Trabecular structures of dental implants formed by 3D printing and their mechanical properties

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Abstract: This paper proposes an overview of the trabecular Ti-6Al-4V 3D-printed titanium alloy used for dental implants. Series of micro and macro mechanical tests were made to help better understand the trabecular structure and the mechanical behavior of the 3D-printed titanium alloy. The work also includes an overview of the current state of knowledge in this area as well as results obtained by experiments. Indentation tests, compression and tensile tests have been performed to obtain the values of reduced modulus and hardness.

Keywords: trabecular; 3D printing; dental implants; porous, nanoindentation.

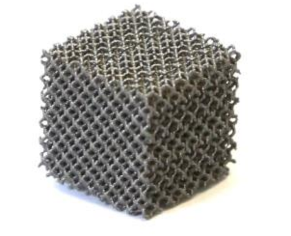
1 Introduction

The advancement in the technology of 3D printing makes it possible to create complex geometric structures, which form the bearing scaffold for the ingrowth of bone cells into the implant [1,2]. This interconnection is beneficial for long term stability at the implantation site [3] and also helps to smoothen the material transition region, where unwanted stresses often cause large deformations, leading to implant loosening. This work is dedicated to the basic mechanical properties of the trabecular structure of the dental implant. In cooperation with ProSpon spol. s. r. o., we were able to create the structure using the M2 Cusing Concept Laser machine with a specialized input media for dental implants Rematitan Cl of the Ti-6Al-4V chemical composition.

2 3D printing technology

The first step towards creating a 3D-printed product is creating a 3D-model. This part is usually done using a computer-aided design (CAD) environment. Upon its completion, an STL model file is divided into thin cross sections [1,2] and sent to the 3D printer to be processed. Up to this point, the process is similar to the common layer-by-layer 3D-printing of plastic.

What differentiates the process of printing metals from the standard technology is using a laser beam to melt down a layer of metal powder, such as Rematitan Cl. During each cycle, the coater applies a thin layer of powder, which is processed by a laser at a pre-set melting point in a pre-determined order [4]. This process solidifies the loose powder into a 3D-layered object, such as our specimens shown on Fig.1.



a) compression test specimen

b) tensile test specimen

Fig. 1: Trabecular structure specimens for global mechanical tests.

3 Methodology

3.1 Nanoindentation

To investigate the micromechanical properties of the alloy, nanoindentation tests were made considering reduced modulus of elasticity, hardness and contact depth. The micromechanical analysis was performed using the CSM Instruments nanoindenter in the mode of directed force and repeated loading. The load program was set with consideration of eleminating surface tension and shear stifness in the atomic material structure (Tab. 1). A typical indentation curve from the cross section the trabecular structure is shown on Fig 2.

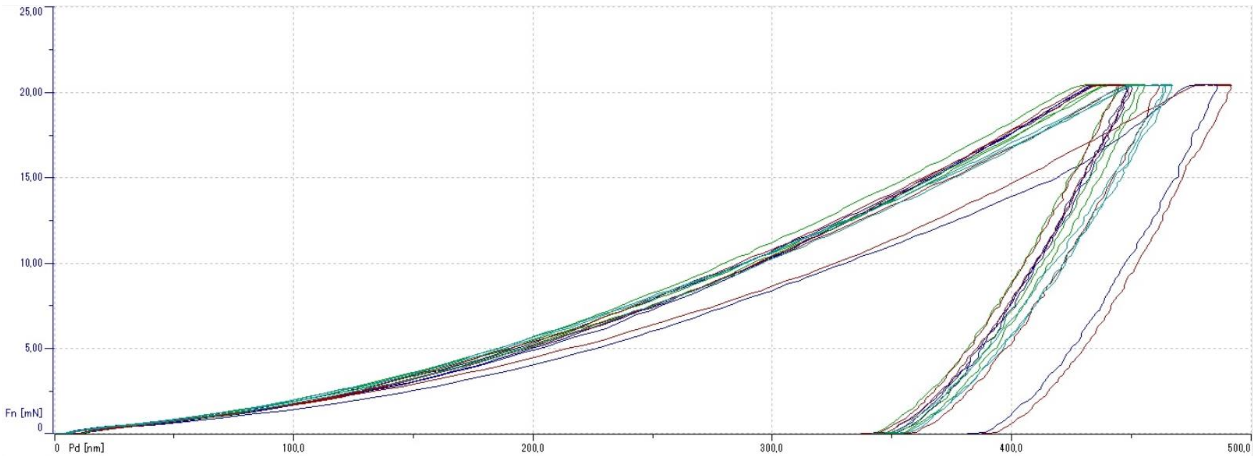


Fig. 2: A typical indentation curve of the trabecular alloy, showing the relation of the loading force F_n and the deformation of the specimen P_d.

Tab. 1: Mean values of reduced modulus E_r, hardness H_{it} and contact depth H_c in individual load cycles.

Physical property	Load cycle						
	1	2	3	4	5	6	7
H_{it} [MPa]	5190.9	5201.4	5187.8	5165.9	5190.8	5202	5190.7
Std. Dev.	251	200	281	343	379	404	395
E_r [GPa]	131	122.4	118.9	118	116.8	117.1	118.1
Std. Dev.	10	6	4	3	3	3	4
H_c [nm]	266.7	381	470.5	543.8	607.5	659.7	732
Std.dev.	7	8	13	22	25	31	45

3.2 Global mechanical tests

To investigate the global mechanical properties, we conducted compression and tensile tests. For this purpose, we used the 3D Dode-Thick [MSG] structures with dimensions of 14x14x14 mm (a cube for the compression test) and a 14x14x42 mm (a block for the tensile test). The tensile test specimen had a 14 mm trabecular middle section and end portions of homogeneous volume for ensuring a better anchor in the MTS Alliance RT-30 machine [5]. The results show an ultimate compressive strength of 31.30 MPa and an ultimate tensile strength of 32.80 MPa. Diagrams showing the stress-strain relations of the specimens obtained by tensile and compression tests are shown on Fig. 3 and Fig.4, respectively.

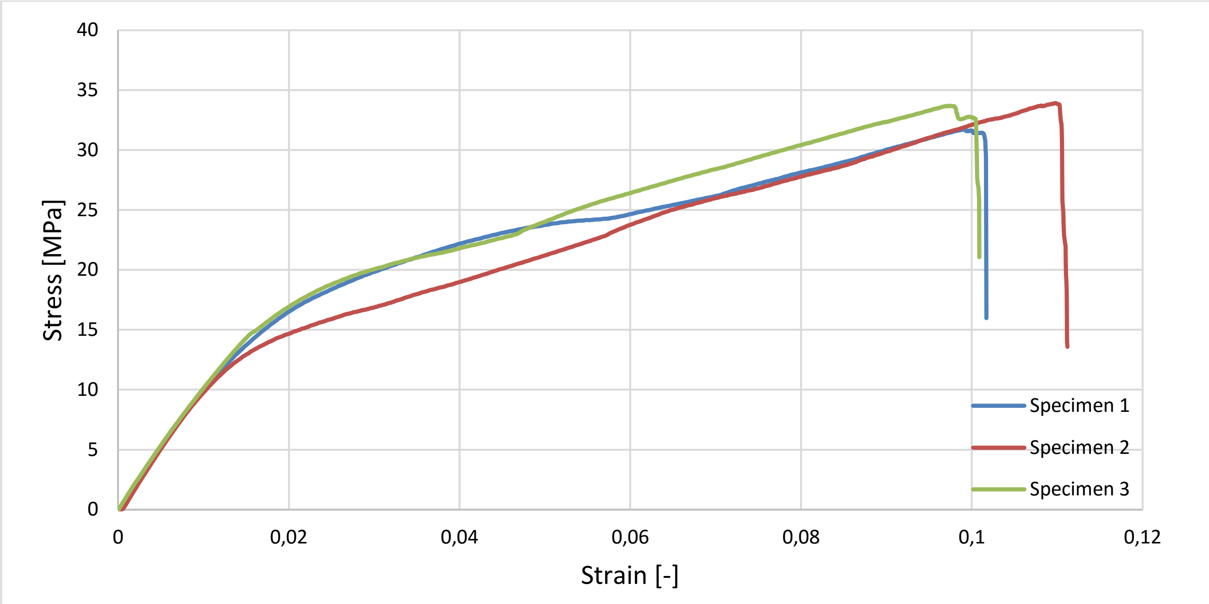


Fig. 3: Stress-strain relation diagram of the tensile test specimens

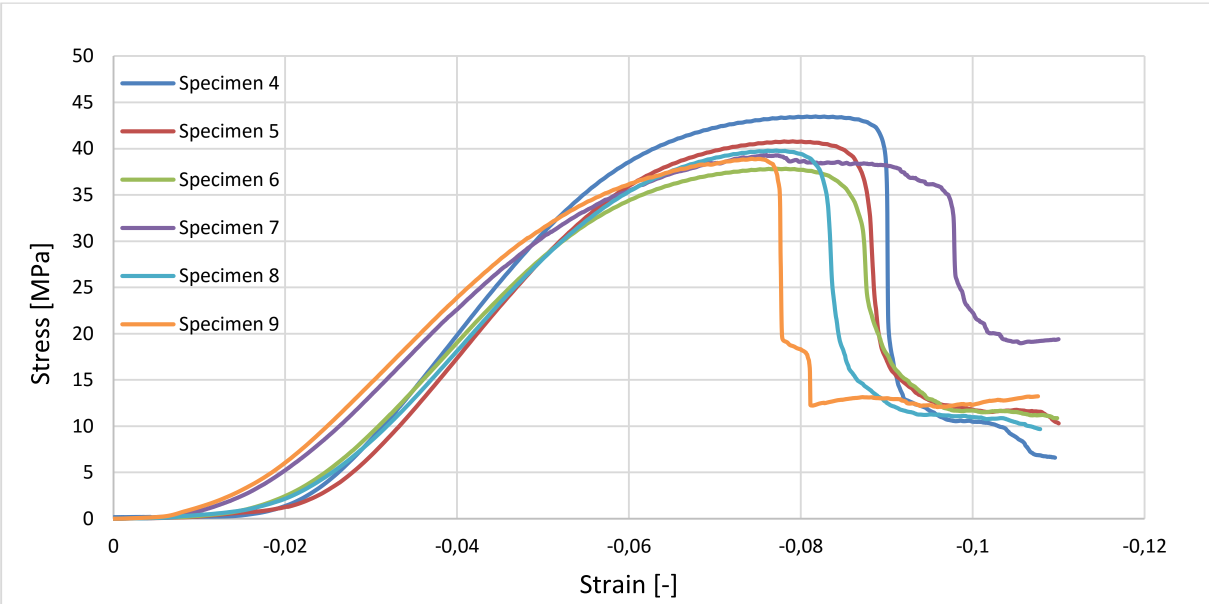


Fig. 4: Stress-strain relation diagram of the compression test specimens

From the linear part of the load curves of the diagrams shown above, we were able to calculate Young's modulus of the whole trabecular specimen (Tab.2). These values represent properties of the whole specimen, contrary to the nanoindentation experiment, where obtained values represent only the material characteristics at the micro level.

Tab.2.: Values of Young's modulus obtained by global mechanical analysis

	Young's modulus E [MPa]									
Specimen	1	2	3	4	5	6	7	8	9	Mean
Tensile test	964.66	975.91	982.20	-	-	-	-	-	-	**974.26**
Compression test	-	-	-	1043.2	1080.6	947.15	879.38	999.58	878.84	**971.46**

4 Conclusion

The micromechanical analysis has proved the properties to be dependent on the depth of the indent (size of the loading force). From a contact depth of H_c ~ 470 nm (corresponding load force of 30 mN), the trend of E_r and H_{it} is constant and therefore we can assume the loading force of 30 mN as a basic value. The corresponding properties of this force are reduced modulus E_r = 118 GPa and hardness H_{it} = 5.187 GPa. For comparison, the mean value of reduced modulus E_r of the stems of the commonly used implants is ~ 118 GPa and their hardness H_{it} is ~ 4.580 GPa [6]. According to the experiment and the obtained values of the micromechanical properties, we can therefore assume that the 3D printed material has very similar behaviour when compared to implants commonly used today.

The macromechanical tests have been conducted as a pilot experiment and cannot be therefore compared with other authors. However, an evaluation based on the experiment is at hand. The tensile tests have shown a bilinear stress-strain diagram with elongation at fracture ranging from 9 to 10 % in all tested specimens, which corresponds with the values given by the manufacturer. The compression tests have proven to be more diverse due to the yet unclear nature of the deformation of the trabecular structure. The elongation at fracture ranges from 7 to 10 %. The mean Young's modulus E of the trabecular specimens calculated from the linear part of the loading curves is E_{ten} = 974.26 MPa for the tensilte test and E_{comp} = 971.46 MPa.

As predicted, the analysis showed that incorporating the trabecular structure into the body of the implant has great effect on lowering the Young's modulus E of the whole implant. As opposed to regularly produced Ti-6Al-4V implants, where values of E are approximately 110 GPa, the values of E of the trabecular implant are below 1 GPa. This is a very significant reduction and the results are still to be compared with other experiments. Explaining the true mechanical behavior of the trabecular structure also requires a more detailed material model, which is the subject of further study.

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