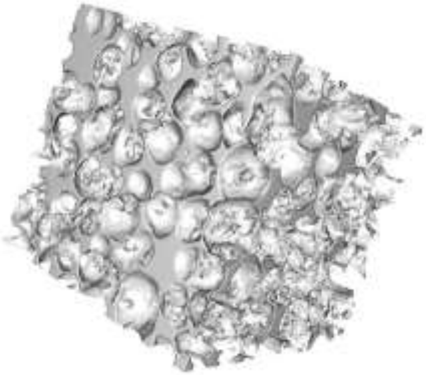

STRUCTURE- PROPERTY RELATIONSHIP IN TITANIUM FOAMS

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FEBRUARY - 2011

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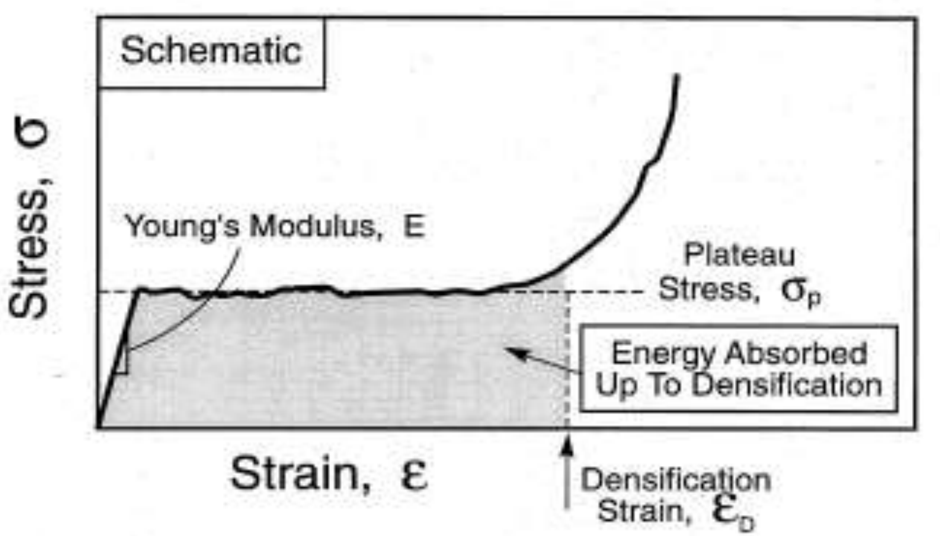
WHY CELLULAR MATERIALS?

"When modern man builds large load-bearing structures, he uses dense solids: steel, concrete, glass.
When Nature does the same, she generally uses cellular materials: wood, bone, coral.
There must be good reasons for it."

M. F. Ashby, University of Cambridge



A.G. Evans, J.W. Hutchinson , M.F. Ashby, *Multifunctionality of cellular metal systems*, Progress in Materials Science, 43, 1999, 171-221.

Source: Evans, A. G., J. W. Hutchinson, et al. *Progress in Materials Science* 43 (1999): 171-221.
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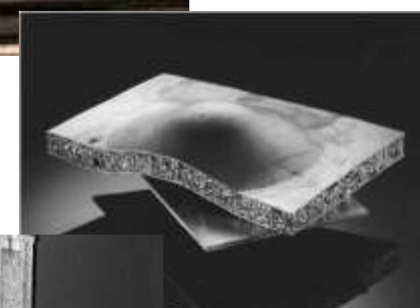
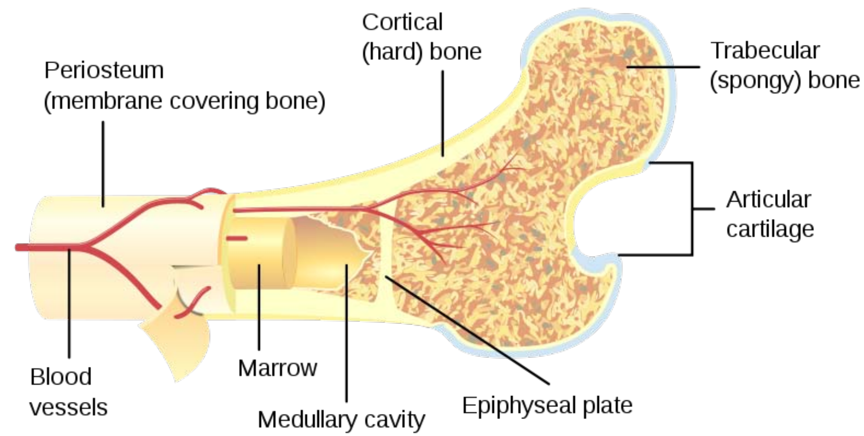
http://www.sciencedirect.com/science/article/pii/S0079642598000048



Source (middle figure): Banhart, J. "Manufacture, Characterisation and Application of Cellular Metals and Metal Foams." *Progress in Materials Science* 46 (2001): 559–632. Courtesy of Elsevier. Used with permission.

WHY TITANIUM?

- ✓ Low density (4.54 g/cm^3)
- ✓ High specific strength
- ✓ Excellent corrosion resistance
- ✓ High fatigue resistance
- ✓ High service temperature
- ✓ Biocompatibility



WHY POROUS TITANIUM?

Bone-like stiffness to avoid stress shielding

Higher surface area, roughness and interconnected pores enhance osteointegration and promote a fast healing.

High service temperature + high energy absorption capacity for space applications.

DESIRED IMPLANT PROPERTIES

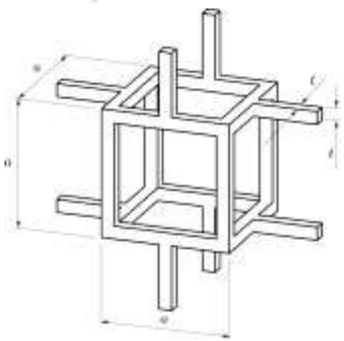
- ✓ Biocompatibility
- ✓ High surface area for cell adhesion
- ✓ Pore interconnectivity for vascularisation
- ✓ Adequate mechanical property to avoid stress shielding
- ✓ High corrosion, fatigue and wear resistance
- ✓ Surface roughness
- ✓ Pores greater than 100-150 μm

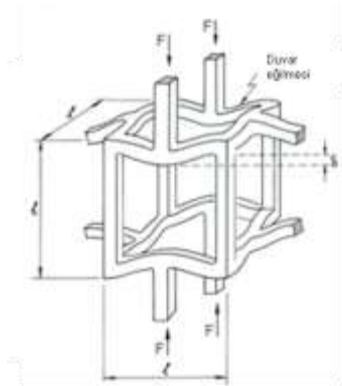
The desired structural and mechanical properties of the implant strongly depend on **substituted bone**, the **age** and **daily activity** of the patient.

	Age (years)						
Property	10 - 20	20 - 30	30 - 40	40 - 50	50 - 60	60 - 70	70 - 80
Ultimate strength (MPa)							
Tension	114	123	120	112	93	86	86
Compression	-	167	167	161	155	145	-
Bending	151	173	173	162	154	139	139
Torsion	-	57	57	52	52	49	49
Ultimate strain (%)							
Tension	1.5	1.4	1.4	1.3	1.3	1.3	1.3
Compression	-	1.9	1.8	1.8	1.8	1.8	-
Torsion	-	2.8	2.8	2.5	2.5	2.7	2.7

MECHANICAL PROPERTY PREDICTION

- ✓ Dimensional arguments based on a single unit cell – ***Gibson & Ashby (1997)***





$$\frac{\sigma^*}{\sigma_s} = C_1\left(\frac{\rho^*}{\rho_s}\right)^{\frac{3}{2}} \qquad \frac{E^*}{E_s} = C_2\left(\frac{\rho^*}{\rho_s}\right)^2$$

Gibson, L. J., and M. F. Ashby. *Cellular Solids: Structure and Properties*. 2nd ed. Cambridge University Press. © 1997. Figures courtesy of Lorna Gibson and Cambridge University Press.

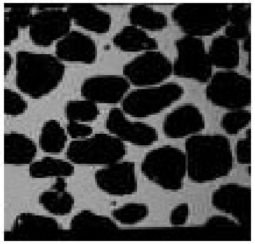
- ✓ Models on periodic cellular geometries- ***Christensen (1986), Grenestedt (1998), Zhu (1997)***

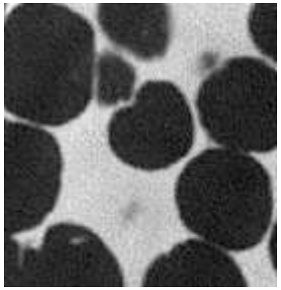
- ✓ Spatially periodic arrangement of random Voronoi cells using FEM – ***Kraynik (1988), Roberts, Garboczi (2001)***

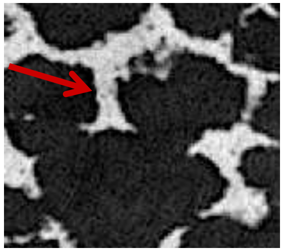
Well defined structures → Expensive

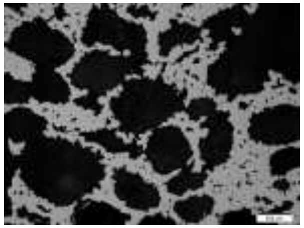
RANDOM FOAMS : IMPERFECTIONS DUE TO PROCESSING

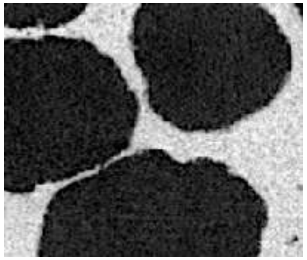
- ❑ Random cell geometry
- ❑ Non-uniform cell wall thickness
- ❑ Non load bearing struts
- ❑ Porous cell walls
- ❑ Cell wall corrugation
- ❑ Cell wall curvature











Source: Tuncer, Nihan. "Structure-property Relationship in Titanium Foams", PhD dissertation, Anadolu University, Turkey, 2011.

APPROACH

Statistical approach
(based on experiment)

Define the effective structural parameters

↓

Produce tailored architectured foams

↓

Measure structural and mechanical props

↓

Relate them to determine the dominant structural features

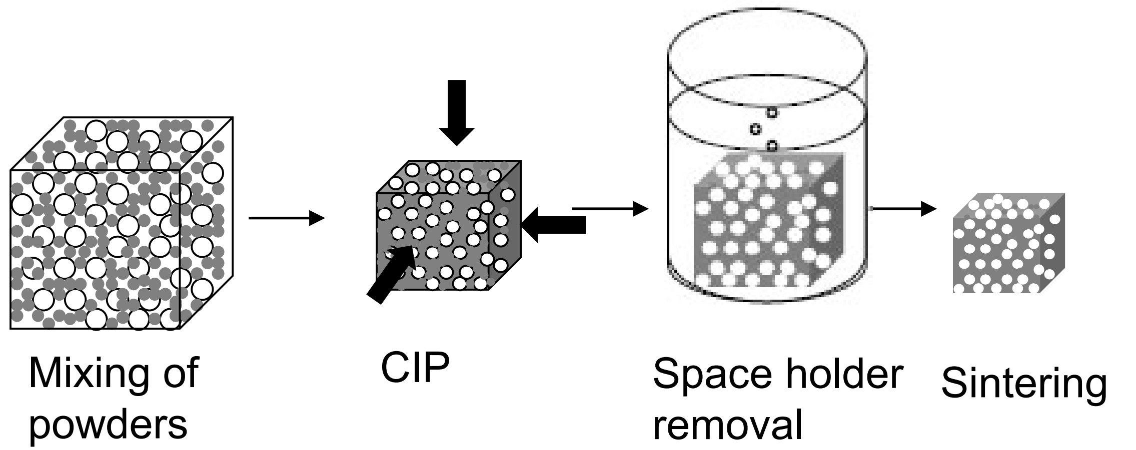
Structural / Architectural properties

- ✓ Pore size
- ✓ Pore wall thickness
- ✓ Pore wall density
- ✓ Pore sphericity
- ✓ Pore aspect ratio
- ✓ Closed pore fraction
- ✓ Interconnect size
- ✓ Specific surface area

PRODUCTION: POWDER METALLURGY WITH SPACE HOLDERS

- Space holder powders
  - Titanium powders (d_{50}=22 μm)

Spacer types
AHC
Carbamide (urea)
NaCl
KCl
KNO_3
$NaNO_3$
Mg



Images removed due to copyright restrictions. See Figures 3a and 3: Tuncer, N., and G. Arslan. Designing Compressive Properties of Titanium Foams. *Journal of Materials Science* 44 (2009): 1477–84.

STRUCTURE-PROPERTY RELATIONSHIP

Powder & process variables → **Foam architecture** → **Mechanical properties**

	Variables	Effect on sintering	Effect on foam architecture
Process	Temperature Atmosphere	➢ Wall densification ➢ O_2 diffusion through titanium ➢ Cell shrinkage	➢ Cell wall porosity ➢ Cell size ➢ Cell wall thickness
Titanium	Size distribution	➢ Compaction efficiency ➢ Wall densification ➢ Cell and wall size distribution	➢ Cell wall porosity ➢ Liquid and gas permeability
Spacer	Amount Size Shape	➢ Compaction efficiency ➢ Sintering shrinkage ➢ Cell wall densification	➢ Relative density (%) ➢ Cell size ➢ Cell shape ➢ Specific surface area ➢ Connectivity ➢ Cell wall porosity

POROSITY IS THE MOST EFFECTIVE PROPERTY

Porosity : 29 – 80 %

Compressive Strength : 25 - 270 MPa

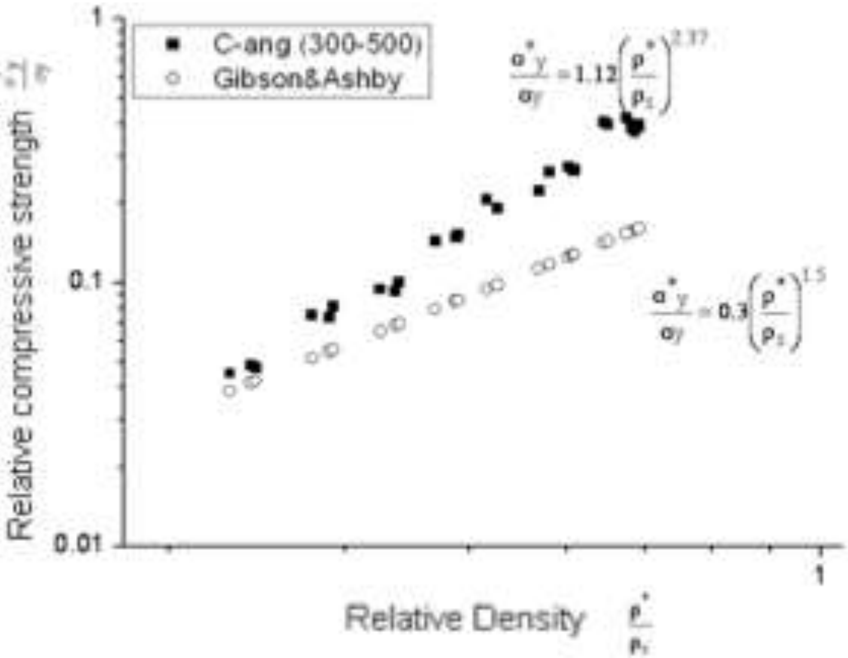
Elastic Modulus : 2.5 – 15 GPa

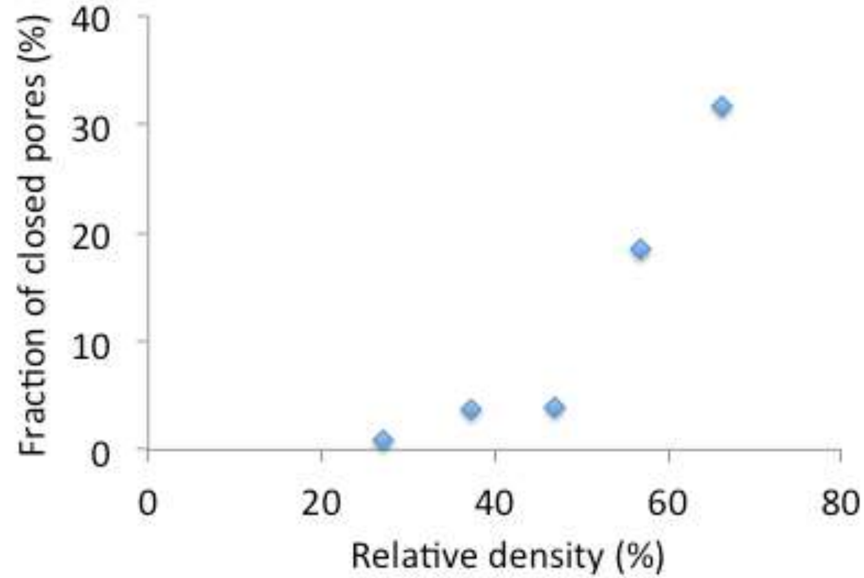
Pore size : 100 – 1750 μm

Images removed due to copyright restrictions. See Figure 5: N. Tuncer, G. Arslan. Designing Compressive Properties of Titanium Foams. *Journals of Materials Science* 44 (2009), pp. 1477–84.

	σ_y (MPa)	E (GPa)
Cortical bone	80-120	3-30
Trabecular bone	2-12	0.05-0.5

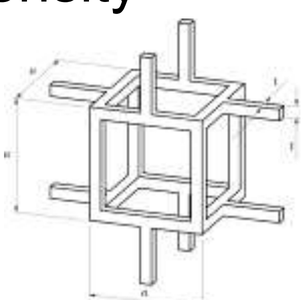
POROSITY – MECHANICAL PROPERTY





Source: Tuncer, Nihan. "Structure-property Relationship in Titanium Foams", PhD dissertation, Anadolu University, Turkey, 2011.

Higher dependency on relative density



$$\Rightarrow \frac{\rho}{\rho_s} \approx \left(\frac{t}{a}\right)^2$$

Gibson, L. J., and M. F. Ashby. *Cellular Solids: Structure and Properties*. 2nd ed. Cambridge University Press, © 1997. Figures courtesy of Lorna Gibson and Cambridge University Press.

Fraction of closed pores increase with relative density

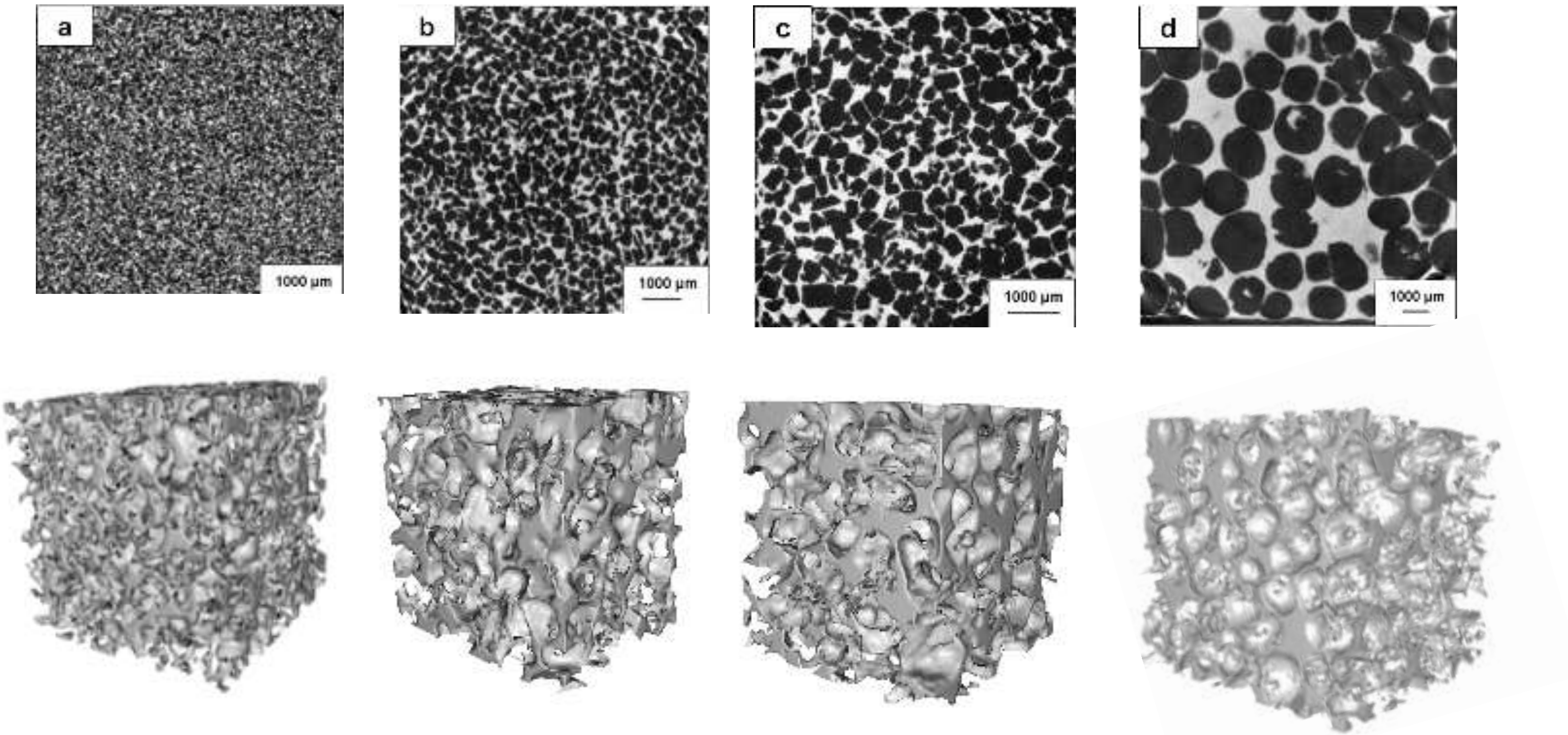
Transition from open cell to partially closed cell with increasing density.

PORE SIZE

ON

ARCHITECTURAL & MECHANICAL PROPERTIES

SPACER SIZE ⟷ PORE SIZE

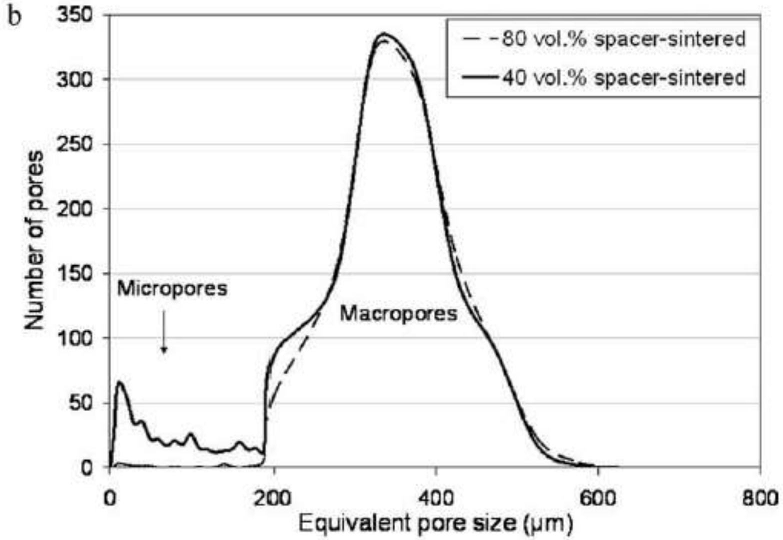


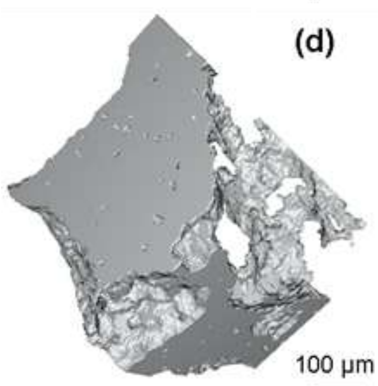
140 µm **375 µm** **575 µm** **1750 µm**

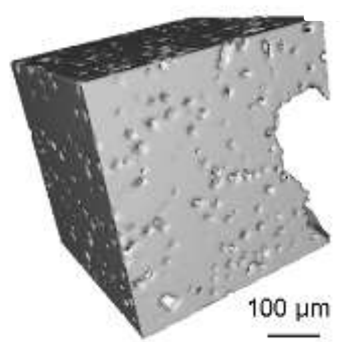
Figures courtesy of Elsevier. Used with permission. Source: Tuncer, N., G. Arslan, et al. "Investigation of Spacer Size Effect on Architecture and Mechanical Properties of Porous Titanium". *Materials Science and Engineering* A 530 (2011): 633–42.

SPACER SIZE ⟷ PORE SIZE

Spacer amount



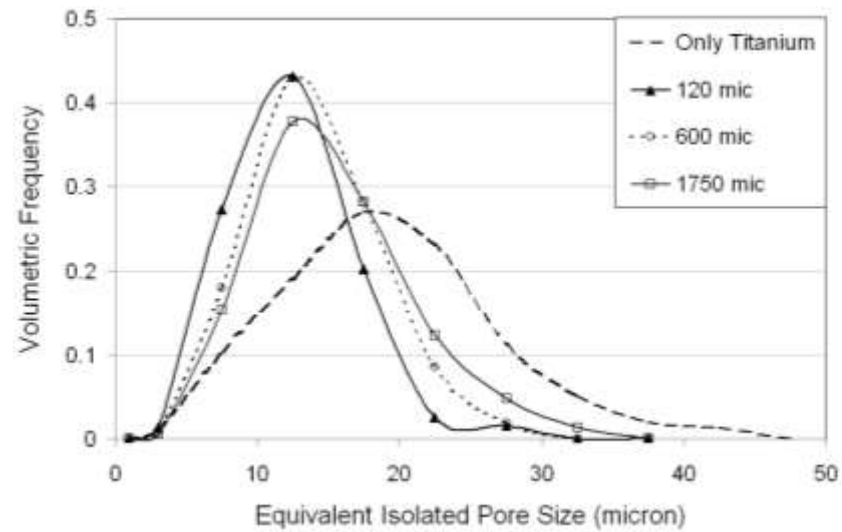


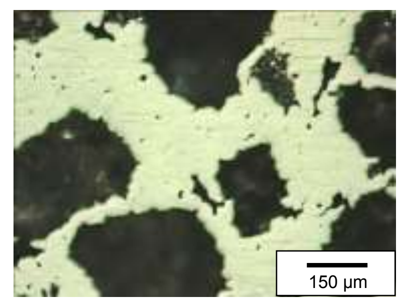


3D rendering of the pore wall parts of the foams produced with **80 vol. %** spacer.

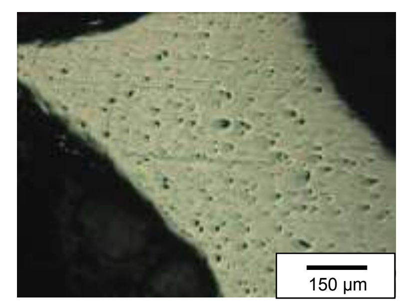
3D rendering of the pore wall parts of the foams produced with **40 vol. %** spacer.

Spacer size





375 µm



1750 µm

Use of coarser spacers results in less dense cell walls.

PORE SIZE - MECHANICAL PROPERTIES

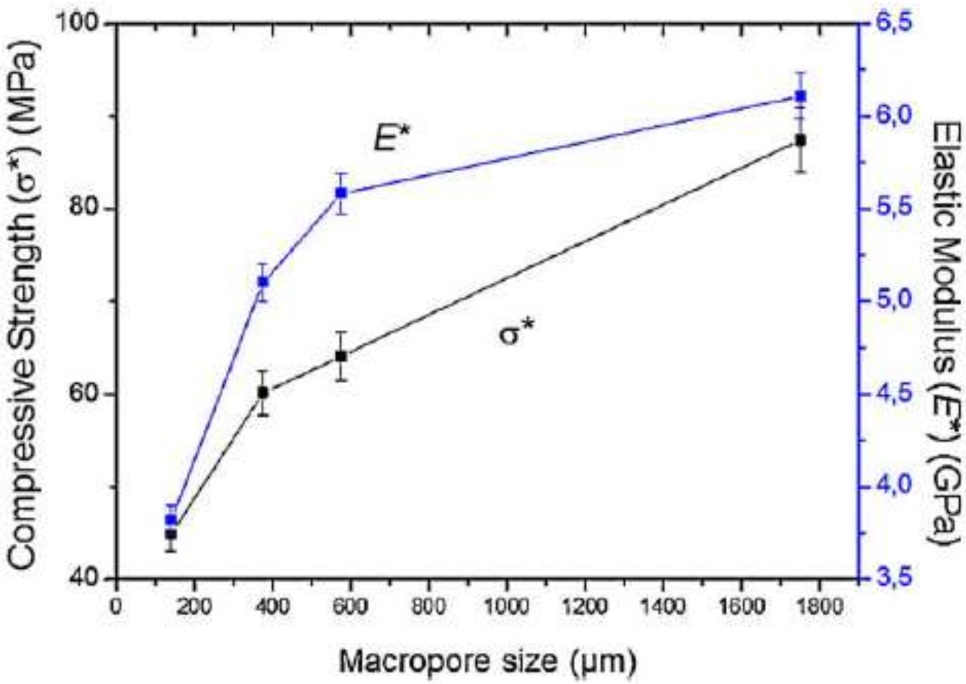


Figure courtesy of Elsevier. Used with permission. Source: Tuncer, N., G. Arslan, et al. "Investigation of Spacer Size Effect on Architecture and Mechanical Properties of Porous Titanium". *Materials Science and Engineering* A 530 (2011): 633–42.

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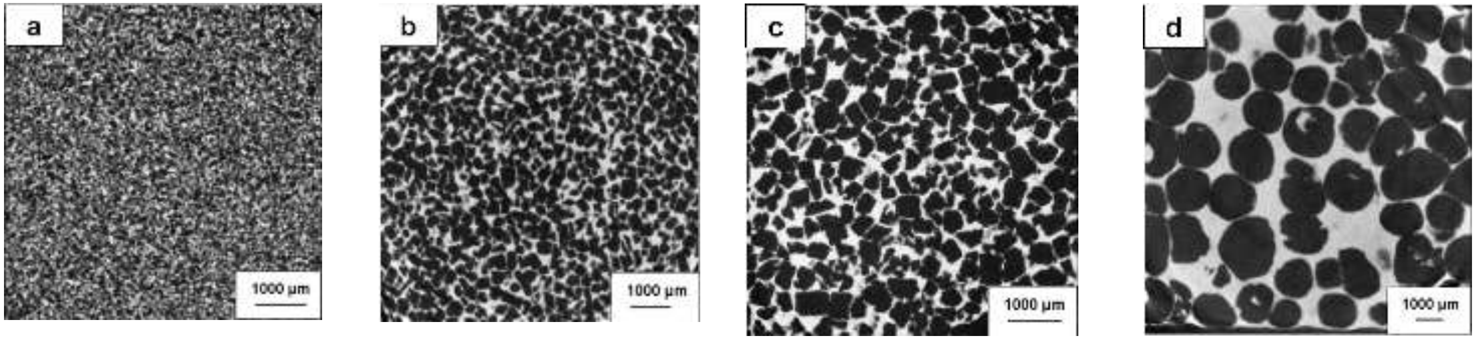
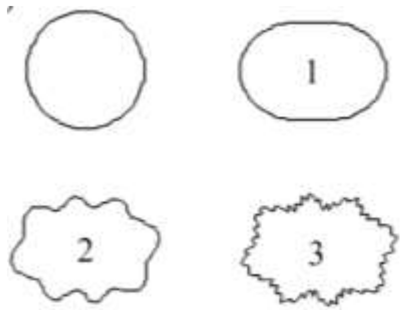


Figures courtesy of Elsevier. Used with permission. Source: Tuncer, N., G. Arslan, et al. "Investigation of Spacer Size Effect on Architecture and Mechanical Properties of Porous Titanium". *Materials Science and Engineering* A 530 (2011): 633–42.

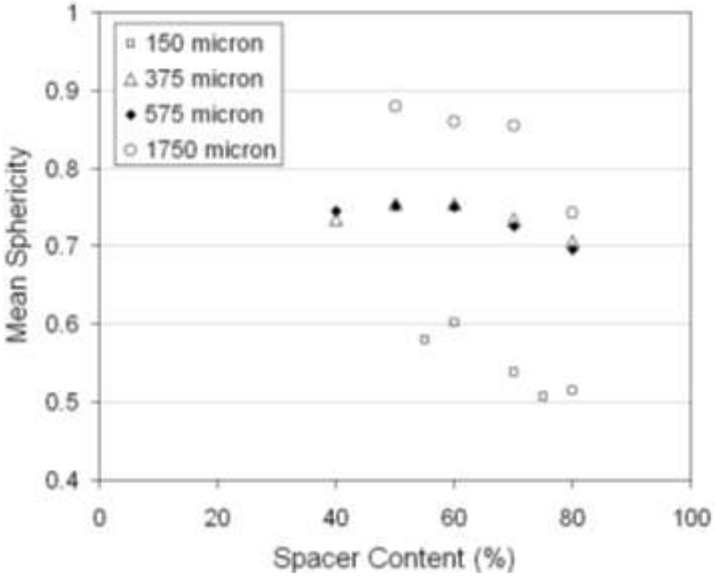
PORE SIZE - MECHANICAL PROPERTIES

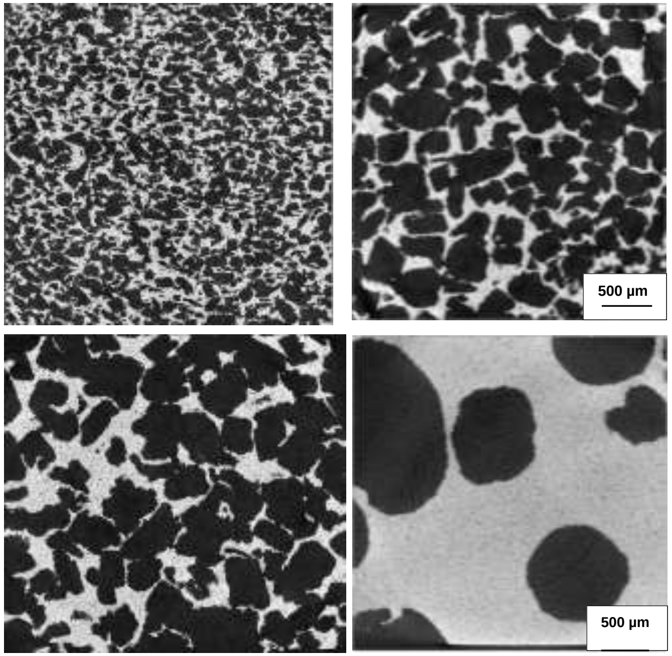
Pore sphericity / pore face roughness



$$S = 6V\sqrt{\frac{\pi}{A^3}}$$

$S_o > S_1 > S_2 > S_3$





When the spacers used in this study considered, sphericity, consequently cell face roughness decreases with decreasing spacer size.

σ (140 μm) < σ (375 μm) < σ (575 μm) < σ (1750 μm)

Figures courtesy of Elsevier. Used with permission. Source: Tuncer, N., G. Arslan, et al. "Investigation of Spacer Size Effect on Architecture and Mechanical Properties of Porous Titanium". *Materials Science and Engineering* A 530 (2011): 633–42.

PORE SIZE - MECHANICAL PROPERTIES

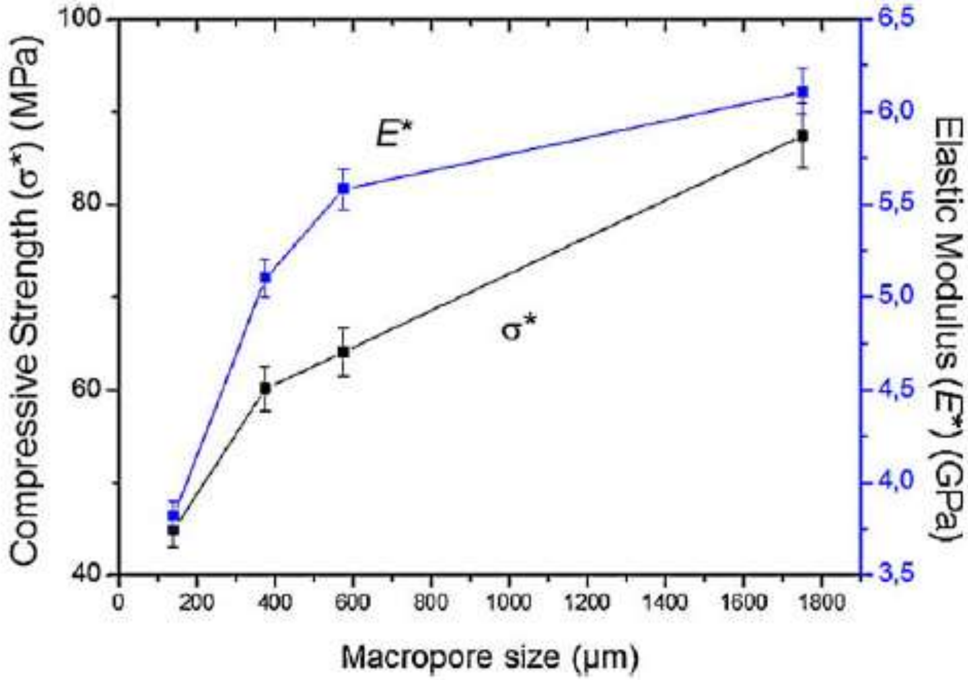


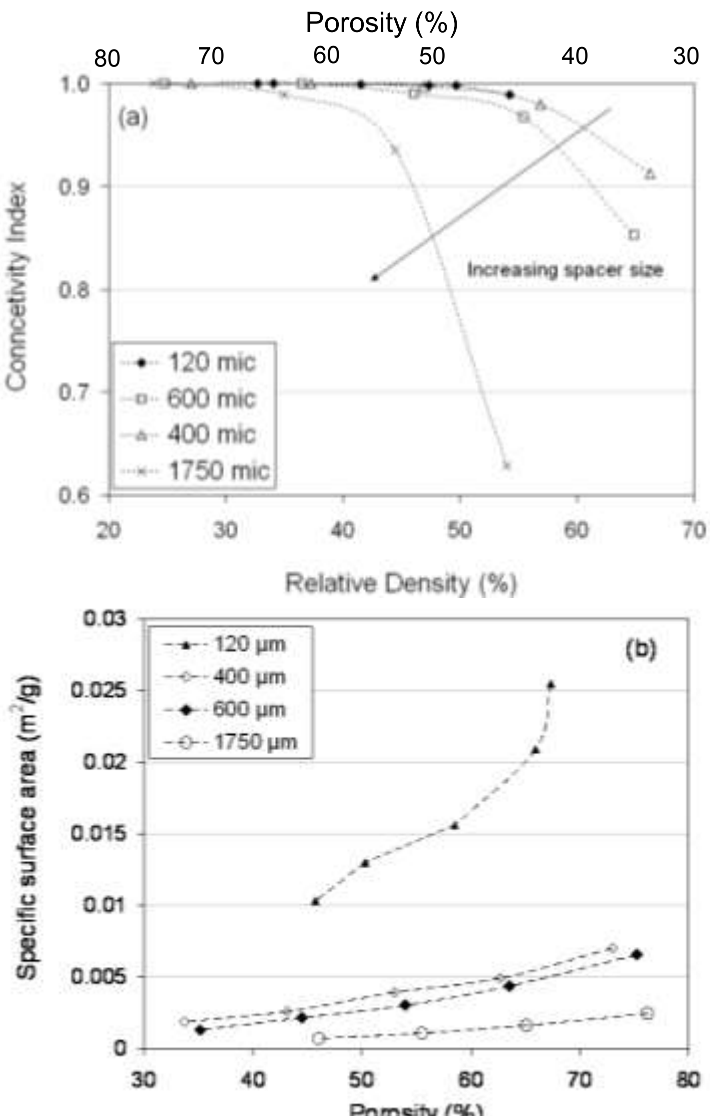
Figure courtesy of Elsevier. Used with permission. Source: Tuncer, N., G. Arslan, et al. "Investigation of Spacer Size Effect on Architecture and Mechanical Properties of Porous Titanium". *Materials Science and Engineering* A 530 (2011): 633–42.

$$\frac{\sigma^*}{\sigma_s} = 0.99\left(\frac{\rho^*}{\rho_s}\right)^{1.5} + 0.1D - 0.159$$

$R^2 = 0.949$

ARCHITECTURAL PROPERTIES

Important properties in terms of permeability and vascularization.



Pore connectivity drops along with porosity

Drop rate is faster in large-pored foams

Foams having average pore sizes below 400 µm are 90 % interconnected down to 30 % porosity.

Specific surface area increases with porosity – decreases with increasing pore size

Increase rate is faster in small-pored foams

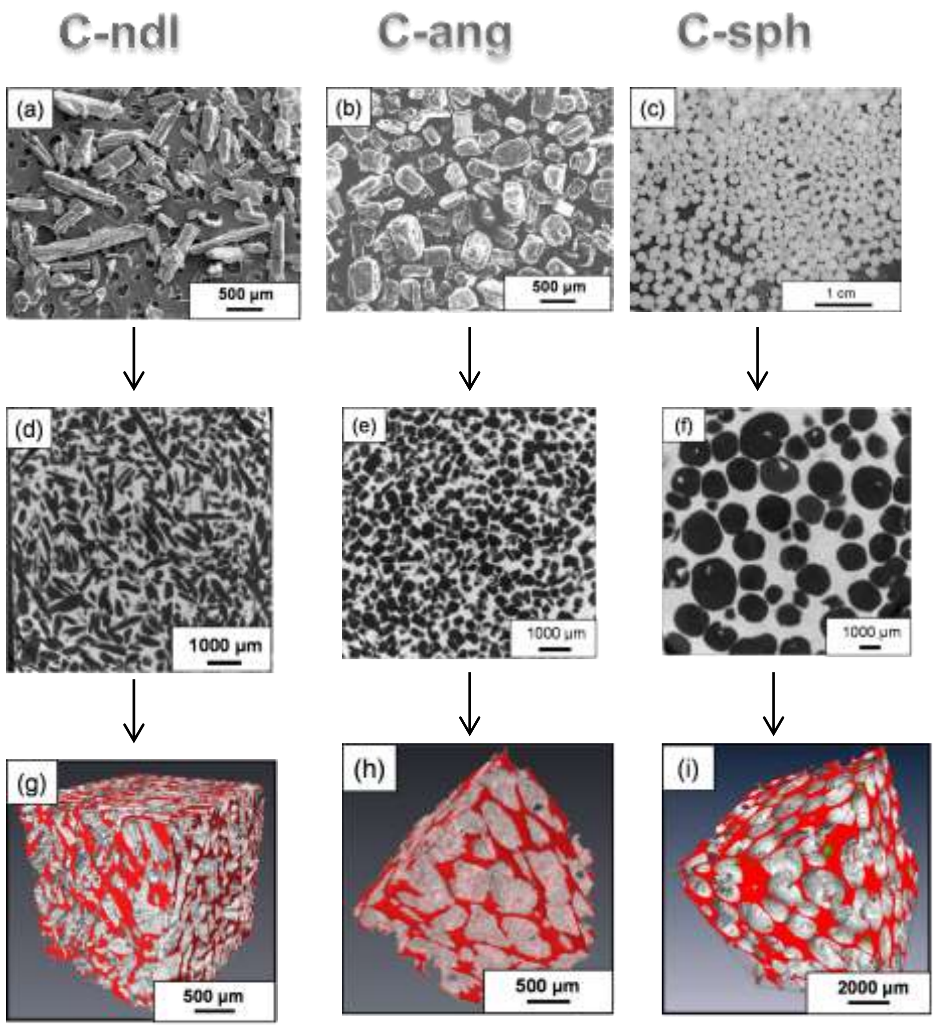
 Source: Tuncer, N., G. Arslan, et al. "Investigation of Spacer Size Effect on Architecture and Mechanical Properties of Porous Titanium". *Materials Science and Engineering* A 530 (2011): 633–42.

PORE MORPHOLOGY

ON

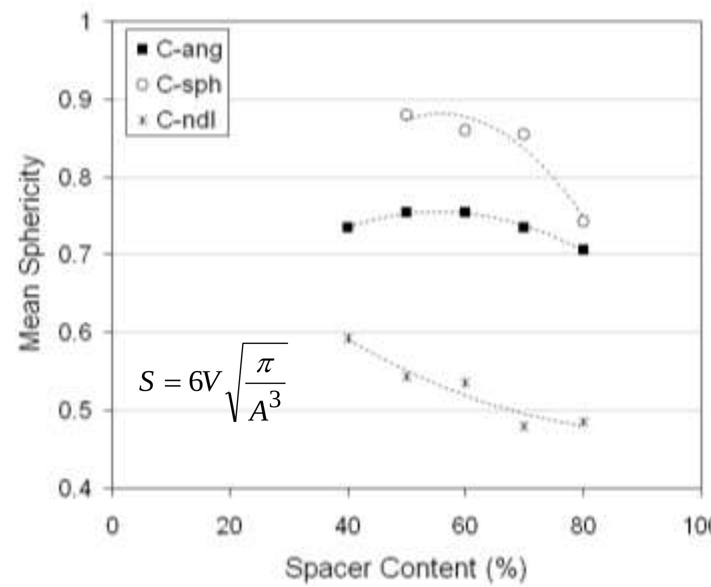
ARCHITECTURAL & MECHANICAL PROPERTIES

PORE MORPHOLOGY



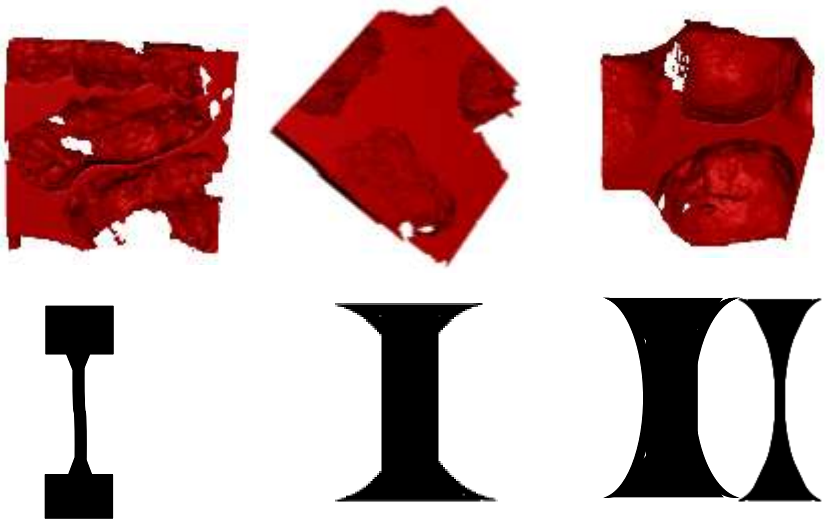
Source: Tuncer, N., G. Arslan, et al. "Influence of Cell Aspect Ratio on Architecture and Compressive Strength of Titanium Foams." *Materials Science and Engineering A* 528 (2011): 7368–74. Courtesy of Elsevier. Used with permission.

Plot removed due to copyright restrictions. See Figure 3: Tuncer, N., et al. "Influence of Cell Aspect Ratio on Architecture and Compressive Strength of Titanium Foams". *Materials Science and Engineering* A 528 (2011): 7368-74.



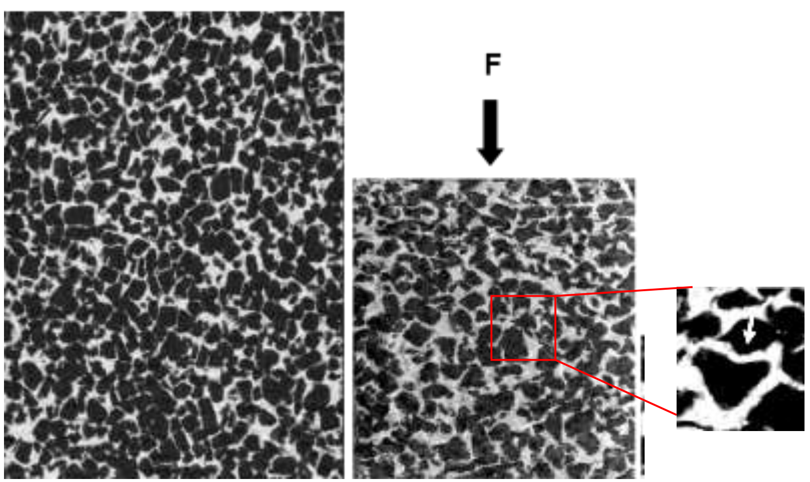
PORE MORPHOLOGY – DEFORMATION MECHANISM

C-ndl C-ang C-sph



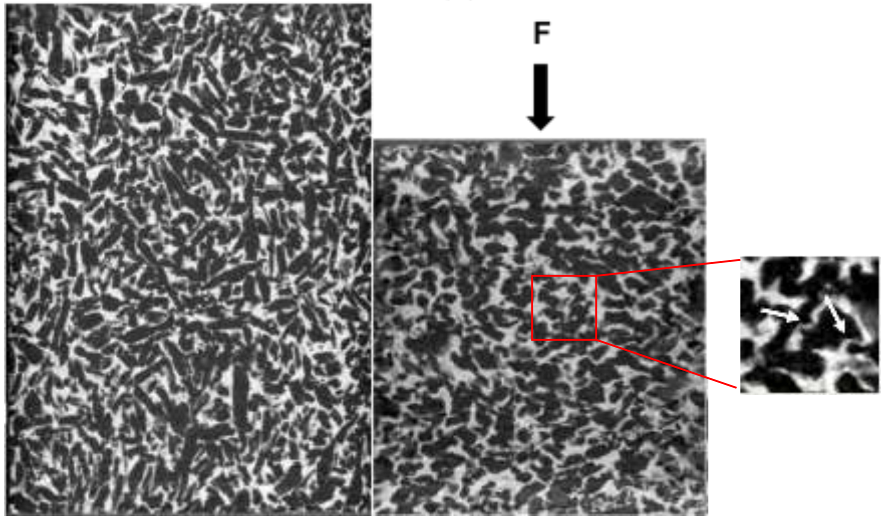
C-ang

(b)



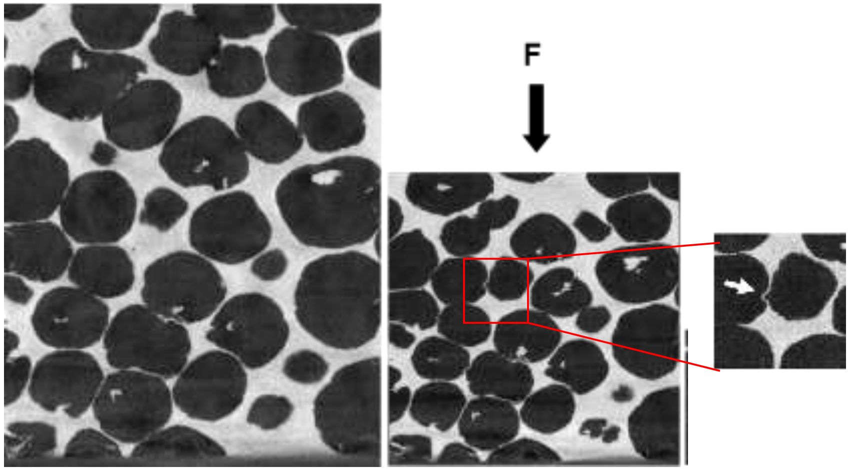
C-ndl

(a)



C-sph

(c)



Source: Tuncer, N., G. Arslan, et al. "Influence of Cell Aspect Ratio on Architecture and Compressive Strength of Titanium Foams." *Materials Science and Engineering A* 528 (2011): 7368– 74. Courtesy of Elsevier. Used with permission.

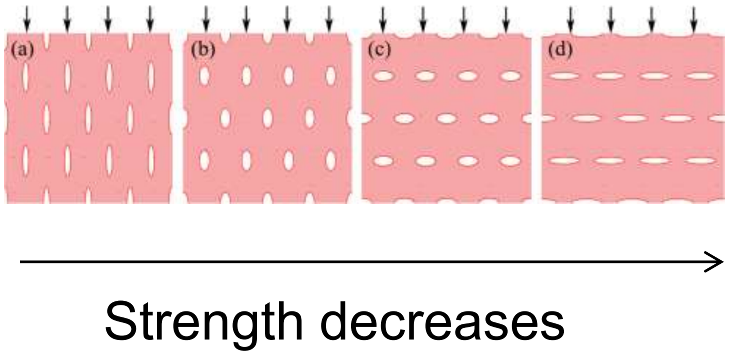
PORE MORPHOLOGY – MECHANICAL PROPERIES

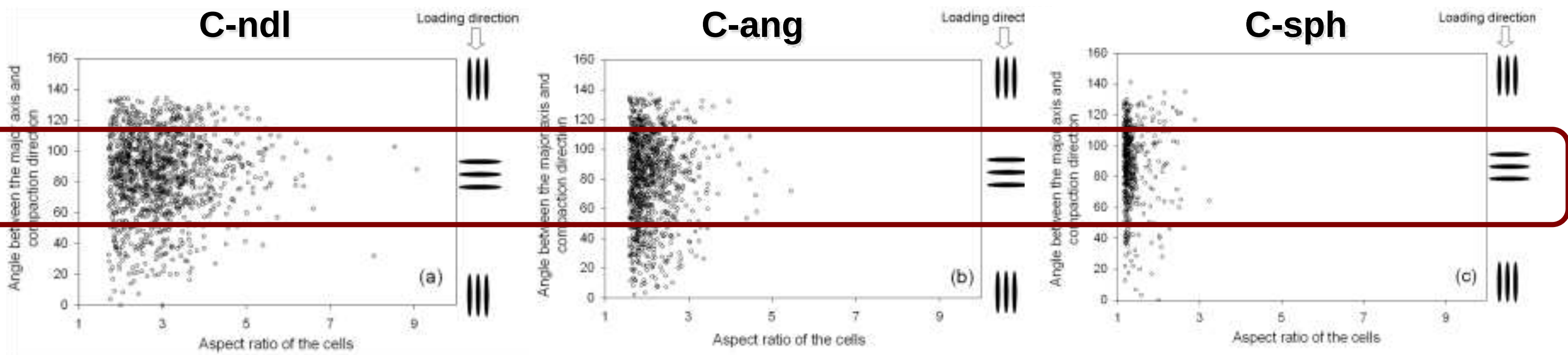
High aspect ratio pores result in lower strength at the same porosity

$$\frac{\sigma^*}{\sigma_S} = 1.017\left(\frac{\rho^*}{\rho_S}\right)^{1.5} - 0.018A - 0.091$$

$R^2 = 0.977$

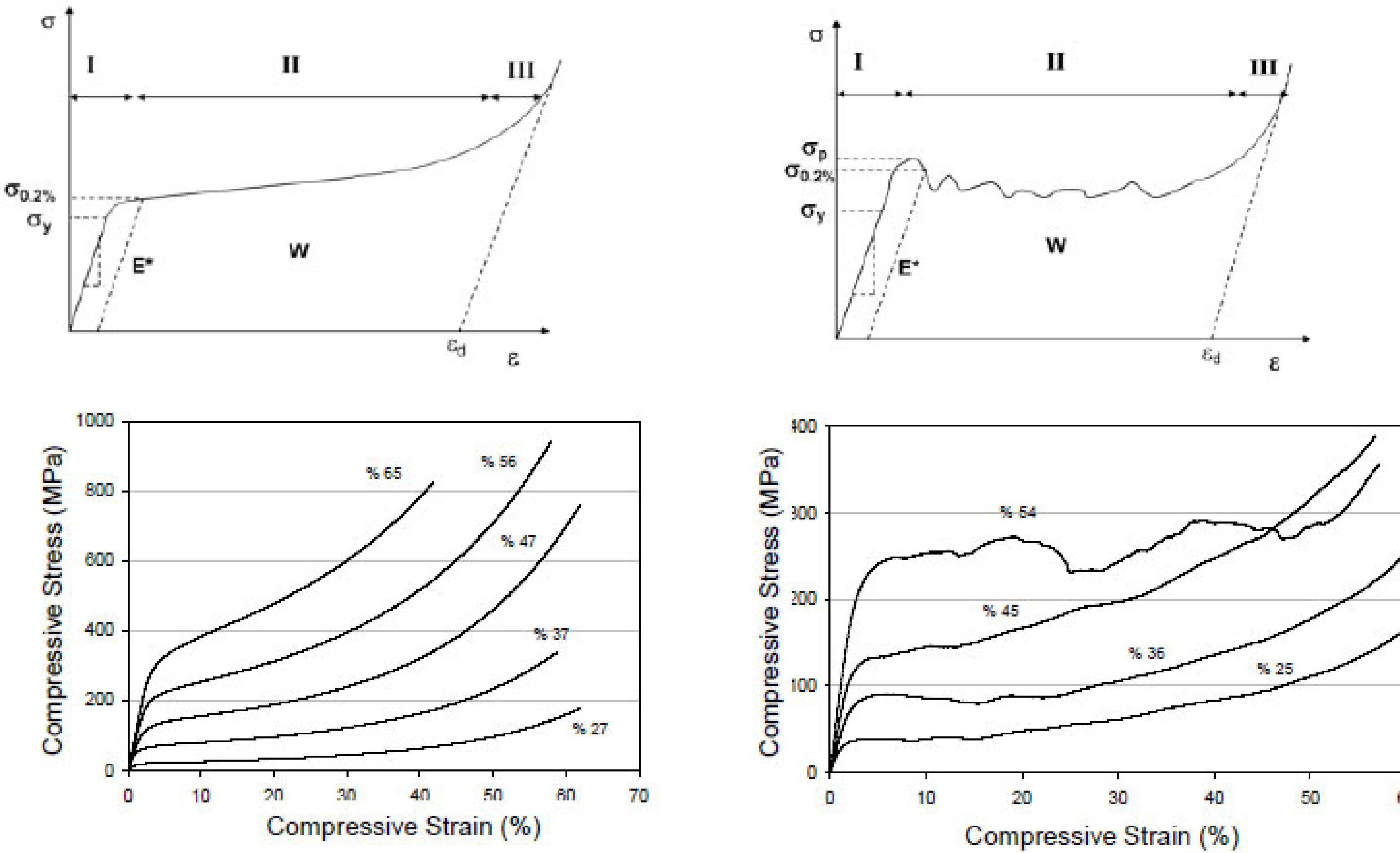
PORE MORPHOLOGY





PORE MORPHOLOGY

Plateau behavior



Small angular pored foams

Large spherical pored foams

Source: Tuncer, Nihan. "Structure-property Relationship in Titanium Foams", PhD dissertation, Anadolu University, Turkey, 2011.

COLLAPSE MODES IN FOAMS

Cell-wall buckling

Layer-wise collapse perpendicular to the loading direction

⇓

Oscillations in stress-strain diagram

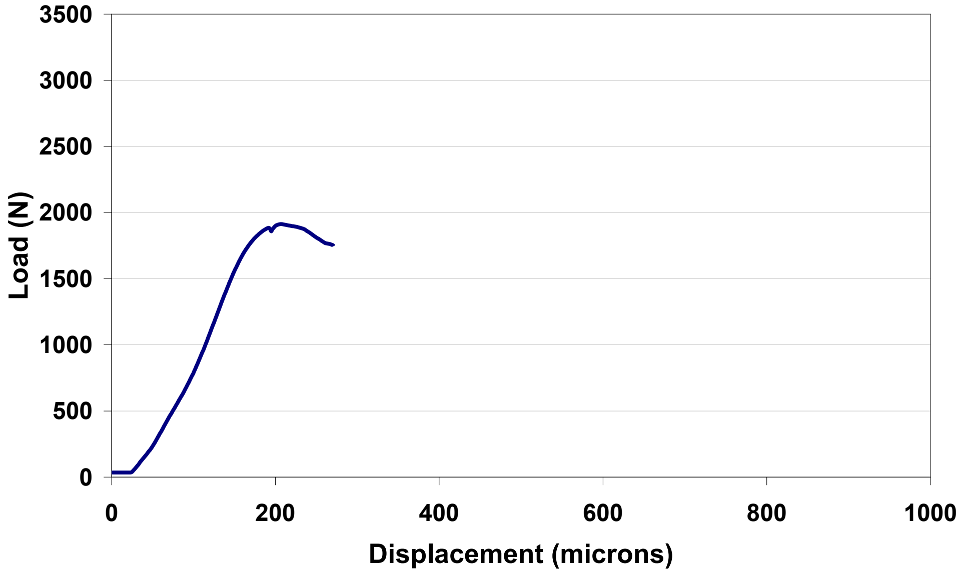
Cell-wall bending

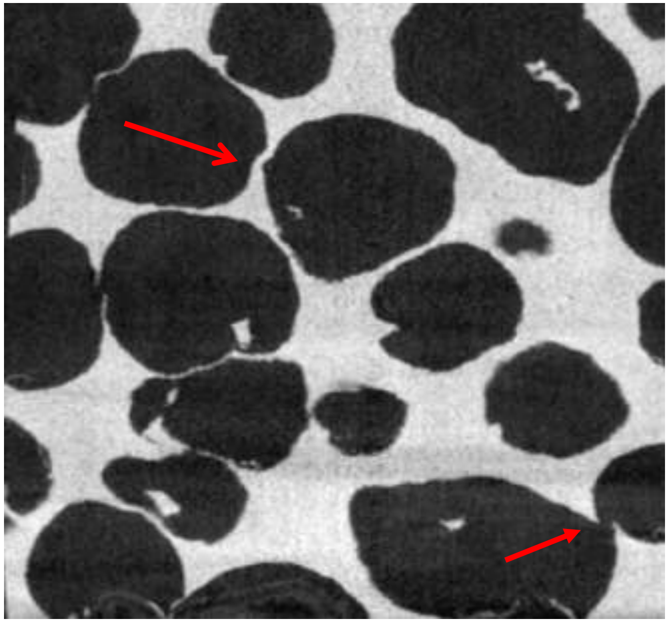
Shear localisation occurs. Deformation at nearly constant applied stress by shear bands

⇓

Smooth stress-strain diagram

PORE MORPHOLOGY





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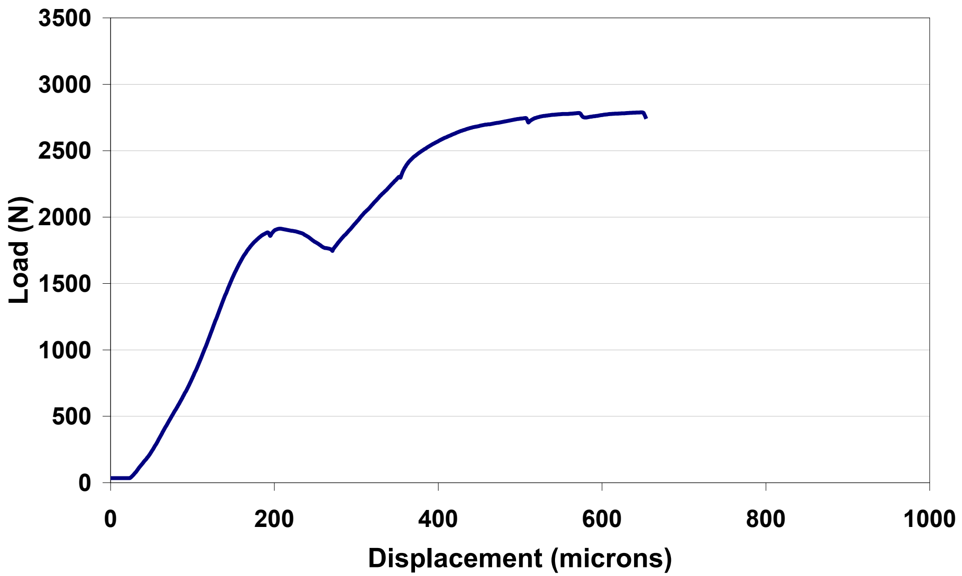
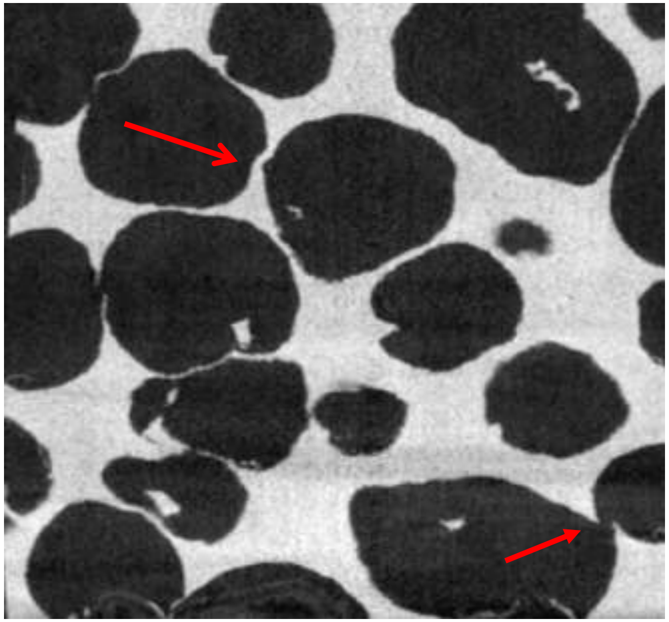
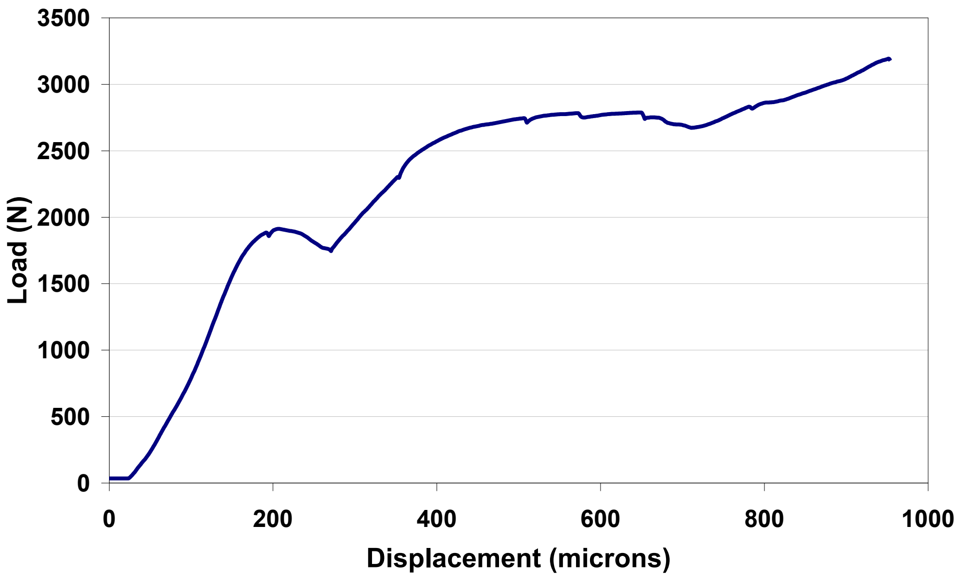
PORE MORPHOLOGY

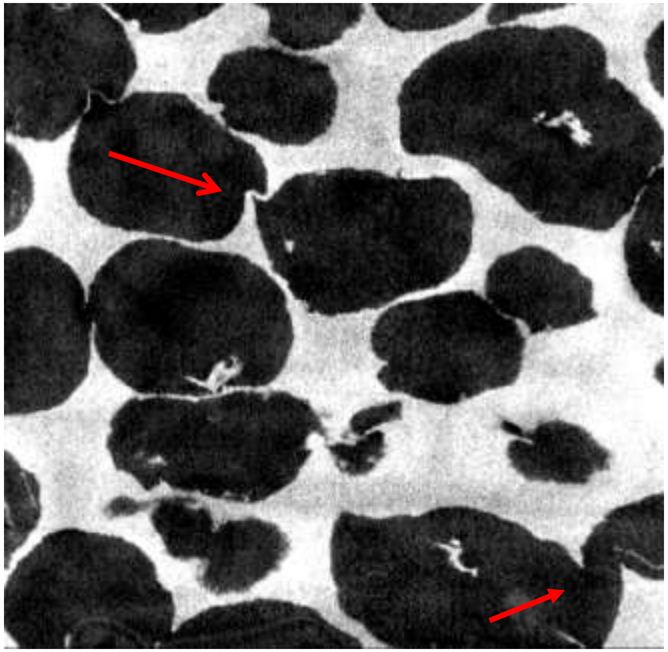




Source: Tuncer, Nihan. “Structure-property Relationship in Titanium Foams”, PhD dissertation, Anadolu University, Turkey, 2011.

PORE MORPHOLOGY





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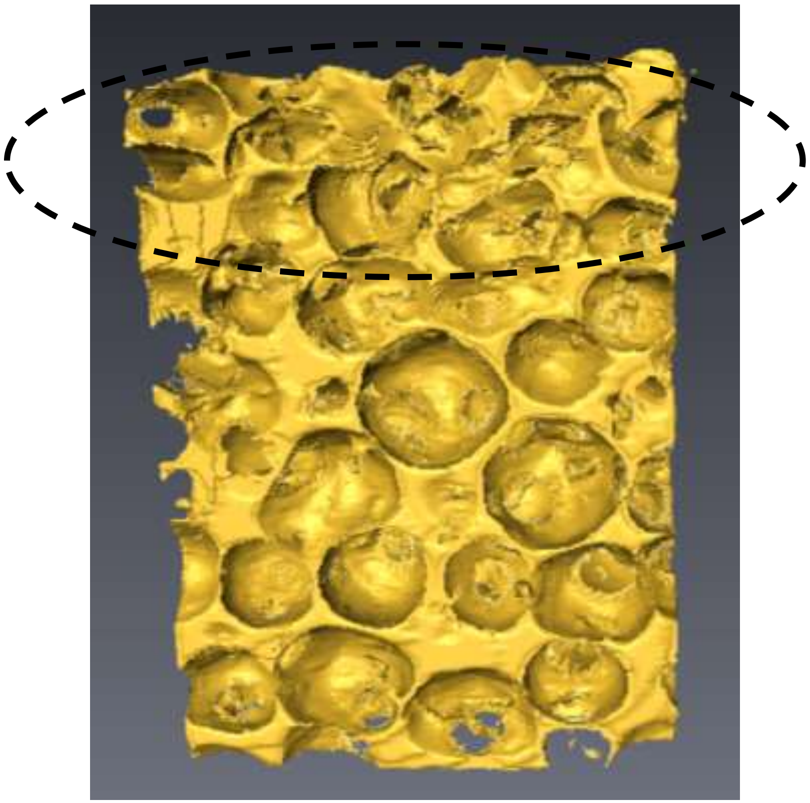
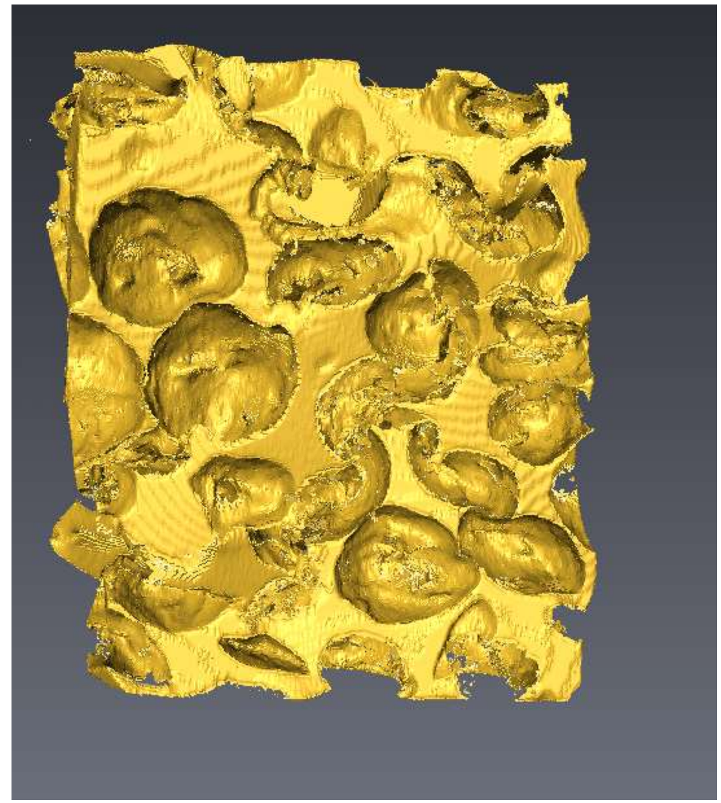
PORE MORPHOLOGY



After the yield point

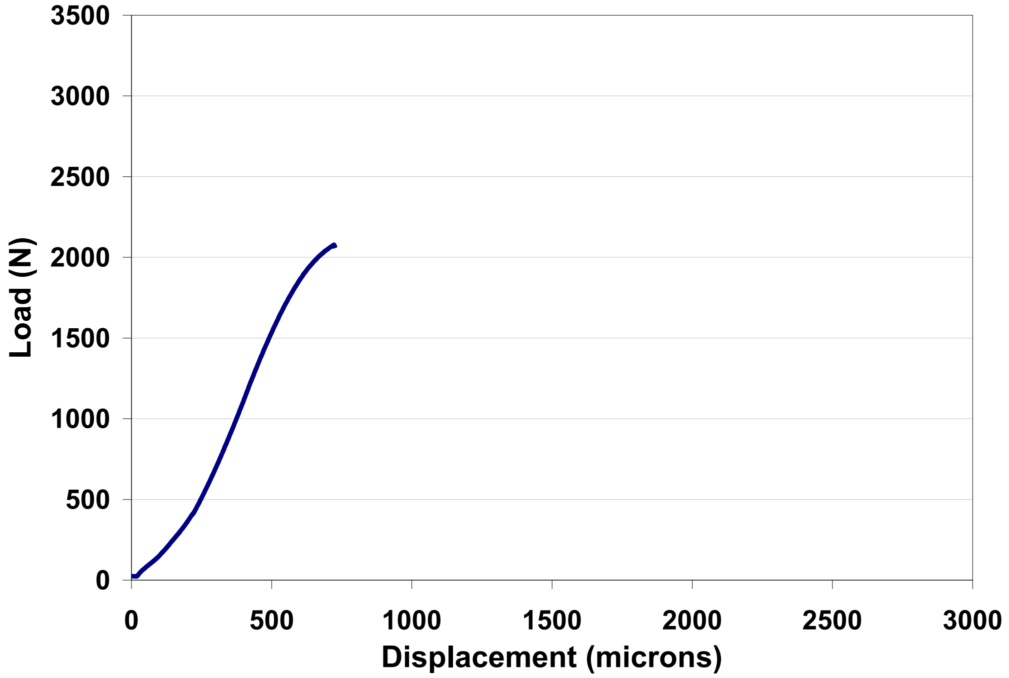


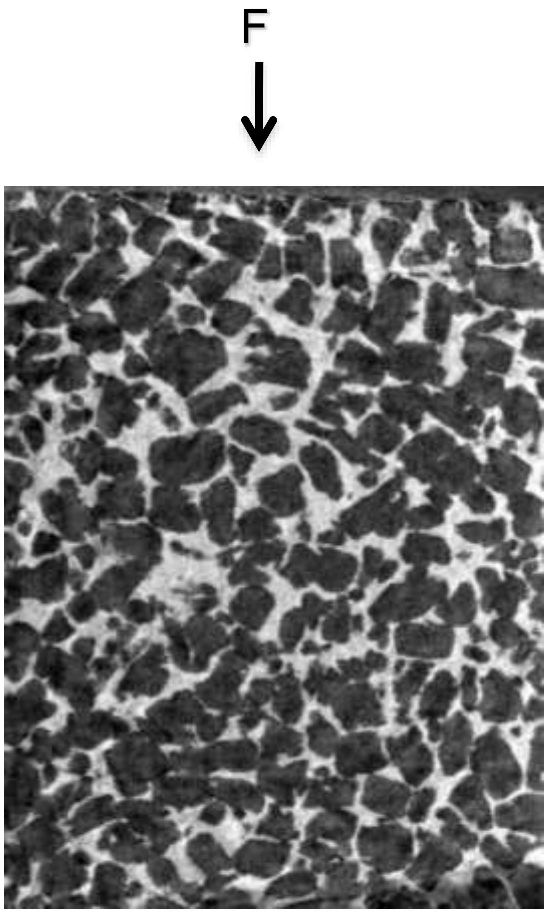
Final state (severe deformation)

Layer-wise collapse in the early stages of deformation

Source: Tuncer, Nihan. “Structure-property Relationship in Titanium Foams”, PhD dissertation, Anadolu University, Turkey, 2011.

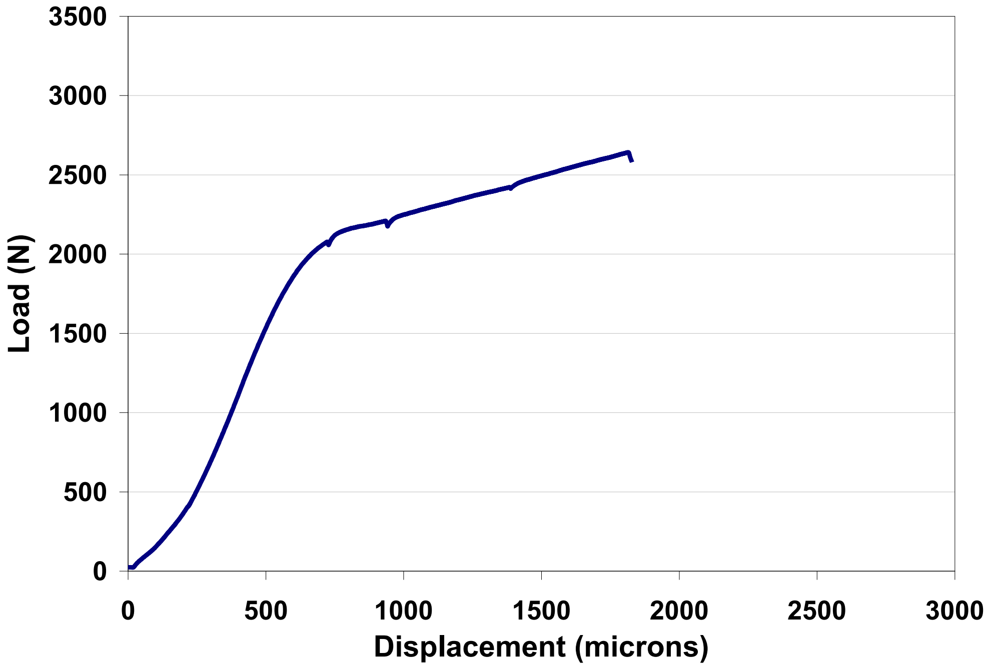
PORE MORPHOLOGY

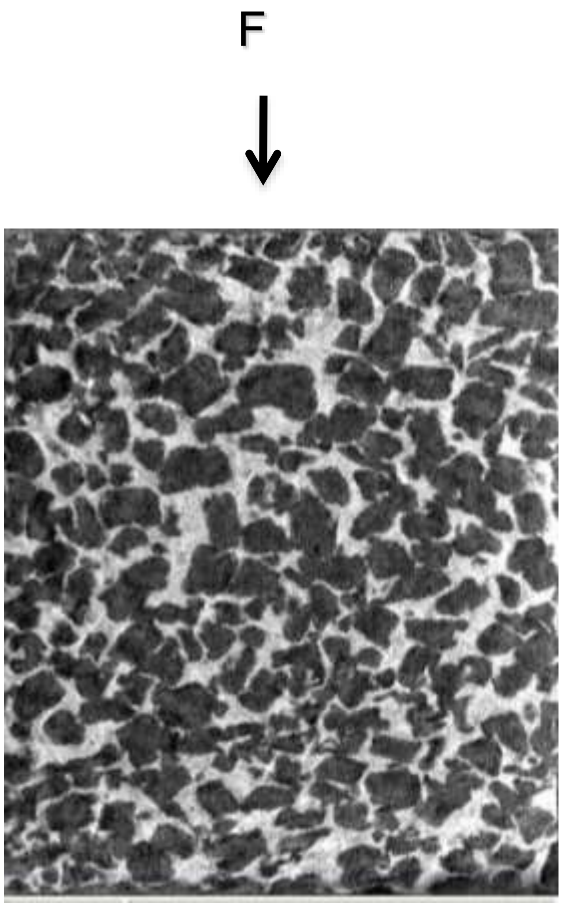




Source: Tuncer, Nihan. “Structure-property Relationship in Titanium Foams”, PhD dissertation, Anadolu University, Turkey, 2011.

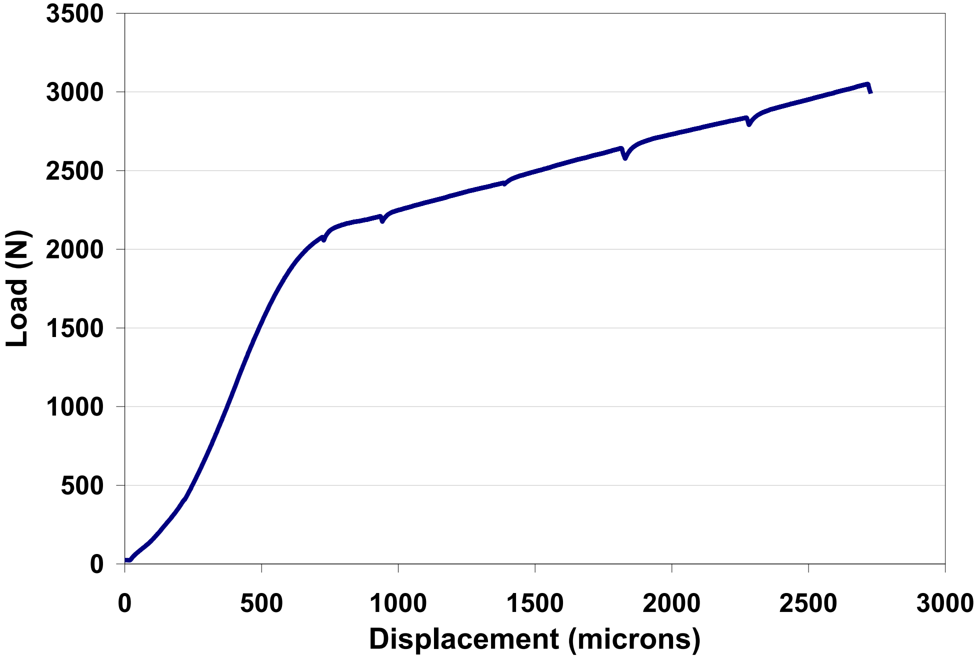
PORE MORPHOLOGY

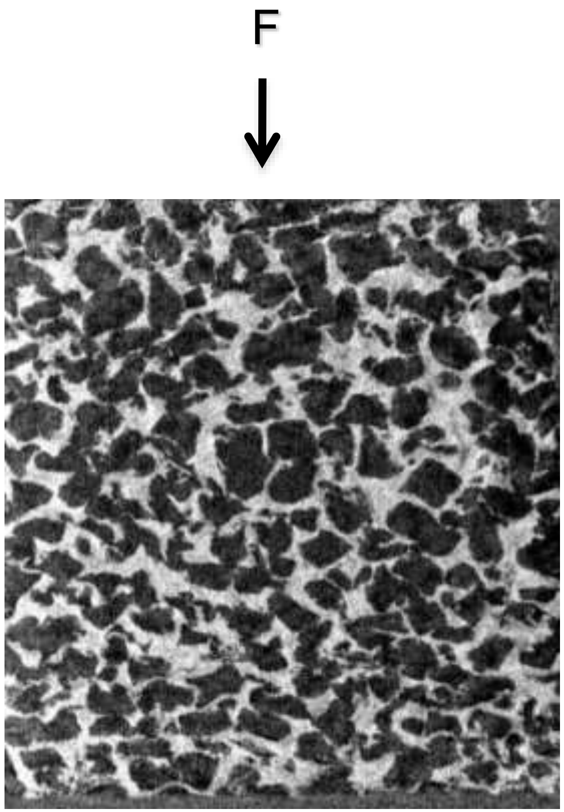




Source: Tuncer, Nihan. “Structure-property Relationship in Titanium Foams”, PhD dissertation, Anadolu University, Turkey, 2011.

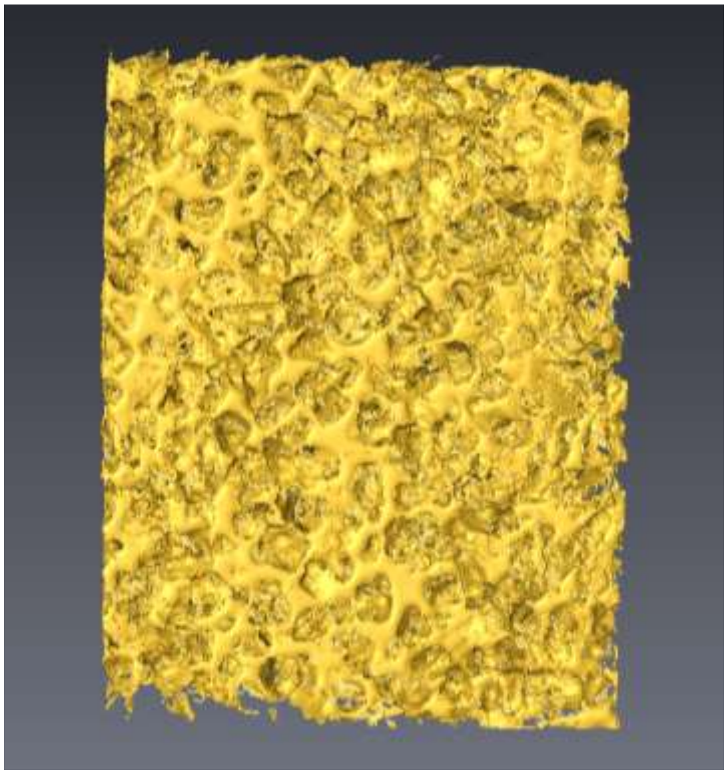
PORE MORPHOLOGY



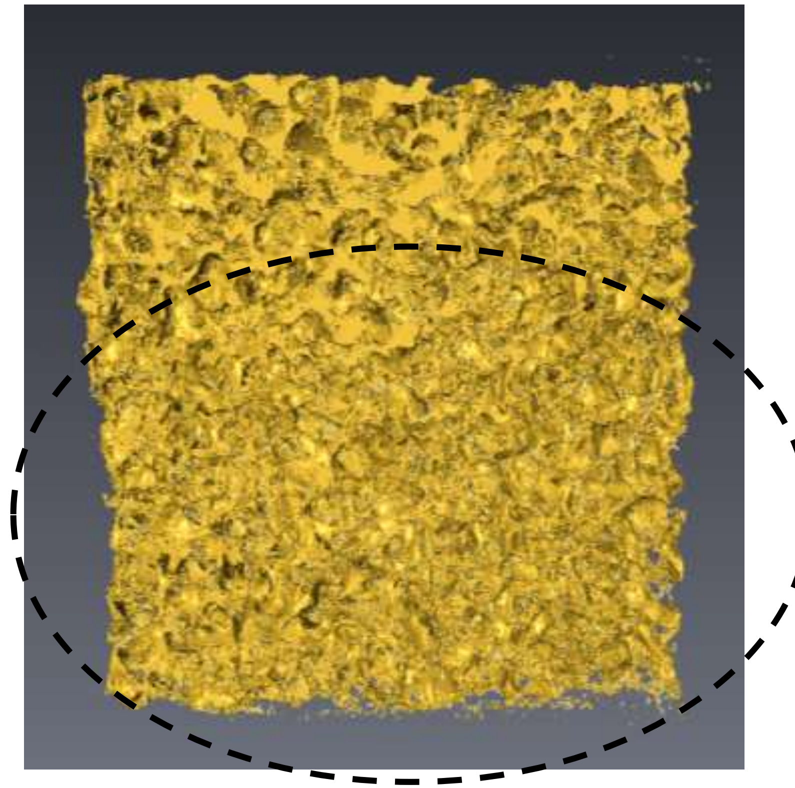


Source: Tuncer, Nihan. “Structure-property Relationship in Titanium Foams”, PhD dissertation, Anadolu University, Turkey, 2011.

PORE MORPHOLOGY



1st step after yield



Final step (severe deformation)

A more homogeneous deformation

Source: Tuncer, Nihan. "Structure-property Relationship in Titanium Foams", PhD dissertation, Anadolu University, Turkey, 2011.

CONCLUSIONS

Random foams deviate from well known models due to imperfections that form during processing. Processing parameters should be watched carefully to address the property variations.

Large and low aspect ratio pores enhance compressive strength at the same relative density.

Dominant collapse mechanism in needle-like-pored foams is buckling whereas in angular-pored foams it's cell wall bending.

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