EAN 2019
57th conference on experimental stress analysis

# Numerical analyses of the gyroid structure for use in dental and orthopaedic implants

VAKRČKA Petr[1,a], JÍRA Aleš[1,b] and ŘEHOUNEK Luboš[1,c]

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

[a]petr.vakrcka@fsv.cvut.cz, [b]jira@fsv.cvut.cz, [c]lubos.rehounek@fsv.cvut.cz

**Keywords:** Numerical, Gyroid, Trabecular, Implant, FEM

**Abstract.** The proposed work deals with the numerical analyses of different variants of the gyroid structure. The analyses were carried out to determine the optimal geometry (wall thickness, spacing) of the gyroid structure for use in dental and orthopaedic implants. Since the human body represents an environment of (compared to metals) soft tissues, it is not always desirable to introduce a structure with high stiffness as an implant. The gyroid structure (on the macroscopical level) represents a porous structure that reduces the overall stiffness of the implant if applied on the outer layer of the implant. What is more, this kind of mesh provides interesting features for tissue scaffolding due to high porosity which gives an opportunity to design a structure that can also meet the requirement for the optimal pore size with regard to the most effective bone ingrowth. Furthermore, we can minimize the stress shield effect which can lead to the bone resorption after implant insertion.

## Introduction

Implants made of titanium and its alloys have a long history of good success rates [1]. Nevertheless, they still share a common shortcoming, which lies in the difference between material properties of the metal and human tissue [2, 3]. This shortcoming can be addressed by reducing the overall stiffness of the implant. This reduction serves to better the conditions for osseointegration and reduce the stress-shielding effect, which is often associated with implant loosening. Aseptic loosening is, in fact, one of the main reasons of implant failure [4]. The proposed solution to this problem is shown in Fig. 1. An outer porous gyroid layer was introduced into the implant body to lower the global modulus of the implant and also to make the conditions for osseointegrations better [5] by allowing bone ingrowth.

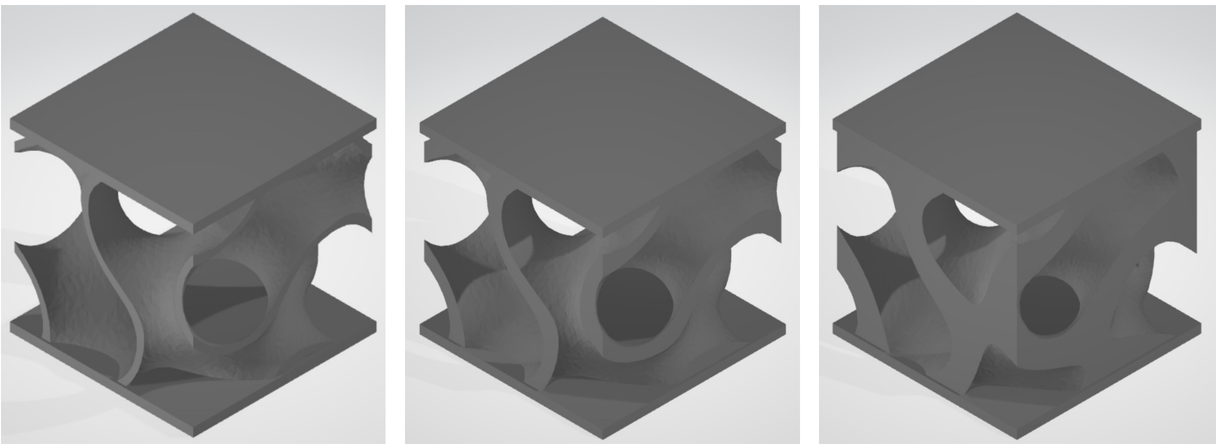
Fig. 1: A scaled 3D-printed PLA demonstration-only dental implant specimen with the gyroid structure applied on its outer surface.

Furthermore, the gyroid structure has other benefits which result from its geometry. Due to the absence of sharp edges, it is much better for osseointegration. Also, since it is not formed by beams, but rather by continuous walls of material, it is much less prone to chipping and local crack defects, which have been observed in the past by the research team. Due to the fluent change of curvature, local stress concentrations are also expected to be lower. Also, wall-like behavior is superior to beam structures in preventing local failure and transferrance of potential implant debris into the body of the patient.

## Numerical Simulations

The numerical analyses were performed in ANSYS Workbench 19.0. The aim of the analyses was to determine the trend of increase in stiffness and prepare for a more complex analysis comparing global moduli in relation to that of human bone ($E_{c,bone} \approx$ 10-25 GPa [6], $E_{Ti\text{-}6\text{-}Al\text{-}4V} \approx$ 120 GPa [7]). The material of both the model and future specimens is the Ti-6Al-4V alloy, the most common alloy in the implant industry [8]. It is a bio-inert material. In general, an implant from the Ti-6Al-4V alloy needs to have a surface modification to be effectively used for osseointegration. A different approach of dealing with the osseointegration problem is using the gyroid morphology which can effectively substitute the surface modification. Based on previous research the authors conducted [9], it was assumed that a structure with a global modulus in the range of units of GPa can be considered low stiffness and viable. The final assigned structure can then be manufactured and uniaxial mechanical tests can verify the precision of the model. After model verification, numerical simulations can serve to design specific structures without prior mechanical tests to conserve the costly material. Images showing three of the analysed structures are shown in Fig. 2.

The loading of individual structures was simulated using the mode of controlled displacement. The speed of displacement was 1 mm/min, according to the speed prescribed in the "ISO 13314:2011 – Mechanical testing of metals – Ductility testing – Compression test for porous and cellular metals" standard [10]. This was done to prepare the models for comparison with data from future mechanical tests of individual structures, which will be done in accordance with this standard.



a) Spec. 0.2 mm b) Spec. 0.4 mm c) Spec. 0.8 mm

Fig. 2: Three basic cells of the gyroid structure varying in wall thickness. Upper homogeneous part designed to meet the criteria for future uniaxial mechanical tests, which the model will be compared against.

**Results**

The specimens with varying wall thickness (0.2, 0.4, 0.6, and 0.8 mm wide) were numerically analysed in order to determine the trend in increase of stiffness as well as to prepare the environment for future analyses after successful manufacturing of real specimens for mechanical tests. Results from the analyses are shown in Fig. 4. The graph demonstrates increase of the vertical force reaction with increasing wall thickness. The force was measured after 1 minute of controlled displacement loading according to the “ISO 13314:2011 – Mechanical testing of metals – Ductility testing – Compression test for porous and cellular metals” standard, which prescribes a loading speed of 1 mm/min. In Fig. 3, the displacement loading is shown, along with the FEM mesh generated and used for the numerical analyses in Ansys Workbench 19.0.

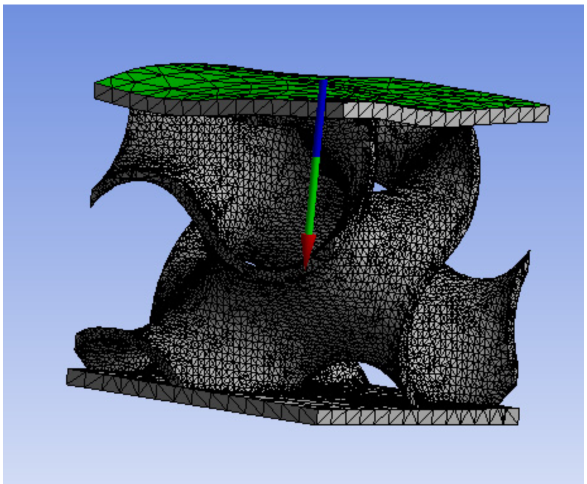


Fig. 3: A figure showing the FEM mesh used to perform the simulation and the deformation of the unit cell of the 0.2mm specimen after 1 minute of loading prescribed by ISO 13314:2011 standard.

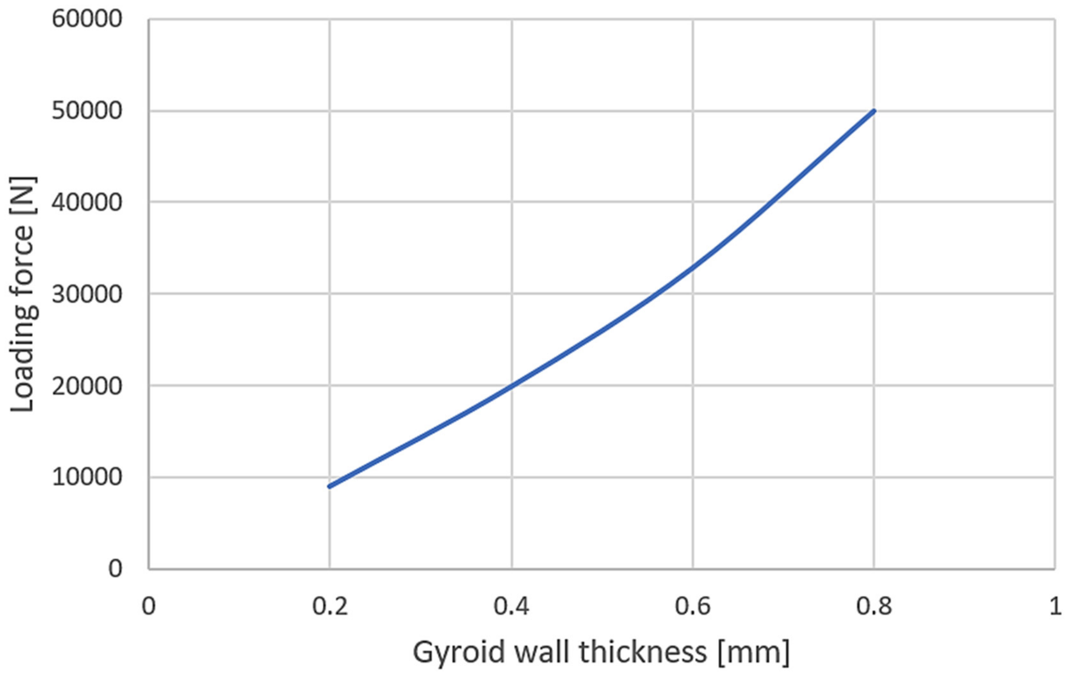



Fig. 4: A graph showing the final loading force against the thickness of an individual gyroid structure after 1 minute of displacement loading prescribed by ISO 13314:2011 standard.

## Conclusions

A total of 5 different variants of the gyroid structure were numerically analysed to determine the trend of increase in stiffness and wall thickness in regard to the potential application in dental and orthopaedic implants. The values obtained from the analyses are also subject to further investigation as other factors, such as bone osteon ingrowth and manufacturability of the 3D-printed parts come into play. Manufacturing fine details and thin walls might prove to be a challenge in the future as the resolution in the xy direction varies from printer to printer. Authors have encountered problems with SLS metal printing in the past and expect the technology to improve and enable manufacture of functional, fine parts, considering the rate of improvement in the field of 3D printing.

The gyroid structure has many benefits as it is unique in its wall-like mechanical behavior that prevents local strain-induced failure and subsequent transfer of the implant material into the body of the patient. Another benefit of the gyroid structure is absence of sharp corners and edges, making it a fit candidate for the implant industry, where predictability, ease of operation and viability for osseointegration make for a successful, long-lasting and practical implant.

## References


[1] T. Hasegawa, S. Kawabata, D. Takeda, et al., Survival of Brånemark System Mk III implants and analysis of risk factors associated with implant failure. International journal of oral and maxillofacial surgery 46(2) (2016) 267–273.

[2] Ridzwan, M. I. Z., et al., Problem of stress shielding and improvement to the hip implant designs: a review. J. Med. Sci7.3 (2007) 460-467.

[3] M. Long, H. J. Rack, Titanium alloys in total joint replacement–a materials science perspective. Biomaterials 19(18) (1998) 1621–1639.

[4] Le Guéhennec, L., Soueidan, A., Layrolle, P. and Amouriq, Y., Surface treatments of titanium dental implants for rapid osseointegration. Dental materials, 23(7) (2007) 844-854.

[5] Řehounek, Luboš, et al., Geometry and mechanical properties of a 3D-printed titanium microstructure. Acta Polytechnica, 57(3) (2018) 104-108.

[6] Rho, Jae Young, Richard B. Ashman, and Charles H. Turner., Young's modulus of trabecular and cortical bone material: ultrasonic and microtensile measurements. Journal of biomechanics 25(2) (1993) 111-119.

[7] Niinomi, M., Mechanical properties of biomedical titanium alloys. Materials Science and Engineering: A, 243(1) (1998) 231-236.

[8] Niinomi, M., Recent metallic materials for biomedical applications. Metallurgical and materials transactions A, 33(3) (2002) 477-486.

[9] L. Řehounek, "Mechanical and numerical analyses of titanium trabecular structures of dental implants formed by 3d printing," Acta Polytechnica, vol. 57, no. 3, pp. 218–228, 2017.

[10] Standard, I. "ISO 13314: 2011 (E) (2011) Mechanical testing of metals—ductility testing—compression test for porous and cellular metals." Ref Number ISO 13314.13314: 1-7.