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Trabecular structures as efficient surface of dental implants

JÍRA Aleš[1,a], HÁJKOVÁ Petra[1,b] and ŘEHOUNEK Luboš[1,c]

[1]Department od Mechanics, Faculty of Civil Engineering, Czech Technical University in Prague, Thákurova 7, 166 29 Prague 6, Czech Republic

[a] jira@fsv.cvut.cz, [b] petra.hajkova@fsv.cvut.cz, [c] lubos.rehounek@fsv.cvut.cz

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Abstract. Fast development of additive manufacturing methods provides for production of advanced porous structures which form external layers of implants. Since implants usually replace parts of missing or damaged bone, its external layers are close to bone structure. Today, most of the porous structures which are used for implants are trabecular structures, composed of beams. Design of the structures depends on the type of implants, width of layers etc. Small implants, such as dental implants, have very thin external layers (~ 200 μm), which means that the structure is very fine. The quality of 3D printed structures therefore depends heavily on accuracy of current 3D printers (SLM method). Problems of 3D printing which can lead to implant failure are cracks inside of beams, their poor interconnection, etc.

The study is focused on the quality control of 3D printed trabecular structures, especially with respect to implant stability in bones and minimization of a risk of structural damage. The quality of the structures was evaluated by optical and microscopic analysis using SEM. Based on the results, we suggest substituting the trabecular structures by a gyroid structure composed of a system of walls. Gyroid structures are not prone to local discontinuities and have other advantages such as absence of sharp corners and edges, which contribute to better proliferation of bone cells.

Introduction

Development of additive manufacturing methods provides for production of complex trabecular structures. The purpose of trabecular structures, as an external layer of implants, is to improve osseointegration. Advantages of the structures lead to rapid scientific and technological development in the field of 3D printed metallic structures [1]. The main advantages are growth of contact area between implants and bone tissue, and a possibility to modify global mechanical properties, which helps to eliminate the stress shielding effect – the main problem of conventional implants. Furthermore, complex morphology of the structures allows the ingrowth of bone cells, which leads to better stability of dental implants in bones.

However, designed mechanical properties of 3D printed structures can be significantly affected by the quality of 3D printing. The current technological possibilities of the SLM method (Selective Laser Melting) are limited by fineness of the powder, which is used for the structures' production, and the machine accuracy. The accuracy of 3D printing is very important especially for dental implants because of its size [2]. Dental implants are ~3–5 mm in diameter, which means that the surface layer is very thin.

Authors [3, 4] who have dealt with the quality of 3D printed porous structures mentioned a mismatch between designed and as-produced width of beams in fine structures. It affects the porosity and therefore mechanical properties of the structures. Furthermore, they implied that there was a problem with production of the structures composed of horizontal and angled beams, for example dodecahedron, because of greater amount of sintered plaque, which is the result of melting. The melting of poor quality can also cause production of small pores (50–100 μm) which were not designed [5]. Bael et al. [6] pointed out that the structures with beams forming corners were often filled with excessive material.

The study is focused on the quality control of trabecular structures, especially with respect to implant stability in bones and minimization of a risk of the structure damage. For this purpose, we produced samples of six different trabecular structures. The beams thickness was ~200–300 μm. After the quality control, the samples were intended for use in mechanical compression and tension tests. Extensive defects were detected by a basic optic analysis. The defects were situated mainly near the interface of the trabecular and homogenous part of the samples. This finding led to a modification of a geometric shape of the samples for the tension tests, and a detailed microscopic analysis.

Materials and Methods

Design of Trabecular Structures. Trabecular structures usually take a form of spatial truss structures composed of beams. For the tests we designed 6 models of trabecular structures with different morphology, i. e. a size and a shape of pores, a width of beams, and orientation of beams in a 3D matrix. The structures were composed of basic units in the shape of Diamond, Dode Thick 30 %, and Rhombic dodecahedron 30 % (Fig. 1). Each of the basic units was used in two sizes for the design of the trabecular structures. Table 1 shows a summary of the structure parameters.

1) Diamond, relative density 30 % — 2) Dode Thick [MSG] — 3) Rhombic dodecahedron, relative density 30 %

Fig. 1: Basic units of the trabecular structures which are composed of beams.

The samples were composed of the trabecular and homogenous parts. The trabecular part of the samples was a cube (14x14x14 mm), which was connected to the homogenous parts from two opposite sides. Shapes of the homogenous parts were set up for the compressive and tension tests, which came after the microscopic analysis.

Tab. 1: The parameters of the trabecular structures which were designed for the microscopic analysis, compression and tension tests.

Trabecular structure	Shape of basic units	Size of basic units [mm]	Width of beams [μm]	Size of pores [μm]
1	Diamond	0,75	200	350
2	Diamond	1,00	260	450
3	Dode Thick	1,00	200	500
4	Dode Thick	1,25	250	630
5	Rhombic Dodecahedron	1,25	230	640
6	Rhombic Dodecahedron	1,50	290	800

Production of Samples. Basic material for the samples production was an alloy of titanium Ti6Al4V, also called Rematitan (Concept Laser, Germany), in the form of powder with maximal granularity of 63 µm. The samples were produced by an additive method, specifically by the method of SLM (Selective Laser Melting). The machine used for the samples production was M2 Cusing (Concept Laser, Germany). The 3D printing was performed in argon atmosphere, the argon purity of 4,6 (Linde, Germany). During the printing, the atmosphere in the welded chamber contained up to 0,5 % of oxygen.

After the samples were printed, it was necessary to perform a heat treatment. The aim of the heat treatment was elimination of inhomogeneities and internal tensions, which came from the metal powder sintering. The heat treatment was performed in a vacuum furnace. A temperature in the furnace increased gradually up to 840 °C in 4 hours. After that, the temperature was held constant for 2 hours. Finally, the samples were cooled down to minimum of 500 °C. During the cooling, the vacuum was substituted by an argon atmosphere [7].

Optic and Microscopic Analysis for Quality Control. The basic optic analysis provided an optical analysis of the surface morphology and quality of the beams. The surface morphology was analysed particularly from the point of view of defects, initiation of discontinuities, and possible local complications. For this purpose, photographs from the camera Canon 6D Mark II and the lens Canon MP-E 65mm f/2,8 Macro 5x were used.

Based on the results of the basic optic analysis, we decided to complete the results by a detailed microscopic analysis. The detailed analysis was performed on an electron microscopy SEM Phenom XL (Phenom World, Netherlands).

Results

The basic optic analysis showed significant uncertainties about a quality of connection between the individual parts of the samples. On the interface between the trabecular and homogenous part, many cracks in the beams and its poor interconnections were detected (Fig. 2). These defects can be a consequence of temperature changes during the 3D printing and the heat treatment. When the trabecular part of the samples is printed earlier than the homogenous part, the fine trabecular structure cools down faster. The difference in cooling down rate causes a difference in shrinkage of the individual parts. As the result of this process, the beams prone to shorten and break away from the warmer homogenous part. This observation is cause for concern that implants which are composed of homogenous internal body and trabecular external layer will contend with the same problem. During development of 3D printed implants with trabecular external layer, it is necessary to remove or eliminate the problem as much as possible.

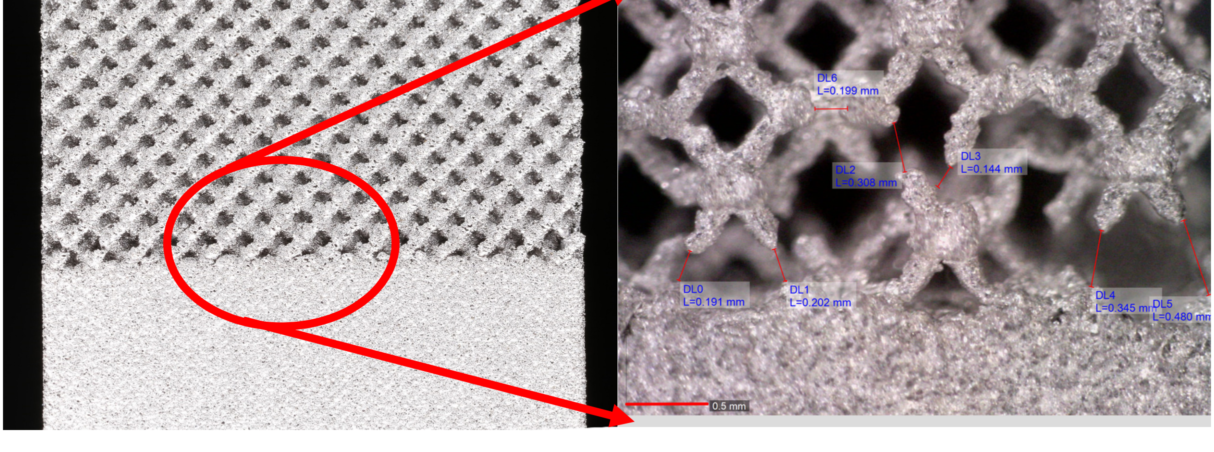
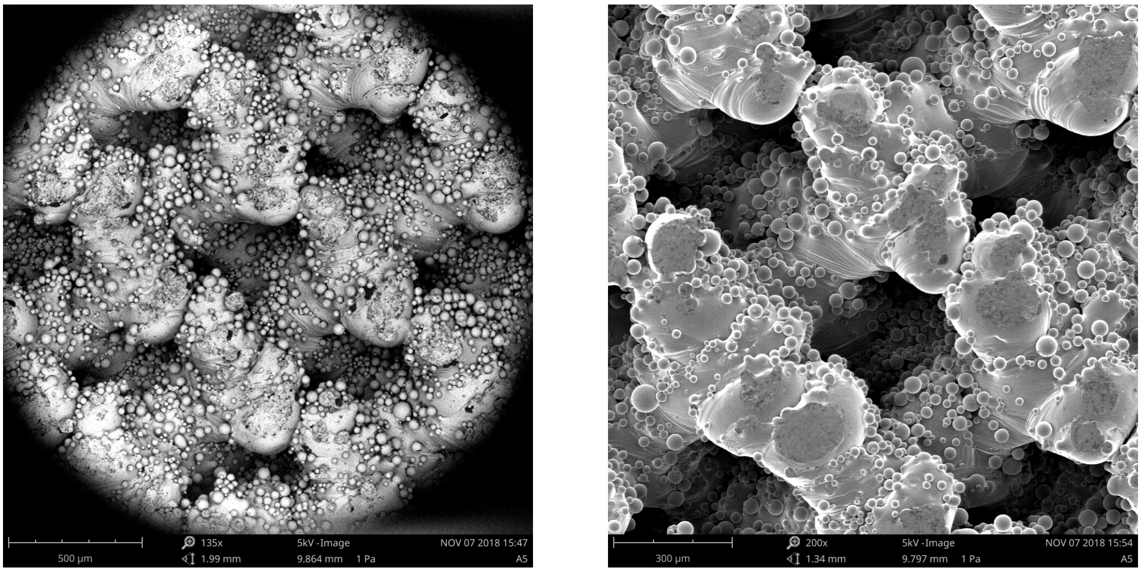


Fig. 2: Defects of the samples on the interface between the trabecular and homogenous part.

Based on the results of the basic optic analysis, we performed a detailed microscopic analysis using SEM. Many discontinuities of the beams (Fig. 3a) and clusters of slag (Fig. 3b) were detected inside the structures. The capillary defects can cause a break of microparticles, a subsequent genesis of necrosis, and aseptic release of implants. The question is whether this phenomenon can be limited by greater thickness of the beams (>300 μm). Another problem is that the beams with greater thickness cannot be used for all types of implants. If thickness of the beams is greater and the mechanical properties stay the same, it is necessary to increase a size of the basic units, which means to increase a size of the whole implants. Therefore, it is possible to increase thickness of the beams of the structures for bigger implants, such as implant for hip and knee replacement, but not for small implants, such as dental implant.

a)



b)

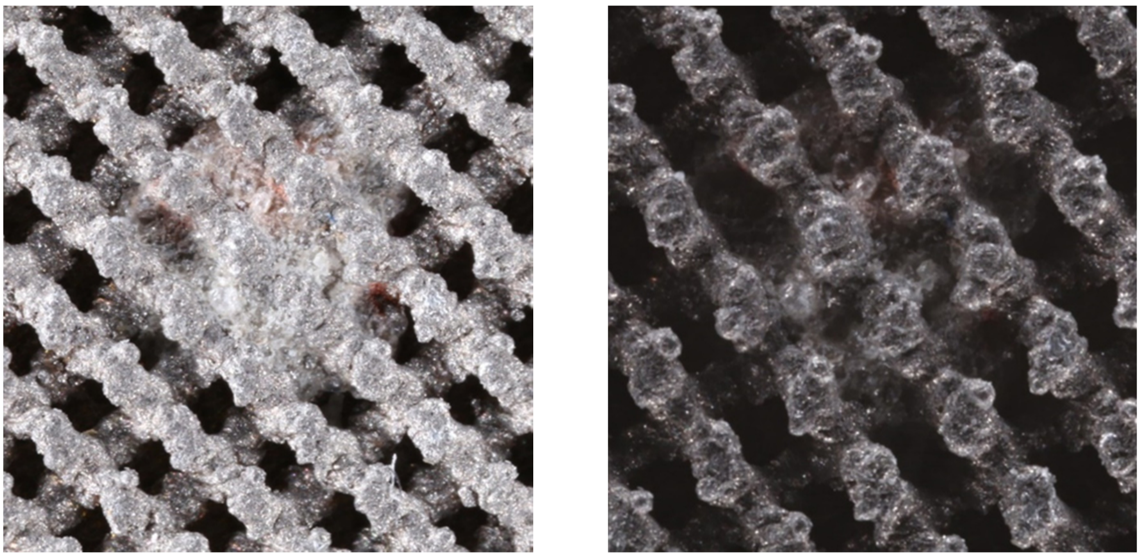


Fig. 3: The detailed microscopic analysis showed: a) discontinuities of the beams, and b) clusters of slag inside the trabecular structures. The photo was conducted by an electron microscope (SEM).

Discussion

The basic optical and the detailed microscopic analysis showed the significant uncertainties and the problems about trabecular structures composed of beams. Apart from the connections between trabecular and homogenous parts of the samples being of poor quality, many discontinuities of the beams and clusters of slag were detected inside the structures. It is necessary to consider if trabecular structures are appropriate for external layer of implants, or it is better to substitute it by other type of porous structures.

A potential solution can be porous structures based on a wall system, which also meet fundamental requirements for bone ingrowth. One of the best examples is the structure composed of walls in the shape of gyroid. This structure has a system of interconnected pores (open porosity), which is necessary for bone ingrowth, and sufficient permeability for proliferation of bone cells [8]. Furthermore, gyroid structures do not comprise sharp edges and corners, which are spanned by cells, and thus eliminate areas prone to damage.

For the verification of the hypotheses that gyroid structures could have greater reliability with respect to crack initiation and other defects, a preliminary optic and microscopic analysis was performed. The preliminary analysis confirmed that gyroid structures were less prone to defects which had been detected at the trabecular structures. Any local discontinuities were visible from the microscopic photos (Fig. 4). It results in elimination of the risk of microparticles release, which can lead, in the worst case, to aseptic release of implants. In addition, porous and homogenous parts are not joined just in local points but linearly. Greater area of joint can prevent breaking away of the parts from each other. All in all, we also reached greater stability of the structure by the transition from a trabecular to wall system. A general analysis of gyroid structures, which includes a microscopic analysis, macro/micro mechanical testing, and a numeric analysis, will be aim of our future research.

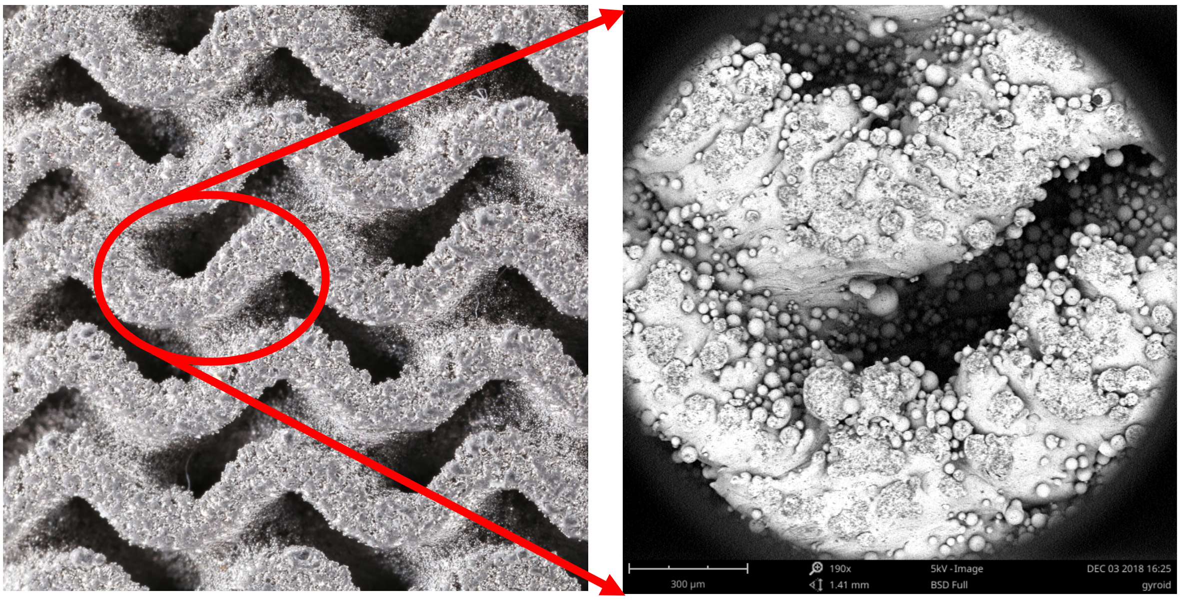


Fig. 4: Microscopic photos of the gyroid structure. Any local discontinuities were visible.

Conclusions

The uncertainties in the trabecular structures make us think over whether trabecular structures are an appropriate external layer for implants. We consider the cracks of the beams near the interface between porous and homogenous material, and inside the structures the biggest problem. The reason is that discontinuities of beams can cause failure of the whole structure, or release of microparticles into patient body. The resolution can be replacement of trabecular structures with porous structures based on a system of walls without sharp changes. The structure fulfilling the requirements is, for example, a gyroid structure. The preliminary optic and microscopic analysis proved that the gyroid structures were less prone to crack initiation and other defects, and therefore it is highly appropriate for inbone parts of implants (dental, acetabular, hip and knee replacements, etc.)

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