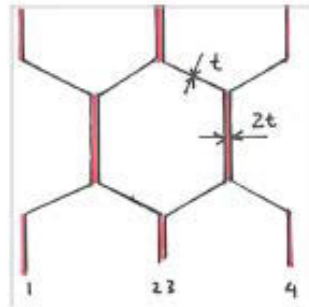
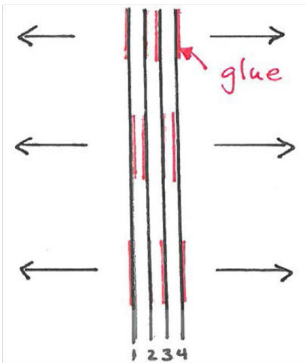


Lecture 2, 3.054

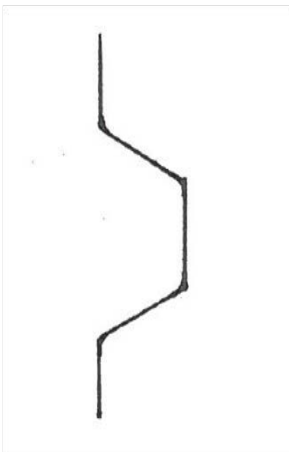
Processing - Honeycombs

Expansion process



- Aluminum honeycombs
- Paper - resin honeycombs
- Kevlar honeycombs
- Note:
 - Inclined walls - t
 - Vertical walls - $2t$.

Corrugation process



- Flat sheet fed through shaped wheel to form 1/2 hexagonal sheets which are then bonded together
- Inclined walls t
- Vertical walls $2t$
- Aluminum/metals

Honeycombs: expansion and corrugation

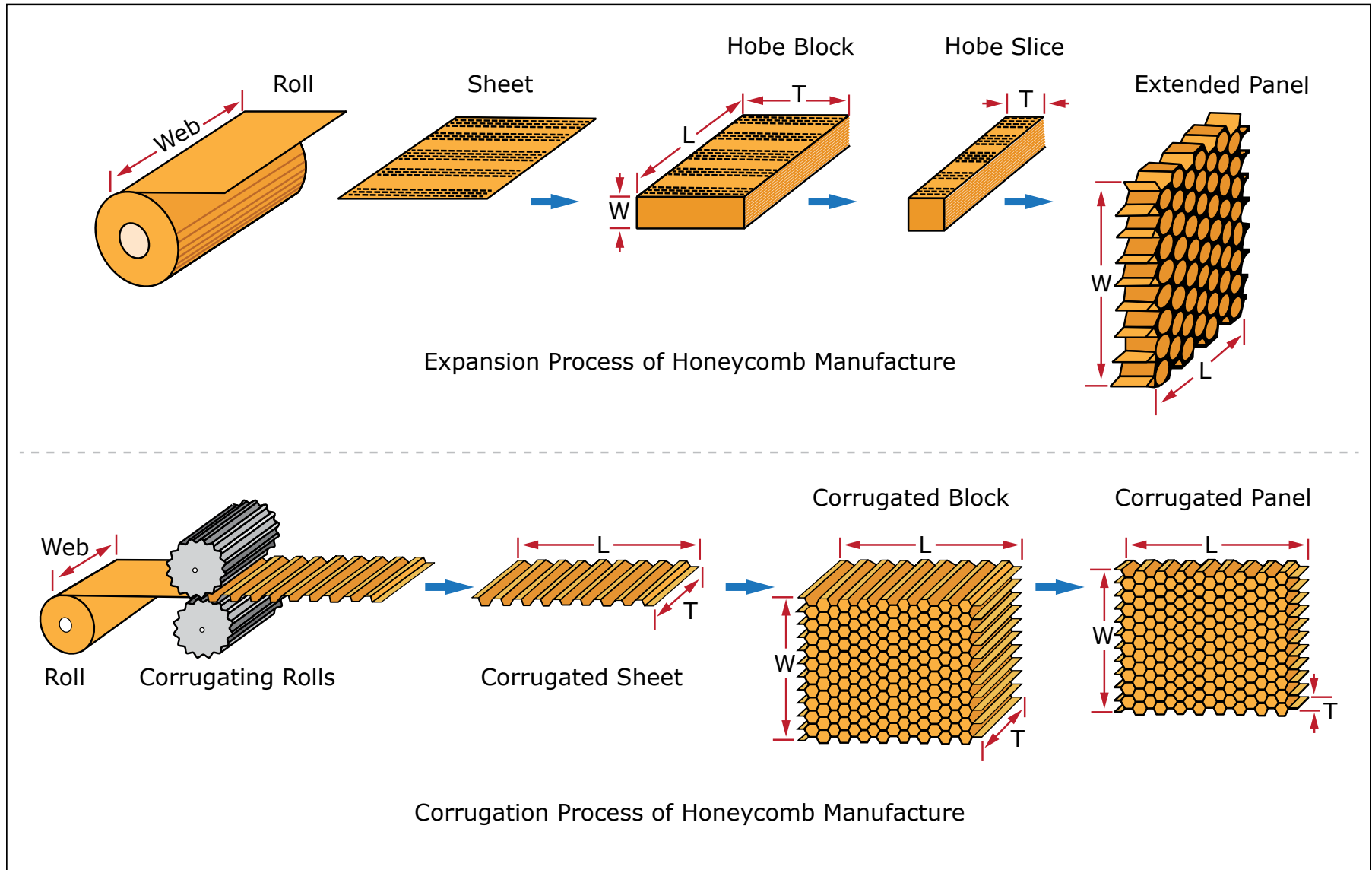


Image by MIT OpenCourseWare.

Winona State University (Course 1)

Honeycombs

- Extrusion process
 - ceramic honeycombs made by extrusion of a ceramic slurry through a die
- Rapid prototyping
 - 3D printing
 - scan photo-sensitive polymer with laser
- Casting
 - silicone rubber honeycombs made by casting liquid rubber into a mold
- Biocarbon template
 - wood has honeycomb-like structure (with cell size of $\sim 50\mu\text{m} \times 1\text{mm}$)
 - biocarbon template replicates wood structure
 - wood is pyrolyzed at 800°C in an inert atmosphere (biocarbon template)
 - structure is maintained, although significant shrinkage ($\sim 30\%$)
 - carbon replica can then be further processed, e.g., infiltrate with gaseous *Si* to form *SiC* wood replica
 - possible applications: high temperature filters, catalyst carriers
 - small cell size gives high surface area/volume

Honeycomb extrusion

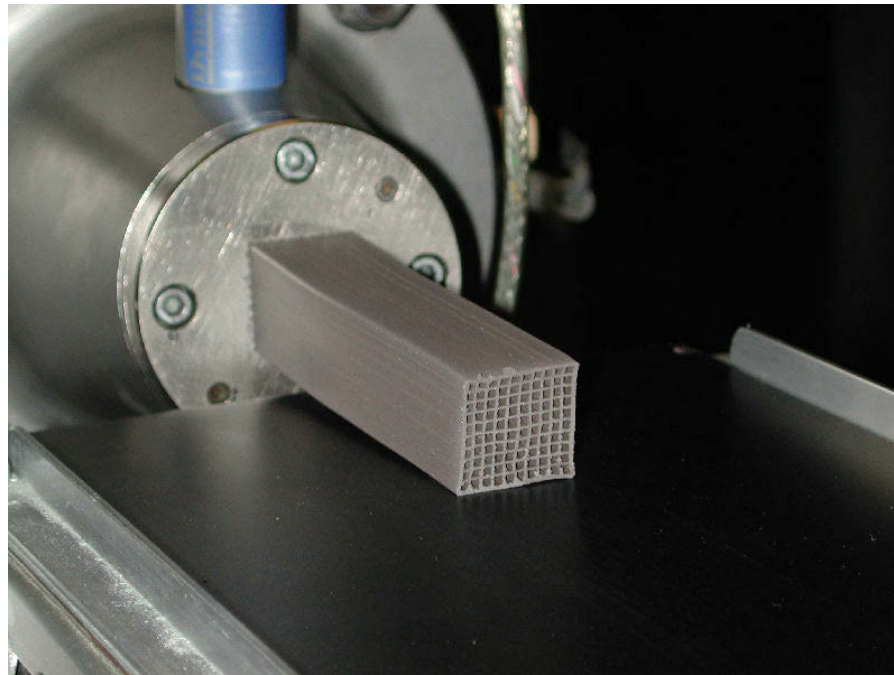
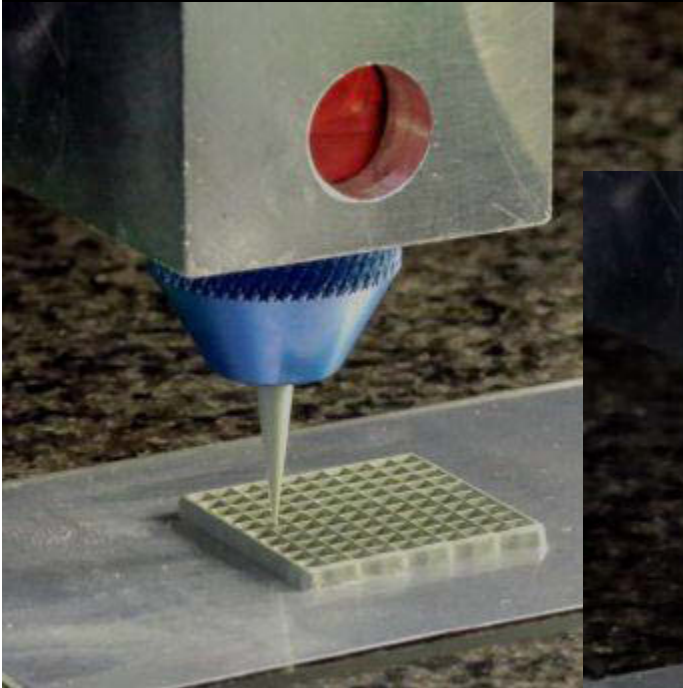


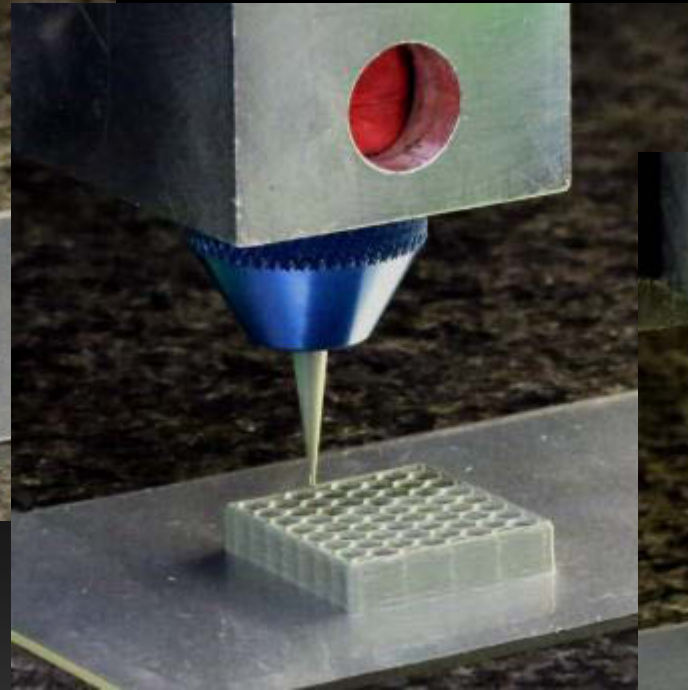
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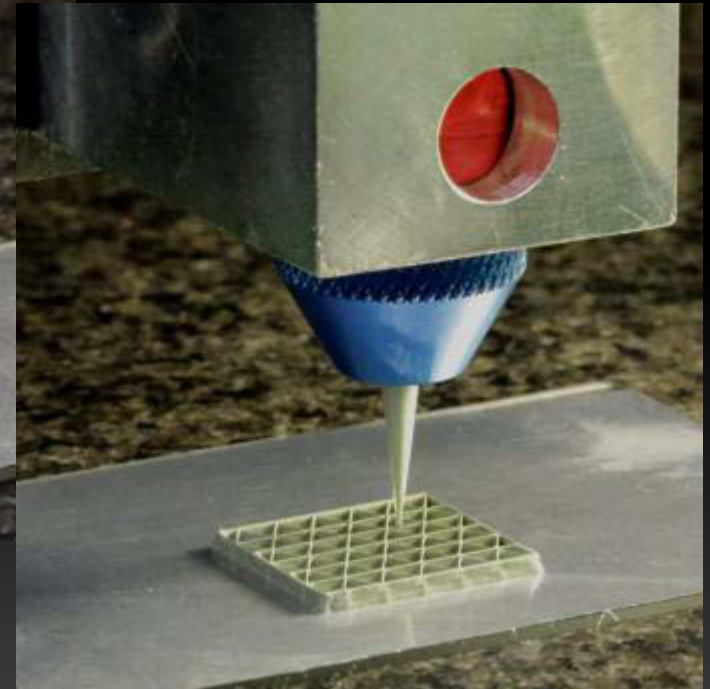
Printing honeycomb specimens



Square honeycomb



Hexagonal honeycomb

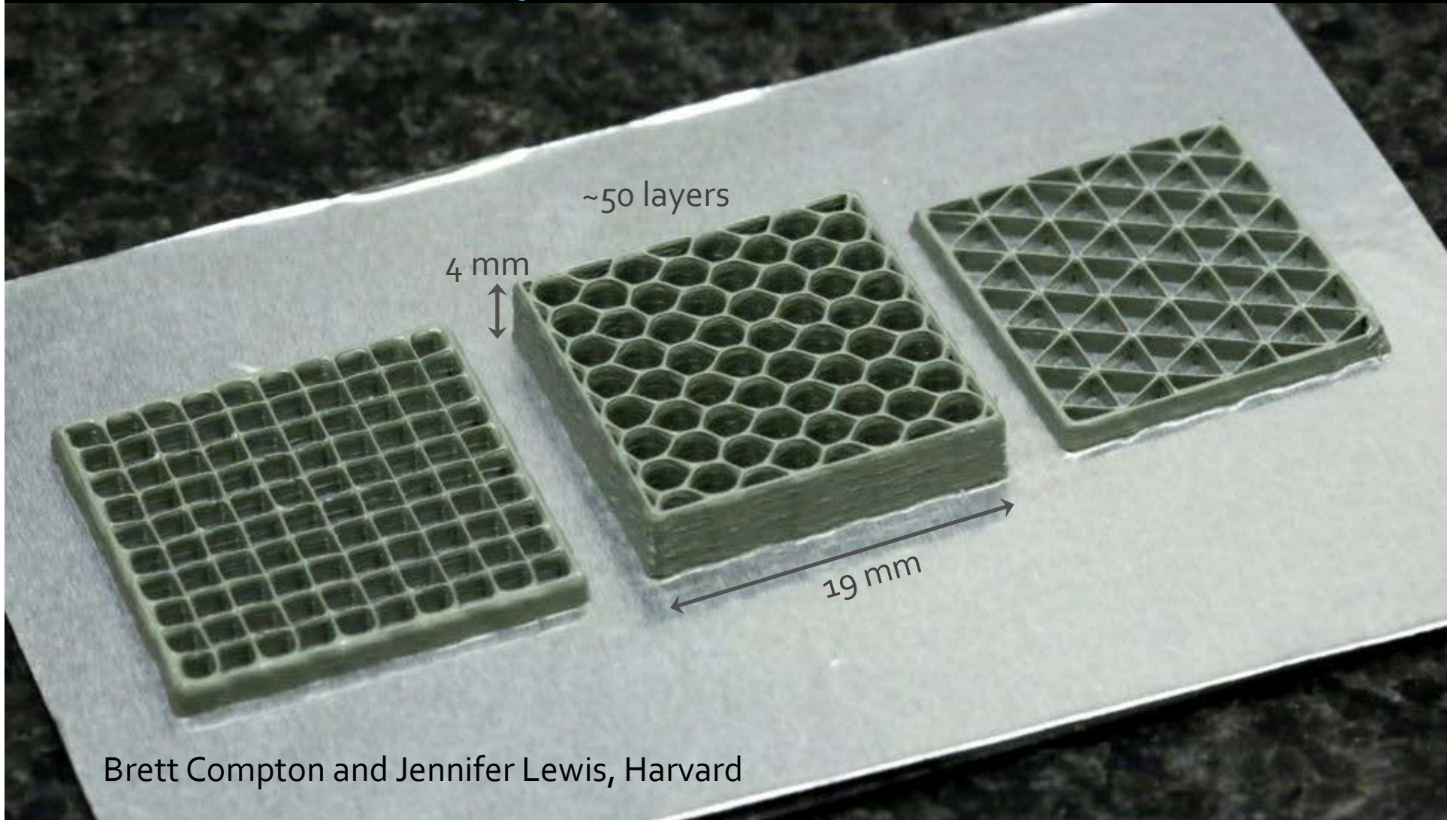


Triangular honeycomb

200 μm nozzle
6 mm/s nozzle speed
126 psi

Brett Compton and Jennifer Lewis, Harvard

Honeycomb specimens

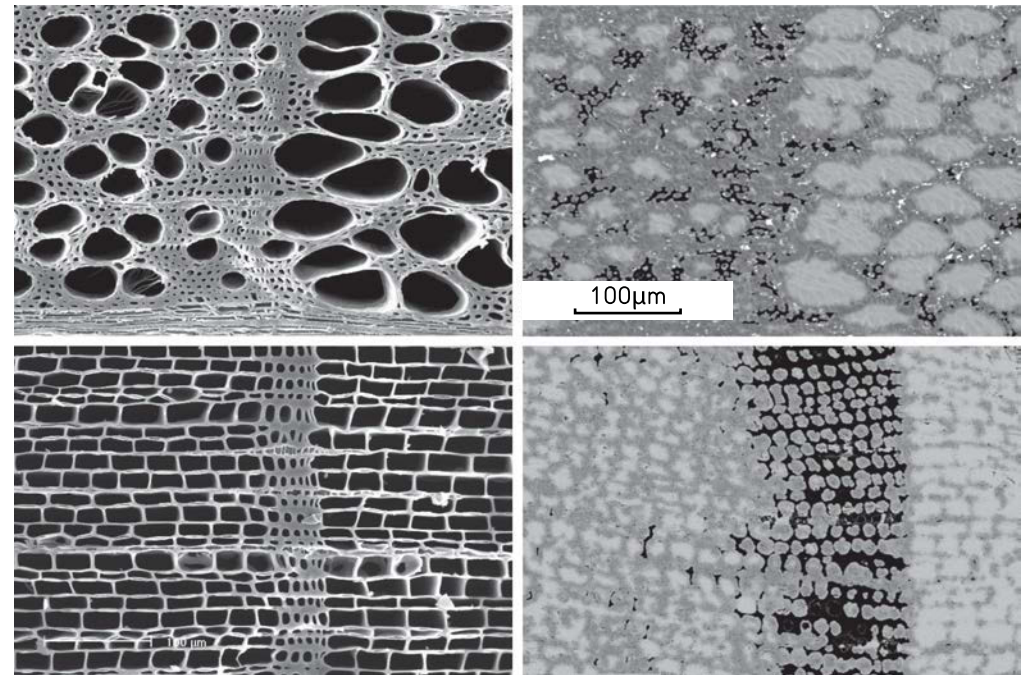
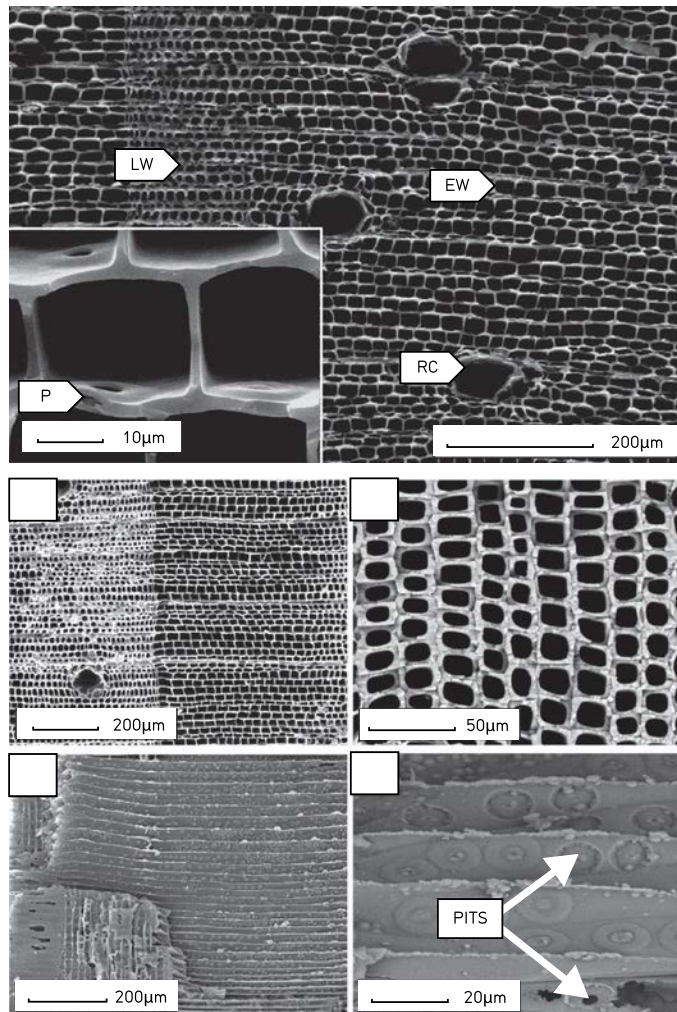


Brett Compton and Jennifer Lewis, Harvard

Relative density ~ 0.25

Courtesy of Brett Compton and Jennifer Lewis. Used with permission.

Biocarbon template



Source: Zollfrank, Cordt, and Heino Sieber. "[Microstructure and Phase Morphology of Wood Derived Biomorphous SiSiC-ceramics](#)." *Journal of the European Ceramic Society* 24 (2004): 495. Courtesy of Elsevier. Used with permission.

Zollfrank and Sieber (2004) *J Europ Ceram Soc* **24** 495

Source: Vogli, E., H. Sieber, and P. Griel. "[Biomorphic SiC-ceramic Prepared by Si-vapor Phaseinfiltration of Wood](#)." *Journal of the European Ceramic Society* 22 (2002): 2663. Courtesy of Elsevier. Used with permission.

Vogli Sieber and Griel (2002) *J Europ Ceram Soc* **22**, 2263

Foams

- Different techniques for different types of solids

Polymer Foams

- Introduce gas bubbles into liquid monomer or polymer; allow bubbles to grow and stabilize and solidify by cross-linking or cooling
- Gas introduced by either mechanical stirring or mixing blowing agent into the polymer
- Physical blowing agents (e.g. CO_2 , N_2) forced into solution in hot polymer at high pressure, then expanded into bubbles by reducing pressure
 - Or, low melting point liquids (e.g. methyl chloride) mixed into polymer, then volatilized on heating to form vapor bubbles
- Chemical blowing agents: either decompose on heating or combine to release gas
- Open/closed cell structure depends on rheology and surface tension of melt
- Syntactic foams: thin-walled hollow microspheres in polymer

Polymer Foams

- Polymer foams sometimes have “skin” on surfaces
- In some cases, process is controlled to give sufficiently thick skin so that it acts like a sandwich structure → increased stiffness and strength/weight.

Metal Foams

- Bubbling gas into molten Al , stabilized by SiC or Al_2O_3 particles
 - Particles increase the viscosity of the melt, reducing drainage from gravity, then stabilizing bubbles until solidification occurs
- Consolidation of metal powder (e.g., Al) with particulate TiH_2 , followed by heating; TiH_2 releases H_2 gas, expanding the material
- Or, TiH_2 can be stirred into molten metal and then pressure-controlled during cooling
- Infiltration of metal into open cell mold; fill open cell polymer foam with sand; burn off foam; infiltrate with metal; remove sand
- Vapor phase deposition or electrodeposition of metal onto polymer foam precursor (which is subsequently burned out)
- Trapping of high pressure inert gas in pores by powder hot isostatic pressing, followed by expansion of gas at elevated temperature

Bubbling of gas into molten Al

Figure removed due to copyright restrictions. See Figure 2.2: Ashby, M. F., A. Evans, et al. *Metal Foams: A Design Guide*. Butterworth Heinemann, 2000.

Ashby, Evans, Fleck, Gibson, Hutchinson, Wadley (2000) *Metal Foams: A Design Guide*, Butterworth Heinemann

Combine metal and TiH_2 powder, consolidate and heat

Figure removed due to copyright restrictions. See Figure 2.4: Ashby, M. F.,
A. Evans, et al. *Metal Foams: A Design Guide*. Butterworth Heinemann, 2000.

Ashby, Evans, Fleck, Gibson,
Hutchinson, Wadley (2000) *Metal
Foams: A Design Guide*, Butterworth
Heinemann

TiH₂ powder in molten Al

Figure removed due to copyright restrictions. See Figure 2.3: Ashby, M. F., A. Evans, N. A. Fleck, et al. *Metal Foams: A Design Guide*. Butterworth Heinemann, 2000.

Ashby, Evans, Fleck, Gibson, Hutchinson,
Wadley (2000) *Metal Foams: A Design
Guide*, Butterworth Heinemann

Replication by casting

Figure removed due to copyright restrictions. See Figure 2.5: Ashby, M. F., A. Evans, N. A. Fleck, et al. *Metal Foams: A Design Guide*. Butterworth Heinemann, 2000.

Ashby, Evans, Fleck, Gibson, Hutchinson, Wadley (2000) *Metal Foams: A Design Guide*, Butterworth Heinemann

Replication by vapour deposition

Figure removed due to copyright restrictions. See Figure 2.6: Ashby, M. F., A. Evans, N. A. Fleck, et al. *Metal Foams: A Design Guide*. Butterworth Heinemann, 2000.

Entrapped gas expansion

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Ashby, Evans, Fleck, Gibson, Hutchinson, Wadley (2000) *Metal Foams: A Design Guide*, Butterworth Heinemann

Hollow sphere synthesis and sintering

Figure removed due to copyright restrictions. See Figure 2.8: Ashby, M. F., A. Evans, N. A. Fleck, et al. *Metal Foams: A Design Guide*. Butterworth Heinemann, 2000.

Fugitive phase with leachable particles

Figure removed due to copyright restrictions. See Figure 2.9: Ashby, M. F., A. Evans, N. A. Fleck, et al. *Metal Foams: A Design Guide*. Butterworth Heinemann, 2000.

Ashby, Evans, Fleck, Gibson, Hutchinson, Wadley (2000)
Metal Foams: A Design Guide, Butterworth Heinemann

Metal foams

- Sintering of hollow metal spheres
- Fugitive phase methods
 - Compaction of metal and leachable powders, followed by leaching (e.g., *Al*/salt)
 - Pressure infiltration of a bed of leachable particles by liquid metal, followed by leaching
- Dissolution of gas in liquid metal under pressure, with controlled release during solidification

Carbon foams

- Heat polymer foam to high temperature in inert atmosphere — similar to biocarbon template of wood (or making carbon fibers)

Ceramic foams

- Infiltrate open-cell polymer foam with ceramic slurry and fire; polymer burns off, leaving hollow cell walls
- Chemical vapor deposition onto open-cell carbon foam

Glass foams

- Processes similar to polymer foams

Lattice Materials

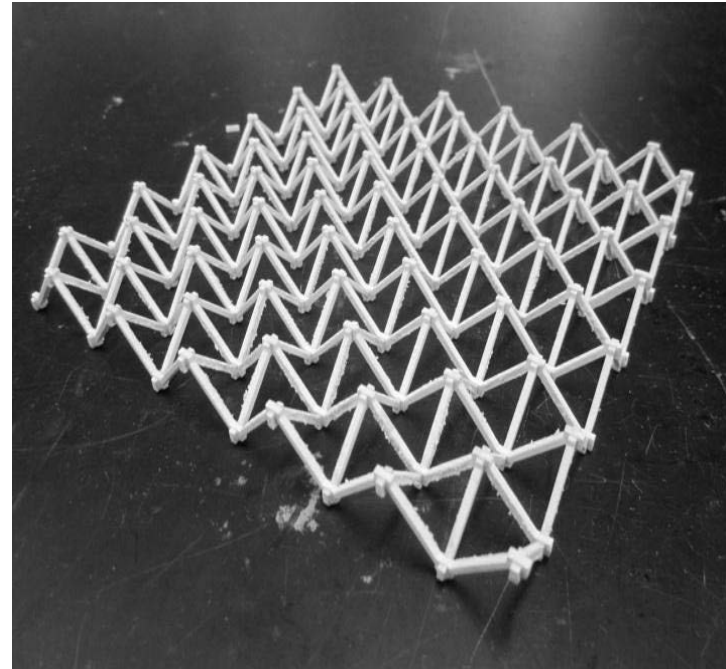
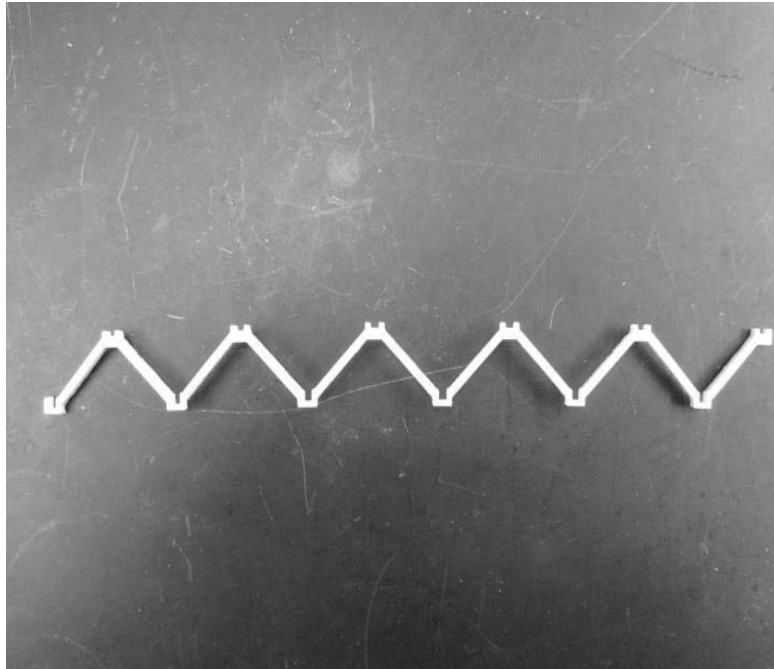
Polymer Lattices

- Injection molding
- 3D printing
- Snap-fit 2D trusses
- Micro-truss from self-propagating polymer waveguides
 - photosensitive monomer below mask with holes
 - shine collimated UV light through holes in mask
 - as light shines through, polymerization happens — solidification
 - solid polymer acts as a waveguide to transmit light deeper into the photosensitive monomer

Metal Lattices

- Infiltrate polymer lattice with ceramic, then burn off polymer and infiltrate metal

Lattice materials: snap fit trusses



Source: Chen, K., A. Neugebauer, et al. "[Mechanical and Thermal Performance of Aerogel-filled Sandwich Panels for Building Insulation](#)." *Energy and Buildings* 76 (2014): 336–46. Courtesy of Elsevier. Used with permission.

Chen K, Neugebauer A, Goutierre T, Tang A, Glicksman L and Gibson LJ, submitted to *Energy and Buildings*

Micro-truss from self-propagating polymer waveguides

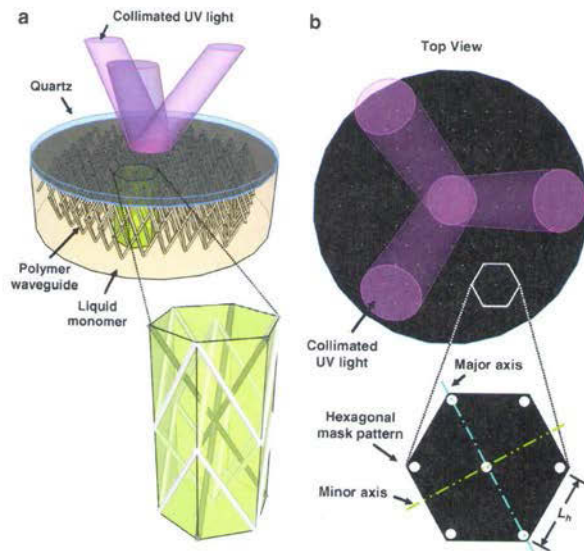
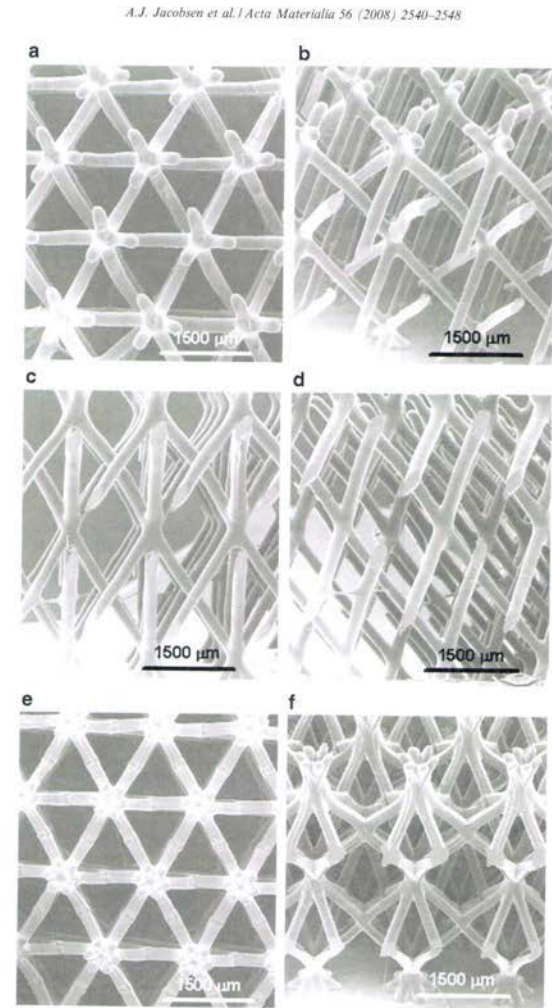


Fig. 1. (a) Schematic of the set-up for creating micro-truss structures with an interconnected array of self-propagating waveguides and (b) the top view of the mask with a hexagonal pattern of circular apertures.

Jacobsen, Barvosa-Carter and Nutt (2008) *Acta Mat.* **56**, 2540



Source: Jacobsen, Alan J., William Barvosa-Carter, et al. "Micro-scale Truss Structures with Three-fold and Six-fold Symmetry Formed from Self-propagating Polymer Waveguides." *Acta Materialia* 56 (2008): 2540-28. Courtesy of Elsevier. Used with permission.

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