FEM CALCULATIONS OF POROUS TITANIUM STRESS-STRAIN BEHAVIOUR UNDER THE TENSILE LOAD

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Abstract: This paper deals with FEM calculations of the porous titanium specimen stress-strain behaviour during the tensile load for two different porosities and two different pores diameters. Moreover, simulations results are compared and discussed with those achieved for cast titanium. Totally, four semi-empirical equations were used for prediction of porous titanium elastic modulus. Three of them, Phani-Niyogi, Coble-Kingery and Maiti relations revealed very good agreement with experimental data. Ideal material used in traumatology should exhibit good strength, fatigue and corrosion resistance and also good bone cells adhesion and osteointegration with reduced risk of the shielding effect. Brand new idea of the titanium implants with gradient porosity is presented.

Keywords: biocompatible, FEM, porous titanium, shielding effect, traumatology, von Mises stress

1 Introduction

Pure titanium and titanium alloys represents frequently used biocompatible materials. Titanium and its alloys are commonly used in traumatology because of its good biocompatibility [1,2,3], favourable osteointegration [4,5], excellent mechanical properties and corrosion resistance [6,7,8]. However, cast titanium elastic modulus is approximately 100 GPa and frequently used titanium alloy Ti6Al4V is about 110 GPa [4,5,6]. Human bones elastic modulus ranges within 15 – 30 GPa and depends on gender, age and health status [1,2,3].

The difference between human bones and titanium implants elastic modulus causes so called shielding effect, that may result in the necessity of reoperation [9,10,11]. Adjustment of the mechanical properties is necessary for reducing and even eliminating of the stress shielding phenomena. On the other hand, porous titanium implants represents perspective trend in development of new generation implants. Porous implants allows improved surface cells adhesion, osteoblastic proliferation and reduced risk of future reoperation [12,13]. The main potential thread of the porous titanium implants usage are insufficient mechanical properties (tensile strength, compression and fatigue resistence). Such as casting defects and/or manufacturing defects. Also pores in titanium matrix represents stress concentrators. The main aim of this paper is the evaluation of the maximal von Mises stress and its dependence on total porosity and pore size. Finite elements method was used for calculation of the porous titanium stress-strain behaviour. Results achieved for porous titanium models were compared with cast titanium model.

2 Calculation methods

Titanium microstructure was programmed using Digimat software. The models designed in Digimat were transferred to Abaqus software. Mesh of FEM model consisted from tetragonal elements with global size approximately 0.05. FEM calculations were performed for cast titanium model and for porous titanium models. Tensile stress with fixed displacement (u = 0.01) was applied for all models. The first variable used in the simulations was total porosity – 0, 10, 20, 30 and 40 %. Meanwhile, 0 % total porosity represents cast titanium implant, total porosities within 10 – 40 % represents porous titanium implants that can be suitable because of its improved bone cells proliferation and reduction and/or supression of the shielding effect [10,11,12]. The second varied variable was pore diameter 200, 300 and 400 μm. Pores diatemeters used in the simulations are commonly recommended due to its positive effect on bone cells proliferation [14,15,16,17].

3 Results and discussion

Firstly, simulation of cast titanium model was realized. If an ideal model is presumed (lack of casting defects and any porosity), homogeneous stress-strain field is achieved. Moreover, for calculated fixed displacement (u = 0.01) ultimate stress of titanium (1000 MPa) was not exceeded, see Fig. 1

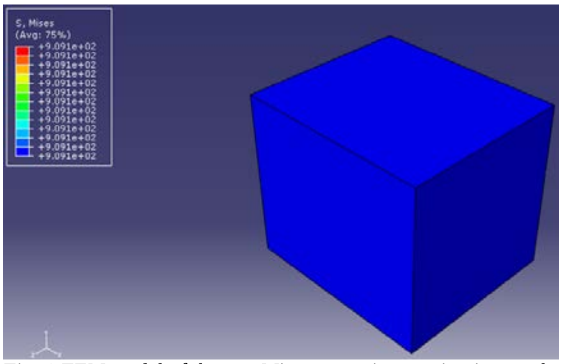

Fig. 1 FEM model of the von Mises stress in cast titanium at the end of tensile deformation (u = 0.01).

Titanium models with 10% total porosity and different pore diameters revealed that ultimate stress was not exceeded in all cases. Maximum von Mises stress values were concentrated in spheric shape pores. With increasing pore size also heterogeneity of stress-strain field increased, see Fig. 2

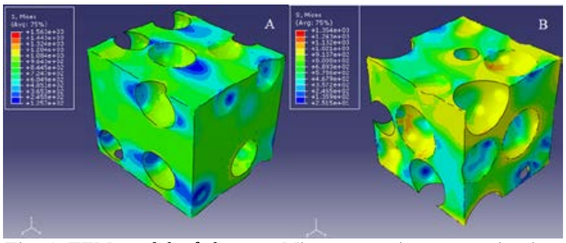

Fig. 2 FEM model of the von Mises stress in porous titanium (10% porosity) at the end of tensile displacement (u = 0.01). Pores diameter: 200 μm – A, 400 μm - B.

Both higher titanium matrix porosity and bigger pores size contributes to the increasing maximal values of the von Mieses stress and also increases stress fields heterogeneity. The porous titanium model with 40% porosity and different pores diameters exhibited the fact that ultimate stress was passed for all three pore diameters. This fact indicates intensive local plastic deformation, see Fig. 3

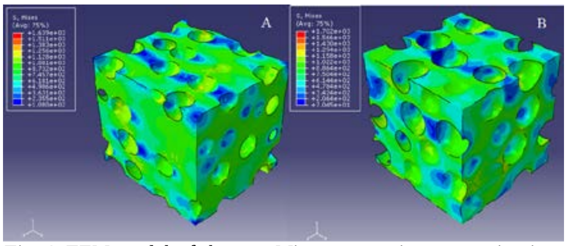

Fig. 3 FEM model of the von Mieses stress in porous titanium (40% porosity) at the end of tensile deformation (u = 0.01). Pores diameter: 200 µm – A, 400 µm - B.

Although, the main variable contributing to the increasing von Mieses stress values in titanium matrix is porosity, proper combination of the porosity and pores diameter may reduce risk that ultimate stress will be passed. As it can be seen on Fig. 4, combination of 30% porosity and 200 µm pores diameter did not exceeded ultimate stress value, as the combination of same porosity and bigger pores diameters did, see Fig. 4

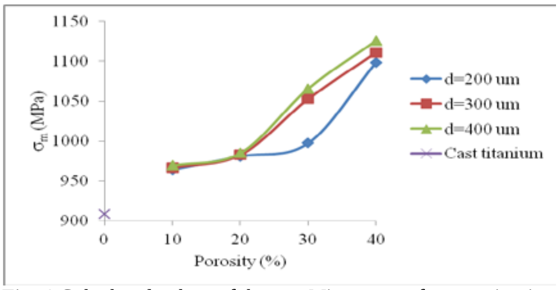

Fig. 4 Calculated values of the von Mises stress for cast titanium and titanium matrixes with different porosity and pore diameters.

However, from the medical point of view, also bigger pores with diameter up to 500 µm are necessary.
In an ideal case, elastic modulus of the titanium implants should be the same and/or similar to the human bone elastic modulus. In our calculations we used four common equations proposed by Phani and Niyogi [18], Coble and Kingery [19], Maiti [20] and Hardin and Beckermann [21]. Phani–Niyogi relation allows to determine elastic modulus of the porous titanium matrix, see Eq.1

$$E = E_0 (1 - \frac{P}{P_C})^n, \quad (1)$$

where E is porous matrix elastic modulus, E_0 is typical cast titanium elastic modulus, P is matrix porosity, P_C is critical matrix porosity (≈ 0.83) when ultimate stress converges to zero and n is material constant (≈ 1.68) [22]. Coble and Kingery used their equation to describe the elastic modulus of porous alumina, see Eq.2

$$E = E_0 (1 - 1.86P + 0.86P^2). \quad (2)$$

Maiti derived equation that can be used both for porous materials with closed (power is 3) and open pores (power is 2), see Eq.3

$$E = E_0 (1 - P)^2. \quad (3)$$

Finally, Hardin and Beckermann proposed their equation for determination of porous 8630 steel elastic modulus, see Eq.4

$$E = E_0 (1 - \frac{P}{2})^{2.5}. \quad (4)$$

Meanwhile, Phani–Niyogi, Coble-Kingery and Maiti relations gives very similar results, Hardin-Beckermann model seems not suitable for determination of porous titanium elastic modulus. According to the Phani–Niyogi, Coble-Kingery and Maiti relations porous titanium implants with 40% porosity exhibited elastic modulus very close to the human bones one, see Tab. 1

Tab. 1 Titanium elastic modulus calculated using Phani-Niyogi relation – E_1, Coble and Kingery – E_2, Maiti – E_3, Hardin and Beckermann – E_4.

Porosity (%)	E_1 (GPa)	E_2 (GPa)	E_3 (GPa)	E_4 (GPa)
0	100	100	100	100
10	81	82	81	88
20	63	66	64	77
30	47	52	49	67
40	33	39	36	57

Moreover, calculated values for elastic modulus (E_1, E_2, E_3) were compared with experimental data [17]. It was confirmed that Phangi-Niyogi, Coble-Kingery and Maiti relations can be used for tentative determination of the porous titanium elastic modulus. The main risk of the porous titanium implants application can be their insufficient strength and fatigue behaviour. These contradictory requirements can be met by appropriately chosen functionally gradient materials and/or by development of the titanium implants with porosity gradient. The implant core made from sintered low porosity titanium can ensure good strength, fatigue and corrosion resistance. On the other hand, highly porous surface layers of the titanium implant can be optimized for perfect bone cells adhesion and osteointegration with minimal risk of the shielding effect and/or reoperation caused by aftersurgery infection.

4 Conclusion

FEM simulations deals with titanium models that are characterized by different porosity and pore diameters. Moreover, elastic modulus of the porous titanium is calculated using Phani–Niyogi, Coble-Kingery and Maiti relations. According to our simulations the most influential variable that affects stress-strain concentration and stress-strain fields heterogeneity is matrix porosity. Although, increasing pores size also contributes to the maximal values of the von Mises stress. Due to the fact that optimal titanium implants properties are contradictory, new proposal of the porous titanium with gradient porosity is presented. The future works will be focused on development and testing of the new progressive materials intended for biomedical applications.

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