STRUCTURE- PROPERTY RELATIONSHIP IN TITANIUM FOAMS

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“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


**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.

Diagram courtesy of Pbroks13 on Wikimedia Commons. License: CC-BY.
The desired structural and mechanical properties of the implant strongly depend on substituted bone, the age and daily activity of the patient.
MECHANICAL PROPERTY PREDICTION

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

![Dimensional arguments diagram]

\[
\frac{\sigma^*}{\sigma_s} = C_1 \left( \frac{\rho^*}{\rho_s} \right)^{3/2} \quad \frac{E^*}{E_s} = C_2 \left( \frac{\rho^*}{\rho_s} \right)^2
\]


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

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<sub>50</sub>=22 μm)

**Spacer types**

- AHC
- Carbamide (urea)
- NaCl
- KCl
- KNO<sub>3</sub>
- NaNO<sub>3</sub>
- Mg

STRUCTURE-PROPERTY RELATIONSHIP

Powder & process variables → Foam architecture → Mechanical properties

**Effect on sintering**
- Wall densification
- $O_2$ diffusion through titanium
- Cell shrinkage

**Effect on foam architecture**
- Cell wall porosity
- Cell size
- Cell wall thickness

**Process**
- Temperature
- Atmosphere

**Titanium**
- Size distribution
- Compaction efficiency
- Wall densification
- Cell and wall size distribution

**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: 29 – 80%
Compressive Strength: 25 - 270 MPa
Elastic Modulus: 2.5 – 15 GPa
Pore size: 100 – 1750 µm

<table>
<thead>
<tr>
<th></th>
<th>σ_y (MPa)</th>
<th>E (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cortical bone</td>
<td>80-120</td>
<td>3-30</td>
</tr>
<tr>
<td>Trabecular bone</td>
<td>2-12</td>
<td>0.05-0.5</td>
</tr>
</tbody>
</table>

Higher dependency on relative density

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

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

Use of coarser spacers results in less dense cell walls.

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.

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Figure removed due to copyright restrictions. See Figure 10:


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

\[ \sigma (140 \, \mu m) < \sigma (375 \, \mu m) < \sigma (575 \, \mu m) < \sigma (1750 \, \mu m) \]

\[
\frac{\sigma^*}{\sigma_s} = 0.99 \left( \frac{\rho^*}{\rho_s} \right)^{1.5} + 0.1D - 0.159 \quad R^2 = 0.949
\]
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

PORE MORPHOLOGY

ON

ARCHITECTURAL & MECHANICAL PROPERTIES
PORE MORPHOLOGY

S = 6V√(π/A^3)

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

\[
\frac{\sigma^*}{\sigma_s} = 1.017 \left( \frac{\rho^*}{\rho_s} \right)^{1.5} - 0.018A - 0.091
\]

\[ R^2 = 0.977 \]
Strength decreases

Plateau behavior

Small angular pored foams  Large spherical pored 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
After the yield point

Final state (severe deformation)

Layer-wise collapse in the early stages of deformation

1st step after yield

Final step (severe deformation)

A more homogeneous deformation

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.