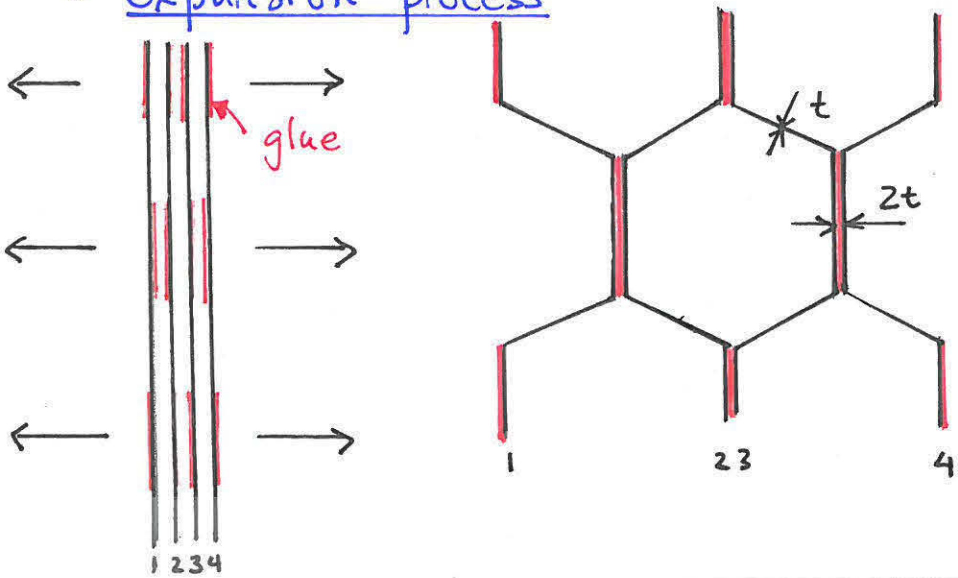
Processing - Honeycombs.

- 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 ½ hexagonal sheets which are then bonded together

- inclined walls t
  vertical walls 2t

- aluminum/metals

Honeycombs: expansion and corrugation

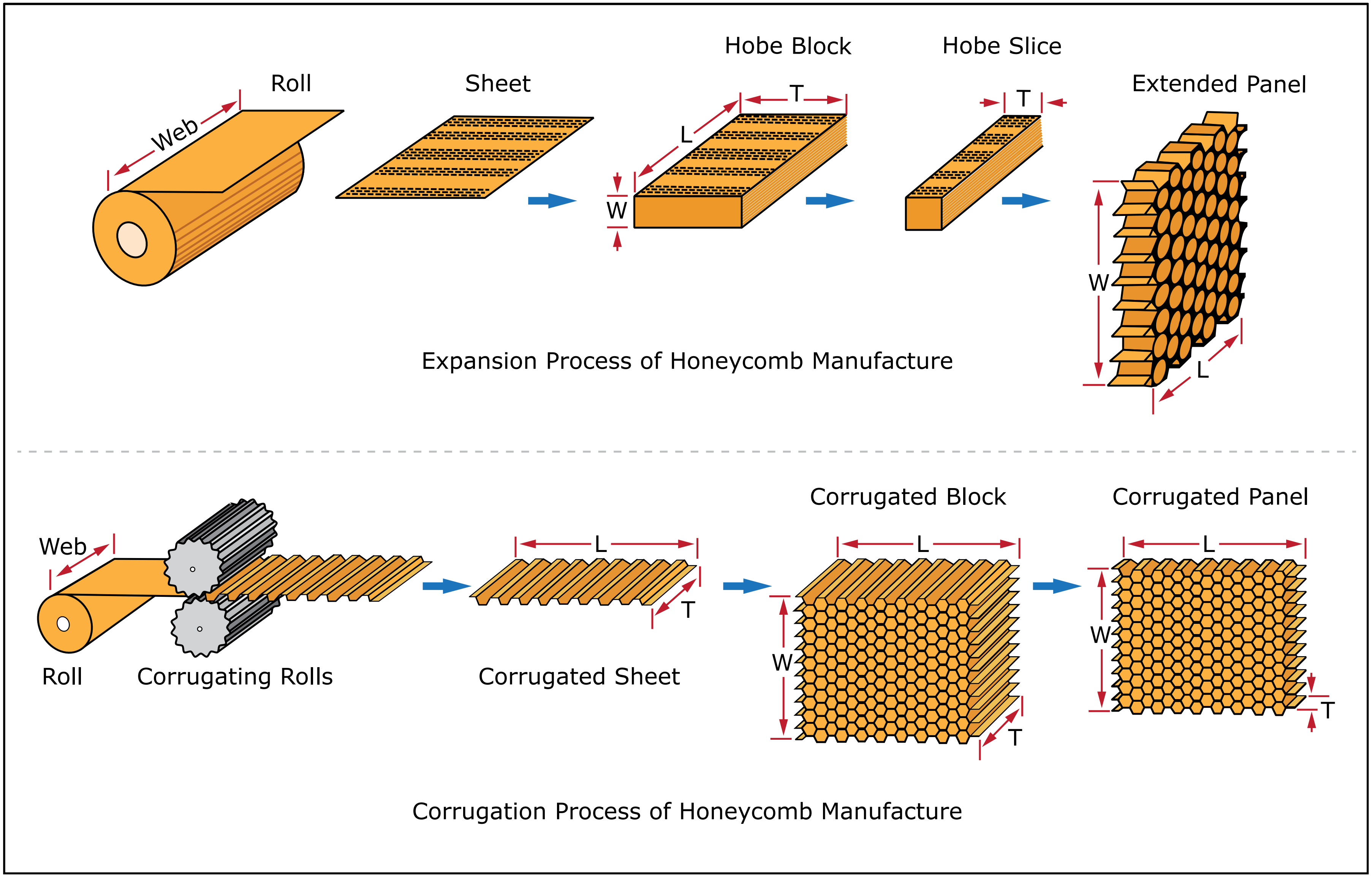


Image by MIT OpenCourseWare.

Honeycombs

- extrusion process
  - ceramic honeycombs made by extrusion of a ceramic slurry through a die
- rapid prototyping
  - 3D printing
  - scan photosensitive polymer with laser.
- casting
  - silicone rubber honeycombs made by casting liquid rubber into a mold

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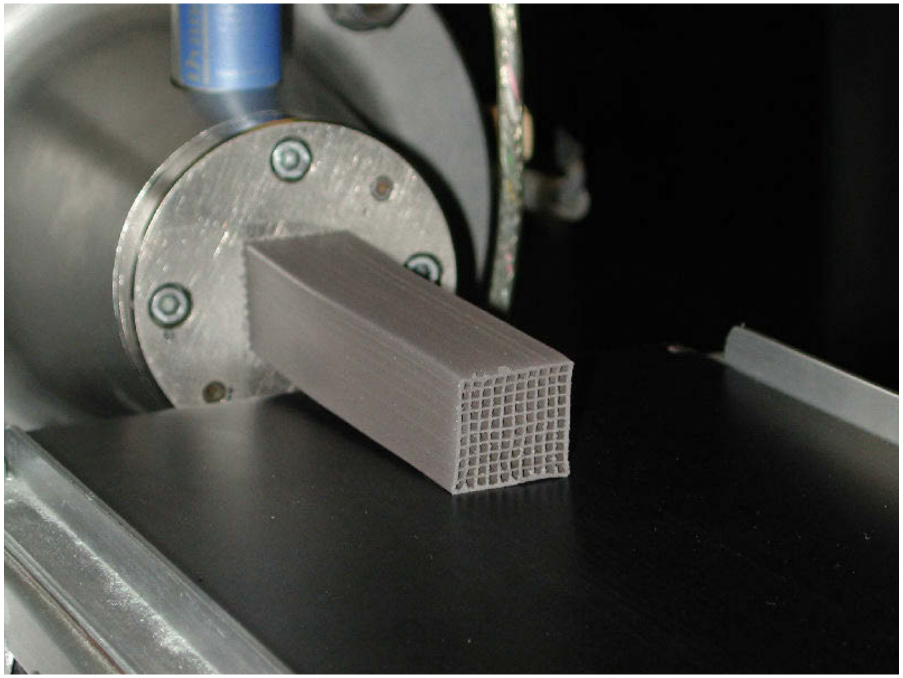
- biocarbon template
  - wood has honeycomb-like structure (with cell size ~ 50μm x ~1 mm)
  - biocarbon template replicates wood structure
  - wood is pyrolized at 800°C in an inert atmosphere (biocarbon template)
  - structure is maintained, although significant shrinkage (~30%)
  - carbon replica can then be further processed

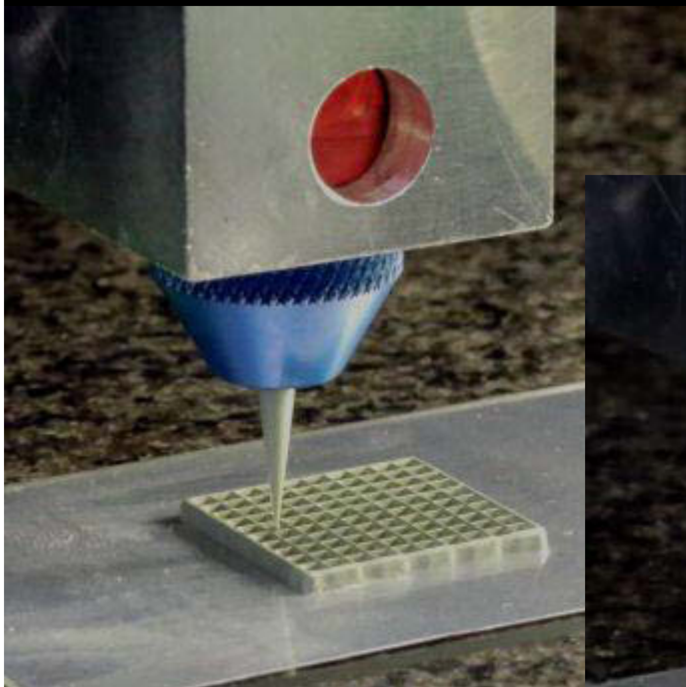
    e.g. infiltrate with gaseous Si to form SiC wood replica
  - possible applications: high temperature filters, catalyst carriers
    - small cell size gives high surface area/volume

Honeycomb extrusion

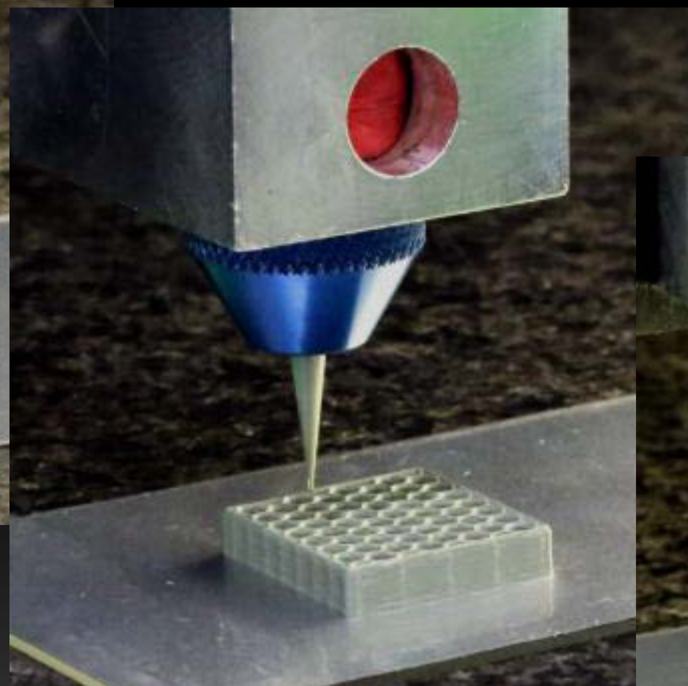


www.ikts.fraunhofer.de

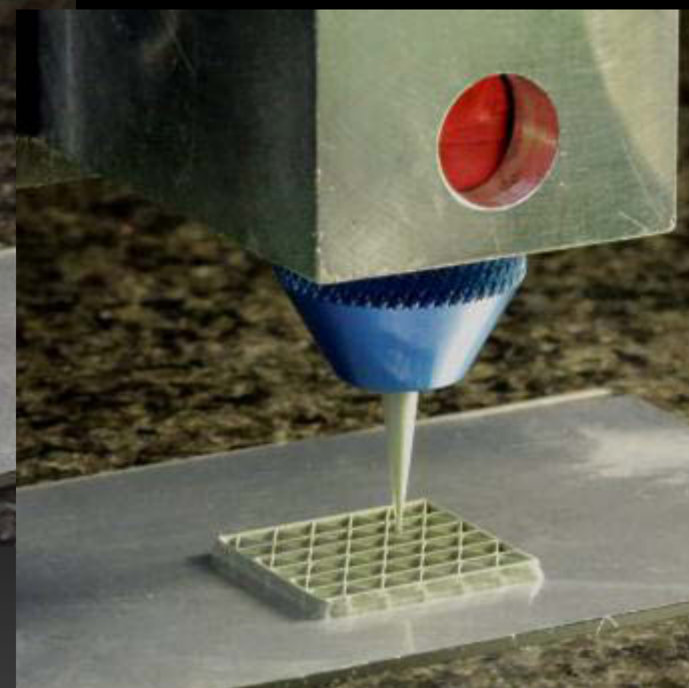
Printing honeycomb specimens



Square honeycomb



Hexagonal honeycomb

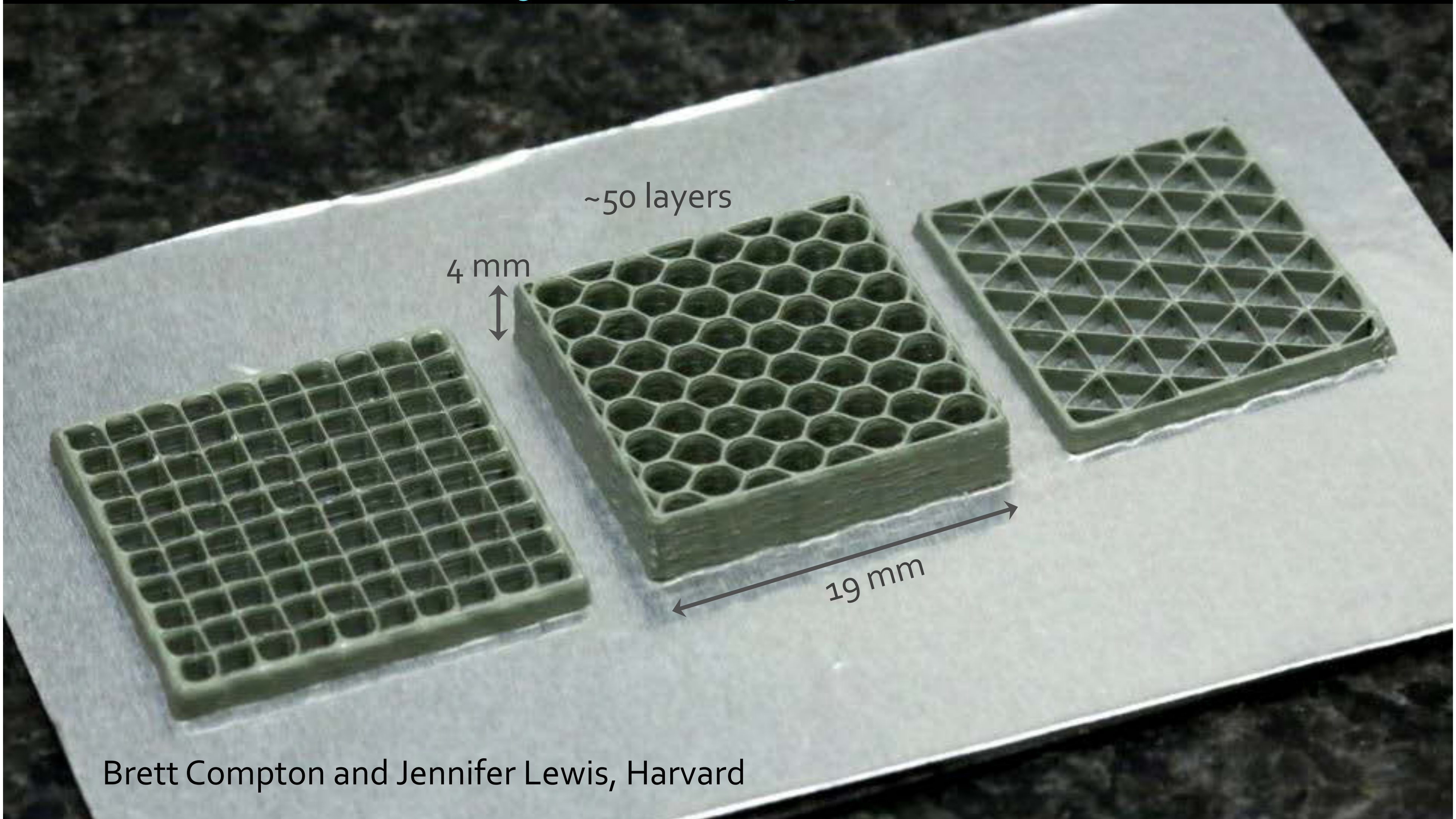


Triangular honeycomb

200 µm nozzle
6 mm/s nozzle speed
126 psi

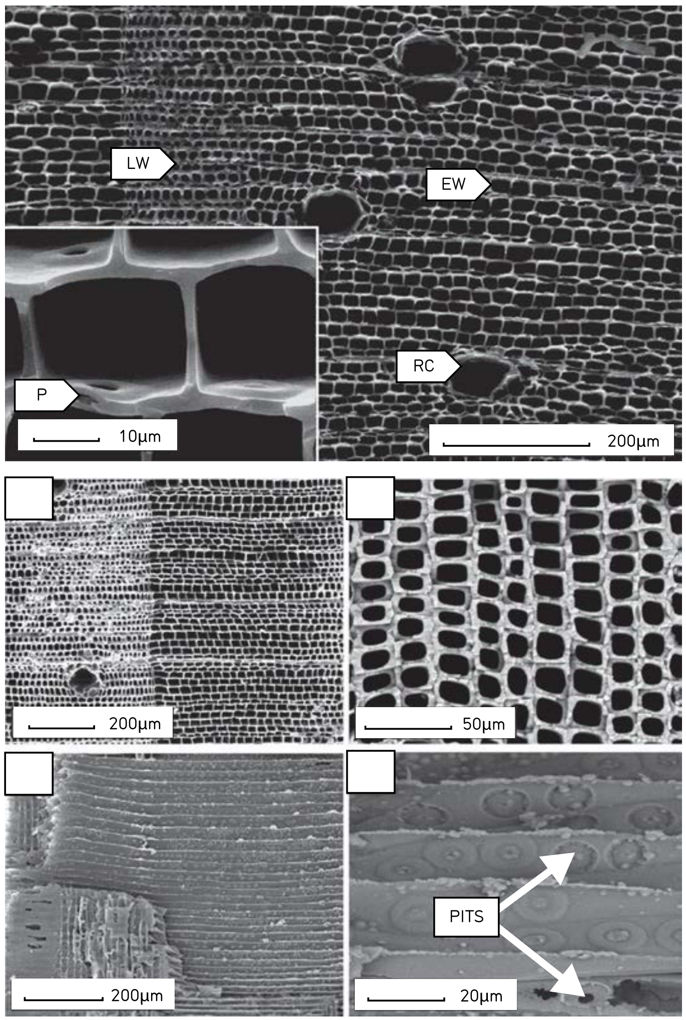
Brett Compton and Jennifer Lewis, Harvard

Honeycomb specimens



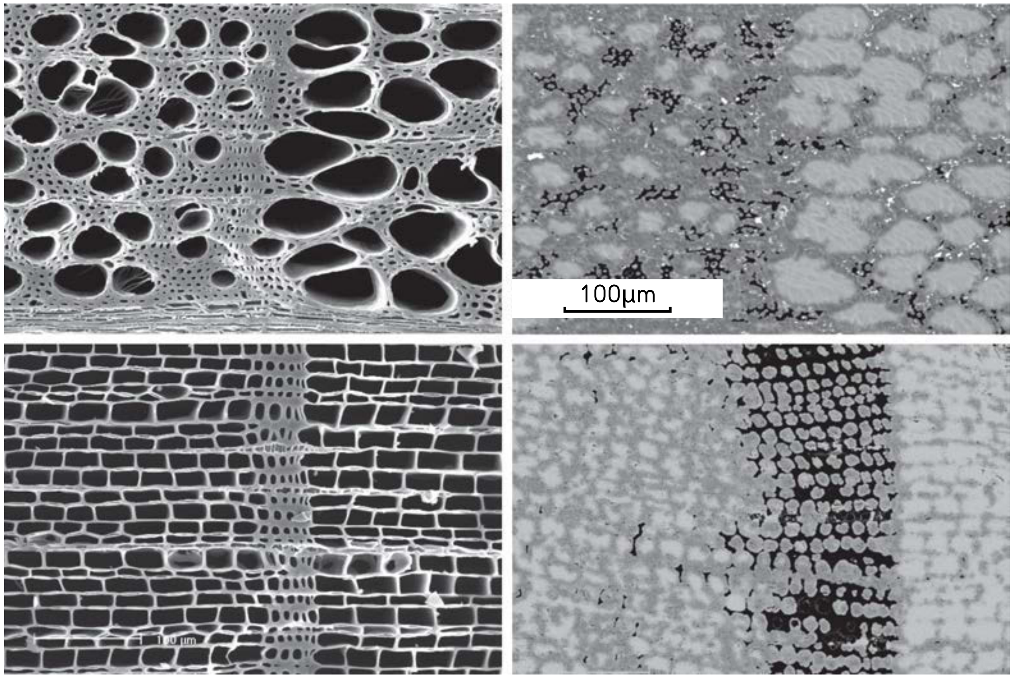
Relative density ~0.25

Biocarbon template



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



Source: Zolfrank, 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

Foams

- different techniques for different types of solids

Polymer foams

- introduce gas bubbles into liquid monomer or hot polymer
  allow bubbles to grow & stabilize & solidify by cross-linking or cooling
- gas introduced by either mechanical stirring or mixing blowing agent
  into the polymer

- physical blowing agents (eg. CO_2, N_2) forced into solution
  in hot polymer at high pressure + expanded into bubbles by
  reducing pressure
  - or, low melting point liquids (eg. methyl chloride) mixed into
    polymer + volatilize on heating to form vapour bubbles
- chemical blowing agents: either decompose on heating
  or combine to release gas
- open/closed cell structure depends on rheology + 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 + 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, + stabilizing bubbles until solidification occurs

---

- consolidation of metal powder (eg. 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 & 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
- vapour 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

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

TiH_2 powder in molten Al

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.

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

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

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

Fugitive phase with leachable particles

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 + leachable powders followed by leaching (eg. 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 temp in inert atmosphere - similar to biocarbon template of wood (or making carbon fibers)

Ceramic foams

- infiltrate open-cell polymer foam with ceramic slurry + fire; polymer burns off leaving hollow cell walls
- chemical vapour deposition onto open-cell carbon foam

Glass foams

- processes similar to polymer foams

Lattice materials

Polymer lattices

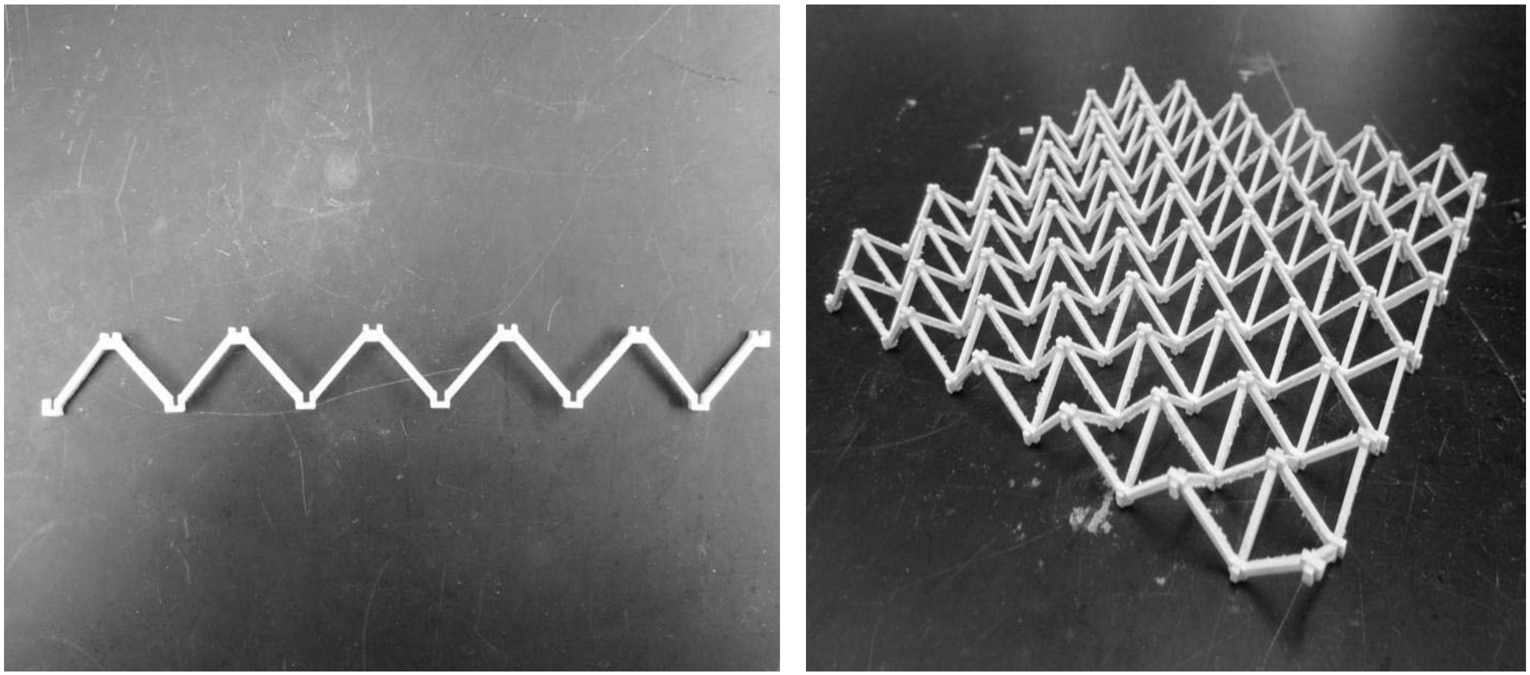
- injection molding
- 3D printing
- snap-fit 2D trusses
- micro-truss from self propagating polymer waveguides
  - photosensitive monomer below mask with holes
  - shine collimated UV light through holes in mask

  - as light shines through, polymerization → solidifies
  - solid polymer acts as waveguide to transmit light deeper into the photosensitive monomer

Metal lattices

- infiltrate polymer lattice with ceramic, then burn off polymer + 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 (2014) Energy and Buildings 76, 336-346

Micro-truss from self-propagating polymer waveguides

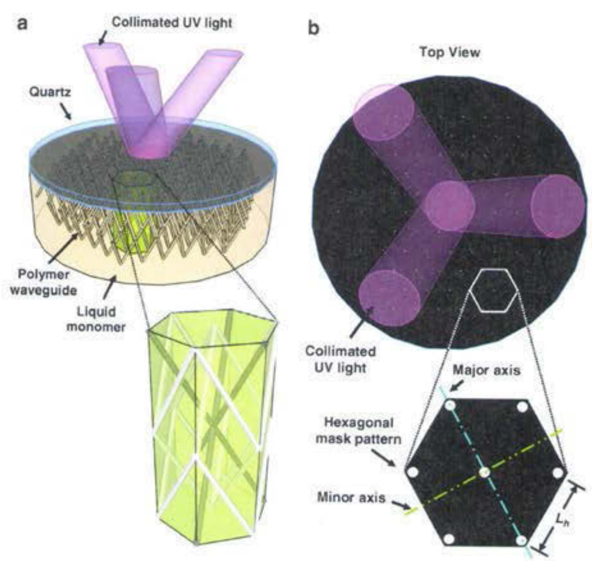
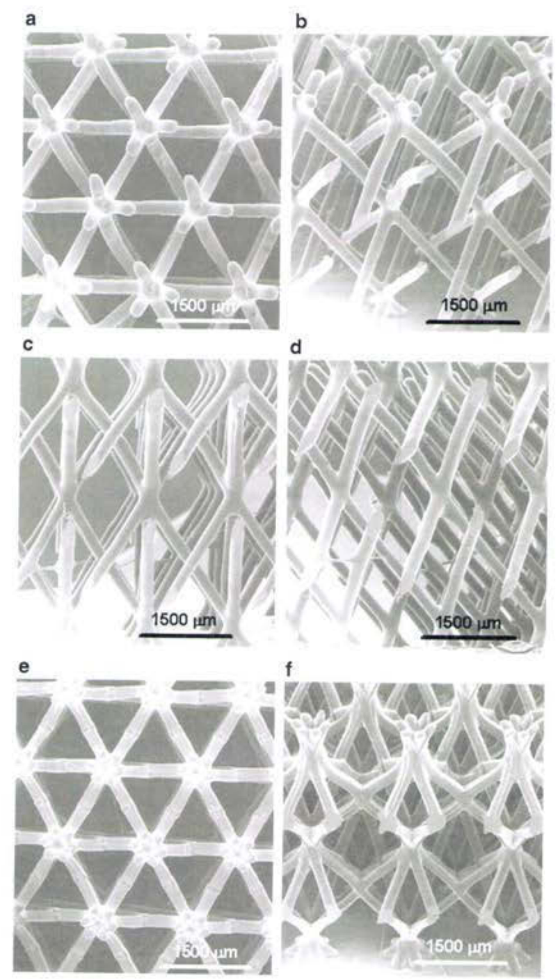


Fig. 1. (a) Schematic of the set-up for creating micro-truss structures with an interconnected array of self-propagating waveguides and (b) the top view of the mask with a hexagonal pattern of circular apertures.

A.J. Jacobsen et al. / Acta Materialia 56 (2008) 2540–2548



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

3.054 / 3.36 Cellular Solids: Structure, Properties and Applications
Spring 2015