Cellular Solids

L.J. Gibson, Guest Editor

Abstract

This brief article describes the content of this issue of *MRS Bulletin* on Cellular Solids. Cork, wood, sponge, and bone are all examples of cellular solids in nature. Engineered honeycombs and foams are now made from polymers, metals, ceramics, and glasses, and their structure gives them unique properties that can be exploited in a variety of applications. The articles in this issue provide an overview of the fabrication, structure, properties, and applications of such porous solids as cellular ceramics, aluminum and other metallic foams, and scaffolds for tissue engineering, as well as discussions of techniques for understanding, modeling, and measuring their behavior and properties.

Keywords: *cellular solids, foams, honeycombs.*

Many materials have a cellular structure: an assembly of prismatic or polyhedral cells with solid edges and faces packed together to fill space. Cork, wood, sponge, and trabecular bone are all examples of cellular solids in nature (Figure 1). Engineered honeycombs and foams are now made from polymers, metals, ceramics, and glasses (Figure 2). Their cellular structure gives them unique properties that are exploited in a variety of applications. Their light weight makes them attractive for the cores of structural sandwich panels in products ranging from downhill skis to lightweight building panels. In compression, cellular solids can withstand large strains at nearly constant stress, allowing them to absorb the kinetic energy of an impact without generating high peak stresses. For this reason, they are often used in energy-absorption devices such as helmets and automobile bumpers. Closed-cell foams can be made with low-conductivity gases that remain trapped inside the cells, making these foams excellent materials for thermal insulation. Open-cell metallic foams, with their high thermal conductivity and interconnected pores allowing fluid flow, are used in heat-exchange devices. The interconnected porosity of open-cell foams is also exploited in their use as filters. Porous scaffolds used in tissue engineering can be considered open-cell foams; their interconnected porosity is essential for cells to penetrate the scaffold and migrate through it.

The structure of cellular solids has been studied since the 1660s, when Robert Hooke examined a section of cork in his microscope[1] and first used the term "cell" to describe its structure. Sir William Thomson (later Lord Kelvin) identified the space-filling unit cell that minimizes surface area per unit volume as a tetrakaidecahedron with slightly curved faces.[2] Recently, Weaire and Phelan[3] identified a unit cell of even lower surface area per unit volume, composed of six 14-sided cells and two 12-sided cells. Both are described in Kraynik's article on foam structure in this issue of *MRS Bulletin.* Today, computer software for generating foam structures and minimizing their surface energy[4] makes detailed descriptions of the structure of cellular solids possible, as Kraynik reports.

The mechanical response of cellular solids in compression is characterized by three distinct regimes of behavior: an initial linear elastic region associated with bending edges in open-cell foams and stretching faces in closed-cell foams; a roughly constant stress plateau, corresponding to cell collapse by buckling, yielding, or fracture and extending up to large strains (typically 70–80%); and a final sharp increase in stress with further strain, corresponding to densification of the material, with opposing cell edges and faces compressed against each other.

The mechanical behavior of honeycomb-like cellular solids with repeating prismatic cells can be analyzed using standard methods of structural mechanics.[5–7] Foams, with their complex cell geometry, are more difficult to analyze. Initial modeling studies represented the cellular structure as a repeating unit cell (for instance, the tetrakaidecahedron) and analyzed it using structural mechanics.[8–10] Another approach uses dimensional arguments, which assume that different foams are geometrically similar, to analyze the mechanisms of deformation and failure in the cells. The geometrical parameters of the analysis are then combined into one constant that is measured experimentally.[7]

While both the unit-cell and dimensional-analysis approaches provide useful results for the bulk properties of foams, they are

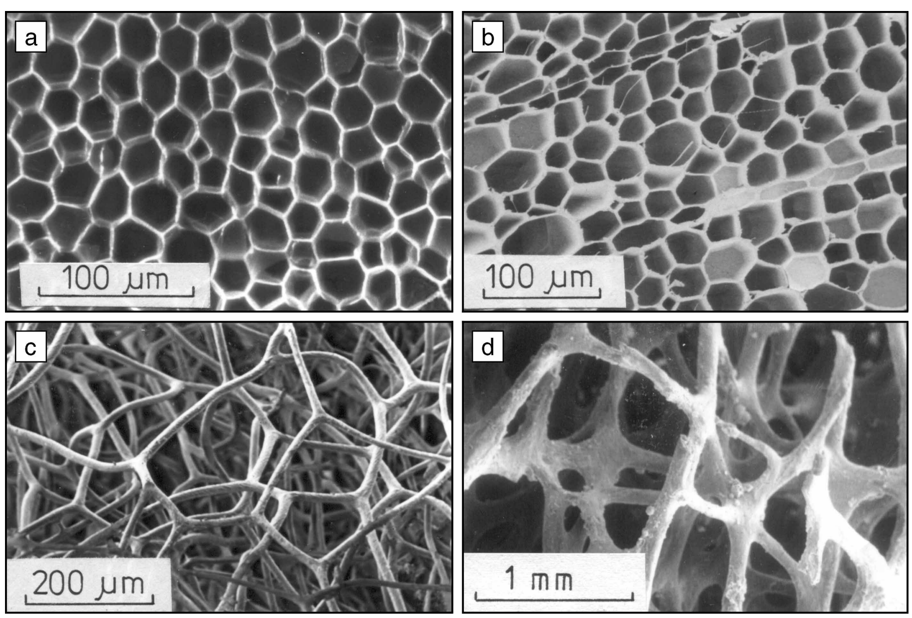

Figure 1. Natural cellular materials: (a) cork, (b) balsa wood, (c) sponge, and (d) trabecular bone.[7]

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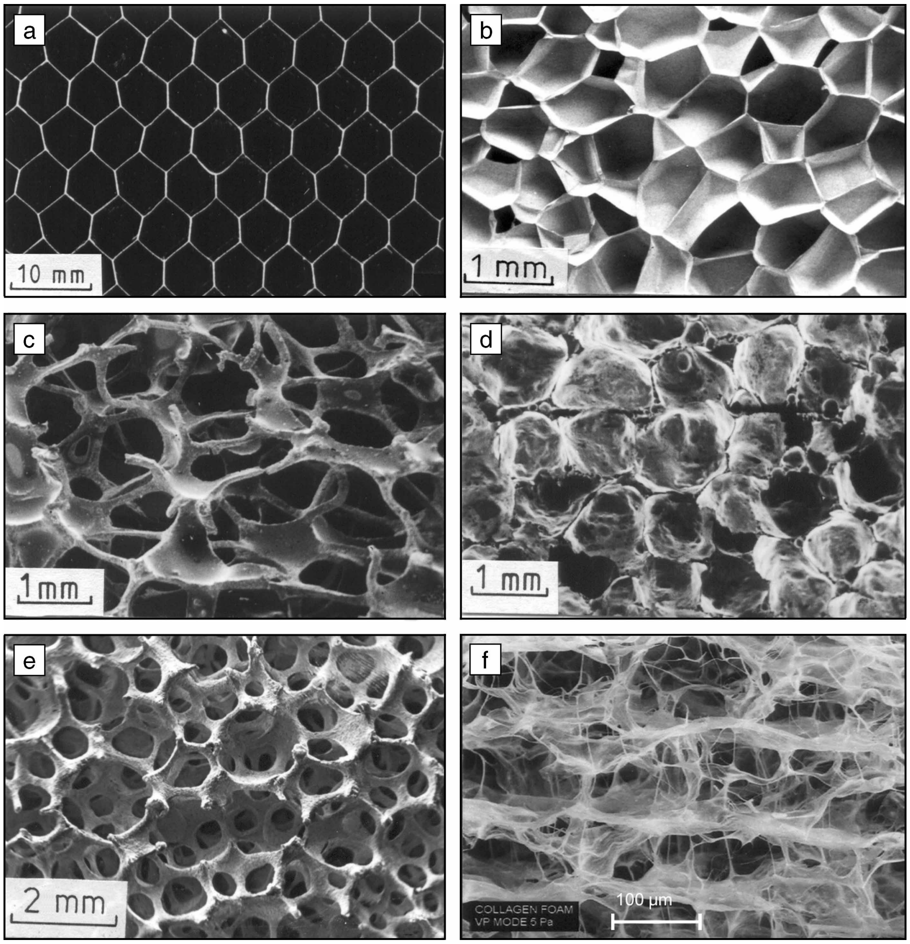

Figure 2. Engineered cellular materials: (a) aluminum honeycomb, (b) closed-cell polyethylene foam, (c) open-cell nickel foam, (d) closed-cell glass foam, (e) open-cell zirconia foam, and (f) collagen-based porous scaffold used in tissue engineering.[7]

unable to characterize local effects (e.g., the effect of broken struts on residual strength, the effect of the cell size to sample size ratio on modulus and strength, or the local response around an indenter or a crack). Local effects are best studied using numerical techniques such as finite element analysis. In this issue, Onck uses finite element analysis to describe size effects and stresses around notches. Improved imaging techniques, such as microcomputed tomography, enable detailed observation of local deformations within the bulk of a sample; Maire et al. discuss this technique to characterize the generation of local deformation bands in metallic foams. The availability of microcomputed tomography, as well as increased computational power, has also led to detailed finite element models of the mechanical response of cellular solids.[11]

Metallic and ceramic foams are described in the articles by Banhart and by Green and Colombo, respectively. Metallic foams can be made by both liquid- and solid-state processing routes. They are particularly attractive for lightweight construction, impact-energy absorption, acoustic damping, and heat-transfer applications. (See also the sidebar article by Leyda within Banhart on applications of open-cell metallic foams.) Ceramic foams are typically made either by replication techniques (e.g., using a polymer foam as a form) or direct foaming of a liquid in which a ceramic powder is dispersed. Applications for ceramic foams include filters for metal-casting operations, porous-medium burners, and traps for diesel particulate emissions.

Calcium-phosphate-based foams are being developed for biomedical applications, particularly for bone-graft materials and scaffolds for tissue engineering of bone. The final article in this issue, by Karp et al., and the accompanying sidebar by Cahn describe this use of porous scaffolds for tissue engineering of bone, nerves, and skin. The aim of tissue engineering is to regenerate diseased or damaged tissue. The porous structure of scaffolds used for tissue engineering must meet several requirements:[12] the pores must be interconnected, enabling cells to enter, attach, and migrate through the scaffold; the pore size must be large enough for cells and nutrients to pass through, yet small enough that the specific surface area is sufficient for large numbers of cells to attach; and the scaffold material must be biocompatible and degrade over time as the cells produce their own extracellular matrix.

The structure and properties of cellular solids have fascinated scientists and engineers for centuries. Modern imaging and analysis techniques allow their properties to be understood in greater detail. The range of materials from which cellular solids can be made is constantly increasing, allowing new applications such as the tissue-engineering scaffolds described in this issue.

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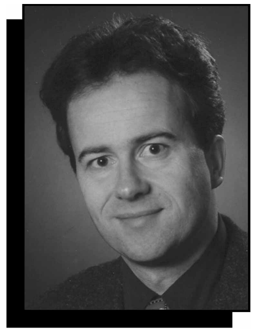
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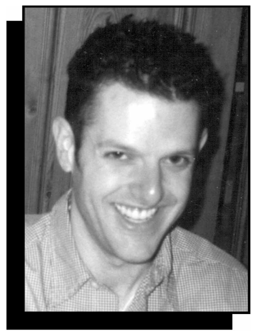
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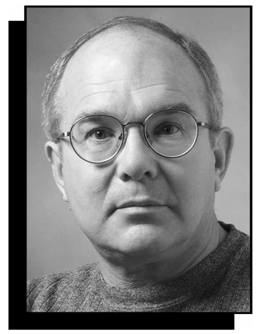
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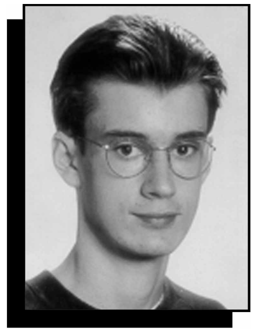

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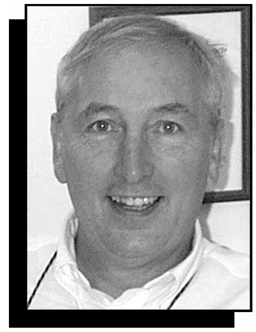

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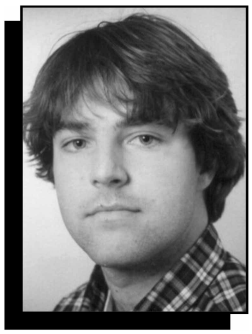

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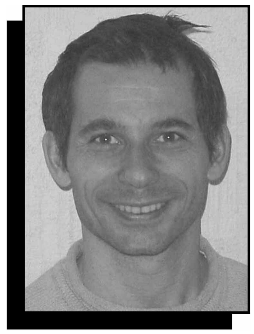

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