Mechanical property evaluation of closed and open-cell foam structures with finite element method

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Abstract. In this study, different lattice structures were examined with finite element method. Mechanical stress evaluations were performed on porous structured lattices that consisted simple cubic, face-centered cubic, body-centered cubic, and diamond unit cells. Finite element method simulations showed that structured foams with open and closed cells produced significantly different stress levels depending on their packing fraction. The aim of this study is to provide a basis for the design of an implant system that would promote the process of osseointegration.

1. Introduction
Estimates show that 70 to 80 percent of medical implants are made from metallic materials [1]. Medical implants are utilized to replace hard tissues and are mostly made from pure titanium or titanium alloys. Their most important characteristics are outstanding mechanical, physical and biological properties [2]. As a result of these, titanium-based alloys soon became widely-used for medical applications. Porous titanium alloys possess excellent mechanical properties and have low modulus of elasticity. Moreover, porous titanium structure and rough surface provides improved biological stability and biocompatibility compared to other porous materials [3,4]. In recent past, different technologies were studied to manufacture porous titanium alloys including precision casting [5], titanium powder sintering [6], rapid prototyping [7], and mixed titanium powder sintering [8]. In recent times additive technology has been chosen to manufacture porous structures. Exceptionally precise and computable structures can be created that have numerous advantages over conventional technologies [9-13]. Chen et al. manufactured open-cell porous structures with selective laser melting from Ti-6Al-4V titanium alloy. They studied lattices with 40 to 80 percent porosity and pore sizes between 600-1000 µm. Their aim was to design open-cell porous structures that best resembled human bone tissue. Specimens were designed with CAD software and were printed with SLM (Selective Laser Melting) technology. Lattices in CAD environment were compared to the printed specimens, and the largest difference was found at 80% porosity. The rest of the specimens showed minimal difference. Elastic moduli of printed lattices were studied, and they concluded that specimens with 67% porosity were the best compatible with the elastic modulus of human bone [14]. Ahmadi et al. studied six different lattice structures manufactured with additive technology. Material testing was conducted on printed specimens to determine maximum stress, elastic modulus, and energy absorption. Type of studied lattice structures were simple cubic, diamond, truncated cube, truncated cuboctahedron, rhombic dodecahedron, and rombicuboctahedron [15]. Finite element method (FEM) is a calculation technique used in engineering practice to approximate solutions in boundary value problems. A boundary value problem is a mathematical problem in which one or
more variable must fulfil differential equations within the known boundaries of independent variables and must fulfil special conditions on the boundaries themselves [16]. Steps of finite element method-based calculation process are the following: modelling, pre-processing, calculation, post-processing, and evaluation [17].

2. Presentation of evaluated structures
The purpose of this study is to create an implant system that makes osseointegration faster. Osseointegration is a structural and functional connection between bone tissue and implants. Studies previously mentioned in the introduction part were investigating different foam-like structures, but porous structures resembling crystal structures have not been found in literature. That is why we started to investigate these configuration types. The starting body was a 20x20x20 mm cube for each simulation.

2.1. Simple cubic structure
In simple cubic structure, atoms sit in the corner points of the single cell. In this work, porous structures were designed as negatives of crystal structures. It means we have cut the spheres from the corner points of the solid cell. Figure 1. represents phases of volume reduction for simple cubic structure. Volume was first reduced by increasing the diameter of these spheres. Volume was further reduced by rounding sharp edges. The lattice with the simple cubic alignment remained a closed-cell structure after these reduction steps. As spherical diameter increased, strut thicknesses decreased.

2.2. Face-centered cubic structure
In face-centered cubic structure, atoms sit in the corner points and, also in the centre of each side of the cube. Porous structures were designed as negatives of the crystal structure. It means we have cut the spheres from the lattice points of the solid cell. Figure 2. represents phases of volume reduction for face-centered cubic structure, which was achieved by increasing spherical diameter and rounding edges. Due to growing cut-out sphere size, the structure changed from closed-cell to open-cell lattice. It is notable that face-centered cubic alignment allowed extensive volume reduction.

2.3. Body-centered cubic structure
In body-centered cubic structure, atoms sit in the corner points and in the middle of the body diagonal. Porous structures were designed as negatives of the crystal structure. It means we have cut the spheres from the lattice points of the solid cell. Figure 3. represents phases of volume reduction for body-centered cubic structure, which was achieved by increasing spherical diameter and rounding edges. Due to increasing cut-out sphere diameters, the structure changed from closed-cell to open-cell lattice. Extensive volume reduction can also be observed here.
2.4. Diamond structure
Diamond structure can be derived from face-centered cubic structure. Atoms sit in the corners, face-centres, and mid-octan centres of the cube. Porous structures were designed as negatives of the crystal structure. It means we have cut the spheres from the lattice points of the solid cell. Figure 4. represents phases of volume reduction for diamond structure, which was achieved by increasing spherical diameter and rounding edges. Due to growing cut-out sphere size, the structure changed from closed-cell to open-cell lattice. Three phases in the change of cell openness could be identified. We could also achieve extensive volume reduction with this cell type.

3. Results of finite element analysis
Finite element simulations were carried out in Ansys software. Starting body of the previously presented structures was always a cube with the size of 20 mm x 20 mm x 20 mm. First, spherical diameter and edge rounds were increased by 0.5 mm. Smallest rounding radius was 0.1 mm for each structure. They were then increased in 0.1 mm increments until it was geometrically allowed for each structure. Due to the transition from closed-cell to open-cell structure, sphere diameters reduced by 0.1 mm were evaluated as well. Constraint and load definitions remained the same for every test. Distributed force acting on the bodies was 500 N, and friction-free fixation was chosen. Maximum stress levels were evaluated during result analysis, irreal results were neglected. Maximum stress level was the highest equivalent stress in the entire body. These stresses arised in different areas of the structures depending on their geometry. In our simulations, a sample data representative of Ti-6Al-4V (Additive Manufacturing Materials) was considered, and a corresponding isotropic material model was used by the software.

3.1. Results for simple cubic structure
1408 calculations were conducted with different spherical diameters and round edge radii for simple cubic structures. The largest cut-out sphere diameter was 19.5 mm. Figure 5. represents maximum stress levels in simple cubic structures. It is notable that up until 80%, result distribution is very dense. Simple cubic structure did not transform into open-cell structure. Due to its closed-cell structure, high volume fraction could not be achieved. In this case, volume reduction did not reach even 50%. Maximum stress was around 17 MPa. The diagram shows correlation between maximum stress levels and the extent of volume reduction. Thus, cut-out sphere diameters were increased in 0.1 mm increments and calculations were performed again without rounding edges. Calculation results can be seen in Figure 6. The tendency is clear, an outlier at 20 mm diameter is observable when comparing it with to the rest of the results. Calculated stress results were low, but they came along with low levels of volume fraction. The curve starts at the volume fraction of 100% with gentle slope. Curve gradient slowly increases after the volume fraction of ca. 60%.
3.2. Results for face-centered cubic structure

761 calculations were made with increasing spherical diameters and round edge radii for face-centered cubic structure. The largest cut-out sphere diameter was 15.5 mm. Figure 7 represents maximum stress levels in face-centered cubic structures. It is notable that up until 70%, result distribution is very dense. Face-centered cubic structure transformed from closed-cell to open-cell architecture by reducing volume fraction. Compared to simple cubic structure, low volume fraction values were achieved during our simulations. Result points were distributed sparsely below 55% volume fraction. Maximum stress was 382 MPa at the volume fraction of 13%. Cut-out sphere diameters were increased in 0.1 mm increments due to the transition from closed to open-cell structure, which can be seen in Figure 8. Result point distribution was very dense until 60% volume fraction, then result data points became sparser. Until 28% volume fraction, the structure remained closed, and at 25% it was perforated and turned into an open-cell structure. Meanwhile, maximum stress level was raising above 85MPa. From this threshold value, maximum stress gradient was increasing: at 14% volume fraction maximum stress
was 293 MPa. Results here can be considered reasonably good. High fraction volumes could be reached and even at 30% fraction volume, maximum stress remained at 44 MPa.

![Figure 8. Simplified diagram for face-centered cubic structure](image)

### 3.3. Body-centered cubic structure

1268 calculations were carried out with increasing spherical diameters and round edge radii for body-centered cubic structure. The largest cut-out sphere diameter was 19 mm. Figure 9 represents stress levels in body-centered cubic structures. It is notable that up until 48%, result distribution is very dense. Body-centered cubic structure transformed from closed-cell to open-cell architecture. Result points were distributed densely below 48%, but then distribution got more intermittent. 10% volume fraction could be achieved. Stress intensity was 150 MPa at 14% volume fraction. From 100 to 35% volume fraction, the curve had low gradient. This architecture provided the best results so far. New calculations were carried out for body-centered cubic structure without round edges. They are presented in Figure 10. Cut-out sphere diameters were increased in 0.1 mm increments here as well. It is notable that until 32% volume fraction, the set of result points was dense and evenly distributed. There, the architecture remained closed. At 31% volume fraction, stress intensity increased sharply. It is well-defined in the graph where closed-cell architecture opens up. After this transition, stress intensity decreased then started to rise again as volume was reduced.

![Figure 9. Summary diagram for body-centered cubic structure](image)
3.4. *Diamond structure*

589 calculations were carried out with increasing spherical diameters and round edge radii for diamond structure. Diameter of the largest cut-out spheres was 13.5 mm. It was the most complex structure to analyse due to the spheres located in mid-octans of the body. Simulation results can be seen in Figure 11. Result distribution was very dense until the volume fraction of 68%, then there were no result points until 60%. This tendency remained all along. Several quasi-separate set of result points emerged because the open-cell structure became multiphase. To evaluate phases of the open-cell structures, new calculations were carried out where cut-out sphere diameter was increased in 0.1 mm increments with no round edges used. Figure 12. demonstrates results for cut-out sphere diameters increased by 0.1 mm. Calculations were conducted with non-rounded edges. Until volume fraction of 84.9%, the structure stayed closed, the cut-out sphere from the mid-octan appeared at 84.25%. Due to this, stress intensity increased sharply, then plummeted back. Until the volume fraction of 72%, stress level remained quasi-constant, then as cut-out sphere diameter increased at the mid-octans, result values increased again. For the blue-coloured body, which had a volume fraction between 59 and 66%, false results were gained (thousands of MPa-s) due to the unrealistically thin walls formed during the transition to open-cell structure. At the volume fraction of 59%, stress intensity decreased as thin walls were completely wiped out from the structure.
This process lasted until the volume fraction of 40%, where spheres at the mid-octans met those at the face-centres. Due to this, stress increased sharply, then plummeted and increased again. Six stages can be identified altogether for diamond structure.

Figure 12. Simplified diagram for diamond structure

4. Summary
Diagrams presented in the previous sections are summarized in Figure 13. This diagram contains the set of results of both simple cubic, face-centered cubic, body-centered cubic, and diamond structures. Set of result points were attained from spherical dimensions decreased by 0.1 mm. In the summarizing diagram, result points for simple cubic structure are covered by the rest of the results. The lowest volume reduction could be achieved with this type of structure in spite of the low stress levels that remained quasi-constant even until high volume fractions. Neither did the structure transformed to an open-cell architecture. Stress intensity in diamond structures were generally higher at lower volume fractions compared to the other two structure types. Face-centered and body-centered cubic structures produced almost identical results until the volume fraction of 27%. Afterwards, stress levels in face-centered cubic structure started to rise and much higher results were attained. In general, the best result was achieved by body-centered cubic structure if we consider stress levels and volume fractions. Curve discontinuities marked the transition phase to open-cell structure. Namely, open-cell structure comes along with reduced wall thicknesses, which produce extremely high stress levels.
Our research is going to be continued. In the following stages, environmental behaviour of different porous structures are going to be evaluated with great emphasis on stress levels and volume fractions. We are going to investigate structures that make up an entire lattice. Calculations are going to be validated empirically using additively manufactured test specimens.

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References

[1] Chao J et al 2014 Mater. 7 1709-1800
[2] Wen C E et al 2002 J. Mater. Res. 17(10) 2633-2639
[3] Lopez-Heredia M A et al 2008 Biomater. 29 2608-2615
[4] Yamada Y et al 2000 Adv. Eng. Mater. 2 184-187
[5] Oh I H et al 2003 Scr. Mater. 49(12) 1197-1202
[6] Li J P et al 2006 Biomater. 27(8) 1223-1235
[7] Bartolo P et al 2012 CIRP Annals 61(2) 635-65
[8] Gu D D et al 2012 Mater. Rev. 57(3) 133-164
[9] Mironov V et al 2009 Biofabr. 1(2) 1-16
[10] Murr E et al 2010 Phil. Trans. R. Soc. A 368 1999-2032
[11] Hatos I et al 2018 Stroj Vestn-J Mech E 64 121-129
[12] Chen S Y et al 2017 J. Alloys Compd. 713 248-254
[13] Ahmadi S M et al 2018 Mater. 8(4) 1871-1896
[14] Hutton D V ISBN: 0-07-239536-2
[15] Gyimóthy Sz 2003 Ph.D BME VIK