Cellular solids

Structure and properties

Second edition

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(a) Honeycombs

Structures like the honeycomb shown in Fig. 1.1(a) can be made in at least four ways. The most obvious is to press sheet material into a half-hexagonal profile and glue the corrugated sheets together. More commonly, glue is laid in parallel strips on flat sheets, and the sheets are stacked so that the glue bonds them together along the strips. The stack of sheets is pulled apart ('expanded') to give a honeycomb. Paper–resin honeycombs are made like this; the paper is glued and expanded, and then dipped into the resin to protect and stiffen it. Honeycombs can also be cast into a mould; the silicone rubber honeycomb shown in the figure was made by casting. And, increasingly, honeycombs are made by extrusion; the ceramic honeycombs used to support exhaust catalysts in automobiles are made in this way.

(b) Foams

Different techniques are used for foaming different types of solids. Polymers are foamed by introducing gas bubbles into the liquid monomer or hot polymer, allowing the bubbles to grow and stabilize, and then solidifying the whole thing by cross-linking or cooling (Suh and Skochdopole, 1980). The gas is introduced either by mechanical stirring or by mixing a blowing agent into the polymer. *Physical blowing agents* are inert gases such as carbon dioxide or nitrogen; they are forced into solution in the hot polymer at high pressure and expanded into bub-

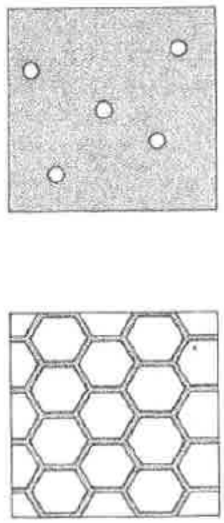

Figure 1.2 Comparison between a cellular solid and a solid with isolated pores.

bles by reducing the pressure. Alternatively, low melting point liquids such as chlorofluoro-carbons or methylene chloride are mixed into the polymer and volatilize on heating to form vapour bubbles. Microcellular foams, with cell sizes on the order of 10μ, can be made by saturating, under pressure and at room temperature, a polymer with an inert gas and then relieving the pressure and heating the supersaturated polymer to the glass transition temperature, causing cell nucleation and growth to occur. *Chemical blowing agents* are additives which either decompose on heating, or which combine together when mixed to release gas; sodicarbonamide is an example. Each process can produce open- or closed-cell foams; the final structure depends on the rheology and surface tension of the fluids in the melt. Closed-cell foams then sometimes undergo a further process called reticulation, in which the faces of the cells are ruptured to give an open-cell foam. Finally, low-density microcellular polymer foams and aerogels with relative densities as low as 0.002 and cell sizes as small as 0.1μ can be made by a variety of phase separation methods: one is to precipitate the polymer as a low-density gel in a fluid and then remove the fluid by evaporation (LeMay *et al.*, 1990).

Metallic foams can be made using either *liquid or solid state processing* (Shapovalov, 1994 and Davies and Zhen, 1983). Powdered metal and powdered titanium hydride or zirconium hydride can be mixed, compacted and then heated to the melting point of the metal to evolve hydrogen as a gas and form the foam. Mechanical agitation of a mixture of liquid aluminium and silicon carbide particles forms a froth which can be cooled to give aluminium foam. Liquid metals can also be infiltrated around granules which are then removed: for instance, carbon beads can be burned off or salt granules can be leached out. Metals can be coated onto an open-cell polymer foam substrate using electroless deposition, electrochemical deposition or chemical vapor deposition. Metal foams can also be made by a eutectic transformation: the metal is melted in an atmosphere of hydrogen and then cooled through the eutectic point, yielding the gas as a separate phase within the metal. Solid state processes usually use powder metallurgy. In the powder sintering method, the powdered metal is mixed with a spacing agent which decomposes or evaporates during sintering. Alternatively, a slurry of metal powder mixed with a foaming agent in an organic vehicle can be mechanically agitated to form a foam which is then heated to give the porous metal. Metal foams can also be formed by coating an organic sponge with a slurry of powdered metal, drying the slurry and firing to remove the organic sponge. In one of the most remarkable processes, single crystal silicon can be made porous by anodization: a silicon wafer is immersed in a solution of hydrofluoric acid, ethanol and water and subjected to a current for a brief time (Bellet and Dolino, 1994). The anodizing process tunnels, giving an interconnected network of pores with a cell size of 10 nm and a relative density as low as 0.1; yet the material remains a single crystal.

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