Mechanical properties of trabecular structures produced by SLM, as a function of the trabecular morphology
This final project work has been carried out at the University of Trento in the subject area materials engineering. The work is a part of the Master of Science program; Product Development and Materials Engineering at Jönköping University, School of Engineering. The authors take full responsibility for opinions, conclusions and findings presented.

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Scope: 30 credits

Date: 2017-05-24
Abstract

Eurocoating, Italy, is a company that works in the biomedical sector. They have for a long time created prostheses from CAD files achieved from customers, and now they want to build their own expertise about the design. The thesis work was a part of a three year long collaborative research project between Eurocoating and University of Trento that was aiming to investigate the prostheses with open-porous surface and trabecular structure, created by Selective Laser Melting.

The purpose of the thesis was to investigate and characterize 30 different trabecular structures of Ti-6Al-4V, fabricated by Selective Laser Melting. That includes investigation the effect on the morphology and porosity fraction caused by the manufacturing and the effect on mechanical and physical properties due to the different characterizations of the structures.

The thesis work had its foundation in literature studies to receive deep knowledge about the subject. Practical tests were performed to investigate mechanical behaviour under compressive and tensile loading, static friction and wear resistance. The findings from these tests were compared to the porosity fraction and the morphological characterizations.

The result stated that the porosity fraction was lower than the designed porosity, and that is was strongly influenced by size of the voids and struts. The strut thickness was higher than the design values, especially on the lateral surface, while the voids size were approximately as designed. Result from the compression test showed a trend of decreasing stiffness and strength with increasing porosity fraction. Also structures with same porosity fraction could have a wide range in mechanical properties which indicates high dependence on the morphological geometry i.e. pore size and shape, strut size and pore distribution. Comparisons between tensile and compression behaviour stated that the structures had a lower strength but a significant higher stiffness in tensile load. All structures from the wear test showed a good resistance while the results from the friction test needs further investigation to be fully understood.

The physical and mechanical properties of the trabecular structures was found to be close to those of cortical and trabecular bone in porosity, stiffness and strength. There is a range of variations leading to possibilities to adopt the application depending on customer. Thus, these can be considered as promising structures used biomedical application to optimize osseointegration and secondary long term fixation.

Keywords
Additive Manufacturing, Selective Laser Melting, Ti-6Al-4V, Trabecular structure, material testing, mechanical properties
Acknowledgements

The authors of this thesis want to take the opportunity to show gratefully acknowledge to the people that has supported us and made this thesis possible.

Alberto Molinari  
Professor  
Metallurgy

For being our tutor and guided us through this thesis work and supported with time, knowledge and a lot of encouragement.

Caterina Zanella  
Associate Professor  
Surface technology

For being our supervisor and helped us with all the administrative part of the thesis work.

Gianluca Zappini, Valerio Luchin and Emanuele Magalini  
The project group at Eurocoating

A special thanks for giving us this opportunity and for providing us with all the specimens and their expertise in the subject.

Matteo Benedetti  
Associate Professor  
Mechanical design & machine construction

For helping us with the set up and knowledge about the compression and tensile tests.

Vigilio Fontanari  
Professor  
Mechanical design & machine construction

For helping us to find a appropriate method to perform the friction test.

Lorena Maines  
Laboratory technician  
Department of Industrial Engineering

For helping us with the morphological investigation in the SEM.

Luca Benedetti  
Laboratory technician  
Department of Industrial Engineering

For all help with the morphological and microstructural analysis.

Massimiliano Tomaselii  
Research assistant  
Department of Industrial Engineering

Our guide and teacher in the laboratories, our helper when we needed something practical and our company during many pleasant “fika” breaks.

Alessandro Dai Pré and Nicola Zambaldi  
Students at University of Trento

For helping us with the morphological investigation in the stereomicroscope.

And all others that in some way helped or guided us through this thesis work. It wouldn’t have been possible without you and we are really grateful! Thanks also to University of Trento for the office with a view and for the access to the facilities.

We also want to thank everyone that made sure that we got an amazing experience during our exchange semester in Italy, including tips about places to visit and restaurants to eat at. A special thanks for teaching us how to drink espresso and how to properly serve red wine. It will not be forgotten.

We also want to thank Salem Seifeddine, professor at Jönköping University, for helping us to search for an interesting thesis work all around the world and to fulfil our dream to go abroad.
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1 Introduction

This master thesis is a part of a three year long collaborative research project between Eurocoating and the University of Trento which aimed to achieve deep knowledge about the construction of orthopaedic prostheses. The thesis consists of an investigation of the effects of a trabecular structure, manufactured by Selective Laser Melting, on different mechanical properties of a Titanium alloy. Also the microstructure and static friction coefficient was investigated. The research was performed at the facilities of University of Trento during a student exchange period. The thesis was performed as the final project work at the master program Product Development and Materials Engineering at Jönköping University, School of Engineering.

1.1 Background

Eurocoating is a company that figures in the biomedical sector. The company specializes in biomedical surface treatments and creating and developing new surface solutions for orthopaedics, dental, trauma and spinal applications [1].

Eurocoating is now producing prostheses with additive manufacturing technologies from CAD models received from their customers. The company has deep knowledge about additive manufacturing, and now they want to build their own expertise about the design of the prostheses. This to be able to help their customers to choose the right product for their specific need and to have a product range to offer. One of the areas that Eurocoating wants to investigate is the prostheses with open-porous surface and trabecular structure, created by Selective Laser Melting. This kind of structure is highly beneficial for secondary fixation (long term fixation) of orthopaedic prostheses.

The pore architecture is one of the important points to make the product optimized for osseointegration (the formation of a direct interface between an implant and bone, without intervening soft tissue) and is also of importance to get the right stiffness on the material. This trabecular structure will affect the mechanical properties of the products. When it comes to the biomedical area there are many requirements in terms of ISO and ASTM standards of mechanical and physical properties such as wear, static friction and compression for the product to fulfil. It is therefore of importance to have knowledge about how a trabecular structure created by Selective Laser Melting affects the different properties. It is this area of investigation that is the scope of the thesis.

1.2 Purpose and research questions

To achieve knowledge about the topical area, the thesis work aimed to investigate and characterize specimens with different trabecular structures, fabricated by the additive manufacturing method Selective Laser Melting. The effect on mechanical and physical properties due to the porosity fraction and morphology of the structures was investigated.

To increase that knowledge the following research questions were established to be answered during the thesis:

- How do the different structures with same porosity fraction manufactured by Selective Laser Melting influence the mechanical properties?
- What is the correlation between Young's Modulus and the porosity fraction?
- Is there a correlation between compression strength and wear resistance measured by the Taber test?
- Is the static friction coefficient affected by the porosity fraction?
- Are the mechanical properties similar in compression and tensile conditions?
- Can the morphological characteristics of the specimens be defined through a metallographic approach on the surface?
- Is the porosity fraction different between the designed values and the real values of the structures?

To answer the determined research questions a suiting research approach was to be considered.

1.3 Research approach

The thesis work was a part of an experimental research project, therefore the approached positivism was used. Positivism is based on deductive reasoning together with hypotheses testing and is related with quantitative methods. In this thesis the positivist researched design described in the book *Research methods for students, academics and professionals* [2] is modified to the thesis work so the hypotheses is replaced by research questions. Figure 1 shows an illustration of the research approach used in this thesis.

![Figure 1. Illustration of the research approach used in this thesis](image)

Initially a meeting with Eurocoating was arranged to acquire information about the company's objective of the research project and to understand the purpose of the thesis. The literature review was restricted to previous research in the area of importance and was the base for the theoretical framework (chapter 2). With knowledge about the trabecular structure, Selective Laser Melting and material properties the research questions could be formulated and with good complement of experienced personnel the test apparatus was defined. The preliminary work was for practice on metallography and also to validate and learn the mechanical test machines by personal instructions. The mechanical and physical test procedures were determined by standards or after literature search. The results were analysed, discussed and conclusions were drawn. A full list of the literature can be found in chapter 6 and the people giving instructions are credited in acknowledgement.
1.4 Delimitations
The thesis work was covering an investigation of 10 different structures in 3 different batches, representing 3 different combinations of voids and strut sizes. All specimens were made by Ti-6Al-4V and manufactured by Selective Laser Melting. The structures and the batches with different characteristics were designed and produced by Eurocoating. The investigated parameters of the batches were void size and strut thickness, and the investigated structures were defined by regular, irregular or fully random unit cells. No other material, other types of microstructure or manufacturing processes was to be considered. The design of the unit cell and the melting parameters used in the SLM process were kept confidential and were therefore not taken into consideration in the analysis. The mechanical and physical properties tested and analysed were density, wear resistance, static friction coefficient and compressive and tensile behaviour. Majority of the tests was performed and analysed according to standards. The microstructural and morphological analysis was limited to porosity fraction, void and strut size and determination of the presence of \( \beta \) phase. The result from the tests was only used for analyses and to find correlations between the porosity fraction, morphology and different properties.

1.5 Outline
The thesis begins with a theoretical background where the reader will be introduced to subjects that were of importance for the thesis work. There will be an introduction to trabecular structure and Selective Laser Melting and there will also be a description of the material used and previous research in the field.

Following the performance of the used methods will be described. For the tests that had a standard to follow there will be a definition of the standard and then how it was adapted to fit the thesis work. Further there will also be a review of the result. A deeper analysis of the result can be found in the subsequent chapter.

The thesis will be closed with a discussion of the methodology used and the findings of the thesis, a brief summary of the main points in the thesis work and propositions for further research.
2 Theoretical background

This chapter describes the theories and previous research found in the literature that covers the subjects of this thesis. The trabecular structure and its pore topology and how the structure affects the mechanical properties is first presented followed by information about Selective Laser Melting, the material used; Ti-6Al-4V and last previous research.

2.1 Trabecular structure

Trabecular bone is the inner part and the cortical bone is the outer part of the natural bone, they belong to porous materials with interconnected voids [3]. The trabecular bone is found in the vertebral bodies of the axial skeleton and at the end of the long bones of the appendicular skeleton. It has a porous structure pattern. This complex patterns assists to maximal strength for minimum mass for the skeleton. The trabecular network has both rod-like and plate-like structures with interconnected voids, which has a random structure and can be found in more or lesser proportion depending on the skeletal site. The trabecular bone provides, due to high mineral surface area, an extensive substrate on which cellular interaction with bone mineral material can occur [4].

![Figure 2. 3D CAD model of trabecular structure [4].](image)

2.1.1 Pore architecture

With additive manufacturing it is possible to obtain similar design, which is interconnected pores as natural bone i.e. pore size and pore distribution (Figure 2). Titanium is known for its good biocompatibility since decades and it is already used as material for medical implants. In form of a trabecular structure it can lead to the development of innovative orthopaedic prostheses [3]. The morphology of porous materials can be both stochastic (random) and ordered (regular) depending on the manufacturing settings [5]. The trabecular structure has an open-cell structure, meaning it is permitting flow of fluid inside the scaffold, the other type of porosity is closed-cell porous, that can be found inside the structure, i.e. it cannot permit flow of fluid [6]. There are criteria that porous biomaterials should be able to achieve for bone replacement. These criteria include: filling of bone defect voids, the pore architecture and the pore interconnectivity should promote osseointegration and sufficiently good mechanical properties to support physiological loading. The function of the porous biomaterial structure needs to consider the microarchitecture like pore shape and size, cell topology and porosity fraction, both of these have a high impact on the osseointegration, interface strength and mechanical behaviour. For optimal osseointegration the pore size should be between 50 μm and 800 μm and have a porosity higher than 50% [7]. With a porosity of 75% to 80% an increase in fixation strength can be obtained and it is needful to have interconnectivity between the pores in order to permit osseointegration [8]. There are limits of the pore size due to the biological factors, pores larger than 700 μm can promote osseointegration but at reduced rates and volumes of bone ingrowth. Pore size less than 100 μm loses the...
support of the growth of capillaries and also allow the bone cells to bridge and close pores [9].

With Selective Laser Melting the microstructure can be designed with the biomaterial titanium to reach the right mechanical properties and also optimize the biological activities (Figure 3). The trabecular structure also allows a larger surface area to apply surface treatment and coatings on. The mechanical properties of a trabecular structure are a function of the morphological properties of the porous structure and also the configured size of the repeated unit cell [10].

**Figure 3.** Orthopedically hip prostheses with trabecular structure [1].

Full dense Ti-6Al-4V has a yield stress of approximately 871.5 MPa [11] and an elastic modulus of 110 GPa [3]. Cortical and trabecular bone has compressive strength of 17-209 MPa [4] [12] and the elastic modulus of full dense Ti-6Al-4V is 5 to 200 times higher than for natural bone, that is ranging from 0.5 to 20 GPa. With a trabecular structure of the prosthesis it is possible to avoid mismatching of elastic modulus thus keep away from the phenomena “stress shielding”. Stress shielding is uneven stress distribution between the orthopaedic prosthesis interface and the bone that can lead to bone resorption around the prosthesis and eventually a high risk for fracture and loosening of the prosthesis [3]. There is evidence that bone responds to mechanical stress-strain stimuli, that below a specific stress-strain threshold, the bone receives a lesser need for remodelling. Remodelling in this context means changes in the trabecular bone orientation and density. This can lead to increased bone resorption levels. On the other hand, increased bone formation can be found by an increase of mechanical stimuli in the specific area [13].

A strong interface reduces the risk of tissue strain and micromotion, thus also support the osseointegration. Shear stress is a measure of the maximal interface loading capacity and need to be considered due to the physical loading [14]. Also for the orthopaedic prosthesis it is important to have a sufficiently high friction coefficient so the bone will enhance initial steadiness with low micromotions at the interface. The stability will encourage and maximize the osseointegration and conduce to mechanical interlock of the prosthesis and ideal mechanical stability [8].

The orthopaedic prosthesis need to have good wear properties to resist particle shedding. This particle shedding is undesirable and can occur during surgical procedure of an orthopaedic prosthesis or as outcome of the micromotion caused by the prosthesis after insertion. If the micromotion can cause weight loss this can result in a third body wear of articulating surface which is highly undesired [15].

### 2.1.2 Biomedical division

A biomaterial is a synthetic or natural material intended to interface with a biological system [3]. Porous biomaterials constitute a smaller subsection of the whole field of biomaterials and are particularly relevant for bone interfacing components. This since they provide a high surface area for bone ingrowths and also for secondary long term biologic fixation in orthopaedic and dental bone implant applications. Thus greater
accentuation on physiological solutions in the biomedical section of orthopaedic devices has led to more focus on the integration of porous structures. Previous studies have shown that trabecular structures can be designed both as the natural structure and with similar mechanical properties of bone compared to full dense counterparts [16].

2.2 Selective Laser Melting

Additive manufacturing, AM, is a technology where an object is created by adding material in layers. The cross sections of the object are obtained from a 3D CAD file. All the current AM processes uses this technique, the way they are different from each other is in how the layers are created and bonded to each other and in what materials that can be used [17].

Selective Laser Melting is one of three different types of Laser Additive manufacturing processes, where a laser is used to bond the layers to each other. The other two processes are Selective Laser Sintering and Laser Metal Deposition [18].

2.2.1 The process

Selective Laser Melting, SLM, is a technique where loose powder material is melted and joined one layer at a time by an infrared fiber laser. The procedure is performed through several steps. First a thin layer of metal powder is distributed on a process platform. Secondly the laser melts the metal powder line by line in the selected areas. When the first layer is finished a new layer of powder is distributed upon the first one and melted by the laser. This procedure is repeated for multiple additive layers [19]. During the process inert gas is used to reduce metal powder oxidation and keep oxygen content into a required standard. In SLM a complete melting/solidification mechanism is used unlike Selective Laser Sintering where the powder is only partial melted. When using this technique the laser beam size and the scan speed is of importance of the duration of the beam on the particles [18].

The SLM system consists in general of a sealed building chamber, laser, automatic powder layering apparatus and computer system for process control. There is also extra mechanism as gas protection system and powder bed preheating system (Figure 4) [18].

2.2.2 Characteristics

SLM makes it possible for any 3D object to be created, it reduces waste material and it saves energy in comparison to traditional manufacturing techniques. Thus has it an
advantage of producing trabecular structures. It is a promising method to have precisely control over the microstructure, e.g. pore size, pore distribution and pore interconnectivity, which is crucial to predict the mechanical properties [20]. Also near fully dense materials can be created of a wide range of metals thanks to that the energy delivered by the laser is controllable [19]. Though, the full melting mechanism that is used in the process is a risk for the instability for the molten pool. During the solidification considerable stresses appears due to a large degree of shrinkage. Stresses that remain are regarded to be responsible for distortion and delimitation in the manufactured parts [18]. It is also hard to obtain homogeneous parts since no mechanical pressure is involved in the procedure [21].

2.2.3 Sustainability perspective
The AM process has several sustainability benefits, both in the environmental and the economical point of view. One reason for that is the reduced material waste [22], [23], [24]. The waste could be reduced with up to 90% in comparison with traditional subtractive manufacturing processes [24]. AM processes are also beneficial since the life cycle material mass and energy could be reduced. Another point is that the manufacturing could be made in multiple locations. That makes it possible to have the manufacturing closer to the point of consumption which leads to a reduction in transportation, meaning a minimised used of freight and lower fuel burden which has an impact carbon footprint and overall energy consumption. Also the part weight can be minimized [25], which means more light weighted transports. Other beneficial points are that it allows complex geometries to be produced [24] and products to be optimized for its function [22].

In the economical point of view AM processes are beneficial since there is no need for tooling which reduces the ramp up time and also the expenses. It is quick and easy to change the design of a product which also is of advantage for design customization. The supply chains can be made simpler which leads to shorter lead times and a smaller amount of inventories [22], [24].

2.3 Ti-6Al-4V
The material used in this research project was the Titanium alloy Ti-6Al-4V, also called Ti64, which is one of the most widely used Titanium alloys [26], [27]. Ti-6Al-4V is used in multiple applications in medical industry since the alloy has an extraordinary biocompatibility, particularly in contact with bone or tissue. Except for the biomechanical sector Ti-6Al-4V is also used in the aerospace industry, chemical industry, gas turbines and marine applications [27].

2.3.1 Composition and microstructure
Ti-6Al-4V is a composition of Titanium (Ti), Aluminium (Al) and Vanadium (V). The composition of the alloy is approximately 6 wt% Al and 4 wt% V [21]. The material can also contain small amounts of Oxygen (O), Hydrogen (H), Carbon (C), Nitrogen (N) and Iron (Fe). In Europe the maximum composition of these substances is around 0.2 wt% O, 0.0125 wt% H, 0.08 wt% C, 0.05 wt% N and 0.3 wt% Fe. The more alloying elements that is added to the Titanium the higher the strength of the material [28]. The material consist of α and β phase, but Ti-6Al-4V parts created by SLM consists of α and martensitic α’ phases and the β phase is missing. This is probably due to the high cooling rates. The microstructure is lamellar where the α phase is coarse and the α’ phase appears as dark needles [26] (Figure 5).
In the microstructure of Ti-6Al-4V elongated laths filled of needle shaped martensitic $\alpha'$ can be found in the building direction. This is a result of the SLM process. When the laser melts the metal powder it also melts underlying layers. When the $\beta$ grains melts they solidify and grow in the same direction as the heat conduction. When the laser moves away the $\alpha'$ laths fill the prior elongated $\beta$ grain [19]. A heat treatment can be used to allow the microstructure to precipitate into a more stable lamellar $\alpha+\beta$ structure [29].

Crystallography

The $\alpha$ and $\beta$ phases has different crystal structures, $\alpha$ has an HCP structure while $\beta$ has a BCC structure. $\alpha'$ has like $\alpha$ an HCP structure [21]. HCP (Figure 6 b) is a Hexagonal Closed-Packed structure and BCC (Figure 6 a) is a Body Centered Cubic structure [30]. In pure Titanium the transformation from $\beta$ to $\alpha'$ occurs easily and cannot be suppressed, therefore the transformation is believed not to be diffusion controlled but a diffusionless martensitic transformation. There is a considerable difference between properties generated from a hexagonal structure and a cubic structure. In the hexagonal structure the plastic deformation properties are much more directional than in cubic structures. This is due to the amount of closed-packed planes that the different crystal structures allow. In HCP there is only one closed-packed plane, while it in cubic crystals a higher amount of closed-packed directions is allowed [31].

Figure 5. Microstructure of Ti-6Al-4V with 3 different magnitudes [27].
Theoretical background

2.3.2 Mechanical behaviour

Ti-6Al-4V is an alloy that has a very good balance of strength, ductility, fracture properties, and fatigue [32]. Ti-6Al-4V objects that are manufactured by SLM are generally strong but have a poor ductility and a certain amount of anisotropy [19]. They also usually have a lower toughness and fatigue strength in comparison to wrought components [28]. Postprocessing methods can be used to find a better balance between strength and ductility and to get properties more similar to Ti-6Al-4V produced by a conventionally manufactured material [19]. When using a heat treatment, either stress relief or hot isostatic pressing, the ductility improves, though the strength decreases [29]. A heat treatment should be done for objects exposed to fatigue [27].

2.4 Previous research in the field

There is a significant amount of previous research on Ti-6Al-4V trabecular structures manufactured by SLM and how it affects mechanical and physical properties, though the research is mostly focused on regular structure and not on irregular and fully random structures. There is also research in the biomedical perspective, i.e. the effect of pore size on bone ingrowth.

In the biotechnical area there can be seen the interest of using an open- porous structure for orthopaedic prostheses is of high rate increasing and a lot of scientific researches confirm this trend. This interest to involve the osseointegration into the trabecular structure, but also to reduce the stiffness of the material that have been connected to early prosthesis loosening due to stress shielding. It is now confirmed that the design of the pore architecture should match the mechanical properties of natural bone to reduce the risk for stress shielding [33]. The challenge is to find the optimal pore architecture in the orthopaedic prostheses to maximize both biological and mechanical performances. There is lack of knowledge and understanding the role of what the pore architecture, i.e. porosity, pore size, pore distribution as well as strut thickness, plays in the mechanobiological response for a trabecular structure [7]. Also to have complete control over the fabrication of the pore architecture needs to be and are under development. There is also a need to have precisely control over the position of the pores in the specimen, its interconnectivity, shape and size [33].

Research on how the trabecular structure affects the mechanical and physical properties of a material has previously shown that stiffness and strength of the lattice decreases with increasing porosity. This may however vary between different topologies, i.e. it has been detected in a study that for Tetrahedron unit cell the stiffness and strength keeps decreasing with an increasing porosity while for Octet basic cell the decrease in strength ends when the porosity reaches approximately 75% [7]. There has also been indicated the size of the unit cell is of importance, the larger the unit cell, the higher the decrease
Theoretical background

of stiffness and strength [34]. Several studies have found that different topologies affect the mechanical properties in different ways [35], [10], [7]. The fatigue behaviour is a complex function that is affected by the type of repeating unit cell, and other factors like unit cell size, porous structure and porosity [35]. Also the deformation and failure mechanisms change by the different unit cells. This can be seen particularly when the plateau region in a stress-strain has been reached, e.g. by the ratio of plateau stress to yield stress. For some structures the ratio is more or less constant while for other structures the ratio increases noteworthy with a decrease in porosity. There has also been shown that the relative density is affecting the stress-strain curve of an object, e.g. by a decreased level of fluctuations after the plateau region as the relative density increases [10]. Irregularities caused by the AM process are found to weaken the structures, both considering the fatigue strength and Young's Modulus [35].

Under compressive strain it is proved that bending and buckling modes are peculiar to porous materials consisting of cell struts. In general specimens with a high porosity deform by bending and buckling and specimens with a low porosity deform by yielding. In curves obtained from compression tests in a previous study it has been found that a decrease in the porosity fraction leads to an increase in stress. The curves of specimens with higher porosity fraction showed three clear deformation regions: first an elastic region followed by a plateau region where the specimens deform under a more or less constant stress, and thereafter a densification region. In the last region the stress increases abruptly to a higher strain. The densification region appears at a higher strain interval for the specimens with higher porosity. Though, it was also shown that curves from specimens with lower porosity did not show clear plateau and densification regions. After the elastic region these two regions seem to emerge simultaneously [36].

In a research study on specimens of metallic foams, in comparison with specimens with regular structure it was detected that under a condition of identical specific modulus (stiffness over density) the regular structure has higher specific strength (stress at failure over density) than the foam. In this study it was also shown that the foam has finer microstructure than the regular structures. This is said to indicate that the fully random structure experiences a faster cooling during manufacturing [37].

Research that have investigate stiffness on metal foams, cortical and cancellous bone characterized from tension and compression have found marginally differences [5], [38]. Further there is experimental studies that have demonstrated a difference in compressive and tensile strength, that tensile strength has slightly lower strength [38], [9]. The result can occur from the manufacturing process that can occasionally contain inherent weaknesses between the bonds of each layer [9].

One phenomena that has been detected in both compression and tensile test in porous structures are successive failure of individual struts in the cellular construction. The failure starts with the one strut, the weakest. This causes a fall in the measured force and after this the other cells takes together over the load again and the force increases until the next failure of the next weakest strut. The stress-strain curve have a jagged behaviour and occurs before the ultimate failure of the specimen [10], [34].

Regarding Ti-6Al-4V and how it is affected by the SLM procedure, previous research indicates that there is a phase transformation from $\beta$ to $\alpha'$ due to the high cooling rates as earlier described [21], [26], [19]. There is also an indication that the $\alpha'$ is responsible for a decreased plane stress fracture toughness with respect to build direction in comparison to cast and wrought materials [17]. Though, the yield stress and ultimate compressive strength is higher for Ti-6Al-4V containing $\alpha'$ phases than for annealed microstructures containing $\alpha+\beta$ [39], [40]. It is also shown to be higher than for Ti-6Al-4V produced by conventional processing [40]. The elastic modulus is on the other hand a property that is not particularly affected by thermal treatments [39], [40].
Theoretical background

Previous research has shown that a part produced by SLM may differ from the designed parameters, e.g. strut thickness, and that the differences increases with increased porosity. However, it is also shown that the porosity fraction is consistent between specimens of the same structures, which show that there are no major morphological differences between replicas. The strut thickness is dependent on the strut angle with respect to the build plane. Struts with an 0° angle with respect to the building plane has been shown to be significantly thicker than their designed values, this due to strut over melting in the SLM process, while for struts normal to the building plane the manufactured thickness is slightly lower than their designed values. In the building plane the thickness of the manufactured struts corresponds with the designed values [21].
3 Method and implementation

The thesis project contained an essential part of practical work including morphological analysis, porosity fraction measurements and microstructural analysis. Also the mechanical testing of the trabecular structures comprising compression, tensile, abrasion and static friction tests. The compression test were performed according to an ISO standard. The test standards for abrasion, tensile and microstructure analysis were destined for characterizing coatings used on surgical implants. These standards were however accepted to be used also for porous structures obtained by AM since there are no standards and the porous structure has the same function as a coating of the prostheses would have. Also the industry guidance document: "Guidance for Industry on the Testing of Metallic Plasma Sprayed Coatings on Orthopaedic Implants to Support Reconsideration of Postmarket Surveillance Requirements" has been used as a reference to the performance of the tests. Initially a preliminary work was carried out followed by two phases where the result from phase I were thoroughly comprised by compressive mechanical behaviour of the all the structures and batches, combined with morphological and microstructural analysis. In Phase II a further investigation was introduced of a few selected structures with the remaining characteristics from static friction, tensile and the abrasion test. During the thesis work regular meetings with the project group from the company together with the tutor were performed to discuss and evaluate the result and make decisions about the proceeding work.

3.1 Preliminary work

A preliminary work was performed to define the test methods, the test apparatus and suitable conformation of the specimens. The methods had to be pretested on preliminary specimens to be sure they were suitable for this project and that reliable data could be achieved before the tests were performed on the real specimens. There were not an ISO or ASTM standard for all the mechanical and physical tests. Though, preliminary test and specimens were needed to ensure the test could be performed in an accurate way and verified if the specimens were suitable for the different mechanical tests.

First the compression test and friction test was defined. These specimens were used both for the microstructural analysis and the porosity measurement. Ongoing during the project the other methods were defined and the specimens were manufactured gradually.

3.1.1 Porosity fraction

The method for calculating the porosity fraction was determined by analysing the reliability of the result from different methods founded in the literature review. The Archimedes method was tried both with water and ethanol but it turned out that the liquid could not infiltrate all the pores. The method that became the final was to use the ratio between density of the specimen and the theoretical density of Ti-6Al-4V \( (4.2 \text{ g/cm}^3) \) [9].

The preliminary part was followed by defining the batches and structures and the conformation of the specimens to be able to perform the mechanical tests with suitable specimens.

3.1.2 Morphological analysis

Concerning the morphological analysis several methods were tested to investigate how the porous structure i.e. pore size and thickness of the struts could be defined. First there was a try-out of different ways to embed the specimens in epoxy plastic to find a suitable recipe for our porous structure. Both warm and cold resin can be used. In the
Method and implementation

Warm embedding a specimen is put in a form and covered by a resin powder that is heated up under pressure to create a compact shape. With the cold embedding a specimen is put in a form and covered by a liquid resin, i.e. an epoxy in liquid form. The form is then put into a vacuum machine to push the resin into the pores before solidifying. In this thesis the cold embedding was used to better fill the pores and since the pressure used in the warm embedding could be too high for the trabecular structure. Both light microscope and stereomicroscope were validated to find out which one that was the most suitable. Images from the different methods were compared and discussed with the tutor of the project. It turned out that the stereo microscope had a software tool that was preferable to measure the void size. To measure the strut thickness the SEM microscope was determined to be used.

3.2 Specification of specimens

The methods used for testing and analysing required different kinds of specimens. To be able to analyse the test results as a function of the trabecular structure 30 different structures with specific characteristics was investigated. The parameters to be analysed were the type of structure, the size of the voids and the strut thickness.

All specimens were heat treated to eliminate the remaining stresses from the SLM process to prevent that they affect the results or deformed the specimens.

3.2.1 Batches

Three different batches (A, B and C) were manufactured with different morphological characteristics (Figure 7). Each batch had 10 different structures; 2 fully random, 3 irregular and 5 regular. The structures occur in all three batches but with different characteristics of strut thickness and pore size that was typical for each specific batch. The characteristics of the batches were defined as following:

Batch A - large pores, large struts
Batch B - small pores, small struts
Batch C - large pores, small struts

In Table 1, the values for pore size and strut thickness from the design can be seen.

Table 1. Designed pore size and strut thickness.

<table>
<thead>
<tr>
<th>Batch</th>
<th>Pore size [μm]</th>
<th>Strut thickness [μm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1500</td>
<td>500</td>
</tr>
<tr>
<td>B</td>
<td>700</td>
<td>200</td>
</tr>
<tr>
<td>C</td>
<td>1500</td>
<td>200</td>
</tr>
</tbody>
</table>
The fourth possible combination would be small pores and large struts. That would however result in structures with pores that are not connected to each other and a low porosity fraction since the struts would be too large in relation to the pores to allow a structures with connected pores. This structure would not support osseointegration and was therefore not of interest for the project.

3.2.2 Structures
Each batch had 10 different structures with different morphological characteristics: regular, irregular or fully random (Table 2).

Table 2. Morphological characteristics for the structures.

<table>
<thead>
<tr>
<th>Structure</th>
<th>Type of geometry</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Irregular</td>
</tr>
<tr>
<td>2</td>
<td>Regular</td>
</tr>
<tr>
<td>3</td>
<td>Regular</td>
</tr>
<tr>
<td>4</td>
<td>Irregular</td>
</tr>
<tr>
<td>5</td>
<td>Regular</td>
</tr>
<tr>
<td>6</td>
<td>Fully random</td>
</tr>
<tr>
<td>7</td>
<td>Regular</td>
</tr>
<tr>
<td>8</td>
<td>Fully random</td>
</tr>
<tr>
<td>9</td>
<td>Irregular</td>
</tr>
<tr>
<td>10</td>
<td>Regular</td>
</tr>
</tbody>
</table>

Regular structures mean that a repeating unit cell easily could be defined while in irregular structures the unit cell is deformed, but still recognizable. In the fully random structures there were no repeating unit cell (Figure 8). The irregular structures had different grades of deformation, structure 1 had a very high grade of deformation and structure 9 had a low grade of deformation. Structure 4 had a deformation grade in between structure 1 and 9.
The designed porosity fraction is evaluated as the ratio between volume of the CAD model and volume of the full element. All structures in the same batch had similar designed average pore fraction but different structures could lead to differences in the porosity fraction (Table 3).

<table>
<thead>
<tr>
<th>Structure</th>
<th>Batch A [%]</th>
<th>Batch B [%]</th>
<th>Batch C [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>75.40</td>
<td>78.45</td>
<td>92.85</td>
</tr>
<tr>
<td>2</td>
<td>75.60</td>
<td>79.99</td>
<td>93.21</td>
</tr>
<tr>
<td>3</td>
<td>70.96</td>
<td>80.91</td>
<td>94.59</td>
</tr>
<tr>
<td>4</td>
<td>75.59</td>
<td>79.68</td>
<td>94.16</td>
</tr>
<tr>
<td>5</td>
<td>76.36</td>
<td>80.56</td>
<td>94.18</td>
</tr>
<tr>
<td>6</td>
<td>63.31</td>
<td>71.96</td>
<td>92.39</td>
</tr>
<tr>
<td>7</td>
<td>49.54</td>
<td>59.03</td>
<td>90.25</td>
</tr>
<tr>
<td>8</td>
<td>63.52</td>
<td>72.20</td>
<td>92.36</td>
</tr>
<tr>
<td>9</td>
<td>78.98</td>
<td>82.61</td>
<td>94.88</td>
</tr>
<tr>
<td>10</td>
<td>78.99</td>
<td>82.82</td>
<td>94.98</td>
</tr>
</tbody>
</table>

The specimens had different size and shape for different test, this however assumed to not have affected the structures since the manufacturing process is able to create the same structure for every replica.

3.2.3 Porosity fraction, microstructural analysis, compression test and morphological analysis

According to the ISO standard 13314 the compression specimens should have a cylindrical (recommended) or rectangular cross-section. The specimen length should be from minimum the same to maximum twice the length of the specimen diameter or edge. The diameter or edge length of the specimen should be at least 10 times the average pore size. The design of the specimens where determined to be cylinders with approximately dimensions of 15×30 mm (Figure 9). These specimens were also used for the porosity fraction measurements, microstructure analysis and morphological analysis.
3.2.4 Friction test
For the static friction test there was no ISO or ASTM standard that decided the design of the specimens, though there was an internal standard for performing the test. The internal test fixture did not suit for porous structures when a too large external weight should be added to reach a nominal stress of approximately 0.28 MPa [8]. This nominal stress was wanted to be able to compare the results achieved with previous research to determine if they were in a reliable range. Therefore the specimens were decided to have small proportions to be able to use lower added weight. The new test fixture were manufactured according to our requirements to fit the specimens but the procedure were remaining the same according to the internal standard. The specimens were cylinders with dimensions of approximately 10×10mm (Figure 10).

3.2.5 Tensile test
The standard ASTM F-1147 is recommended for tension testing of adhesion strength between a solid substrate and porous metal coating, or in this research, between a solid substrate and a lattice structure [41]. The focus of the work was instead on the intrinsic strength of the lattice structure i.e. on the cohesive strength of the lattice structure. Thus the standard is not significant when designing the specimens for the test since it was only applicable for coatings.

For the test another configuration was developed, comprising a trabecular structure between two solid pieces (Figure 11). The trabecular structure is representing the pore topology in the different structure and batches. The threaded sections were designed for the specimen holders used in the fatigue testing machine (for upcoming test in the future). Accordingly are the thread not needed but do not adversely affect the tensile test.
3.2.6 Abrasive test

According to the ASTM standard F1978-12 the abrasion test specimens can be square or circular [42]. Square specimens need to be approximately 100 mm square and circular specimens should have a diameter of 100 mm. The thickness should be at least 1.6 mm but not greater than 6.4 mm. Through the centre there should be a hole with a diameter of 6.4 mm to allow the specimen to be fixed and stay stable on the abrasive wheel.

The specimens used had a square geometry of 95 mm (Figure 12). The structure to be analysed was limited to a circular trail of two cm width located where the abrasive wheels would be in contact with the specimen. The lattice thickness was set to 2 mm and the centre hole to 6.5 mm to fit the machine.

3.3 Method planning

When all the specimens were defined, the order of the tests and analyses could be determined. Since the majority of the different methods to be used would destroy the specimens and some of the test methods were time consuming. It was important to have a plan over the order, selection of right specimens and how many that was needed for each test.

The research was divided into two phases. Phase I focused on compression testing (with emphasis on compression strength and elastic modulus), determination of porosity fraction, assessment of morphological information (real strut thickness and void size, which could be an approximate determination of pore size), microstructure analysis and aesthetic appearance. Phase II introduced a further investigation of a few selected
structures with the remaining testing methods such as friction properties, tensile and abrasion testing. The procedure was stated to be performed as following:

**Phase I:**
1. Porosity fraction
2. Microstructural analysis
3. Compressive test
4. Morphological analysis

**Phase II:**
- Static friction test
- Tensile test
- Abrasive test

In the second phase the order of the tests was not of importance since each test required different specimens in terms of design. According to the method planning the first out to be performed in phase I was the analysis of porosity fraction since the specimens would be destroyed later on in the compression test.

### 3.4 Phase I

Phase I focused on compression testing, determination of porosity fraction, assessment of morphological information, microstructure analysis and aesthetic appearance.

#### 3.4.1 Porosity fraction

The porosity fraction was investigated for all the specimens in the 3 batches. In batch A, 6 specimens of each structure was analysed and in batch B and C, 4 specimens of each structure was analysed. The results from the porosity analysis were representing the porosity for all the different specimens used in the mechanical and physical tests. To determine the porosity of the trabecular structure Equation 1 was used [9]. Where $\rho_{th}$ is the theoretical density of Ti-6Al-4V, the mass is the dry mass and the volume is the total volume of the specimen.

\[
\text{Porosity} = \frac{\rho_{th} - \left( \frac{\text{Mass}}{\text{Volume}} \right)}{\rho_{th}} \tag{Equation 1}
\]

Before the measurement a procedure of cleaning took place to eliminate remaining loose particles from the manufacturing process. This was according to a validated cleaning method from Eurocoating. The specimens was firstly submerged in ethanol and placed 5 minutes in ultrasound. The second step was a drying procedure in a furnace for 2 hours in 120 degrees Celsius.

The mass was determined of a gravimetrically instrument with a precision balance of 0.0001 g (Figure 13). The volume was measured by a digital caliper on 6 different areas; bottom, middle and top, two times at each location with a turn of 90 degrees. These measurements were used to calculate the mean area and with the length retrieve the total volume. The theoretical density of Ti-Al6-V4, 4.42 g/cm³ was used [21]. The standard deviation was used to validate the amount of variation between the specimens of each structure. Moreover a comparison of the designed porosity fraction and the real porosity fraction obtained by the SLM procedure were analysed.
3.4.2 Microstructural analysis
To achieve knowledge about the microstructure and determine the presence of β phase the specimens was analysed with light microscopy. The preparation of the specimens was made in five steps; cutting, embedding, polishing, cleaning and etching.

Cutting
To get a good overview of the microstructure the specimens were cut planar and vertical of the building direction. The cut was made with Struers Secotom -15 (Figure 14).

![Figure 14. Specimen in Struers Sectocom -15 cutting machine.](image)

Embedding
An embedding was made to make it easier to perform the polish procedure and obtain clearer contrasts in the stereomicroscope. Since the porosity was high and the pores small there were problems to fill all the pores completely with resin. This was solved with adding a small amount of contrast solution to the resin to make it more fluid. This made the resin pass through the pores more easily, though there were still some small pores that was not completely filled but still had resin around the edges. This, however,
did not have any influence on the microstructural analyses. Since the embedding was made to get a better grip of the specimens and an optimal contrast in the light microscope this was considered to be in order.

**Polishing**

Since the cutting caused a lot of scratches a polishing had to be performed. The procedure was performed with an Abramin machine with 8 different grinding discs, 5 abrasive and 3 clothed, starting with the roughest one, 400 μm, and ending with a clothed grinding disc. The roughness of the last clothed grinding disc was 2 μm. During the polishing a lubricant was used to reduce friction between the specimen and the grinding disc. A holder was used to be able to polish 8 specimens at the same time and to automate the process (Figure 15).

![Image: Specimens in specimen holder (left) and mounted in polishing machine (right)]

**Cleaning**

To be able to get a good view and clear images of the microstructure the specimens had to be cleaned since they were covered with the lubricant used in the polishing process. The lubricant was oily and could easily penetrate pores that were not completely filled in the embedding process. Usually specimens are dried with compressed air but since that pushed the lubricant out from the pores and soiled the surface the specimens were cleaned with ethanol and air dried instead.

**Etching**

To be able to see the different phases in the material an etching was made with Kroll’s Reagent, a solution of 2 ml Hydrofluoric acid, 3 ml Nitric acid and 95 ml of distilled water. The reagent was poured on the surface of the specimen and was allowed to operate during 15 seconds.
### 3.4.3 Compression test

The mechanical properties retrieved from the compressive test are performed according to ISO 13314:2011. Compression test was implemented as one of the mechanical tests to find the characteristics values; Young’s Modulus, first maximum compressive strength, yield strength and plateau strength. The characteristics values can be extracted from a stress-strain curve (Figure 16). Line 1 and 2 in Figure 16 shows the (quasi) elastic gradient and the offset yield strength. For titanium the yield strength can be hard to identify, therefore yield strength is determined at 0.2% strain. Point 3 in Figure 16 shows the first maximum compressive strength and the Plateau stress ($\sigma_{pl}$), the grey region, is calculated between the compressive strain intervals between 20-30% or 30-40%. The plateau stress was used to determine start and reversal points of the cyclic test (20% and 70% of the plateau load) to obtain the optional measurement of Young’s Modulus [43].

![Figure 16. Typical stress-strain curve for a porous and cellular metal material.](image)

The test was performed according to the ISO standard 13314:2011 [43]. The specimens used are described in section 3.2.3. The compression test was carried out in the Laboratory of Mechanical Testing at Dipartemento di Ingeneria Industriale (DII) at University of Trento with the machine Instron 8516 with constant crosshead speed in room temperature. The procedure steps were:

**Quasi static compression test:**

1. Calculate the area of the specimens and measure the length.
2. Configure the software parameters.
3. Execute the quasi static compression test.

**Cyclic compression test:**

4. Calculate the 20 % and 70 % of the plateau load from the quasi static test.
5. Calculate the area of the specimens and measure the length.
6. Configure the software parameters.
7. Execute the cyclic compression test.

Compressive strain and stress are obtained from the applied force and the displacement of the specimens. Thus the area ($A$) needs to be calculated to receive the compressive stress ($\sigma=F/A$) and also length to receive the compressive strain ($\varepsilon=\delta/l$). The area and length was performed in the same way as in the determination of the porosity fraction. The software *Serie IX* parameters was set according to the length, compression speed 1.
mm/min and data sampling frequency 1 kHz. The quasi static test were performed on 3 specimens from each structure and batch.

After the quasi static compression test the data was converted to Microsoft Excel to obtain the stress-strain curve from the measured force and displacement to estimate the plateau stress. The plateau stress was found observing the curve for a plateau tendency but in some cases the strain did not reached 20-30%. In these tests when the strain did not reach 20-30 % or when there was not a significant plateau region, an estimation of the plateau stress was performed by observing the curve to find where there was a tendency of a plateau region. The cyclic compression test was performed with the same crosshead speed and data sampling frequency as the quasi static test with the software SAX V9.3. An extensometer, Instron LVDT displacement gauge, was mounted with a fixture device beside the specimen, see Figure 17, in order to record the displacement of the specimen without the compliance from the machine. 5 cycles were performed on 2 specimens of each structure and batch.

![Figure 17. Left: test without extensometer. Right: test with extensometer.](image)

During the quasi static test of batch A there was a clear tendency of buckling (Figure 18). Therefore it was decided that the specimens in batch B and C should be cut in half to avoid this phenomenon and to achieve more reliable results. The length of the specimens was the same as the diameter which was anyway in accordance to the standard. In batch B the maximum load of the machine was not enough (100 kN) to fully observe the mechanical behaviours. The problems in batch A and B were taken in consideration during the analysis of the results.
The results from the cyclic compression test seemed unreliable since there was a large range of scattering. With help from professors at the Industrial engineering department at the University of Trento the conclusion that there was something inaccurate with the extensometer was drawn. The stress-strain curves were therefore deceptive because the compliance from the machine was included, and moreover the stiffness of the machine was needed to be calculated and removed. A calibrating compression test was therefore performed with the machine used in the compression test to find the stiffness of the machine to be able to achieve more accurate and reliable data.

**Exclusion of compliance**

The compliance from the machine was due to unwanted movements of the bars that compressed the specimens. That means the change in length, $\Delta l$ measured during the performance of the test was an aggregation of the bars movement and the compression of the specimen i.e. $\Delta l = \Delta l_{\text{specimen}} + \Delta l_{\text{machine}}$.

The strain is calculated by the ratio of the change in length to the original length of the specimen (Equation 2) [44].

$$\varepsilon = \frac{\Delta l}{l_0} \quad \text{Equation 2}$$

This means that the strain obtained with the length values from the test would result in inaccurate values of strain. To achieve reliable values of the strain the movement of the bars had to be excluded from $\Delta l$.

To determine $\Delta l_{\text{machine}}$ for each specific test the stiffness of the machine, $k_{\text{machine}}$, had to be calculated. By performing a calibrating compression test where the bars were in contact with each other, without any specimen, values of $\Delta l_{\text{machine}}$ could be achieved. The stiffness was calculated by using the equation for the feather constant (Equation 3), which also can be used to compute the stiffness of a bar that undergoes an elongation because of a force $F$ [45].

$$k = \frac{F}{\Delta l} \quad \text{Equation 3}$$

In this specific case following values was used (Equation 4):

$$k_{\text{machine}} = \frac{F_{\text{calibration}}}{\Delta l_{\text{calibration}}} \quad \text{Equation 4}$$

The stiffness, $k_{\text{machine}}$, was thereafter used to recalculate the results from the compression tests. $\Delta l_{\text{machine}}$ for every specific test was calculated by restructure the equation for stiffness and use the force applied in the specific test (Equation 5).
\[ \Delta l_{\text{machine}} = \frac{F_{\text{specimen}}}{k_{\text{machine}}} \quad \text{Equation 5} \]

The result from this equation was used to exclude \( \Delta l_{\text{machine}} \) from \( \Delta l \) and finally achieve more accurate values of the stiffness of the specimens.

In the quasi static test the same stress interval was selected for Young's Modulus for all specimens of the same structure. The same interval for Young's Modulus was used in the first uploading in the cyclic test to validate that the result was comparable. The following cycles were measured in the whole uploading interval (20-70\% of the plateau load). The stress interval was defined by observing where the curve was straight. The value for Young's Modulus was obtained by using an Excel function to achieve the linear equation for the chosen interval.

The offset yield strength was found by creating an offset line of 0.2\% parallel to the interval of Young's Modulus, and then perform an observation of the intersection with the stress-strain curve. In batch C there was a clear maximum point, while in batch A and B it was complicated to find the local maximum. Using batch C as reference, the permanent deformation corresponding to the maximum strength was determined. Its difference to the offset line is 4\% as shown by Figure 19. This value was then used for all the curves and further called: offset compressive strength. The value for the offset compressive strength was found in the intersection point of the offset line and the stress-strain curve (Figure 19).

![Figure 19. Determination of offset compressive strength.](image)

**Gibson & Ashby**

There are methods that can be found in literature to model the physical and mechanical behaviour of open and closed cellular materials. One is Gibson & Ashby that analyses the model structures representative of the physical structure [46]. The model is developed from a stochastic open cellular foam, and have been extensively applied to metallic foams such as aluminium alloy, zinc alloy and magnesium alloy [37]. The model is based on a pentagonal dodecahedron and also later a model of Gibson & Ashby were hexagonal model of rod-like columnar structure. Nonetheless the cellular structure with the hexagonal cross section were driven from bones where the loading is principally uniaxial for example the vertebral column. The method has typical expressions in form of equations and the approach is to determine the principal characteristics of the constitutive equation. This is done by experimentally determine the precise values of materials parameters for a given real material. One representative expression for
Method and implementation

Average mechanical properties e.g. stiffness of porous material are found as power laws of density or relative density (Equation 6) [46].

\[
\text{mechanical property} = C_1 \times (\text{density})^{n_1} \quad \text{Equation 6}
\]

Where \( C_1 \) and \( n_1 \) are real numbers determined experimentally [46].

Mechanical properties both from tensile and compression are, as far as porosity is concerned, strongly related to the fraction of load bearing section, \( \Phi \). The load bearing section is in turn directly correlated by the total porosity fraction. Ashby proposed a model simplified from closed cell foam in order to effectively forecast the experimental results [47] (Equation 7).

\[
\Phi = \left( \frac{E}{E_s} \right)^{n_1} \quad \text{Equation 7}
\]

Where \( E \) is Young’s Modulus measured from the specimens, \( E_s \) is Young’s Modulus of full dense Ti-6Al-4V and \( n_1 \) is a factor of 2. Voids reduce the fraction of load bearing section but could also be stress and strain concentrators throughout loading [47].

To more describe the materials behaviour Gibson & Ashby also proposed that the relative stiffness \( (E/E_s) \) and relative density \( (\rho/\rho_s) \) and relative strength \( (\sigma_{pl}/\sigma_{ys}) \) by the following expressions [48], [37]:

\[
\frac{E}{E_s} = C_1 \left( \frac{\rho}{\rho_s} \right)^{n_1} \quad \text{Equation 8}
\]

\[
\frac{\rho_{pl}}{\rho_{ys}} = C_2 \left( \frac{\rho}{\rho_s} \right)^{n_2} \quad \text{Equation 9}
\]

Where experimental evidences suggest that the factors \( n_1=2, n_2=1.5 \) should be used for open-cell foams and \( C_1=1, C_2=0.3 \) for cellular metals and polymers [48], [37].

3.4.4 Morphological analysis

The specimens, one from each structure and batch, were analysed by a stereomicroscope and a scanning electron microscope (SEM) to investigate morphological information. This was performed according to the guidance document, excluding the parts that were only applicable for coatings. Following characteristics was investigated [49]:

1. The shape and size (average, standard deviation and range) of the material between the pores, i.e. the struts;
2. Pore size (average and standard deviation) at the surface, both horizontal and lateral;
3. The minimum pore intercept length or minimum pore size of the interconnecting porosity (average, standard deviation and range); and
4. Micrographs at appropriate magnifications and locations within the modified surface so all geometrical characteristics of the microstructure will be recognizable should be done. If the original magnification is not used a micron bar should be included with each image.

In this thesis work it was the size of the voids on the surface that was measured. That means it was not possible to know if the measurement represented the largest diameter of the pore or just the beginning or end of it. In some cases it was therefore not the actual pore that was measured, according to the definition from some literature. Three different measurement was used to represent the void diameter: the minimum feret diameter (minFeret), the maximum feret diameter (maxFeret) and the equivalent diameter (Eq.Diameter). The feret diameter is the distance between two parallel tangents of the circumference [49]. The minimum and maximum feret diameter is i.e. the
minimum and maximum distance that can be found with this approach (Figure 20).
Since the minFeret seemed to fit the values of the designed pore size better the minFeret was decided to be referred to as the void size.

![Figure 20. Visualization of feret diameter [49].](image)

The morphological analysis was performed with a Nikon stereomicroscope in the Coatings and Industrial Corrosion Control Laboratory at DII at University of Trento. The surface, both the horizontal and lateral interface, of the specimens was analysed. The top surface was used to investigate the horizontal struts since the bottom surface had been cut in the manufacturing process. In batch A the specimens for the friction test were used and in batch B and C the specimens for the compression test were used. The analysis was made by the software NIS – Element To measure the void size the edges of the voids was marked manually, atleast 3 for the regular structure and at least 10 for the irregular and fully random structure (Figure 21 and Figure 22). For the fully random structures and on the lateral surface it was hard to define the voids and therefore mark the edges of the voids, especially in the more dense structures. It was also difficult to measure the voids on the lateral side due to the curved surface (Figure 22). The software tool calculated the minFeret, maxFeret and the Eq.diameter and with these values the mean value, maximum value, minimum value and standard deviation were extracted. The measurements achieved were converted to Microsoft Excel.
The shape and size of the struts, characteristics 1 was investigated by help of SEM (Figure 23). For every specimen at least 3 to 5 measurements were made. Mean value, standard deviation, maximum value and minimum value were calculated. The same specimens that were used in the stereomicroscope were used in the SEM.
3.4.5 Evaluation phase I
To evaluate phase I and continue to phase II, a discussion took place with the project team of Eurocoating and the tutor of the thesis. The methods and results from phase I (section 4.1) were presented and discussed together with aesthetic appearance. The result from the compression test was focused on the offset compressive strength, stiffness and the correlations between the structures and batches within these characterizations combined with porosity fraction. In the assessment of the morphological information the emphasis was on real strut thickness and the void size. The result of phase I was evaluated by the company and structures to perform the remaining test were selected.

The selected structures in phase II were not designated because they were considered to be the most suitable, but to optimize the research information with as few specimens as possible since earlier result had shown that there were a lot of relations and trends to investigate. The chosen structures for the abrasion test were structures 1, 2 and 6 from batch C. The batch was chosen since it should be the least resistant to wear because of its high porosity and low compression strength. By testing structure 1, 2 and 6 all the different morphologies (regular, irregular and fully random) from the batch were tested. The tensile test was performed on structure 1, 2 and 6 in all three batches. Thus all the different types of morphologies were investigated.

3.5 Phase II
Phase II introduced a further investigation of a few selected structures with the remaining test methods: friction, tensile and abrasive.

3.5.1 Friction test
The friction properties were tested according to an internal standard; User’s manual of static friction provided by the University of Trento [51].

To determine the frictional characteristics of a material the coefficient of friction (COF) can be used. COF is the ratio of the force required to slide the surface to the force perpendicular to the surface. Static friction is the force that will resist motion to a
certain maximum force until the friction is overcome and motion of the stationary object begins. It is calculated by finding the initial peak force, $F_{\text{max}}$, required to move the object and divide it by the value of the applied normal force $F_N$ (Equation 10). Thus, any force larger than $F_{\text{max}}$ causes motion [51].

$$\mu_s = \frac{F_{\text{max}}}{F_N} \quad \text{Equation 10}$$

The static friction test (Figure 24) was performed at the Cultural Heritage laboratory at DII at University of Trento in room temperature. The test had a sled-dynamometer principle and was performed by dragging a flat block of known mass and with known load across the material placed upon a flat table. The maximum force required to initiate motion was precisely measured to determine the static COF. A software controls the test and plots a graphical representation of the static friction coefficient [50]. The specimens used are described in section 3.2.4.

![Figure 24. Set up for the friction test.](image)

To ensure that the result would not be affected by an edge effect the edges of the specimens were polished. The artificial bone of solid foam 1522-02 from Sawbone with a density of 0.24 g/cm$^3$ replaced the flat table in the test. The artificial bone had to be cut in several pieces to fit the test setup. When performing the test the cut surfaces were not used since the surface finish were changed by the cut which could affect the result of the test. By the same reason each surface was never used more than once. The specimen and the applied load were weighted before they were placed on the surface with the sample holder and connected to the spring and force transducer. The equipment was controlled so it had a straight axis. The procedure was performed quickly and with approximately the same time for every specimen since the time would affect how attached the specimen got to the bone. The force transducer was calibrated before each test. The parameters were configured into the software, NI myDAQ; motor velocity of 0.1 cm/s and the weight. 3 specimens from each structure and batch were tested.

### 3.5.2 Tensile test

Tensile test is a common way to determine the basic data of a material’s mechanical behaviour. The specimens are suitable designed to subject an increasing axial or uniaxial load until it fractures. With frequent intervals the load and elongation are measured and expressed as average stress and strain. The obtained data from the test is usually extracted to stress-strain curves, (Figure 25), and can show the mechanical characteristics of Young’s Modulus, ultimate tensile strength and yield strength. The ultimate tensile strength is the maximum load divided by the original area of the specimen. The linearity region of the curve, $A'$, shows the modulus of elasticity. $B$ shows
the intersection point where the yield strength can be found, often 0.2% of offset strain to A’ [31].

![Stress-strain curve](image)

*Figure 25. Schematic drawing of a stress-strain curve from a tensile test [44]*.

To obtain the stress-strain curve the cross sectional area and the length of the trabecular structure were measured before the test. The specimens, section 3.2.5, were gripped in the testing machine by their threaded end section with 100 bar to make sure that the specimen did not slip during the test. All parameter settings were then configured into the software *Serie IX*; constant crosshead speed of 1 mm/s and sampling rate of 1 kHz. The measurements were performed by the same machine as in the compression test in the Laboratory of Mechanical testing at DII at University of Trento. An extensometer, Instron dynamic extensometer 12.5 mm, was mounted on the surface in the edges of the trabecular structure in order to accurately record the displacement without including the artefacts from the machine (Figure 26).

![Tensile test](image)

*Figure 26. Tensile test*

For each specimens of same structure the same stress interval (20-70% of the yield strength) were selected to determine the Young’s Modulus in both the quasi static and cyclic test. The test was performed with the same software as in the cyclic compression test. Values for Young’s Modulus were obtained by using an Excel function to achieve the linear equation. The yield strength was defined by observing the curve since the 0.2% offset line did not show the yield point according to the shape of the curve. The ultimate tensile strength was found by searching for the maximum stress value in the stress-strain curve.
3.5.3 Abrasion test
The abrasion test was performed according to the ASTM standard F1978-12 which proposes that a Taber Abraser should be used. The test method is used to evaluate the resistance to particle shedding which can occur during surgical insertion of the prosthesis or due to micromotion of the prosthesis after insertion [42].

The Taber test can be used to measure wear, the test is characterized by the rubbing and rolling wear action and it is produced by contact of the specimen against the sliding rotation of two abrading wheels. The wear is quantified as total mass loss of the test specimen [42].

The test method propose a Taber Abraser model 5150 with H-22 Calibrade wheels, or equivalent, and no added weight to the abrading head. The specimen is abraded by turning it on a vertical axis against the sliding rotation of two abrading wheels. Controlled conditions of pressure and abrasive action are of importance. One abrading wheel rubs the specimen outward and the other inward toward the centre which results in abrasion marks in form of a pattern of crossed arcs. The test will be performed repeated times for a cumulative amount of cycles (2, 5, 10, and 100) [42].

Before every cycle the specimens should be cleaned for 10 minutes with an ultrasonic cleaner. The specimens should then dry for 10 minutes in an oven, 100°C. After each cleaning the specimens are weighted. In short, the procedure steps were:

1. Cleaning with an ultrasonic cleaner for ten minutes.  
   Drying in a 100°C oven for ten minutes.  
   Weighting = start weight
2. Test 2 cycles  
   Cleaning, drying and weighting
3. Test 3 cycles = total 5 cycles  
   Cleaning, drying and weighting
4. Test 5 cycles = total 10 cycles  
   Cleaning, drying and weighting
5. Test 90 cycles = total 100 cycles  
   Cleaning, drying and weighting

The measure of the abrasive wear is calculated from the mass loss of the specimen with Equation 11 [42]:

\[
\Delta w_n = \langle w_0 \rangle - \langle w_n \rangle \tag{Equation 11}
\]

Where \( n \) is number of cumulative cycles to which specimen has been exposed (2, 5, 10 or 100), \( \Delta w_n \) is cumulative mass loss for \( n \) cycles, \( \langle w_0 \rangle \) is average mass at the start of the test and \( \langle w_n \rangle \) is average mass after \( n \) cumulative cycles [42].

According to the industry guidance document the weight loss should be less than a total of 65 mg by weight after 100 cycles [49].

The tests were performed in the Materials Characterization Laboratory at DII at University of Trento (Figure 27). The specimens used are described in section 3.2.6. Since there was a metallic structure and not a coating that was tested the standard procedure was deviated. This since the weight loss was predicted to be much lower than the accepted weight loss. The test was made as an investigation and not to validate the substrate, so a deviation from the standard was considered to be acceptable. To make the test procedure faster and simpler step 4, testing 5 cycles to reach a total of 10 cycles, was skipped. That resulted in a total of 95 cycles. Step 2 and 3 was decided to both be
performed to see if there were some interesting occurrences in the first cycles of the test.

Since abrasive wear is defined by the indentation of a hard body into a softer body. A high hardness of the base material is therefore a good protection against abrasive wear [52]. The mass loss was therefore compared with the offset compressive strength.
4 Findings and analysis

This chapter is divided in two parts; phase I and phase II. The results achieved are analysed as a function of the trabecular geometry, regarding both porosity fraction and structure.

4.1 Phase I

The results achieved from phase I were mainly focusing on the compressive behaviour of the 30 trabecular structures, combined with morphological and microstructural analysis.

4.1.1 Porosity fraction

From the porosity fraction measurements the differences between the batches are clear (Figure 28). Batch C has the highest amount of porosity (78 ± 5 %), followed by Batch A (59 ± 5 %) and last batch B (42 ± 7 %). This is also stated in the variances in the weighted mass between the batches. Also the difference in porosity fraction between the structures in each batch are demonstrated in the chart, where structure 7 stands out as the structure with lowest porosity. Table with the results and standard deviations can be seen in appendix 2.

![Figure 28. Porosity fraction from every structure and batch.](image)

The differences in terms of designed porosity compared to the effecting relative porosity are significant. Batch A and batch C had a decreased value of 16.4% and batch B 45.4 % (Table 4). When comparing the real porosity values for the irregular structures with the values from their original unit cell it can be seen that structure 9 which is least deformed has values close to structure 10, while structure 1 that is the most deformed has a larger difference to its non-deformed unit cell, structure 2. The difference from structure 4 to its basic cell is slightly higher than the difference between structure 9 and 10.
Findings and analysis

Table 4. Comparison between real porosity and designed porosity.

<table>
<thead>
<tr>
<th>Structure</th>
<th>A [%]</th>
<th>Ao [%]</th>
<th>B [%]</th>
<th>Bo [%]</th>
<th>C [%]</th>
<th>Co [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>57.13</td>
<td>75.40</td>
<td>38.87</td>
<td>78.45</td>
<td>75.60</td>
<td>92.85</td>
</tr>
<tr>
<td>2</td>
<td>59.62</td>
<td>75.60</td>
<td>44.28</td>
<td>79.99</td>
<td>77.30</td>
<td>93.21</td>
</tr>
<tr>
<td>3</td>
<td>60.14</td>
<td>70.96</td>
<td>43.32</td>
<td>80.91</td>
<td>81.53</td>
<td>94.59</td>
</tr>
<tr>
<td>4</td>
<td>60.49</td>
<td>75.49</td>
<td>44.25</td>
<td>79.68</td>
<td>80.50</td>
<td>94.16</td>
</tr>
<tr>
<td>5</td>
<td>60.56</td>
<td>76.36</td>
<td>44.31</td>
<td>80.56</td>
<td>80.82</td>
<td>94.18</td>
</tr>
<tr>
<td>6</td>
<td>58.28</td>
<td>63.31</td>
<td>45.42</td>
<td>71.96</td>
<td>76.27</td>
<td>92.39</td>
</tr>
<tr>
<td>7</td>
<td>47.80</td>
<td>49.54</td>
<td>22.22</td>
<td>59.03</td>
<td>67.73</td>
<td>90.25</td>
</tr>
<tr>
<td>8</td>
<td>58.92</td>
<td>63.52</td>
<td>44.53</td>
<td>72.20</td>
<td>76.15</td>
<td>92.36</td>
</tr>
<tr>
<td>9</td>
<td>64.55</td>
<td>78.98</td>
<td>46.01</td>
<td>82.61</td>
<td>82.28</td>
<td>94.88</td>
</tr>
<tr>
<td>10</td>
<td>64.67</td>
<td>78.99</td>
<td>46.19</td>
<td>82.82</td>
<td>82.61</td>
<td>94.98</td>
</tr>
</tbody>
</table>

In Figure 29, a comparison between the designed porosity and the real porosity is visualized, where it can be seen that batch A is closest to its designed values, followed by batch C and last batch B.

![Real porosity - Designed porosity](image)

Figure 29. Comparison between real porosity and designed porosity.

4.1.2 Microstructural analysis
The result from the microstructural analysis showed clearly that there are two phases in the material. Since the specimens were heat treatment the martensitic α' phase should have transformed into β phase. As mentioned in section 2.3.1 Composition and microstructure the micrographs shows a lamellar α+β phase where the α phase is coarse and a very fine α+β phase is appearing as dark needles (Figure 30 and Figure 31). In the micrographs there can be seen that the α grains are larger in the building plane than in the lateral plane.
Findings and analysis

4.1.3 Compression test

The data extracted from the compression test was imported to Microsoft Excel to generate stress-strain curves, in total 150 curves; 90 quasi static and 60 cyclic. Also tables with Young's Modulus, offset compressive strength, yield strength and plateau stress were created. Figure 32 shows one typical and representative curve from each batch with the mechanical properties generated from Excel. Batch B required a compressive load higher than the maximum load capacity from the machine. The test was not completed and all mechanical behaviours could not be analysed. Batch C reaches a higher strain, and has clear densification stage and a local stress maximum. Batch A showed instead a long stable plateau and a downward densification stage.
Findings and analysis

Figure 32. Typical stress-strain curve from each batch.

Figure 33 shows a typical chart of the stiffness from the cyclic compression test. Between the first and second cycle there is an increase in stiffness, and thereafter it stabilizes.

Figure 33. Stiffness from cyclic compression test.

Elastic modulus and offset compressive strength versus porosity fraction

To obtain clear and comparable result the characteristics of the compression test was arranged in tables and charts. The results from each batch can be found in appendix 3. Comparisons were made between stiffness, offset compressive strength and porosity fraction to investigate possible correlations and significant behaviours.
Table 5 shows the differences between the mean value of Young's Modulus in the quasi static test and the first uploading in the cyclic test with appurtenant standard deviation. The values are in general quite similar for the quasi static and cyclic test besides some exceptional specimens that got a result that differed from the other specimens of the same structure. These specimens were removed from the analysis since they were considered not reliable (appendix 4).

Table 5. Comparison of stiffness between quasi static test and first uploading in cyclic test

<table>
<thead>
<tr>
<th>Struc.</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mono</td>
<td>St.dev</td>
<td>Cyclic</td>
</tr>
<tr>
<td>1</td>
<td>9,15</td>
<td>0,68</td>
<td>10,18</td>
</tr>
<tr>
<td>2</td>
<td>11,88</td>
<td>0,15</td>
<td>12,79</td>
</tr>
<tr>
<td>3</td>
<td>3,21</td>
<td>0,50</td>
<td>3,45</td>
</tr>
<tr>
<td>4</td>
<td>4,31</td>
<td>0,12</td>
<td>4,42</td>
</tr>
<tr>
<td>5</td>
<td>4,48</td>
<td>0,14</td>
<td>4,58</td>
</tr>
<tr>
<td>6</td>
<td>6,83</td>
<td>0,48</td>
<td>7,15</td>
</tr>
<tr>
<td>7</td>
<td>16,31</td>
<td>0,94</td>
<td>15,37</td>
</tr>
<tr>
<td>8</td>
<td>5,92</td>
<td>0,17</td>
<td>6,05</td>
</tr>
<tr>
<td>9</td>
<td>2,30</td>
<td>0,17</td>
<td>2,28</td>
</tr>
<tr>
<td>10</td>
<td>2,37</td>
<td>0,08</td>
<td>2,18</td>
</tr>
</tbody>
</table>

In Figure 34 all batches and structures are included. The porosity fraction is on the horizontal axis and the Young's Modulus on the vertical axis. As can been seen the stiffness decreases with increasing porosity. Batch B with a low porosity fraction, 38.9-45.4 %, shows a high stiffness; 7.99-25.14 GPa. In batch C where the porosity increased to 75.6-77.3%, the stiffness was only 0.42-6.24 GPa. Batch A was ranging in between with a porosity of 57.1-59.6 % and stiffness of 3.12-20.48 GPa. The black circles highlights structure 9 and 10 in all batches that particulary stands out of the trend.

Figure 34. Stiffness-porosity chart all batches.

The same trend can be seen in Figure 35 were porosity fraction is on the horizontal axis and the offset compressive strength on the vertical axis. The compression strength
shows the same trend as the elastic modulus with a decrease in strength with increased porosity. The compressive strength is ranging from 16.3-139 MPa for batch C, 90-295 MPa for batch A and 193-533.3 MPa for batch B (Figure 35). The black circles highlights structure 9 and 10 in all batches that particularly stands out of the trend.

A correlation between Young’s Modulus and offset comp. strength versus porosity can be seen, but a scatter can also be noticed (Figure 34 and Figure 35), i.e. some specimens with same porosity has different values of strength and stiffness. In batch B, 8 structures with porosity between 43-46 % and had stiffness ranging between 15.3-25.1 GPa and corresponding offset compressive strength 193.3-373.3 MPa. In batch A, 7 structures with 57-61 % porosity had stiffness between 9.3-14.5 GPa and offset compressive strength 150-210 MPa. Batch C, 5 structures, 80-83 % porosity and stiffness between 0.4-2.3 GPa and corresponding 16.3-49 MPa offset compressive strength.

A compilation of Young’s Modulus and offset compressive strength in Figure 36 proves a clear trend with higher stiffness and higher offset compression strength. Also a clear visualization which structures that is interesting to select for any specific requirement, e.g. minimum stiffness with maximum strength, can be seen. The black circles highlights structure 9 and 10 in all batches that particularly stands out of the trend.
Observing Figure 37 where the porosity fraction is on the horizontal axis, Young’s Modulus on the vertical left axis and the offset compressive strength on the vertical right axis. It is the same structure that is compared between different batches. The chart shows that the difference between the characteristics in structure 5, the batches is similar and the trend is typical and can be seen in all the other structures.

Figure 38 shows irregular and regular structures in same chart where correlation between stiffness and porosity are investigated. The trend is typical for all the batches and demonstrates that the irregular deformation of the regular structure has similar properties. Structure 1, which had a higher grade of deformation, shows a slightly difference to the original unit cell (structure 2).
Findings and analysis

Gibson & Ashby

The load bearing section, according to the Ashby model (Equation 7), as function of porosity is shown in Figure 39. All the batches are included and there is no clear correlation between porosity and the fraction of the load bearing section. Batch B has values widespread in the vertical direction while batch C has values more widespread in a horizontal way. Once again the black circles are highlighting structure 9 and 10 in batch A, B and C.

The generate Gibson-Ashby (Equation 8 and Equation 9) charts the data were imported into a Matlab script. The relative elastic modulus ($E/E_s$) as function of the relative density ($\rho/\rho_s$) of all structures and batches is shown in Figure 40. In Figure 41, relative strength ($\sigma_{pl}/\sigma_{ys}$) as function of the relative density ($\rho/\rho_s$) is shown. For comparison the classical foam model, Gibson-Ashby, are also included in both figures. It can be seen that the experimental data do not fit the Gibson-Ashby model in both cases. Espacially not structure 9 and 10 in all batches that particulary stands out of the trend, see the black circels.
Findings and analysis

Figure 40. Relative elastic modulus ($E/E_s$) as function of relative density ($\rho/\rho_s$) and prediction of Gibson & Ashby model for the studied trabecular structures.

Figure 41. Relative strength ($\sigma_{pl}/\sigma_{ys}$) as function of relative density ($\rho/\rho_s$) and also the prediction of Gibson & Ashby model for the studied trabecular structures.

It is clear that the experimental data in the present work are lower than the predicted values by the Gibson & Ashby model in Figure 40 and higher for the data in Figure 41. In Table 6 the values for the linear regression are shown for all the batches. Also the R² is included in the table to show the proportion of variability in the data from the linear regression. As seen batch B has in both cases significant low R² values and all batches have notable low values in the second case.
Findings and analysis

Table 6. Evaluation of the linear regression for experimental data.

<table>
<thead>
<tr>
<th>Batch</th>
<th>LogC₁</th>
<th>n₁</th>
<th>R²</th>
<th>LogC₂</th>
<th>n₂</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>-0.28</td>
<td>0.91</td>
<td>0.86</td>
<td>-0.39</td>
<td>1.95</td>
<td>0.62</td>
</tr>
<tr>
<td>B</td>
<td>-0.42</td>
<td>1.32</td>
<td>0.46</td>
<td>-0.22</td>
<td>1.08</td>
<td>0.45</td>
</tr>
<tr>
<td>C</td>
<td>-0.04</td>
<td>0.30</td>
<td>0.80</td>
<td>-0.10</td>
<td>1.32</td>
<td>0.77</td>
</tr>
</tbody>
</table>

Structure 9 and 10

Structure 9 and 10 (Figure 42) as previous shown in the charts, marked with black circles, were out of trend in all cases. They stood out more with decreasing porosity i.e. they particulary stand out in batch B and lesser in batch C. If comparing the stereographic images of 9 and 10 with the other structures they do not have any struts that runs in the building direction of the structure (Appendix 1).

![Figure 42. Structure 9 and 10, batch C](image)

4.1.4 Morphological analysis

From the measurements of the horizontal surface (Table 7) the characteristics of the batches can be seen. Batch B and C has small struts and batch A large struts, and for the voids batch A and C has a large diameter while Batch B has a small diameter. Though, the values differs slightly from the designed dimensions. The thickness of the struts has increased with approximately 200 μm and the minFeret is slightly smaller for batch A and B. The minFeret in batch B is however in consistent size.

From the result of the lateral surface there can be seen that it differs from the result of the horizontal surface (Table 8). The strut thickness is larger on the lateral than on the horizontal surface. The minFeret did on the other hand not show any clear trend in the deviation from the horizontal surface. In batch B and C the minFeret is larger on the horizontal surface, while it for batch A is larger on the lateral surface. Tables with all the result can be found in appendix 5.
Table 7. Morphological analysis of the horizontal surface

<table>
<thead>
<tr>
<th>Batch</th>
<th>MinFeret [µm]</th>
<th>St.dev.</th>
<th>Strut size [µm]</th>
<th>St.dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Batch A</td>
<td>1310</td>
<td>187.72</td>
<td>773</td>
<td>39</td>
</tr>
<tr>
<td>Batch B</td>
<td>677</td>
<td>144.37</td>
<td>415</td>
<td>52</td>
</tr>
<tr>
<td>Batch C</td>
<td>1366</td>
<td>161.12</td>
<td>436</td>
<td>36</td>
</tr>
</tbody>
</table>

Table 8. Morphological analysis of the lateral surface.

<table>
<thead>
<tr>
<th>Batch</th>
<th>MinFeret [µm]</th>
<th>St.dev.</th>
<th>Strut size [µm]</th>
<th>St.dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Batch A</td>
<td>1350</td>
<td>150.84</td>
<td>832</td>
<td>55</td>
</tr>
<tr>
<td>Batch B</td>
<td>491</td>
<td>100.80</td>
<td>507</td>
<td>27</td>
</tr>
<tr>
<td>Batch C</td>
<td>1231</td>
<td>161.14</td>
<td>500</td>
<td>21</td>
</tr>
</tbody>
</table>

A comparison between the void size, both on the horizontal and the lateral surface, and compressive strength shows a trend which the strength decreases with an increase in void size, even though the result is scattered and not very clear (Figure 43). Though there can also be seen that batch A and batch C that has the same range of void size do not have the same strength, batch A has a higher strength. Moreover the result shows that batch B with a smaller void size has the highest offset compressive strength.

![Offset comp. strength - Void size](image)

Figure 43. Comparison between offset compressive strength and void size.

A comparison between the strut thickness and the offset compressive strength do not show any clear trend or correlations (Figure 44). Batch C and batch A are in the same range of strut thickness but batch A has a higher strength than batch C. Batch B, with a larger strut thickness, has a strength that is overlapping the border of the two other batches.
4.2 Phase II

The result from phase II are presented here; static friction test, tensile test and abrasive test.

4.2.1 Friction test

From the static friction test no clear trend could be found, neither when comparing the structures (Figure 45) or batches (Figure 46). Figure 45 and Figure 46 shows mean values of the results. Table with result and associated standard deviation can be found in appendix 6. An exception is the regular structure, structure 2, where the static friction coefficient increased linear with a higher porosity fraction.
Findings and analysis

4.2.2 Tensile test

The data extracted from the tensile test was imported into Excel to generate stress-strain charts. The mechanical properties, such as elastic modulus, ultimate tensile strength, and yield strength, were determined. In total, 45 charts were obtained, 27 from the quasi-static test and 18 from the cyclic test.

Experimental stress-strain curves from the quasistatic test that are typical for each batch are provided in Figure 47. Batch B reaches higher stress values, followed by batch A and last batch C, but under approximately the same strain interval. Batch B has also an apparent failure point compared to batch A and C.

![Static friction coefficient](image)

**Figure 46. Comparing results of the batches.**

![Stress-strain curves for batch A, B and C.](image)

**Figure 47. Typical stress-strain curves for batch A, B and C.**

Figure 48 shows typical behaviour from the cyclic test, 3 specimens from each structure in batch A. The stiffness is nearly stabilized already from the first cycle.
The result from the tensile test shows that the elastic modulus increased with decreasing porosity. The specimens with a low porosity fraction, batch B 38.9-45.4 %, showed a high stiffness of 43.7-47.3 GPa. In batch C where the porosity increased to 75.6-77.3%, the stiffness was only 7.8-12.4 GPa. Batch A ranging in between with a porosity of 57.1-59.6 % showed stiffness of 16.2-20.2 GPa. The tensile strength shows the same trend as elastic modulus with a decrease in strength with increase porosity. It is in the range from 48.6-73 MPa for batch C, 77.7-127.4 MPa for batch A and 235.5-272 for batch B.

Comparison between the compressive test and tensile test

The mechanical properties extracted from the stress-strain curves from the tensile test and the compression test are compared against each other. In the tensile test structure 1, 2 and 6 in all batches were tested and thus were they set against same structures from the compression test. In Figure 49, Figure 50, Figure 51 the tensile structure are named with a T and compression with a C before the code name for batch and structure.

Figure 49 shows the elastic modulus versus porosity fraction. The elastic modulus is higher in tensile in all the structures and batches, significant higher in batch B. Batch A ranging from: 16.2-20.2 GPa in tensile and 6.6-11.9 GPa in compression. Batch B: 43.7-47.3 GPa versus 9.8-16.2 and Batch C: 7.8-12.4 GPa versus 1.1-3 GPa. Accordingly the effect of porosity on tensile stiffness is larger than on compressive stiffness.
In Figure 50 strength in correlation with porosity are visualized. In tensile the ultimate tensile strength is used and in compression the offset strength. The tensile test showed that the ultimate tensile strength of the structures followed the same trends as the offset compressive strength, but lower in all structures in batch A and B. In batch C the tensile strength is marginally lower.

Figure 51 shows the comparison between the elastic limit versus porosity. The yield strength is higher in compression in all the structures and batches. The tensile strength and elastic limit of the trabecular structures followed the same trends as the compression strength and elastic limit but were slightly lower or lower. Tensile strength and elastic limit in batch A ranging from 77.7-127.8 MPa and 50-100 MPa versus 170-210 MPa and 150-160 MPa in compression. Batch B: 235.5-272 MPa and 185-200 MPa versus 316.6-395 and 210-266.7 MPa. Batch C: 48.6-73 and 25-56.7 MPa versus 56.3-86.3 and 53-59 MPa. Only slightly higher in batch C but remarkable higher in batch A and B, except for B_6 that is slightly higher than tensile batch B. The effect of porosity on tension versus compression is ambiguous.
4.2.3 Abrasive test

In the result from the abrasive test it can be seen that all the structures have a weight loss far under the maximum allowed value (Figure 52). In the two first cycles the weight loss per cycle is higher than in the following cycles. There can also be seen that structure C_2, the regular structure, has the lowest weight loss. Structure C_1 and C_6 are slightly overlapped, but the mean value for C_1 is marginally lower.

In a comparison between the weight loss and the offset compressive strength there is indications that a higher strength leads to a decreased weight loss (Figure 53). This in general means that the wear resistance increases with a higher value of porosity fraction.
Findings and analysis

Figure 53. Mass loss in Taber test compared to offset compressive strength.


5 Discussion and conclusions

In this chapter both the methodology and the result are discussed. The discussion is the foundation for both the conclusions and the suggestions for future work within this subject.

5.1 Discussion of method

The various methods used in this thesis are discussed and evaluated.

5.1.1 Preliminary work

To put some extra effort in the preliminary work was needed since it was vital to have knowledge of the performance of the tests on trabecular structures. The tests had to be validated for suitability and that reliable data could be achieved. Only a limited amount of methods found in literature were tested, so there might have been other methods more suitable. Though, most of the test methods had to follow ISO or ASTM standards and other test methods would only have been options if the methods had been proved unsuitable in this specific case.

For the microstructure analysis numerous different methods were tested. The method chosen for embedding did not work completely since there still were some unfilled holes in the resin. However, all the edges of the specimens were in contact with the resin and this was good enough in order to have proper images for the subsequent evaluation.

5.1.2 Porosity fraction

The measurement of the volume might have been possible to perform in a more accurate way. The specimens had a quite high roughness on the lateral surface. Therefore, the measurements with the caliper were different depending on where the caliper was placed. Though, since several specimens were tested and six measurements were made for the diameter of each specimen the errors from the roughness should have been reduced. Also, in the preliminary work Archimedes principle was tried as an alternative for the porosity measurements but was neglected. By measuring the porosity on several specimens and use the mean value as the porosity of the structure the errors should have been reduced even more. The low standard deviation indicated the result was reliable.

The cleaning and drying procedure were performed according to an approach from the company with the same amount of time in the oven, no calculation or comparison to previous research was made to confirm this data. There can be a change that the specimens should have been in the oven for a longer time for all the fluid to disappear or maybe two hours was more than needed and the procedure could have been performed more efficiently.

5.1.3 Compression test

During the compression test there was a buckling phenomenon in batch A, therefore the specimens in batch B and batch C were cut in half which means the result was not fully comparable to batch A. This bending and buckling have been detected before and are peculiar to porous materials consisting of cell struts under compressive strain. Another critical sequent point was that the planes was not planar on both surfaces. This led to the whole cross section was not in contact from the start of the test. Also the mechanical behaviour in batch B could not fully been seen due to load limitations of the machine.

In the cyclic test only 2 specimens was performed whereof only one of structure A_1 due to mistakes of the operators. Further 6 specimens of different structures were removed from the analysis because of scattering compared to the monotonic test (that moreover had a low standard deviation). This scatter may due to the calculated stiffness from the
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machine, the deformation would have been more accurate with an extensometer rather than in this case; without an extensometer and with calculated and removed stiffness from the machine. The structures where the specimens were removed had only one value to rely on and this is not statistical enough to have reliable results.

The plateau stress was used to determine start and reversal points of the cyclic test (20 % and 70 % of the plateau load) to obtain the optional measurement of the elastic modulus by the cyclic test. According to the ISO standard the plateau stress should be found in 20-30 % or 20-40 % of the strain. In some cases where the strain did not reach 20-30 % or cases where there was not a significant plateau region, an estimation of the plateau stress was performed. This cause lower validity on the elastic modulus.

According to the standard, compressive strength corresponds to the first local maximum in the stress-strain curves. This was only obtained in batch C and some specimens in batch A. To have a value on compressive strength in all the stress-strain curves an offset line was implemented, based on the mean value for an offset line from the stress-strain curves who had a local maximum. As a result comparisons and correlations could be drawn between the batches and the structures, but need further investigation to validate the method and the results should be taken with consideration.

In lack of a validated plateau stress in several structures and also an invalidated compression method there are important points for future work. There should be a specific parameter for representing the elastic gradient interval in the standard. As an alternative if the plateau stress is not reaching 20-30 % strain of additive manufactured porous structure based on different unit cells and percent of porosity. Another point is also to implement a method for compressive strength since it is an important mechanical characteristic and due to the standard it cannot not be determined if no local maximum occurs in the stress-strain curve.

A new and untested extensometer with a new manufactured fixture was implemented to the cyclic test. The extensometer with belonging device could have been tested and analysed before executed on the real specimen since it turned out it did not work properly. As a result of this a calculation of the stiffness of the machine needed to be done to achieve validated and reliable data.

To obtain more accurate and reliable results new specimen with smaller dimensions, tentatively 10x10mm, should be performed to have optimal comparable result between the batches. The specimens should be retested in advance and also the planarity needs to be controlled and checked before. To get more statistics at least 5 specimens should have been tested in the cyclic test. Also a validated extensometer should be used to avoid the compliance of the machine.

5.1.4 Morphological analysis

When measuring the void size the marking of the edges were performed manually, which might cause some errors, especially on the lateral surface where the voids often were difficult to define. Taking several measurements gave more accuracy. The analysis was only performed on the outer surface. This made it possible to get a good view of the struts but it also meant that there were a lot of pores that could not be fully defined. However, by comparing the results to the theoretical values it could be seen that the values were in a reliable range.

The dimension of the voids might be different from the real pore size, depending also on the definition of pore size itself. Literature reports for example the use of tomography that could be relevant to provide insight about the internal morphology of the porous structure. However, by measuring a large amount of voids with different diameter the
mean value of the void size should be comparable to, or correlating with the pore size calculated by tomography.

Also the thickness of the struts was marked manually so there could also be some errors by the human factor. Though, these measurements was made by an operator at the SEM laboratory that was an expert in using the SEM microscope which minimized the errors.

5.1.5 Friction test
During the friction test some troubles were detected when trying to stabilize the added weight on the fixtures. The specimens had small diameters which made it difficult to find the balance to keep the whole contact surface against the artificial bone. Consequently the specimens was closed to a tilt problem which would negatively affect the result. For this test the specimens should preferably have a larger area and lower height to reach better stability. Also the new fixture should have been validated more thoroughly before the test started.

Another problem that occurred was the angle of the spring (Figure 24) which arose because of the new design of the fixture. The angle means that the force used for the calculations is not completely right and that might have led to another tilting of the specimens. Even though the edges of the specimens were polished, some of the structures got an edge effect, because of their topology. Thus, repeated test were made on the specimens to neglect edge effect results. In this thesis work with high porosity structures and where high stresses was wanted maybe another more stable method should have been preferable to achieve a more reliable and accurate results.

When it comes to the design of the specimens the size was determined to get the same pressure as in a previous research. The specimen was also adapted to available equipment, though some different solutions were discussed to find the one most accurate and easily performed. There might have been other kind of specimens that could have been used as well, when using the same pressure as in a previous research the result achieved could be compared. To adapt the specimens to the available equipment the method used was already well tested and validated.

5.1.6 Tensile test
The mechanical testing of the tensile behavior was performed similarly as the compression test. Same operator was managing the upstart of the test, in similar conditions, with the same machine and software. The setting parameters, in sense of crosshead speed and sampling frequency were identical. This in order to achieve comparable result to previous analysed data collected from the compression test.

One out of the 45 tensile specimens was neglected from the analysis. During the test the specimen was slipping in the grip of the machine. This movement was resolved by increasing the grip pressure of the machine and prevented the movement of the other remaining specimens.

5.1.7 Abrasive test
The Taber test was only performed on a total of 95 cycles due to miscalculations, which was five cycles less than according to the standard. Probably after 5 more cycles the weight loss would increase linearly and the values would be marginally higher, probably 5% higher, than the achieved value. Opposite the weight loss could suddenly increase and the value become higher than expected. This was however not considered likely and the values were far from the allowed weight loss.

Only structures from batch C were tested since they were considered to be most critical but the densest structure, B.7, should preferably been tested to confirm that. In this way the two extreme characteristics, both regarding amount of porosity and type of
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geometry, would be investigated. The remaining structures would probably show results somewhere in between. However, batch C should have been the batch of most interest for the company since it were the only batch that fulfilled a porosity of 75% to 80% to get the increase in fixation strength.

5.2 Discussion of findings
In this chapter the result of the findings is analysed and evaluated.

5.2.1 Porosity fraction
The result showed that there was a decrease of 16.4% from the designed porosity to the real porosity in batch A and C, and an decrease of 45.4% in batch B. However, according to the company the decrease is not surprising, though the expectations was a lower decrease of 10-15%. That means there is a need to design the structures with a higher porosity fraction than aspired. According to previous research it is difficult to achieve same values of the real strut size as the designed values. In this case there was a significant difference between designed and measured values. Previous research also shows that the differences increase with increased porosity, but that the porosity fraction is consistent between replicas of the same structure. The consistency was true also in this thesis work where the standard deviations showed that the replicas was more or less the same. Though, the differences did not increase with increased porosity but decreased instead.

By observing Figure 29 it is shown that with decreased dimensional values for the designed struts and pore size, there is an increased deviation from the designed porosity. Batch A and B had a designed porosity that was quite similar had a large difference in deviations. That indicates that the sizes of the pores and struts are of more influence than the porosity fraction. How much influences each one of the two different morphological characteristics has, cannot be told with the available data. That means that the company needed to investigate the porosity fraction after designing a new structure to evaluate the real porosity. Further investigation was needed to achieve knowledge about how the porosity fraction depends on the morphological characteristics. The fourth batch with the last combination of small pores and large struts was not of interest for the project, but to achieve a better understanding about how much influence the void size have respectively to the strut thickness, that batch should be investigated as well.

Batch C and A except structure A_7 has higher porosity than 50% which is optimal for osseointegration. This even though batch B has a higher designed porosity than batch A. Batch C is the only batch that fulfilled a porosity of 75% to 80% to get the increase in fixation strength.

5.2.2 Compression test
The result from the compression test shows clear differences between the batches according to porosity fraction and also between the various structures. The different shapes of the stress-strain curves followed by the mechanical characteristics are evaluated.

Stress- strain curves
The curves in general do not show the typical behaviour according to the standard 13314:2011 for porous and cellular metals, (Figure 16), more than the first elastic deformation stage (Figure 32). Batch A had commonly no local maximum and no plateau stage even if the strain was up to about 30% and no densification stage. Batch B had either no plateau stage or local maximum but seemed to go directly to a densification stage where the flow stress rapidly increased. Batch C had a clear local maximum
followed by a plateau stage and in general a densification stage. There are similarities
with the stress-strain curves from this result compared to characteristics of the curves
mention in previous research. The specimens in the research that had higher porosity,
same range as batch C, had the three clear deformation regions: first an elastic region
followed by a plateau region where the specimens deform under a more or less constant
stress, and thereafter a densification region. The study also showed that curves from
specimens with lower porosity, comparable to batch B, did not show clear plateau and
densification regions.

Mechanical characteristics

The stiffness of the trabecular structures is one of the most important mechanical
properties due to stress shielding. According to the findings all structures, except 4
structures, 3 from batch B and 1 from batch A, are in the interval for trabecular bone and
cortical bone (0.2-20 GPa). The low modulus of the trabecular structures would prevent
stress shielding and the osseointegration from the surrounding tissue would produce a
good matching with the mechanical properties of bone the orthopaedic prostheses it is
intended to replace. Considering, as mention before, that batch B has low porosity
(below 50%) and it is therfore not very attractive for osseointegration purposes. Batch
A (with relative high stiffness) could be used in applications were high stiffness is
required, and batch C in applications where lower stiffness is required.

The offset compressive strength and the plateau stress also exhibit an apparent
dependence of porosity; both the mechanical characteristics decreases with an
increasing porosity. The plateau region get also more evident with increasing porosity
(Figure 32). The offset compressive strengths of the batches are in range of 16.3 and
533.3 MPa, which are comparable or even higher to those of trabecular and cortical
bones (25±8-209 MPa). The compression strength is of highly importance because the
trabecular structure must sustain high loads during its clinical service and for the
physical loading.

Figure 37 shows the characteristics: stiffness, strength and porosity of structure 5. It is a
good visualization on which properties the structure could have depending on porosity.
This make it highly useful in advance to be able to select and design a structure for any
specific requirement.

Structure characterization

Several studies have found that different topologies affects the mechanical properties in
different ways, which also were found in this research. In batch B, 8 structures have
porosity between 43-46 % and the stiffness ranging between 15.3-25.1 GPa with
corresponding offset compressive strength 193.3-373.3 MPa. In batch A, 7 structures
with 57-61% porosity had stiffness between 9.3-14.5 GPa and offset compressive
strength of 150-210 MPa. Batch C, 5 structures, 80- 83 % porosity and stiffness 0.4-2.3
GPa with corresponding 16.3-49 MPa offset compressive strength. This indicates the
structure is of importance but also the size and form of the unit cell. According to
previous research the larger unit cell the more is the stiffness and strength decreasing
[34].

There were no significant difference between the structures: regular, irregular and fully
random. The regular structures showed marginally differences from their deformed
irregular structure and the fully random structures had slightly lower values in general.
This indicates it is more of importance of the morphological geometry i.e. pore size and
shape, strut size and pore distribution. Though, the test was only performed in the
building direction of the specimen and an actual prosthesis will be affected from all
directions. For the fully random structures the direction shuld have less influence, but
for the irregular and especially the regular structures the result might look different in
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another direction. Therefore it would be interesting to use a shear test to analyze the structures. Structures 9 and 10 that did not had ay struts in the building direction might be stronger in another direction, and other structures might be weaker.

Cyclic test
The cyclic test shows gradient differences between 1st and 2nd uploading. The percentage increase in stiffness were compared to porosity but there was not any evident correlations. This can be due to the supposed plasticizing of the cross section of the struts. It could also be the effect of the rough surface profile (micro notch effect) of the struts. Or to the notch effect promoted by the link between vertical and horizontal struts. More investigation need to be done to understands these phenomena’s, if it is just depending on geometrical features or strain hardening or a combination.

Gibson & Ashby
The result from analysing the relative elastic modulus and relative strength versus relative density were not in agreement with the Gibson-Ashby model. The model is based on a stochastic open cellular foam and accordingly no regular structures other than cubic arrays of struts. This can be a factor why the experimental data did not fit because there is complex correlations depending on the size of the unit cells, strut size and pore size. Further there is lack of experimental data to understand the exponential factors. Also because of our wide range of elastic modulus within the same porosity there were expectations that the R² would be low and affect the n₁,₂ factor that determine the slope of the line. The complex dependence of the factors needs to be more understood and the suitable factors needs to be modified. Suggestion for further work is to start with a fit on the stiffness-porosity diagram. Thereafter it can be used to determine the elastic matching with natural bone and avoid the critical phenomena stress-shielding and thus enhance the osseointegration.

5.2.3 Morphological analysis
According to previous research the strut thickness is depending on the strut angle to the building plane: struts parallel to the building plane is shown to be significantly thicker than their designed values due to strut over melting in the SLM process, while struts normal to the building plane has slightly lower values. This could be one possible reason that affected the result in the thesis work. When comparing the real dimensions on the horizontal plane with the designed dimensions there is an increase with about 200±70 μm. Though, the void diameter is around the right value. Most of the structures usually had struts in an angle between 0 degrees and normal to the building plane, so to compare the results from the lateral side to struts normal to the building plane is inconsistent. The struts on the lateral surface are even larger which probably also is because they are exposed to strut over melting in the SLM process. The results in the thesis work indicates that struts in an angle between 0-90 degrees are the ones most exposed to over melting since they are significantly thicker than the horizontal struts. The thickness of the struts might be reduced by changing the parameters of the laser beam so it did not reach so deep, but that would probably have some more effects as well. Another solution is to find a constant value to add or subtract to the wanted dimension, e.g. -200 μm for the struts.

The porosity of batch B was quite low, however, as seen before, this was a consequence of the fact that the real struts size was 200 μm thicker than the designed size. The next developments should focus on adjusting, i.e. lowering, the designed strut thickness and to keep the pore size on the same level, so that the porosity will increase to a value above 50-60%. For optimal osseointegration the pore size should be between 50 μm and 800 μm. That means that batch B is the only batch with pore sizes in the right range while the diameter of batch A and C 66 μm respective 128 μm above the limit. The void
diameter in batch B were 491-677 μm, which are within the biological limits of 100-700 μm (Section 2.1.1). That means the rates and volumes of bone ingrowth of the osseointegration is good, it supports the growth of capillaries and also allow the bone cells to bridge pores. As mentioned in the previous section, it is of importance to have knowledge about the SLM influences from design to the real outcome. The size of the voids and struts have a strong impact on the deviation from the designed porosity. Decreased dimensional values for the designed struts and pore size leads to an increased deviation from the designed porosity. Which affecting the osseointegration and also the mechanical properties which are the underlying factors for bone replacement with secondary long term biologic fixation.

When comparing the compressive strength there is no clear trend. It’s seen that batch A has a higher strength than batch C even though they are in the same range of the void size, and that batch B is stronger than batch C while they are in the same range of the strut thickness. That indicates that the strength are more dependent on the porosity than on the size of the voids and struts.

5.2.4 Friction test
When observing the result from the friction test there should be noted that because of the different porosity fractions of the structures it is not the real contact surface that has been calculated in the result. Batch C should e.g. have a much smaller contact surface than in batch A. If they have a different contact surface they are exposed to different values of stress, since the actual load on the structure changes, which will affect the result. A deeper research in the contact surface and its effect is needed to understand the fact that there is no trend in the results.

5.2.5 Tensile test
The result from the tensile test showed clear differences between the batches according to porosity fraction and also between the various structures. Accordingly, structures with similar porosity had different values of tensile strength. Batch A ranging from 77-128 MPa, Batch B 236-272 MPa and Batch C 49-73 MPa. If the trabecular structure must sustain high loads during its clinical service, the company have the ability to advise the designer to choose a specific structure. It is also of importance to know which structure can achieve higher strength than a specific value and at the same time have a preferable porosity range.

The mechanical test results from the compression and tensile test indicate that the mechanical properties are not similar in cohesive strength and pressure. These test showed that the tensile strength and elastic limit of the trabecular structures followed the same trends as the compression strength and limit but were marginally lower. One reasons that was mentioned in previous research is that the manufacturing can have an influence that occasionally contains inherent weaknesses between the bonds of each layer and therefore generates reduced tensile strengths. The most significant mechanical characteristic was the elastic modulus in tension that was significant, unexpected, and higher in all structures and batches compared to elastic modulus in compression. Previous research does not show similar results but there is lack of literature studies that investigated compressive versus tensile stress on trabecular or high porous metal structures. To investigate this more, the same load interval selected as start and reversal point for the cyclic tensile test should be tested in the compression test. This to see if the gap reduces between the tests and also to achieve more comparable results. Accordingly, a larger sampling size of tensile specimens with the 7 remaining structures, with same dimensions as the compression specimens and same stress interval as in tensile test would be preferable as a start in future work in order to investigate the trend and the influence on different structures.
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The successive failure of individual struts that was mentioned in previous research can be seen at the stress-strain curves in both compression and tensile (Figure 32 and Figure 47). The jagged part is more distinct in batch C followed by A and in B mostly nothing. A high speed camera recording the fracture behaviour can be used for deeper analysis and investigate where it fractures, which struts and the influence of the different geometries. As in the compression test also this test was performed only in the building direction, but while in use the prosthesis can be exposed to tension in all directions.

The Gibson-Ashby model was investigated by the tensile structures as compression. Since there were only 3 structures per batch it was difficult to find a relationship. More structures are needed with same structure but different porosities to evaluate the function between the relative elastic modulus and relative strength versus relative density.

5.2.6 Abrasive test
The weight loss per cycle from the Taber test was high the two first cycles, and then it stabilized with a low rate. A possible reason is that the wheels have not stabilized against the surface in the first two rounds, but this was something that needed further investigation since there are several possible reasons.

The result showed that the higher compression strength the structures had the more resistance against wear. This result was expected because of the fact that a high hardness of the base material is a good protection against wear as earlier mentioned [25]. In this thesis work it was shown that the regular structure were the strongest ones, followed by irregular structures and last fully random structures. That means that with respect of wear resistant the regular structures is to prefer. Never the less, the difference in weight loss was limited between the structures.

The results were acceptable for all the structures since the values were clearly below the maximum allowed value. That leads to a minimized chance of any third body wear from a prosthesis because of particle shedding during a surgical procedure or from micromotions after insertion no matter what structure that is considered, even though structures with higher strength are more resistant to wear.

5.3 Conclusions
In the research, trabecular structures of Ti-6Al-4V were fabricated by additive manufacturing (AM) using Selective Laser Melting (SLM) and their morphology, microstructure, physical and mechanical properties were investigated. The result are summarized by restate and answering the research questions that were stated under section 1.2.

- How do the different structures with same porosity fraction manufactured by Selective Laser Melting influence the mechanical properties?

In this research the trabecular structures with same porosity fraction showed high dependance on the morphological geometry i.e. pore size and shape, strut size and pore distribution. There were in all characteristics a large range of mechanical properties. In batch B, 8 structures with porosity between 43-46 % and had stiffness ranging between 15.3-25.1 GPa and corresponding offset compressive strength 193.3-373.3 MPa. In batch A, 7 structures with 57-61 % porosity had stiffness between 9.3-14.5 GPa and offset compressive strength 150-210 MPa. Batch C, 5 structures, 80-83 % porosity and stiffness between 0.4-2.3 GPa and corresponding 16.3-49 MPa offset compressive strength.
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There was no significant difference between the structures: regular, irregular and fully random. The regular structures showed marginally differences from their deformed irregular structure and the fully random structures had slightly lower values in general. This indicates once again that the morphological geometry is of more importance.

- **What is the correlation between Young’s Modulus and the porosity fraction?**

From the compression result it was stated that the stiffness increased with decreased porosity. There was no strong trend between the 30 different trabecular structures, since the result showed structures with same porosity fraction could have a wide range of stiffness. In batch B, 8 structures with porosity between 43-46 % had stiffness ranging between 15.3-25.1 GPa. In batch A, 7 structures with 57-61 % porosity had stiffness between 9.3-14.5 GPa. Batch C, 5 structures, 80-83 % porosity and stiffness 0.4-2.3 GPa. Which indicates that the morphological structure had a significant impact on the stiffness.

- **Are the mechanical properties similar in compression and tensile conditions?**

There were similarities between the compression test and tensile test: the stiffness, strength and elastic limit increased with decreased porosity but the effect of porosity on tension versus compression were still ambiguous. Accordingly, the results from these test showed that the trabecular structures had no similar properties when exposed to cohesive strength and pressure. The stiffness were significantly higher in tensile. Batch A: 16.2-20.2 GPa in tensile and 6.6-11.9 GPa in compression, Batch B: 43.7-47.3 GPa versus 9.8-16.2 and Batch C: 7.8-12.4 GPa versus 1.1-3 GPa. The tensile strength and elastic limit of the trabecular structures followed the same trend as the compression strength and elastic limit but were slightly lower or partial lower. Tensile strength and elastic limit in batch A ranging from 77.7-127.8 MPa and 50-100 MPa versus 170-210 MPa and 150-160 MPa in compression. Batch B: 235.5-272 MPa and 185-200 MPa versus 316.6-395 and 210-266.7 MPa. Batch C: 48.6-73 and 25-56.7 MPa versus 56.3-86.3 and 53-59 MPa.

- **Is there a correlation between compressive strength and wear resistance measured by the Taber test?**

The result showed a trend with an increased resistance to wear with increased strength. There is a correlation between the type of geometry where regular structures has a better resistance, but more test in a wider range of structures and porosity needed to be performed to be able to confirm that. The result was much lower than the maximum allowed value and the difference between the structures was small.

- **Is the static friction coefficient affected by the porosity fraction?**

The result achieved from the friction test did not show any clear trend except for the regular structures that increased linearly with increased porosity. There were also structures with a significant variation in contact surface that had the same friction coefficient. When comparing the result to the amount of contact surface there was no clear trend which made the result not seems trustworthy. To achieve a more accurate result the test had to be performed again with another setup and with a deeper investigation about the contact surface of the different specimens.

- **Can the morphological characteristics of the specimens be defined through a metallographic approach on the surface?**

The mean value of morphology of the batches showed a consistent deviation from the designed morphology. As an example the values of the struts on the horizontal surface
had an increase with approximately 200 μm for each batch, same for the lateral surface but with a larger increase of for approximately 300 μm each batch. The consistency indicates that a metallographic approach on the surface is a possible method to measure the morphological characteristics. The minFeret was approximately in the designed size with a slight decrease for batch A and C that had a large input parameter.

To confirm that the result is valid or to achieve a more accurate result there is a need to investigate the internal pore size. This investigation can be performed either by a tomography or by stereomicroscopy in several layers of the specimens. If these layers are made really thin the whole cross section of the pores can be investigated and the real diameter can be stated.

- Are the porosity fraction different between the designed values and the real values of the structures?

There is a difference between the designed values and the real values of the porosity fraction, which differ depending on the batches. That is an indication that the deviation is depending on the pore size and strut thickness. How much influence each one of the two different morphological characteristics has, cannot be told with the available data. Therefore an investigation was recommended to achieve knowledge about how the porosity fraction depends on the morphological characteristics.

The physical and mechanical properties of the trabecular structures found to be close to those of cortical and trabecular bone in porosity, elastic modulus and strength. There is a range of variations leading to possibilities to adopt the application depending on customer. Thus, these can be considered as promising structures used biomedical application to optimize osseointegration and secondary long term fixation. Beneficial both in a social perspective and the manufacturing process in an environmental and economic perspective.

5.4 Future work

This thesis was a part of a three year long collaborative research project within the biomedical sector between Eurocoating and the University of Trento. Continuations of the thesis work, summarized from the discussion, are presented here:

- Compression tests of specimen with smaller dimensions and collateral planarity should be performed to avoid the buckling phenomena in batch A and receive a fully behaviour in batch B. This to achieve more comparable results between the batches.
- Investigate the cross section (geometrical features and strain hardening) to understand the gradient differences between 1st and 2nd uploading in the cyclic compression test.
- Perform a cyclic compression test with same load interval selected as in the cyclic tensile test to achieve more comparable results.
- Further investigations of the Gibson & Ashby model starting with a fit on the stiffness-porosity diagram. Thereafter it can be used to determine the elastic matching with natural bone. The complex dependence of the factors needs to be more understood and the suitable factors needs to be modified to the specific structures.
- Perform a tensile test of the 7 remaining structures, with same dimensions as the compression specimens in order to investigate the trend and the influences on the different structures.
- Investigate the failure mechanism during the compression test and tensile test.
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- Validate the pore size by a complimenting methodology to investigate the internal morphology.
- Investigate the influence of the morphology on the difference between the designed porosity and the real porosity by manufacturing a fourth batch with other input parameters.
- Investigate structures with values of designed strut thickness lower than 500 μm, in order to obtain structures with a pore size of 600-700 μm as in batch B, but with higher porosity.
- Redo the static friction tests with another, stabilized set up and investigate the effect of the contact surfaces.
- Perform a complementary Taber test with a more dense structure to confirm the hypothesis that batch C is the most critical batch in terms of wear resistance.
6 References


[40] M. Simonelli, Y. Y. Tse and C. Tuck, “Effect of the build orientation on the mechanical


## 7 Search terms

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8 Appendices

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## Appendix 3

**Result compression test**

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### Appendix 4  Young's Modulus comparison – with excluded numbers

#### Quasi static and first uploading in cyclic compression test

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### Appendix 5  Result morphological analysis

#### Geometrical analysis - Mean values per batch - Horizontal surface

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#### Geometrical analysis - Mean values per batch - Lateral surface

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## Appendix 6  Result static friction test

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