Composite Materials

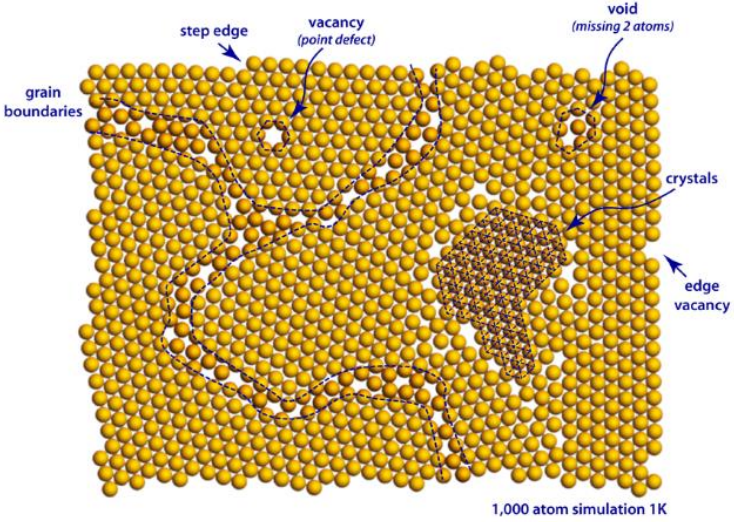
Porous Engineering Materials

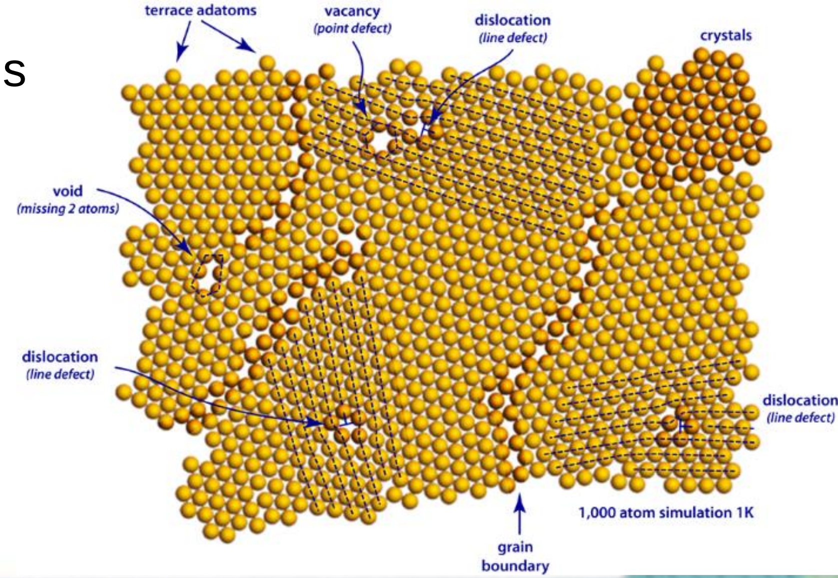
Porosity is often a defect in structural load bearing materials

Bubbles formed during pouring should be removed in metal casting

Ceramics which are in solid phase during manufacturing need to be sintered to high temperatures to eliminate pores

Hence elimination of uncontrolled porosity is an engineer’s goal.





Effect of porosity on mechanical properties of ceramics

The relation between compressive strength of brittle ceramics and porosity is approximated by Rice et al in the form of an exponential function as

$$\sigma = \sigma_o e^{(-bP)}$$

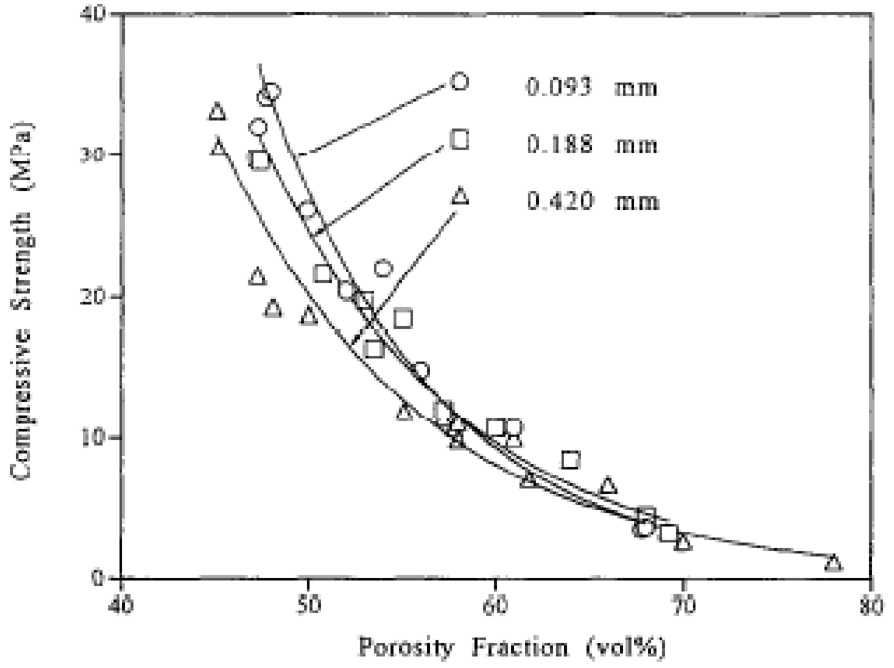
where σ_o is zero-porosity strength, σ is the strength at porosity P, and the constant b is the stress concentration factor that is mainly dependent on pore morphology

b is between 4 and 7 for most ceramics with regular pore morphology
Most ceramics contain pores that are ellipsoidal in shape
Large macropores are known to intensify the stress more than smaller macropores

As a general rule of thumb, strength of ceramics decreases to half by every 10% increase in macroporosity

Influence of pore size on the compressive strength of hydroxyapatite

$$\sigma = \sigma_0 \exp(-bp)$$



Similarly, elastic and shear moduli of ceramics depend on porosity exponentially

$$G = G_0 \exp(-b_G P)$$

For quantifyable porosity

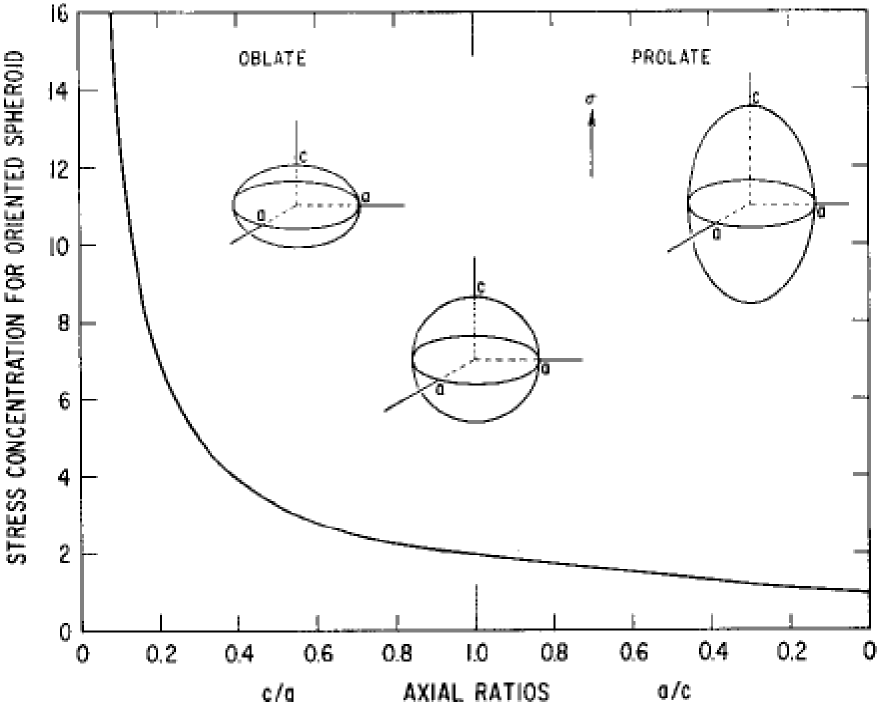
$$E = E_0 \exp(-b_E P)$$

$$G = G_0(1 - b_G P)$$

For low porosity

$$E = E_0(1 - b_E P)$$

$$E = E_0\left[1 - \left(\frac{5a}{4c} + \frac{3}{4}\right)P\right]$$



Stress concentration factor is much higher for disc-like pores

Desirable effects can be produced in a material by introducing pores in a controllable way

Pores are a specific second phase (air) in a matrix of metal, ceramic, polymer or glass

Any material property can be modified by leaving its pieces out or replacing by air

10 ppi

30 ppi

60 ppi

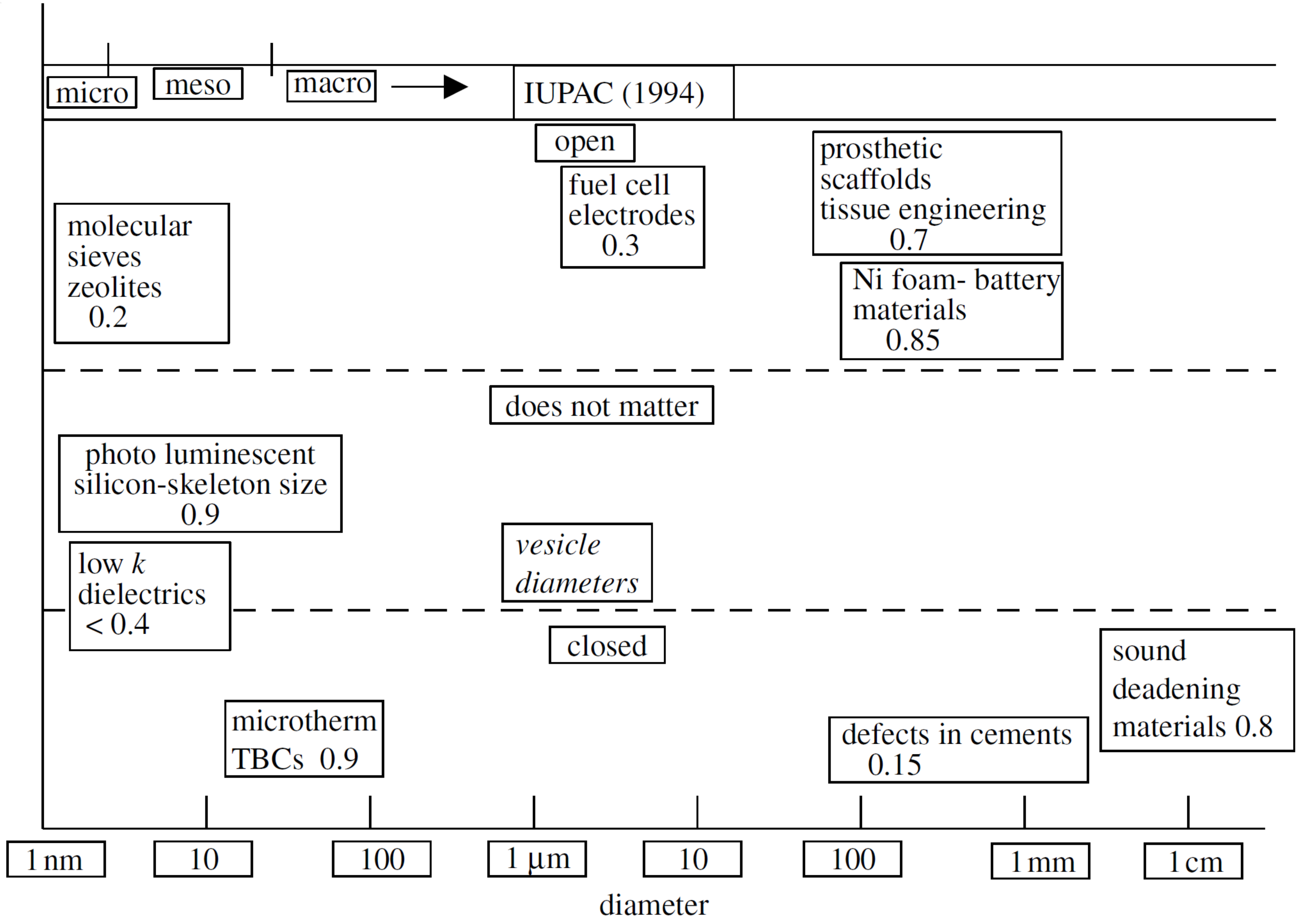
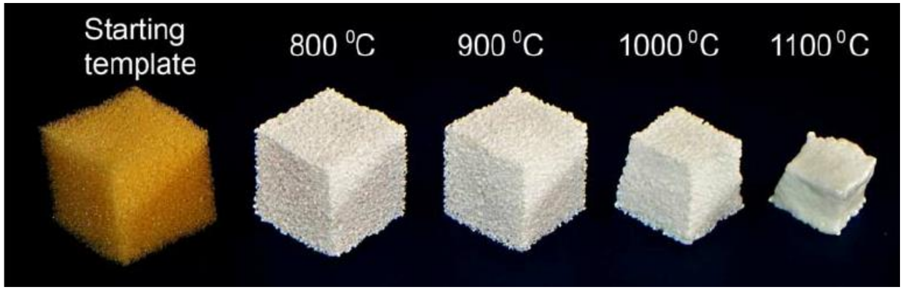


Figure 1. The range of optimum pore size and volume fraction for a number of applications of porous solids.

Porous ceramics are used as heat insulators, catalyst supports, radiant burners and hot gas or molten metal filters. They are usually made by sintering, and porosities up to about 40% are produced



The fracture strength is decreased more than would be expected from the change of Young’s modulus or fracture energy. The effect on thermal shock resistance is variable

Highly porous mullite is a useful matrix for Al_2O_3 or other fibres in a ceramic matrix composite
Porous ceramics provide a weak interface to inhibit crack growth into the fibres.

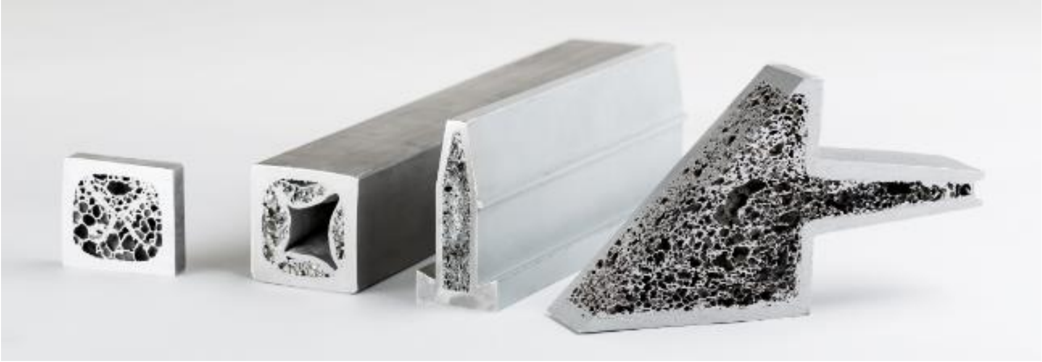
Porous carbon of high thermal conductivity is used in brakes

Highly porous metallic foams are commonly finding use in aerospace and automotive industry

Commonly used metals are Al, Ti and Ni

These have much of the properties of the parent metal, but are much lighter.

The most prominent application is in the core of sandwich structures used in structural applications, where saving weight is important (for example bumpers in cars)



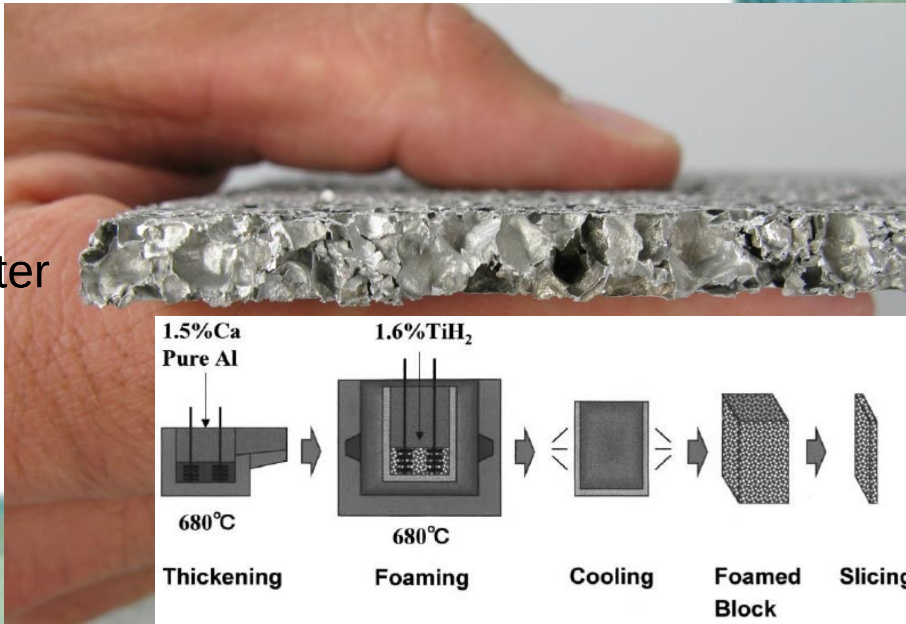
They have excellent energy absorption because porous metals convert much of the impact energy into plastic work and absorb more energy than the bulk metal at relatively low stresses

Compared with ceramic foams they are much more ductile and conduct heat and electricity much better, but are generally less stiff and less heat and corrosion resistant.

Compared with polymer foams they are stronger, stiffer and show higher conductivities of heat and electricity; they are heavier and much more expensive to make.

A good example of a porous aluminum used in energy and sound absorption is a closed cell foam of 80–90% porosity with pore sizes in the millimetre range.
Such a material called Alporas is also used for electromagnetic shielding.

Open cell nickel foam used in Ni–Cd rechargeable batteries has a cell diameter varying from 400 mm to 1 mm with a mean cell diameter of 0.5 mm

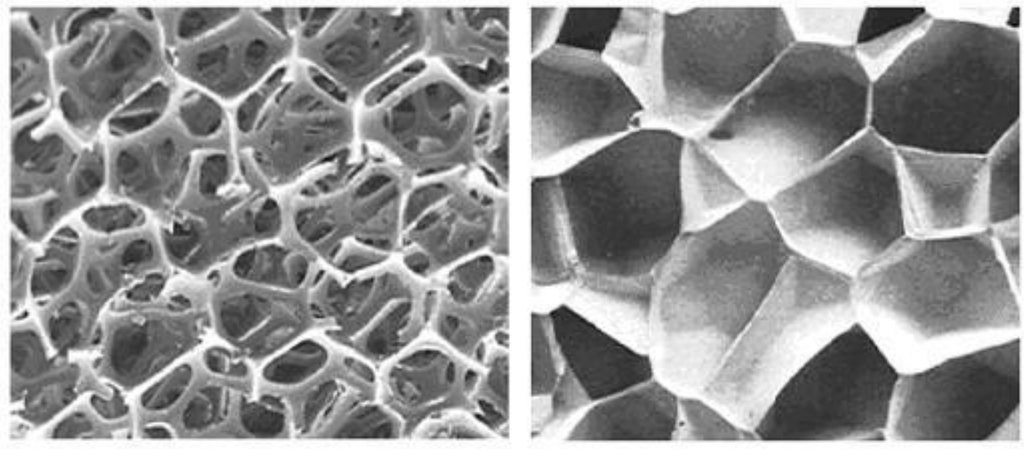


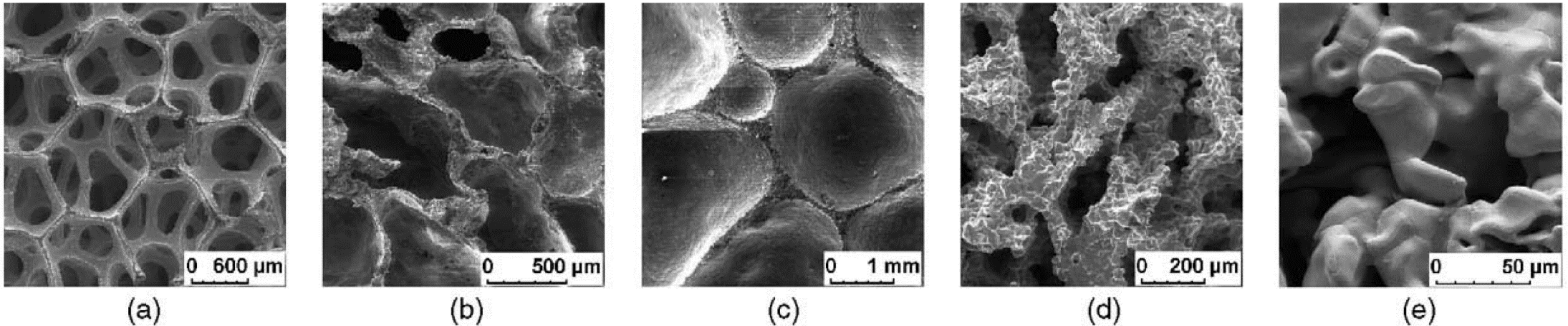
Different cellular structures result in different mechanical properties

Space in a cellular metal material (CMM) is divided into distinct, empty cells separated by boundaries of solid metal

Basic definitions

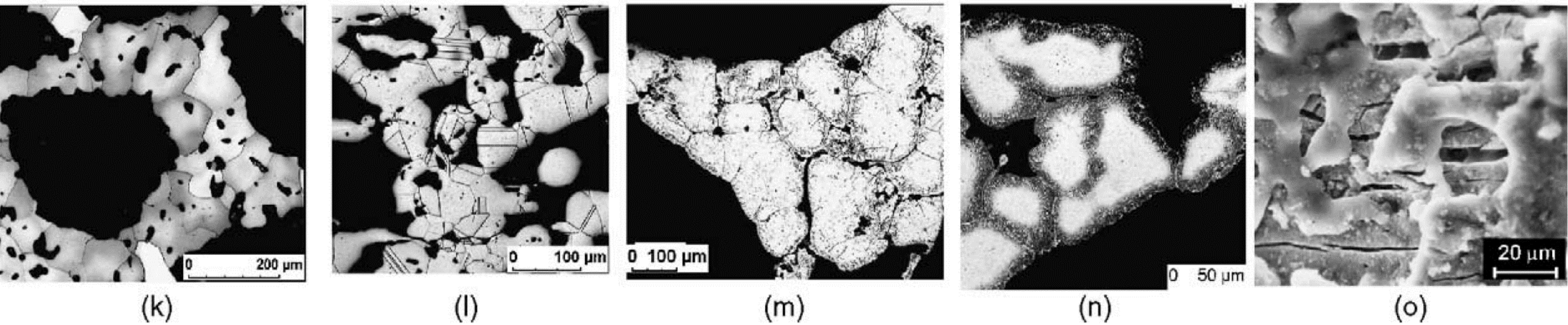
- porous metal (containing closed, convex gas pores),
- metallic foam (special case of porous metal: a solid foam originates from a liquid foam with dispersed gas bubbles),
- metal sponge (co-existing, continuous networks of both metal and empty space).





(a) (b) (c) (d) (e)

(a) Ni-based sponge, P ≈ 96%; (b) not perfectly close cell Zn foam, P ≈ 88%; (c) close cell Al foam (Alporas®), P ≈ 86%;(d) foam-like porous Ti P ≈ 68%;, (e) sponge-like porous 316L steel, P ≈ 45%.



(k) (l) (m) (n) (o)

Details of some CMM “micro” structures: (k) micro and macro pores in sintered Ti (FZJ); (l) twins in 316L porous steel (GKN); (m) grains in vertex of AlSiMn0.6 foam; (n) heterogeneity of grains in cell wall and vertex of AlCu foam; (o) micro cracks in the cell wall of AlSi12 foam

The main engineering parameter of porous materials, porosity, is defined as P = 1 − ρ∗/ρs, where ρ∗ is the density of the porous material and ρs is that of the solid of which it is made.

the relative density ρ∗/ρs is a function of cell wall thickness (t) and cell edge length (l)

$$\frac{\rho^*}{\rho_\mathrm{s}} = C_\mathrm{o}\left(\frac{t}{l}\right)^2$$

open cell

$$\frac{\rho^*}{\rho_\mathrm{s}} = C_\mathrm{c}\left(\frac{t}{l}\right)$$

closed cell

where Ci are constants which depend on the details of the cell shape. Other important parameters of CMM are the volume fraction φ of solid contained in the cell edges (or 1 − φ in the cell wall faces; for ideal open-cell structures φ = 1), the sphericity SP = 6V√(π/S3) ≤ 1 (S and V are surface and volume of cells), the connectivity factor C = 1 − N/Nic (Nic is the number of interconnected cells and N is the number of all cells in a given volume), and the morphological factor R (cell elongation).

Mechanical properties of CMM are in principle influenced by all of the above parameters. Therefore, data for different CMM normally do not fit to a single line when plotted as a function of just one parameter like ρ∗/ρs

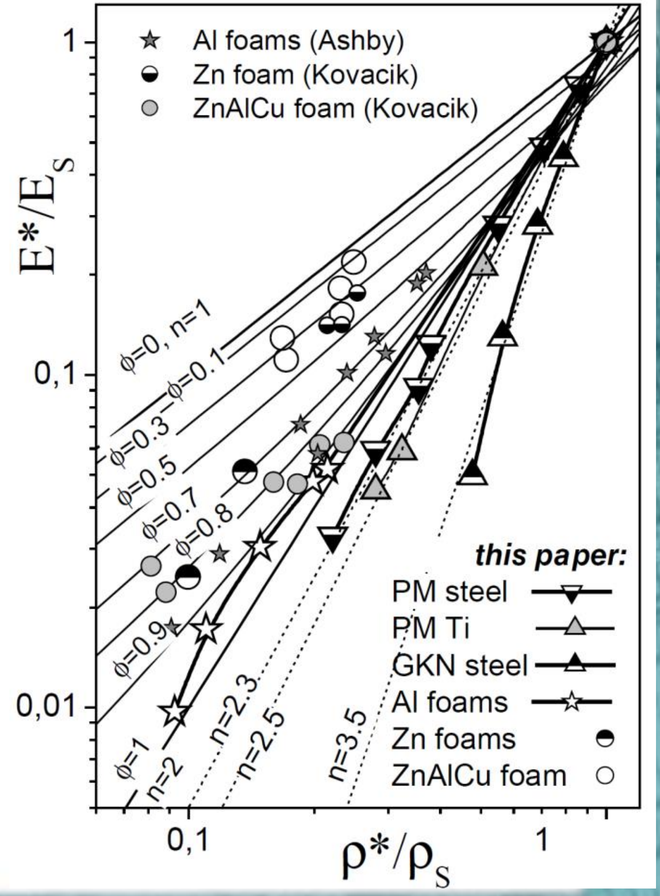
For open cell structures

$$\frac{E^*}{E_s} = C\left(\frac{\rho^*}{\rho_s}\right)^n$$

For closed cell structures

$$\frac{E^*}{E_s} \cong \xi_1\phi^2\left(\frac{\rho^*}{\rho_s}\right)^2 + \xi_2(1-\phi)\left(\frac{\rho^*}{\rho_s}\right)$$

with constants ξ1 and ξ2, which roughly fits to $1 < n < 2$



Thermal insulation applications

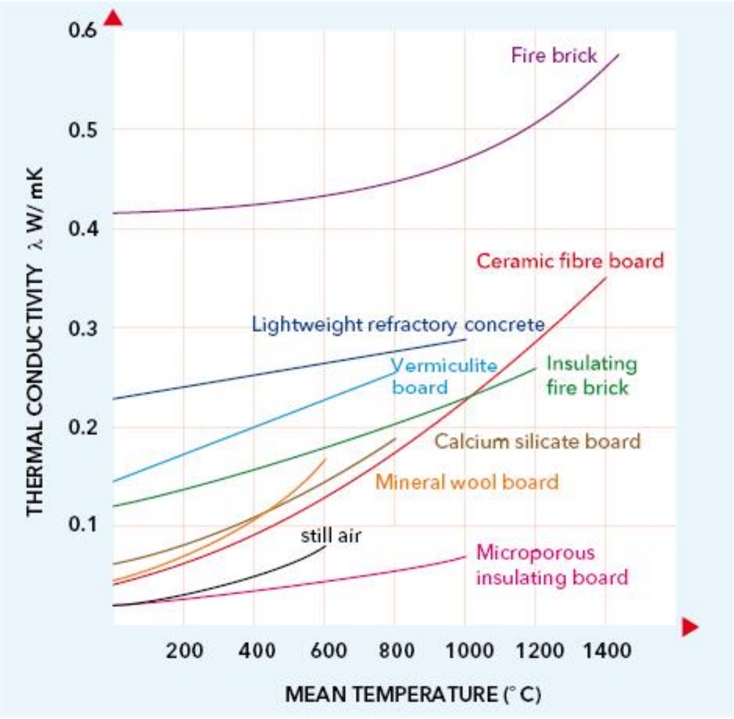
To provide the lowest possible thermal conductivity of a solid we must minimize

i. solid conduction
    attained geometrically by providing as small a cross-section as possible of solid material in the conduction path
    and by forming the material from a highly imperfect inorganic solid
ii. gaseous convection
iii. transmission of infrared radiation
    The dominant conduction process at temperatures above 100 C
    Opacifiers (semiconductors of a certain band gap) or scatterers with high refractive index such as metal oxides are used
iv. gaseous molecular conduction

To minimize heat transfer across the porous material, voids should be present at as high a proportion as possible
These must be small so that transmission of heat by convection currents is reduced

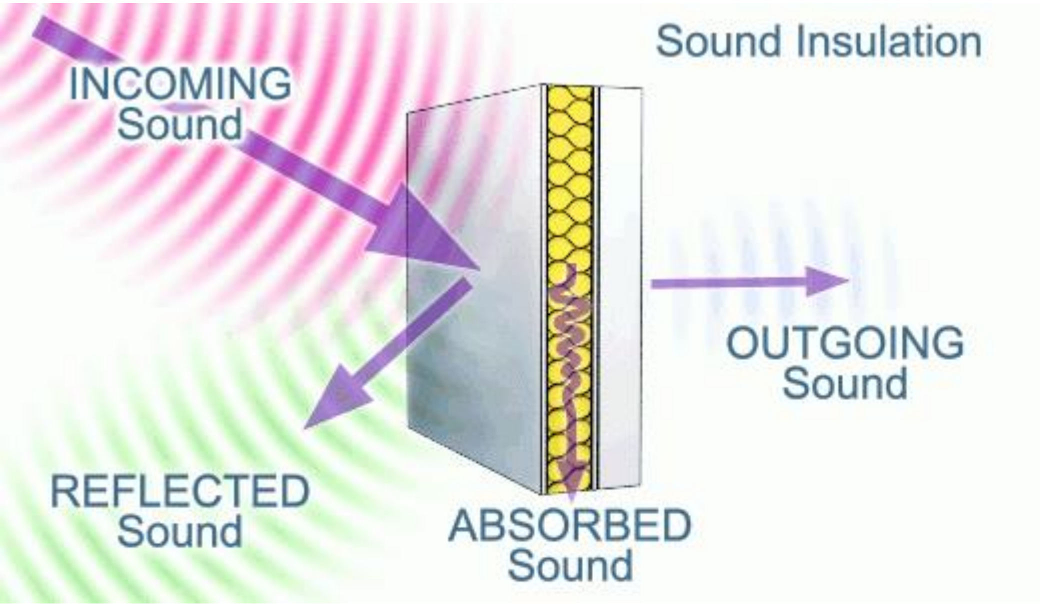
The ideal material is an oxide ceramic with about 90% closed porosity with mean pore size less than 100 nm (the mean free path of still air at standard temperature and pressure).

The mean free path is the average distance traveled by a moving particle such as a molecule between successive collisions which modify its direction or energy



The physical principles involved in the transmission of other kinds of waves are similar to thermal waves

Transmission of sound waves (acoustic isolation) or shock waves also depend on the area of the direct path in the solid material and any microstructural feature added for reflection and absorption of the waves



So a foam also provides the most efficient acoustic and vibrational isolation.

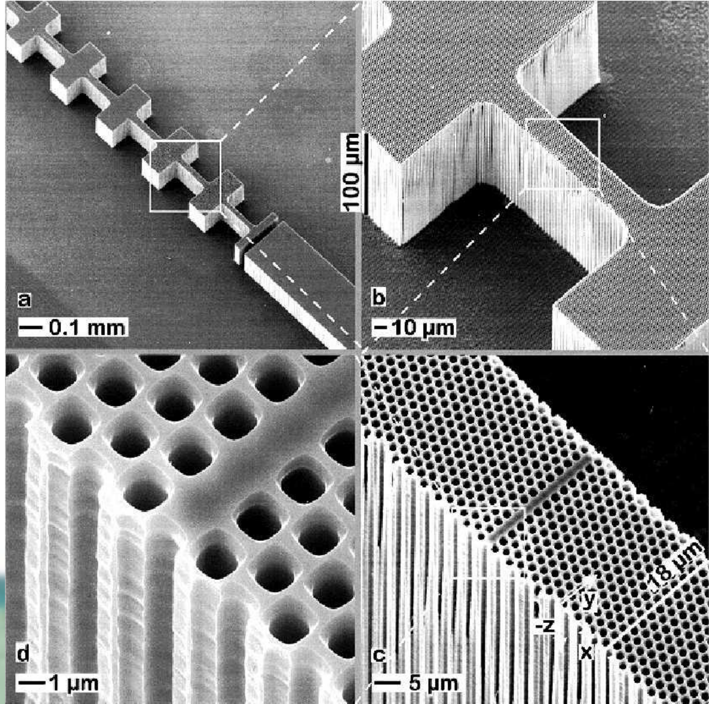
Electronic applications

A foam of a small cell size is a way to produce very large number of small pieces of a material in the form of the cell walls

Typically cell diameters are about 10 times the cell wall thickness

Porous silicon is used in microelectronic devices as the skeleton in a porous structure with mean cell wall thickness greater than 5 nm and cell diameters greater than 50 nm. These materials with about 90 % porosity should be supported mechanically

Porous silicon has applications also in sensors and medical devices



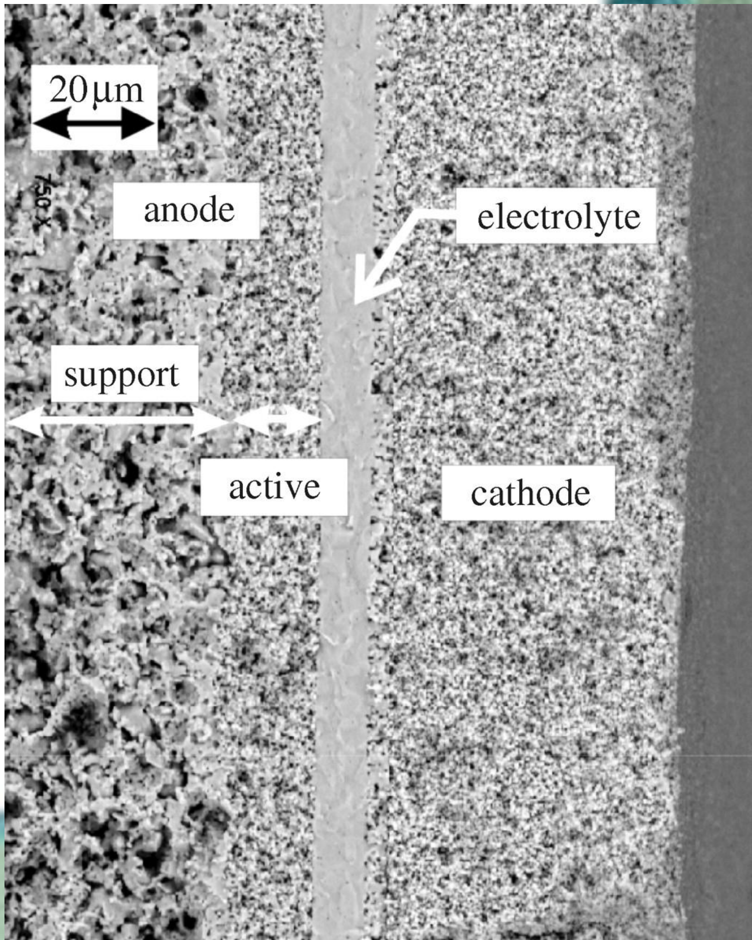
The electrodes in the fuel cells enable transport of gaseous or liquid species and react with them to produce electric current.
So they must be

- electronically conducting,
- electrochemically active,
- have large surface area
- have interconnected pores

(open cell foam structure)

In this application mechanical strength is important so the volume fraction of voids is limited to about 30% and the pore size is between 1 and 10 micrometers

A typical material is yttria-stabilized zirconia containing nickel oxide



Filtering and membrane applications

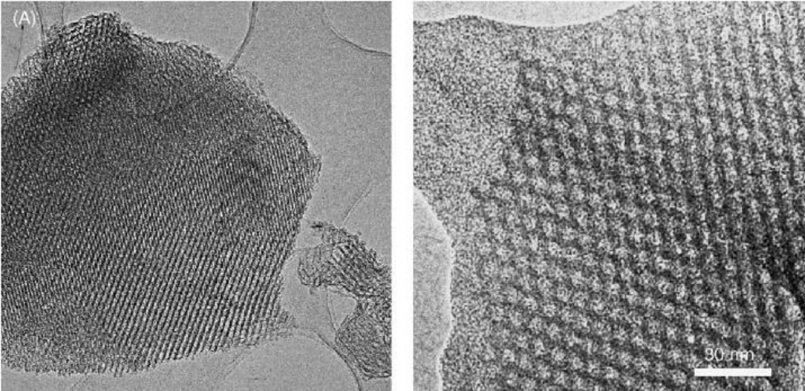
Microchanneled materials around 1nm in diameter can be used as filters for molecules

Zeolites are natural materials made of silicon, aluminium, oxygen, etc, that are highly porous crystals veined with tiny channels

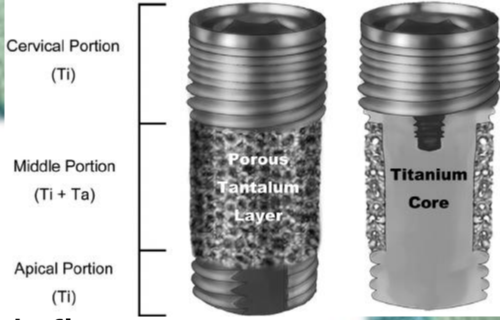
These channels contain water which bubbles out when heated
(zeo: to boil, lithos: stone)

Synthetic zeolites can be produced by sol-gel techniques

The structure of a zeolite is that of an open cell foam with pore diameters between 1=10 n and a pore volume fraction of about 20%
They are also used as catalysts and membranes similar to carbon and amorphous silica



Othopedic and tissue engineering applications



A synthetic material implanted in the body should cause no inflammatory reaction and be quite stable against corrosion by body fluid

Polyethylene reinforced with hydroxyapatite has elastic modulus similar to bone

The modulus of metals need to be reduced to match that of bone by introducing pores or holes

Titanium is corrosion resistant and biocompatible, and is much stiffer than cortical bone (100 GPa>30 GPa)

A volume fraction of pores of about 70% is needed to reduce the modulus near to that of bone

As a prerequisite of the application, bone ingrowth to the implant requires an optimum open pore size of between 100-400 micrometers

Producing a scaffold for use as a bone graft using a porous material is a major area of tissue engineering research

Controlled porosity polymer ceramic composite scaffolds with three-dimensional interconnectivity can be designed to promote a richer supply of blood, oxygen and nutrients to promote growth of bone cells

Polypropylene containing various amounts of tricalcium phosphate is a common material used to make scaffolds with pore volume fractions between 36-52% with pore diamaters between 150-200 micrometers by rapid prototyping method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