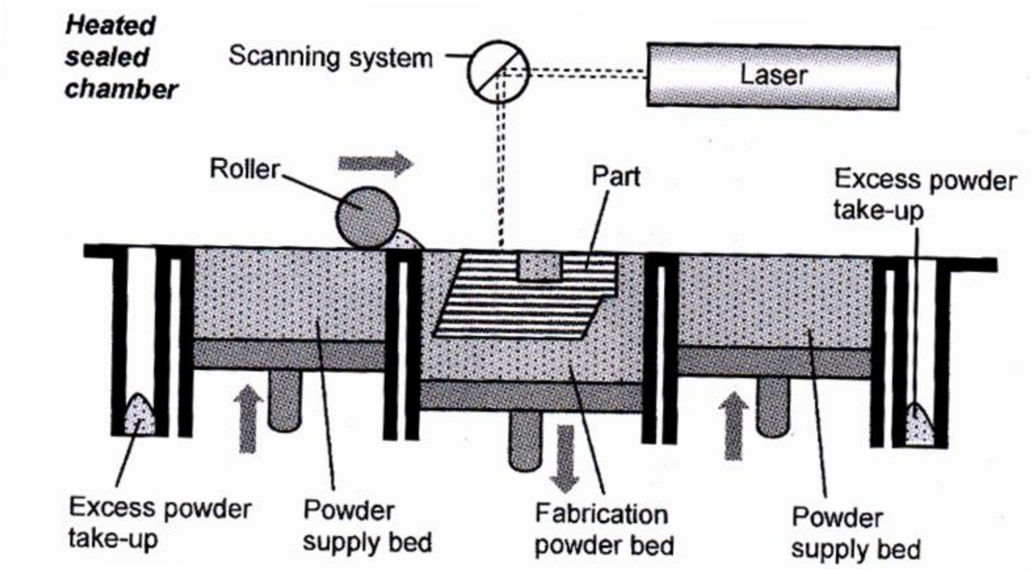


Figure 2.1 : The schematic diagram of SLS process [12].

The advantage of the SLS technique are good mechanical properties, no support required, fast, non-toxic material, easy to use and material can be recycle [10, 11].

The disadvantage of the SLS technique are little rough and porous surface finishing and the feature detail of the object are not sharp and crispy as the object fabricate by the SLA technique [10,11].

2.2.2.2 Laser–engineered net shaping

Laser-engineer net shaping (LENS) was develop by Sandia National Laboratories and the Optomec company had delivered its commercial system to Ohio Sate University in 1998. The LENS system normally is use to fabricate and repair the high-value metal component like aircraft engine part and medical implant. LENS process fabricate an object in an additive manner from powdered metal by using the Nd:YAG laser beam to fused the powdered into a solid state. The figure 2.2 had shown the schematics diagram of the LENS process. As shown in the figure the deposition head supplies the metal powdered to the focus of the laser beam to be melted. In LENS process the laser beam will focused onto powdered metal to melt the upper surface of the powdered particle. The platform is moving in rather fashion as the laser beam traces the cross section of the part being produced. When a layer is done the deposition head will raises up and continue with next layer. This process will repeated until the object is complete [10,12].

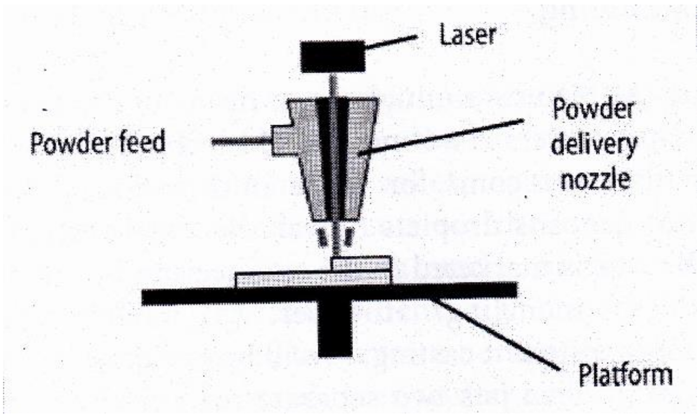


Figure 2.2 : The schematic diagram of the LENS process[10]

The advantage of the LENS process are superior material properties, complex part can be fabricate, post-processing is minimized which mean the cost and cycle time also been reduces [12].

The disadvantage of the LENS process are limited material can be use, large physical unit size, and high power consumption need for the system [12]. There are two type of SLS of metal process which are the direct laser sintering and indirect laser sintering.

2.3 Indirect laser sintering

In Indirect SLS process, the polymer will be use as the raw material to bind the metal powder particle in order to fabricate a model. There are two ways to combine the polymer and the metal powder in indirect SLS, which are coated the metal powder particle with the polymer or mix the polymer and metal powder. The polymer is melted by the laser to produce the green part in which to bond the metal particle together by the solidified polymer. Then the green part is heating in the high temperature furnace to remove the polymer and sinter the metal powder to produce metal to metal bond. The green part produced through the indirect SLS will consists of large amount of pore space and there is large shrinkage companion to the density consolidation. This problem is overcome by the infiltration process in order to produced a high density metal model. Infiltration process bunch a molten phase into the open pore of porous structure by looping to a temperature between the melting point of the infiltration and skeleton [3,11].

Further investigation about this two different method (coating and mixing) had been conducted. The strength of green part from coating method is more higher than the green part from the powder mixture method. The figure 2.3 had show the graph of comparison bending strength of the green part that produce by the mix powder method and coating method. Moreover, the mix powder had the segregation problem but this problem can be overcome by the coating method due to the coated powder is more homogeneous than the mixed powder [11].

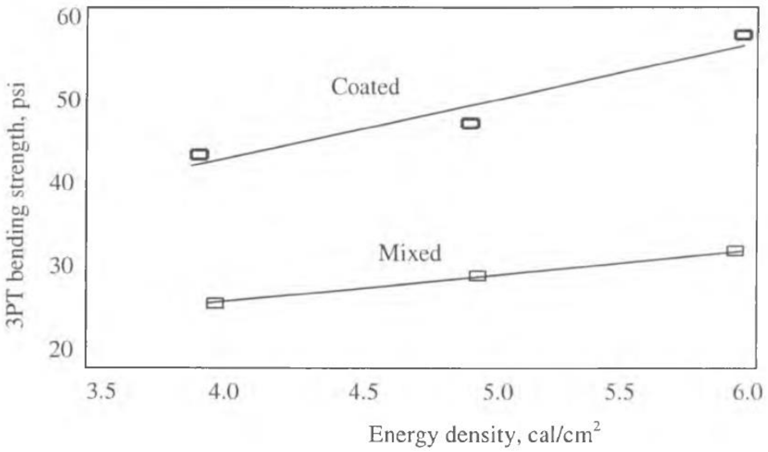


Figure 2.3 : Graph of comparison the bending strength between the mix powder method and coating method[11]

There are many different polymer had been investigated to use as the binder for the indirect SLS process, such as polymethyl methacrylate, copolymers of methyl methacrylate, polystyrene, polyethyleneglycol and butylmethacrylat.[11]. The advantage of indirect SLS processing is only binder material needs to be melted, thus the mechanical properties of the metal powder will not be affect so much [3].

The disadvantage of the indirect SLS process are limited type of material can be use, post processing needed (Depolymerization), large amount of pore space and density consolidation, poor mechanical, thermal properties, accuracy and take long time to build the mold insert [3,11].

2.4 Direct laser sintering

Direct SLS processes is directly use the high energy laser beam consolidate the metal powders without any binder and minimal or no post processing. The first attempts to use SLS to fabricate single phase metals such as tin or zinc were unsuccessful due to the melt molten powder will merger together into a sphere shape rather than consolidating into the thin single layer. The sphere diameter approximately equal to the laser beam diameter and this situation is known as balling To overcome this problem, a two-phase powder idea was developed [3,11]. The laser beam power will only sinter the metal powder that had lower melting point and the lower melting point powder employed as a matrix in which the higher melting point components sit. The typical binary phase metal powder systems investigated are Ni-Cu, Fe-Cu and Cu-Pb/Sn [14, 15].

The advantage of the direct SLS process is can operate at more competitive build rate due to the powder mix material can be used in this process [3].

The disadvantage of the direct SLS process is the object exhibit the mechanical properties and characteristics of the weakest composite phase material that used to fabricate the object [11].

2.5 Direct Metal Laser Sintering (DMLS)

Direct Metal Laser Sintering (DMLS) is a new laser-based Rapid Tooling and Manufacturing (RTM) process. This technique was developed by EOS GmbH of Munich, Germany, and has been available commercially since 1995. Similar to

SLS, Direct metal laser sintering (DMLS), as a typical RP technique, enables the quick production of complex shaped three-dimensional (3D) parts directly from metal powder. This process uses a laser that is directly exposed to the metal powder in liquid phase sintering and creates parts by selective fusing and consolidating thin layers of loose powder with a scanning laser beam process. Additionally, due to its flexibility in materials, shapes and control of parameters in the construction may also lead to produce porous metallic components. [7]

2.5.1 DMLS Principle

A schematic diagram of the DMLS system is show in Figure 2.4. To build of any part the machine performs the following steps. The building and dispenser platform are lowered by one layer thickness for that the recoater blade can moving without collision. When the recoater stands in right position the dispensor platform rise to supply the amount of powder for the next layer. Then the recoater moves from the right to the left position, in this way the metal powder is spread from dispenser to the building area and the excess metal powder falls into collector. Then the head scan move the laser beam through two-dimensional cross section and is precisely switched on and off during exposure of designated areas.

The absorption of energy by metal powder will generate the cure and sinter of the already solidified areas below. This process proceeds layer-by-layer until all parts in a job are completed. Thus in few hours the machine can produce three-dimensional parts with high complexity and accuracy. In addition, during the building process, sintered parts reach more or less their final properties, but, depending on the application of piece it is necessary a post-processing treatment, like tempering or surface treatment. [7]

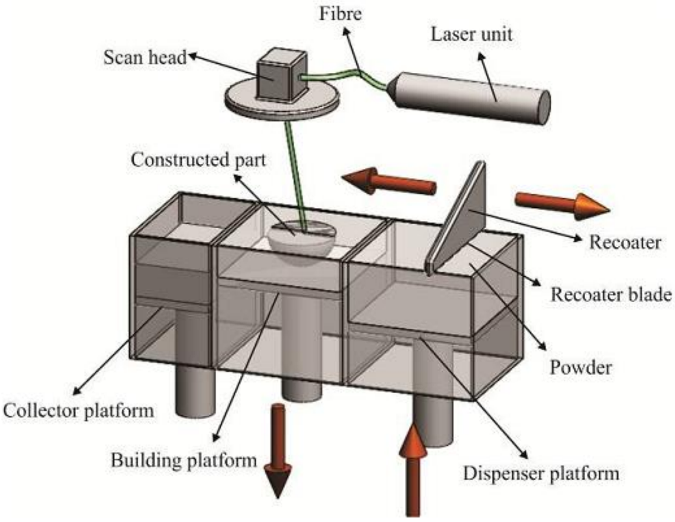


Figure 2.4. Schematic diagram of the DMLS system. [7]

2.6 The laser sintering process

2.6.1 Physical process

The basic principle of the laser sintering process comprises the melting of layers of metal powder using a Yb fibre laser. Figure 2.5 show the principle of the process. During the laser sintering process, the metal powder is heated to a temperature above the melting point by exposure with the laser beam. A solid body is produced by this heating and the subsequent cooling. In each layer the cross-section of the parts is exposed using the laser beam such that the exposed areas are joined to the layer underneath that has already been solidified. In this way three-dimensional parts are produced layer by layer. [8]

2.6.2 Building process

Figure 2.6 show the building of the process. For the start of the building process, the building platform is moved to its start position and a bottom layer of metal powder applied to the building platform. Then the machine and peripherals connected are flooded with the appropriate inert gas. Once the oxygen content in the machine is below a defined limit, the automatic building process starts.

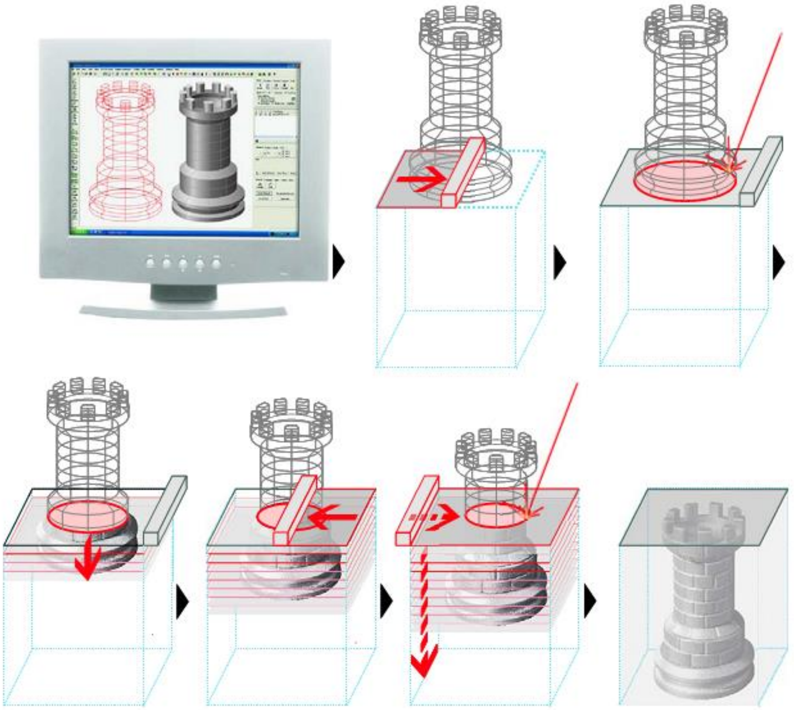


Figure 2.5. Principle of the process. [8]

By exposure using a computer-controlled laser beam, the metal powder is solidified to suit the calculated part geometry data. Then the building platform is lowered by one layer thickness and a new layer of metal powder applied. The metal powder is exposed again, the building platform lowered and metal powder applied. This process is repeated continuously to produce the part. [8]

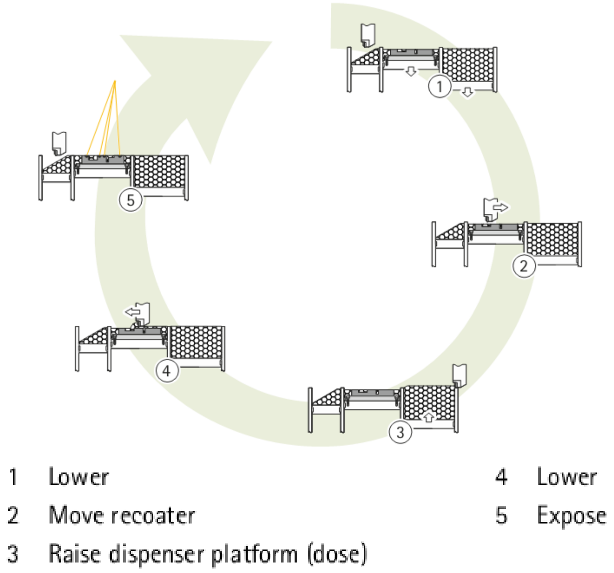


Figure 2.6 Building of the process [8]

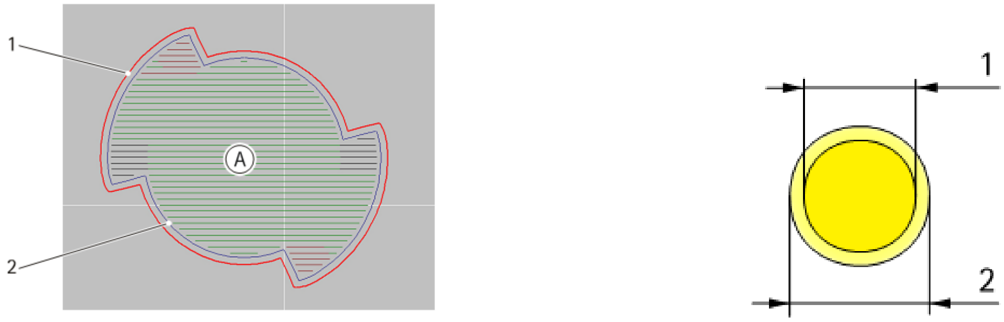
2.7 Factors that affect the laser sintering process

To ensure the sintered part meets the quality requirements, these factors must be consider to be taken into account on setting the machine parameters. The material parameters as well as on the selection of the exposure type. Generally the laser sintering process is affected by the following factors:

1. Exposure
2. Support
3. Process-related effects
4. Ambient conditions.

2.7.1 Exposure

During the exposure of a layer, the contour, the periphery of the part and the enclosed area of the layer are exposed using a laser beam. During this process the metal powder is melted and bonds to the layer underneath. During the exposure, a curing zone of solidified metal powder forms around the laser beam.



2. Laser beam curing zone

1 Contour
2 Contour line (centre of the path of the laser beam for the exposure of the contour)
A Hatch lines (centre of the path of the laser beam for the exposure of the enclosed area of the layer)

1. Diameter of laser beam
2. Laser beam curing zone

Figure 2.7 Exposure and laser beam [8]

For the dimensional accuracy of parts, the size of the curing zone must be taken into account during exposure. It is dependent on the powder material used and the exposure type selected. The dimensional variation is compensated by offsetting the laser beam.

2.7.1.1 Beam offset on exposure of the contour

If the path of the centre of the laser beam moves along the nominal contour of the part during exposure, the contour of the part is enlarged by the radius of the curing zone of the laser beam. The beam offset compensates for this contour enlargement. It displaces the centre of the path of the laser beam inwards.

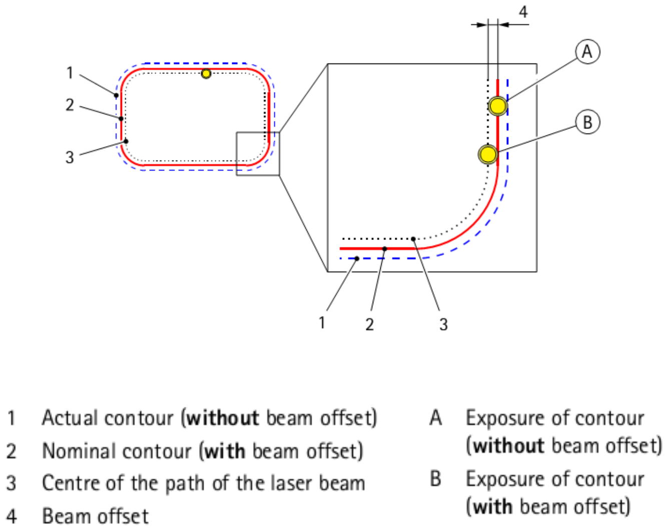


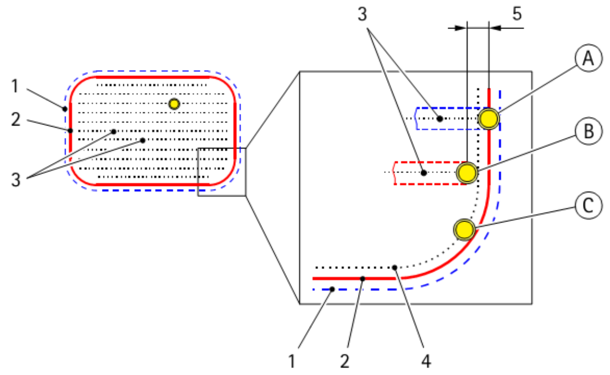
Figure 2.8 Beam offset on exposure of the contour [8]

2.7.1.2 Beam offset on exposure of the enclosed areas of the layer

During exposure of the enclosed areas of the layers, the beam offset displaces the path of the centre of the laser beam from the nominal contour by the value entered towards the inside.

2.7.1.3 Exposure types

The exposure types contain defined material and process parameters for the exposure. Depending on the parameter settings, these types affect the mechanical properties and the surface finish quality of the part, as well as the building speed. An exposure type can be allocated to any part.



1 Actual contour (**without** beam offset)
2 Nominal contour (**with** beam offset)
3 Centre of the path of the laser beam (exposure of enclosed area of the layer)
4 Centre of the path of the laser beam (exposure of contour)
5 Beam offset

A Exposure of enclosed area of the layer (**without** beam offset)
B Exposure of enclosed area of the layer (**with** beam offset)
C Exposure of contour (**with** beam offset)

Figure 2.9 Beam offset on exposure of the enclosed areas of the layer [8]

2.7.2 Process-related effects

The geometrical properties of the parts affect the laser sintering process. The optimisation of the part geometry and effective positioning and orientation of the parts in the building chamber contribute positively to the part quality. Along with these factors that can be influenced, process-related phenomena such as temperature-related shrinkage or distortion must also be taken into account.

2.7.2.1 Shrinkage

During cooling the part contracts due to physical processes and becomes smaller. This shrinkage behaviour varies depending on the material used and can be of varying magnitude in all directions.

2.7.2.2 Distortion

Distortion occurs in the case of large thermal differences during the building process or during cooling after the end of the building process and results in warped parts. The distortion is equally dependent on the part geometry and the material used.

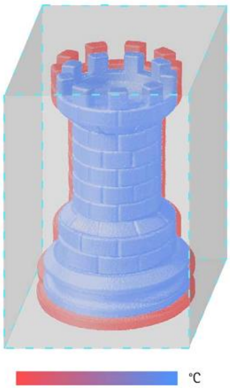


Figure 2.10 Shrinkage behavior of the part during cooling phase [8]

2.7.3 Ambient Conditions

Compliance with the ambient conditions is essential for a trouble-free building process for maintaining the value of the machine and the accessories. Non-compliance with the ambient conditions can affect the result in malfunctions in the building process and will be damage the machine and the accessories

2.8 Data Preparation

There are two stages figure 2.11 that include the data preparation stage and the part building stage in the whole procedure. The data preparation stage is the digital treatment process that slices the 3-D model into 2-D layer model. The second stage is the actual part fabrication using the machine. Some process parameters that have close relationship with the final part quality need to be identified.

In the first stage, the original 3-D CAD model is sliced into a set of parallel layers filled by hatch lines. The layer information is then used to drive the machine directly. There are normally three sub-stages in the data preparation stage, and these are described in the following sub-sections:

2.8.1 Build the CAD model

Data preparation stage 3-D digital model 3-D .STL model 2-D layer model 3-D physical part built by DMLS. The initial purpose of RP techniques is to rapidly create the concept prototype in the early design stage of the product development. Firstly a 3-D model is designed with a CAD system.

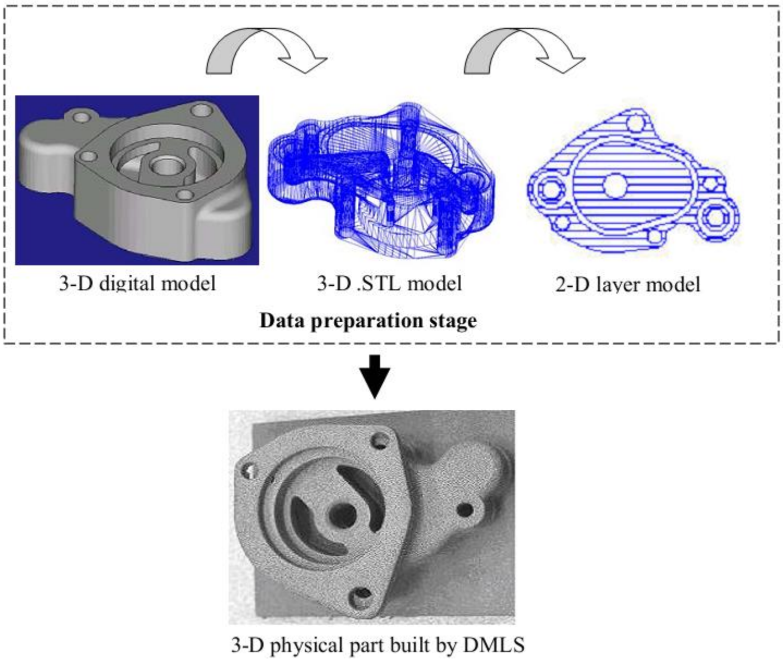


Figure 2.11 Part fabrication stages from 3-D digital model to physical part [9]

2.8.2 Triangulation of the object

The surface of the model is represented by a set of small triangles. To record the information of these triangles, the standard STL file format is adopted. Because STL files use planar elements, they cannot represent curved surfaces exactly. Increasing the number of triangles improves the approximation, but at the cost of larger file size.

2.8.3 Transition of 3-D models into 2-D layer models

The STL model is sliced into a series of cross-sectional layers. Each layer is recorded as a machine-readable data file with information on the contour and internal section. The internal section of each layer is filled by a specific scanning pattern.

2.8.4 Part building

In this second stage, a laser is controlled to selectively sinter layers of material continuously to create the 3-D physical model in figure 2.12. A metallic powder system is equipped with the powder supply cylinder filled up with two kinds of mixed metallic components. The powder is provided to the working cylinder in a thin layer of a fixed thickness. After that the powder surface in the working cylinder will be scanned with a high-energy CO2 laser system according a definite pattern. The layer sintering process is repeated till the whole part is created.

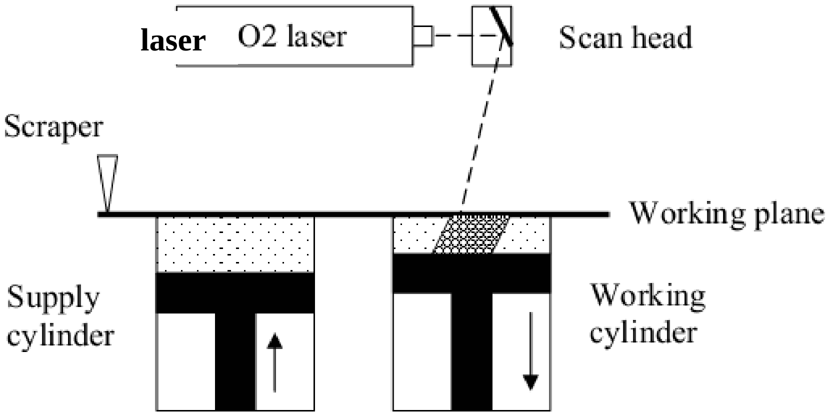


Figure 2.12 Part building of DMLS [9]

2.9 Type of parameter in DMLS

There are many parameter that will influence the object that fabricate by SLS system. Each of these parameter has bring some effect to the object either during the fabrication process or the feature definition of the finished object. Different process parameters will affect the sintering quality and finally affect the quality of part. Usually, the following properties of the built part are the primary concern to the user:

1. Dimensional accuracy
2. Mechanical strength
3. Processing time
4. Surface roughness

2.9.1 Part Accuracy

The ability of a Solid Freeform Fabrication (SFF) process to produce accurately shaped geometry is critical to its overall acceptance in the market place. [9] To achieve an accurately built part is a time-consuming and complicated task because many factors can affect the final dimensional accuracy. There are several of the following factors;

2.9.1.1 Pre-processing error

Rapid prototyping of 3-D models are performed by generating and stacking in two dimensional (2-D) cross sections of uniform thickness. In rapid prototyping, the fabricated part has a quantification error when the height is not a multiple of the finite layer thickness. To process the 2-D layer data, 3-D model is first converted to a faceted model (in STL format). This incurs another pre-processing error during the tessellation of the faceted model when a sufficiently high tessellation resolution is used to meet the accuracy requirement.

2.9.1.2 Machine errors

Machine errors can be measured, appropriately calibrated and compensated. The effect of the overall system errors can be controlled to a reasonable scale.

2.9.1.3 Material processing errors

The dimensional errors arising from the material processing are the most complicated factors. In the SLS process, the temperature of part or all of the powder is raised above its softening (such as for plastic powder) or melting (such as for metallic powder) temperature to bond and solidify the particles during the laser sintering process. After the process, the sintered part shrinks as it cools. To compensate the effect of material shrinkage, the 2D-layer model needs to be scaled first.

The final part accuracy is mainly influenced by the shrinkage of sintered material. The difference in the length of hatch lines filled in the different 2-D layered geometry causes uneven shrinkage rate. If the shrinkage rate is not uniform, the compensations become hard to implement. Additionally, the material warpage and distortion related to the inhomogeneous material shrinkage are other serious problems in the laser sintering process. Currently, none of the technologies has the capability to effectively avoid or control the heterogeneous effect caused by the variation of geometry shape. [9]

2.9.2 Part Mechanical Strength

Part mechanical property is an important resulting property of concern to users especially if they want to build functional prototypes by RP systems. Research works have been done on the effect of different process parameters on part mechanical properties with different RP processes. For parts built by selective laser sintering (SLS), some models are created based on the understanding of the laser energy delivery system. Nelson (1993) constructs a physical model of the sintering process that relates the sintering depth and laser control parameters. [9] In this model, the Andrew number (An) is proportional to the part strength and is shown to be a combination of the scanner parameter to yield:

$$An = \frac{Laser \quad Power}{Beam \quad Speed \quad \times \quad Hatch \quad Space} \tag{2.1}$$

It shown that green strength of composite parts is related to the Andrew number. However, the equation achieved is based on the amount of the energy delivered to the surface where the energy lost though heat transfer is not considered.

2.9.3 Process Time

Processing time is an important factor affecting the product cost. Several process parameters such as thickness, scanning speed, the orientation and hatch distance can affect the build time of the prototype significantly. Unlike the other properties, for processing time, there is normally a clear quantitative relationship with the parameters, so that a direct mapping function can be deduced based on different processes.

2.9.4 Part Surface Roughness

As an important issue affecting the part quality, surface roughness is most important when prototyping is used for casting. Two different types of surfaces are formed when the 3-D physical model is created. The first type of surface is created along the sintering direction by a continued accumulation of the 2-D contour of each layer. It defined as contour accumulation surface. This type of surface is smooth when the thickness of each layer is small enough. But because the existence of height of each layer, the surface smoothness when created initially in a CAD system will be broken. On sloping or curved surfaces, a stair-case error will appear. The most popular method to evaluate this stair-case effect is using the cusp height. It is defined as the maximum distance between the CAD model and the built layer measured along the surface normal.

2.10 Process parameter

The DMLS process is characterized by some important process parameters that determine the quality of the sintering part. The parameters in SLS system normally are divided into two groups which are, building parameters and materials parameters. The building parameter include the spot diameter, laser power and scan speed, scan spacing, and layer thickness. These parameter play an important role in SLS system to get a more accuracy and high quality object.

2.10.1 Spot diameter

In SLS system the spot diameter is the spot size of the laser beam diameter at the laser material interaction surface and it also defined in terms of the stand-off distance. When the spot size decrease and the power density will be increase, which mean the energy absorption will also increase. The increase of the energy absorption will lead to a reducing of the exposure area and it will improve the accuracy due to the part definition during the SLS process also had increase, but this will equally increase the raster time. Moreover, smaller feature sizes can be achieve when scanning fine details and to decrease curling due to a smaller spot size is apply [4, 11].

Spot diameter can be change if different type of laser apply in the SLS system, this is because of different type of laser has different magnitude of wavelength. Basically there are two type of laser use in the SLS system which are the CO_2 laser and the Nd:YAG laser. The wavelengths of the CO_2 laser is 10.6µm, while the wavelengths of the Nd:YAG laser is 1064nm which is much more smaller than the CO_2 laser [13].

The formula of diffraction limited minimum spot diameter, d_{min} to which the laser beam can be focused is given by :

$$d_{\min} = \frac{4M^2 f\lambda}{\pi D_l} \qquad (2.2)$$

Where λ is the radiation wavelengths, f is the focal length of the focusing lens, M^2 is the beam propagation factor and D_l is the beam diameter at the lens [13].

This formula had clearly show that, when wavelengths is decrease the spot diameter will also be decrease which the spot diameter is directly proportional to the wavelengths.

If compare the CO_2 laser and the Nd:YAG laser at a comparable beam diameter and beam quality condition, the spot diameter by using the Nd:YAG laser is 10 time smaller than the spot diameter that using the CO_2 laser [13].

2.10.2 Laser power and scan speed

Before the fabrication, two important process parameters, scan speed and laser power, need to be decided based on the laser system and powder material properties. The presence of the liquid phase results in rapid sintering since mass transport can occur by liquid flow and particle rearrangement. [9] Therefore, high laser power and slow scan speed are normally used in the metal sintering. Normally, a higher laser power and slower scan speed also bring higher part strength because more energy is absorbed by the loose metallic powder.

The result of the build part is a higher density. But over-sintering will occur when the energy is too high. The resulting properties will then decrease sharply. The higher laser energy will bring a larger fused zone each time but will affect the part accuracy. In general, the sintering layer surface roughness will increase with increasing laser scan speed. [9] Therefore, it is important to make a trade-off between the scan speed and laser power setting.

The main effect of increasing power of laser is to melting the powder particle more faster and/or greater depths of heat penetration. Once the powder particle has absorbed the high power of laser, the heat will generate in the powder particle instantaneously. The rapid heat generation inside the powder particle will cause the powder particle melt and bond together in a short time. The increasing of the scan speed, the shorten time needed for heating thus, for a given laser power, less time for the heat to diffuse sideways, causing a narrowing of the melt region and heat affected zone. When the speed increase, it will cause ad sharpened pencil effect in the Gaussian laser beam, which there is only sufficient energy focus at the tip of the Gaussian curve to melt the powder particle. Thus, increasing the laser power is needed in high scan speed to readdress the balance between the scan speed and the laser power [4, 11, 16].

There is strong relationship between power and speed, thus a suitable way of expressing their influences on the interaction of time as powder density in the form of a compound variable which is consult to as the specific energy density (Es) is given by :

$$\mathrm{Es} = \frac{P}{v_b \cdot d} \tag{2.3}$$

Where the E_s is the specific energy density, P is the average laser power, d is the beam diameter / spot diameter, v_b is the scan speed [13].

From the formula 2.3, it had show that when energy density increase the laser power will also be increase but the scan speed and the beam diameter will be decrease. If the energy density remain, when the laser power increase, the scan speed will also need to be increase in order to maintain the energy density [16]. This formula can be use to compared the interaction parameter found in it, by change the pool size and the density which it almost in linear. The formula 2.3 only support limited melting response image, due to the number of assumption that had been made to get this formula. These assumptions are included:

REFERENCES

1. *Pero Raos, A.S., Rapid prototyping and rapid tooling. An approach in Manufacturing of Medical Implant, 2005: p. 683-686.*

2. *Ben Vandenbroucke and Jean-Pier re Kruth .Selective laser melting of biocompatible metals for rapid manufacturing of medical parts*

3. *Dewidar, M.M., J.-K. Lim, and K. Dalgarno, A comparison between direct and indirect laser sintering of metals. Journal of Materials Science and Technology, 2008. 24(2): p. 227*-232.

4. Eane, R.B., *"Metal powder effects on selective laser sintering". PhD thesis*, 2002, University of Leeds.

5. Sponaugle, C., *History of Haynes International, Inc.* 2006.

6. Moharrami, N., et al., *Why does titanium alloy wear cobalt chrome alloy despite lower bulk hardness: A nanoindentation study?* Thin Solid Films, (0).

7. Aulus Roberto Romão Bineli, Ana Paula Gimenez Peres, André Luiz Jardini, Rubens Maciel Filho. Direct Metal Laser Sintering (DMLS): Technology For Design And Construction Of Microreactors April 11th to 15th, 2011 – Caxias do Sul – RS – Brazil

8. Training Manual – EOSINT M 280,Article number: 9229-3511.

9. NingYu, "Process Parameter Optimization for Direct Metal Laser Sintering (DMLS)" PhD thesis, 2005, National University Of Singapore.

10 Raja, V. and K.J. Fernandes, *Reverse Engineering: An Industrial Perspective*2007: Springer Publishing Company, Incorporated. 242.

11. Dewidar, M.M.A., *"Direct and Indirect Laser Sintering of Metals". PhD thesis*, 2002, University of Leeds.

12. Chua, C.K., K.F. Leong, and C.C.S. Lim, *Rapid prototyping: principles and applications*2010: World Scientific.

13. Glardon, R., et al., *Influence of Nd:YAG Parameters on the Selective Laser Sintering of Metallic Powders.* CIRP Annals - Manufacturing Technology, 2001. **50**(1): p. 133-136.

14. J.P.Kruth, L.F., L.Van Vaerenbergh, P.Mercelis, M.Rombouts and B.Lauwers: J. Mater, *Process.Technol.* 2004. **149**: p. 616.

15. L.Lu, J.Y.H.F.a.Y.S.W., *Laser-Induced Materials and Processes for Rapid Prototyping*2001, Norwell, USA: Kluwer Academic Publishers.

16. Hauser, C., *"Selective Laser Sintering of a Stainless Steel Powder". PhD thesis*, 2003, University of Leeds.

17. Agarwala, M., et al., *Direct selective laser sintering of metals.* Rapid Prototyping Journal, 1995. **1**(1): p. 26-36.

18. Niu, H.J.C., I. T. H. , *Selective laser sintering of gas atomised M2 high speed steel powder.* Journal of Materials Science and Technology, 2000: p. 31-38.

19. Laoui, T., et al. *Process optimization of WC-9Co parts made by selective laser sintering*. in *Proceedings of the 8th International Conference on Rapid Prototyping*. 2000.

20. Simchi, A. and H. Pohl, *Effects of laser sintering processing parameters on the microstructure and densification of iron powder.* Materials Science and Engineering: A, 2003. **359**(1–2): p. 119-128.

21. Sherman WO. Vanadium steel bone plates and screws. Surg Gynecol Obstet 1912;14:629-34

22. Habibovic P, Barrère F, Blitterswijk CAV, Groot Kd, Layrolle P. Biomimetic hydroxyapatite coating on metal implants. J Am Ceram Soc 2002;83:517-22.

23. Lahann J, Klee D, Thelen H, Bienert H, Vorwerk D, Hocker H. Improvement of haemocompatibility of metallic stents by polymer coating. J Mater Sci Mater Med 1999;10:443-8.

24. Yang K, Ren Y. Nickel-free austenitic stainless steels for medical applications. Sci Technol Adv Mater 2010;11:1-13.

25. Hermawan H, Mantovani D. Degradable metallic biomaterials: The concept, current developments and future directions. Minerva Biotecnol 2009;21:207-16.

26. Rahman, N.b.a., *Fabrication of Cobalt Implant Composite Material Using Rapi Prototyping Machine For Reconstructive Surgery* 2009, UTHM.

27. Monroy, K., J. Delgado, and J. Ciurana, *Study of the Pore Formation on CoCrMo Alloys by Selective Laser Melting Manufacturing Process.* Procedia Engineering, 2013. **63**(0): p. 361-369.

28. Dourandish, M., et al., *Sintering of biocompatible P/M Co–Cr–Mo alloy (F-75) for fabrication of porosity-graded composite structures.* Materials Science and Engineering: A, 2008. **472**(1): p. 338-346.

29. Gao, Z., et al., *Preparation and Characterization of Ti-10Mo Alloy by Mechanical Alloying.* Metallography, Microstructure, and Analysis, 2012. **1**(6): p. 282-289.

30. Pilliar, R.M., in *Biomedical material, Chapter 2:Metallic Biomaterials*2009, Springer Science. p. 41-81.

31. Rodrigues, W.C., et al., *Powder metallurgical processing of Co–28%Cr–6%Mo for dental implants: Physical, mechanical and electrochemical properties.* Powder Technology, 2011. **206**(3): p. 233-238.

32. Robert, *Material data sheet of EOS CobaltChrome MP1 for EOSINT M 270.*

33. J.P. Kruth, L. Froyen, J. Van Vaerenbergh, P. Mercelis, M. Rombouts, B. Lauwers. Selective laser melting of iron-based powder. Journal of Materials Processing Technology 149 (2004), p. 616-622.

34. Emmelmann C, Scheinemann P, Munsch M, Seyda V. Laser additive manufacturing of modified implant surfaces with osseointegrative characteristics. Phys Proc 12 (2011), p. 375-84.

35. ISO 13314:2011, Mechanical testing of metals - Ductility testing - Compression test for porous and cellular metals International Organization for Standardization, 2011.