Additively Manufactured CP-Ti (Grade 2) Single Strut Size Effect of Mechanical Response Under Building Direction

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Abstract. The open cell structure is commonly used in the medical device industry and consists of small struts connected to each other. Relatively new additive manufacturing technique “SLS” has been used in this study. This approach allows to create a sufficiently small specimens to represent each strut in a commercially available orthopaedic porous structure. Pure titanium Grade 2 (CP-Ti grade 2) powder has been used during the experiments because of higher resistance to corrosion and it is one of the most biocompatible metal. The mechanical response of each strut affects the general behaviour of the porous system which influences stress shielding and bone attachment. In this study, small strut size effect and building direction of mechanical response have been investigated in order to provide vital data for upcoming rhombic dodecahedron structure FEM research.

1. Introduction

Materials are vital for medical application and supposed to have a specific parameters to achieve their role. Metal materials are widely used in the medical application and their properties should be suitable to survive in human or animal body [1][2]. Commercially available pure titanium has the high specific strength which makes them good for medical application. Also, it can deliver excellent biocompatibility [3][4][5][6]. Surface coatings and porous architecture designs have been developed to improve the biological fixation of the implant due to increasing subtract surface [7]. Rapid prototyping allows creating titanium porous parts with mechanical response near to bone like material. New rapid prototyping technologies, like selective laser melting (SLM) and selective electron beam melting (SEBM) can produce porous titanium parts with multifaceted geometries and organized inner architectures [8]. 3D printed porous structure does not only provide low density, also lower stress shielding which may help to bone remodeling [9]. Cellular materials are also known as a porous structure and it acts like trabecular bone. SLS applications have been used with different unit cell shape such as cubic, octahedron, rhombic dodecahedron. Several types of research and commercial product use rhombic dodecahedron for biological and mechanical response close to the trabecular bone. Therefore, rhombic dodecahedron consists of 12 identical rhombic faces with 24 struts [10]. Each strut mechanical performance would affect the complex 3D porous structure and there is a lack of literature regarding the subject. In this work, additively manufactured pure titanium (grade 2) small strut has been investigated. The size of the small samples was chosen according to real rhombic dodecahedron unit cell in commercially available implants.
2. Material and Test Method

2.1 Material

The chemical composition of CP-Ti can be found in Table 1. During specimen preparing Arcam CP-Ti Grade 2 powder has been used. The particle size is between 45 to 100 μm [11]. Table 2. Shows the mechanical properties of CP-Ti grade 2. It has been expected that additively manufactured material is supposed to be higher yield strength than reference material data [12].

|                     | C     | Fe    | O     | N     | H     | Ti    |
|---------------------|-------|-------|-------|-------|-------|-------|
| Arcam Grade 2 CP-Ti | 0,005%| 0,05% | 0,19% | 0,004%| 0,0009%| Balance|
| CP-Ti Grade2, Required* | <0,08%| <0,3% | <0,25%| <0,03%| <0,015%| Balance|

*ASTM F67 (Unalloyed Titanium for Surgical Implant Applications)

Table 2 Mechanical properties of titanium grade 2[11]

|                     | Yield Strength (σYs) | Ultimate Tensile Strength (UTS) | Elongation | Reduction of Area |
|---------------------|----------------------|----------------------------------|------------|------------------|
| Arcam Grade 2 CP-Ti | 540 MPa              | 570 MPa                          | 21%        | >20%             |
| CP-Ti Grade2, Required* | 275 MPa              | 345 MPa                          | 55%        | >30%             |

*ASTM F67 (Unalloyed Titanium for Surgical Implant Applications)

2.2 Designing struts and SLS process

Plate tensile specimens were designed with SolidWorks CAD software (SolidWorks Corp., Dassault Systemes, Concord, MA, USA) and imported to Materialize (Leuven, Belgium) software for final orientation to run in ConceptLaser the M2 Cusing (ConceptLaser, Lichtenfels, Germany) 3D printer. The thickness of the samples are designed to be 0.5mm however, their printed parameters might be slightly different due to the accuracy of the printing machine. The length of the samples is adjusted with 22mm and 7 mm thickness on the machine grip part. Parameter “a” has been changed the range of 0.15mm to 4.2mm and 74 samples were printed in order to reach a fine result, Figure 1.

![Figure 1 Technical drawing of small tensile specimens (mm)](image)

The cross-sectional area was calculated by multiple with parameter “a” and “b”. All samples were printed perpendicular to the platform surface (z-direction). Cross-sectional area (S₀) of the samples are up to 2.4 mm². 46 samples were printed orientation of ZXY and 27 samples were built with YZX orientation, Table 3. Illustrates the number of printed samples with building orientation respectively.
Figure 2 Sample printing direction on the platform

Table 3 Specimen numbers and orientations

| Orientation | Number of samples |
|-------------|-------------------|
| ZXY         | 46                |
| YZX         | 27                |

During additive manufacturing, Concept Laser M2 cusing (Lichtenfels, Germany) 3D printer has been used. Fundamental building parameters are, building chamber is not pre-heated, the laser beam power is set at 200W, the scan speed is 7m/s, the layer thickness is 20μm and 75μm offset distance. The scan strategy used was Concept Laser’s patented ‘island’ scan strategy in which each layer is divided into 5 mm × 5 mm square islands and exposed in a zig-zag fashion. Scan vectors in each island are exposed at 90° with respect to the neighboring island and alternating layers. A shift of 1 mm with respect to the previous island layer is used to limit porosity build-up [13], Figure 3.

![Figure 3](image)

2.3 Test Method

The tensile test has been accomplished in room temperature. And it was carried out with the use of a small-sized linear drive-based testing system with a capacity of 5 kN using valid calibration certificate [14]. The test has been completed regarding the ASTM E8 requirements, initial displacement rate set as 0.2 mm/min. The tensile direction is perpendicular da printing layers. Chyba! Nenalezen zdroj odkazu. In order to maintain traceability, each sample kept in the pocket for the further surface analysis. Additively manufactured CP-Ti parts have tested without any chemical and mechanical post process.

2.4 Geometrical investigation

Since the tests sample has the significant small cross-sectional area, the accuracy of the SLS machine performance worth to be investigated. The powder size is approximately 50 μm therefore the smallest specimen would contain very few melted powder particle if we compare to specimens have bigger
cross-section area. As a result of that, it may affect the general mechanical properties or elongation, further argument will be carried out in discussion part. Even minor unmelt particles would lead to a weak point around fracture areas. Scanning electron microscope (SEM) (Tescan VEGA-3 LMU) and RedLUX (RedLux Ltd. Southampton, UK) machines have been used to investigate surface accuracy. Although during the tensile test laser measurement have been done, the load bearing area of the samples were validated with different aspects.

![Figure 4](image)

**Figure 4** RedLux cross-sectional measurement on the XY plane. Result of sample with ZXY printing orientation.

After the tensile test, the samples were analysed with the RedLux measurement. RedLux is non-contact coordinate measuring machine (CMM) which provides 3D capture. It is mounted on an anti-vibration platform, the machine is unaffected by environment and gives on-screen results for analysis as soon as the measurement is completed. The machine has a white light confocal sensor, which of allows for analysis relevant surfaces without touching them and therefore potentially affecting the extent of the damage of the small fragile sample [15]. Scan performed with z-direction and it created helix on XY plane. The helix slice thickness is 0.05mm so, it contains a considerable number of cross-section area. Each section was projected onto the XY plane, and an envelope was constructed using the convhull function in MATLAB software environment, **Figure 6** illustrates the closed cross-sectional area. In **Figure 4**, the points represent cross-sectional areas on the XY plane.

![Figure 5](image)

**Figure 5** Redlux and tensile test machine measurement of cross-section area and dimension errors vs frequency

The method can provide also the statistical accuracy of geometry as well. Moreover, the closed loop result presents a load bearing area. Each sample has been investigated by the mentioned method and
compared with the test result. In order to understand the geometrical accuracy, tensile test machine and Redlux machine measurement of cross-section area have compared. Figure 5 shows statistical difference between two methods to validate load bearing area.

Figure 6 shows single slice cross-section area on the XY plane of the sample printed with ZXY orientation. ZXY and YZX building orientation surfaces have been investigated with scanning electron microscope (SEM) Tescan VEGA-3 LMU. Melt pool may affect the building properties. Besides, melt pool is affected by thermal properties such as heating-cooling cycle [16]. These parameters are also considered during the investigation.

3. Result
The cross-sectional area and surface analysis have been carried out in order to identify the difference between additively manufactured samples and cad files. Cad design and laser scan micrometers gives comparable values of cross-sectional area. While So is getting smaller, accuracy of SLS technique is decreasing. As it can be said that cross-sectional area is becoming more circular than rectangular. Additively manufactured small samples contain unpredictable mechanical response while the cross-sectional area has smaller diameters such as less than 1.5mm². It has been mentioned previously that samples are grouped in two according to building orientation. Table 3 illustrates samples number were built with ZXY and YZX orientation. Sample with ZXY orientation yield strength is generally higher than samples with YZX orientation. This affect can be noticed that strongly while So is getting smaller.

4. Discussion
3D printed technology does not only provide design freedom, it can also offer good mechanical response and lightweight structure. The open cell structure is commonly used in the medical device industry and it consists of small struts connected to each other. The mechanical response of each strut affects the general behavior of the porous system. This mechanical performance may affect the stress shielding in the medical application. During the experiment small sample mechanical response is significantly different in the cross-section area smaller than 0.5mm² and this is the range of complex 3D structure strut thickness. Moreover, the finer microstructure can produce good mechanical performance and the mechanical response of AM samples may even have better performance than wrought or machine titanium [17][18]. This is the promising feature can improve by post treatment method such as heat treatment of HIP (Hot Isostatic Process) application.

5. Conclusion
As a result of conducting this research, the following findings have been concluded:

- The size effect of building orientation occurs until certain cross-section area. Particularly, the yield strength distribution of the samples is considerable differences in this section with small cross-section area, So<1.5mm² respectively. While the cross-section area is getting bigger than 1.5mm², the trend of yield strength reaches a stable result regardless of building orientation.
The result of yield strength changes with the cross-section diameter respectively, this may influence the design aspect. The porous structure is used in the medical device has small struts due to the open cell diameters and it helps to allow bone ingrowth [19].

In addition, the paper demonstrates that additively manufactured pure grade 2 titanium parts tend to have higher yield strength than conventionally manufactured pure titanium grade 2 since SLS can provide finer microstructure.

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