Acoustical and Poromicromechanical Characterization of Titanium Scaffolds for Biomedical Applications

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General

Bone biomaterials should match the original properties of bone as precisely as possible, in order to preserve standard physiological stress fields around the implant. Precise determination of these stress fields requires profound knowledge of the 3D material properties of both bone and bone replacement materials, such as titanium. We here present a corresponding experimental campaign on dense and porous titanium samples, the latter having recently been proposed [1] as to enhance bone ingrowth characteristics.

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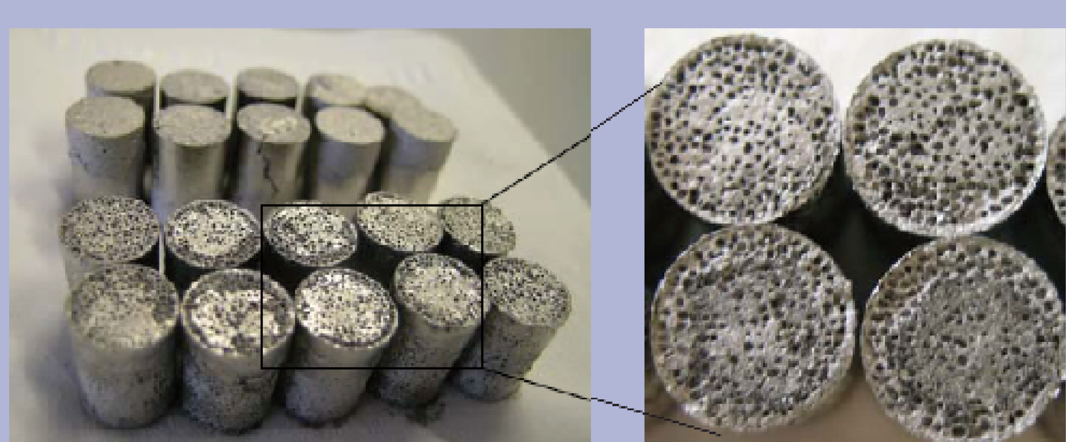
Literature:

[1] S. Thelen, F. Barthelat, L.C. Brinson: Mechanics considerations for microporous titanium as an orthopedic implant material, Journal of Biomedical Materials Research Part A, 601-61, 2004.
[2] L. Dormieux: Poroelasticity and strength of fully or partially saturated porous materials, in: Applied Micromechanics of Porous Materials, L. Dormieux, F.-J. Ulm (eds.), Springer, Wien, New York, 2005.
[3] A. Fritsch and C. Hellmich, Journal of Theoretical Biology, 2006, doi: 1016/j.jtbi.2006.09.013.

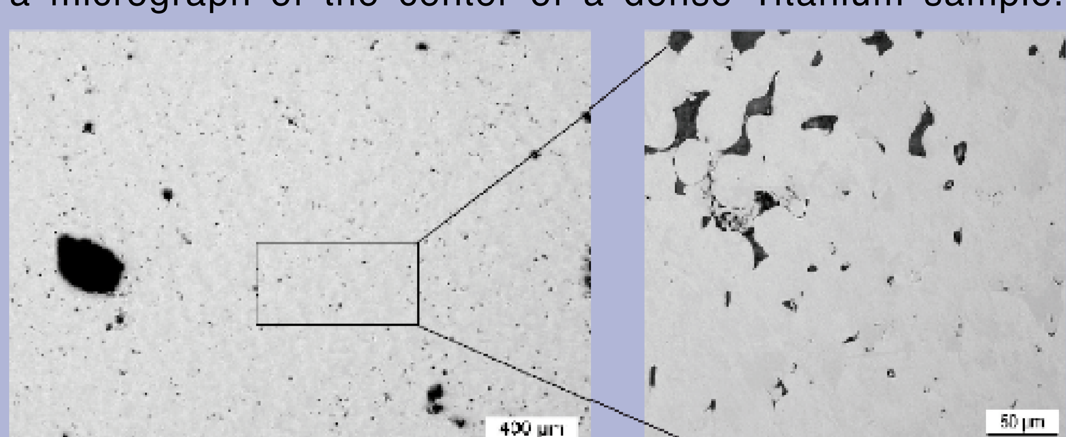
Processing

Dense (low porosity) and porous (high porosity) cylindrical samples of diameter 9 mm and height 14 mm were produced by a powder metallurgical process, involving the use of organic space holders (polymers spheres of para-formaldehyde with mean diameters of 500 microns):

1. Mixing of metal powder and polymer space holder material, together with process aiding chemicals dissolved in water or organic solvent, ensuring satisfactory metal-polymer bonding
2. Axial pressing of mixture in a powder press
3. Removal of polymer / bonding agent through a catalytic process
4. Sintering in a high vacuum atmosphere



The upper figures show the produced samples with two different porosities (Titanium dense and porous). The lower figures show a micrograph of the center of a dense Titanium sample.



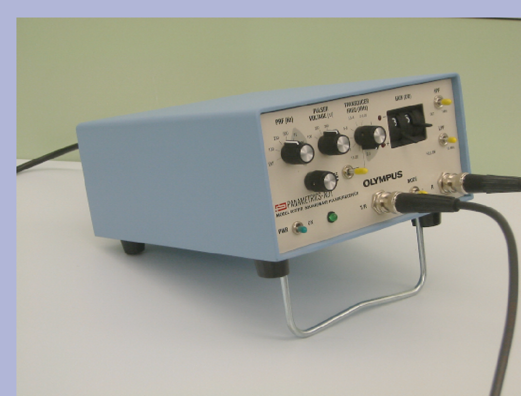
Acoustical testing - elasticity

Employing ultrasonic transducers (see right image) with frequencies of 0.1, 5 and 10 MHz, a pulser-receiver (see left image) and an oscilloscope, four dense and four porous Titanium cylindrical specimens were characterized by means of the transmission-through technique. The frequency f of the ultrasonic wave determines the wavelength $\lambda = f/v$, being much larger than a representative volume element (RVE), which is, by definition subjected to homogenous stresses (see figure in Micromechanics Box). This material of characteristic length l_{RVE} contains even smaller inhomogeneities of size $d \ll l_{RVE}$, so that $d \ll l_{RVE} \ll \lambda$ (see Table below for measurements).
If the wavelength is much smaller than the diameter of the specimen, longitudinal and transversal ultrasonic bulk waves propagate, with phase velocities v_L and v_T, giving access to isotropic stiffness tensor components as well as to technical constants Young's modulus E and Poisson ratios ν of the material with $l_{RVE} \ll \lambda$ [3],

$$C_{1111} = \rho \cdot v_L^2 \qquad C_{1212} = \rho \cdot v_T^2 \qquad E = \rho \cdot \frac{v_T^2 \cdot (3 \cdot v_L^2 - 4 \cdot v_T^2)}{v_L^2 - v_T^2} \qquad \upsilon = \frac{E}{2 \cdot G} - 1$$

If the wavelength λ is much larger than the specimen diameter the bar velocity v_{bar} is measured, giving direct access to the modulus of elasticity

$$E = \rho \cdot v_{bar}^2$$



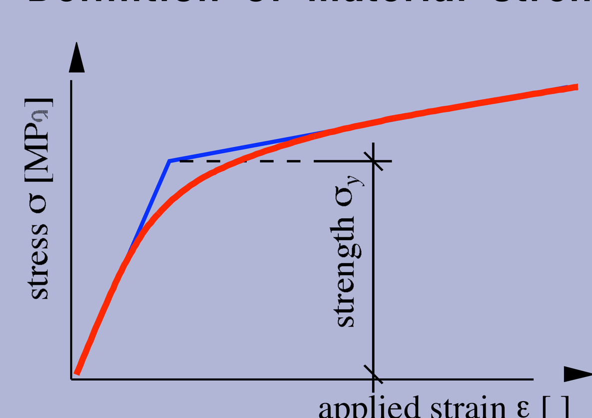
Remarkably, two independent test series at different frequencies, providing Young's modulus directly (f = 0.1 MHz) and via C_{1111} and C_{1212} (f = 5; 10 MHz), respectively, differ by only 3 %.

	porosity	density	f	v_L, v_T, v_{bar}	λ	d	l_{RVE}	C_{1111} , C_{1212}	E , G	ν
	%	g/cm³	MHz	km/s	mm	mm	mm	GPa	GPa	-
Ti dense	**14.9** ± 1.2	**3.83** ± 0.05	L - 10	**5.59** ± 0.02	**0.56** ± 0.00	**0,02**	**≥ 0.10**	**119.7** ± 2.3	**94.3** ± 4.0	**0.28** ± 0.03
			T - 5.0	**3.11** ± 0.12	**0.62** ± 0.02			**37.0** ± 2.3	**37.0** ± 2.3	
			L - 0.1	**5.06** ± 0.09	**50.6** ± 0.9				**98.1** ± 4.4	
Ti porous	**62.4** ± 2.1	**1.69** ± 0.09	L - 0.1	**3.39** ± 0.05	**33.9** ± 0.5	**0,50**	**≥ 2.50**		**19.5** ± 1.7	

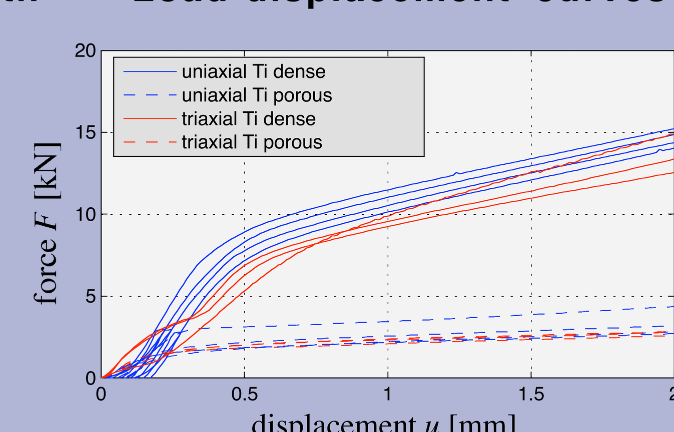
Mechanical testing - strength

Experimental setup for uniaxial and triaxial tests at TU Vienna:
(a) testing machine
(b) pressure control
(c) 150 bar triaxial cell
(d) fixing of specimen
(1) specimen
(2) plasticine
(3) upper die
(4) lower die

Definition of material strength



Load-displacement curves

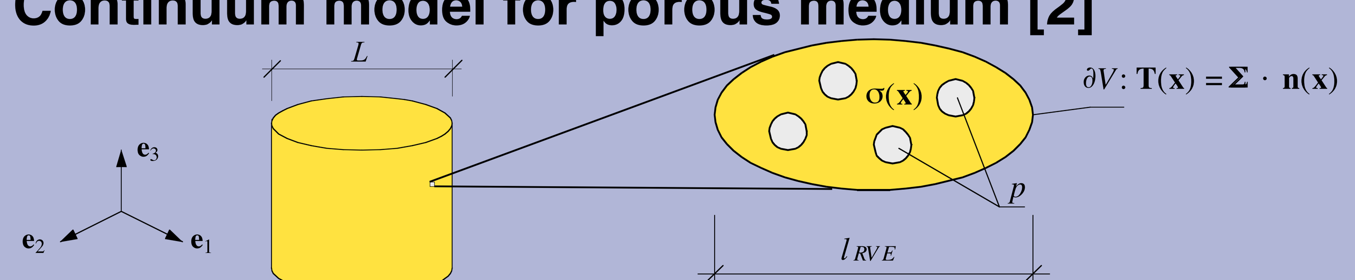


Images of tested material
(a) Titanium dense
(b) Titanium porous

For resulting strength data, see figures in Micromechanics Box.

Poro-micromechanics - prediction of mechanical properties from porosity / microstructure

Continuum model for porous medium [2]



Upscaling stiffness of porous medium

$$\boxed{C_{ijkl}^{hom} = C_{ijkl}^{s} : \left(I_{ijkl} - \varphi \left[I_{ijkl} - (1-\varphi) S_{ijkl} \right]^{-1} \right)}$$

C_{ijkl}^{hom} ... effective stiffness of porous medium
φ ... porosity

$$C_{ijkl}^{s} = 3 J_{ijkl} k^s + 2\mu^s K_{ijkl}$$

$$J_{ijkl} = \frac{1}{3}\delta_{ij}\delta_{kl} \qquad K_{ijkl} = I_{ijkl} - J_{ijkl}$$

$$S_{ijkl} = \frac{3k^s}{3k^s + 4\mu^s} J_{ijkl} + \frac{6(k^s + 2\mu^s)}{5(3k^s + 4\mu^s)} K_{ijkl}$$

k^s ... bulk modulus of solid
μ^s ... shear modulus of solid

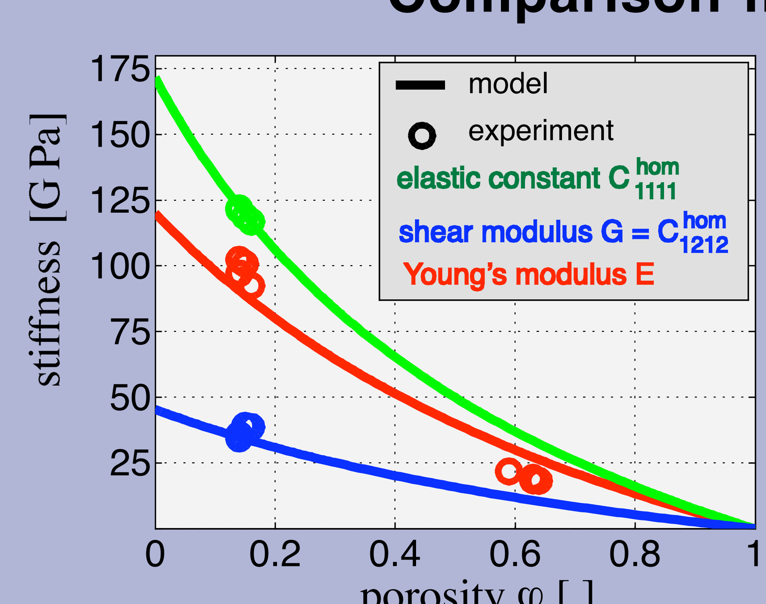
Upscaling strength of porous medium

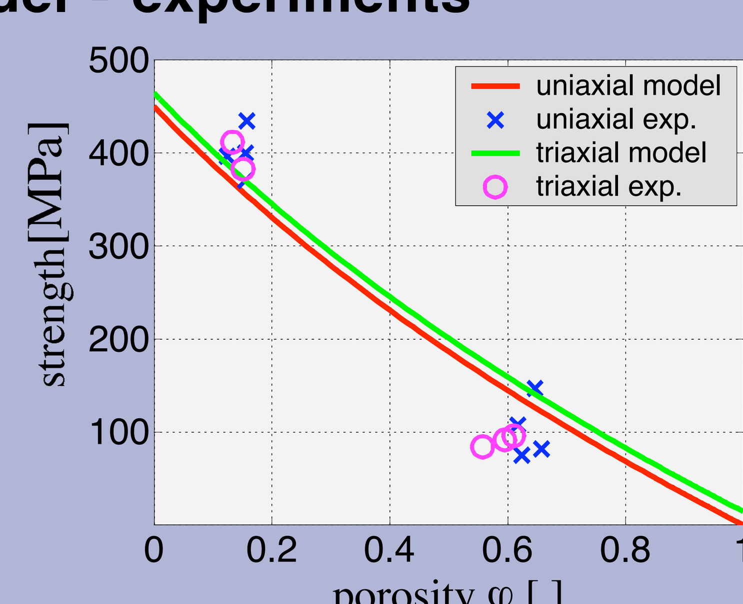
$$\boxed{F(\Sigma_m, \Sigma_d, p) = \frac{3\varphi}{4(1-\varphi)^2}(\Sigma_m + p)^2 + \frac{1 + \frac{2}{3}\varphi}{(1-\varphi)^2}\Sigma_d{}^2 - k^2 = 0}$$

$\mathbf{\Sigma}$ ... stress tensor of porous material
Σ_m ... mean stress
Σ_d ... deviatoric stress
p ... pore pressure
k ... von Mises strength of solid phase

uniaxial$(p = 0)$: $\mathbf{\Sigma} = \Sigma_{11}\, e_1 \otimes e_1$
triaxial$(p = \bar{p})$: $\mathbf{\Sigma} = \Sigma_{11}\, e_1 \otimes e_1 - \bar{p}\, e_2 \otimes e_2 - \bar{p}\, e_3 \otimes e_3$

Comparison model - experiments





On the basis of the mechanical properties of the solid matrix of pure Titanium (E = 120 GPa, ν = 0.32, uniaxial strength 450 MPa), the micromechanical model predicts, with remarkably low error, stiffness and strength of dense and porous samples from their microstructure and porosity.