× 100

Many substances—
aqueous solutions, polymers and
glass—can be foamed. Foaming metals is
a challenge, made difficult by the high
temperatures needed and the reactivity of the
molten metal. Only recently has high quality
metallic foam been possible. It's an intriguing
material for the new millennium and may soon
be used to improve car passenger safety

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Foam Metal: The Recipe

*G*iven the three states of matter—liquid, solid, gas—there are many possibilities for dispersing one substance in another, as shown in *table* 1. Foams are just one special case of such dispersions. The term "foam" is usually reserved for a dispersion of gas bubbles in a liquid. The morphology of such foams can be preserved by letting the liquid solidify thus obtaining what is called a "solid foam" (often just called "foam").

These solid foams are a special case of what are more generally called "cellular solids." As in a liquid, the need to minimize surface energy allows only certain foam morphologies; the solid foam, which is just an image of its liquid counterpart, is also restricted. Cellular solids, in contrast, can have almost any morphology, the open structure of sintered powders, for example.

It is perhaps surprising that metals can be foamed. Actually, almost any material that can be melted can be foamed. For each of the following materials: metals, aqueous solutions, beer, milk, polymers and glass, the foaming process and the mechanisms stabilizing the cells are very different. However, there are some universal features common to all foams which will become clear when the foaming process is analysed later. Solid foams made from their corresponding liquid

systems have some interesting properties, which is the reason for their industrial relevance, *see* Cellular Solids by Gibson and Ashby.

In the past 40 years many attempts have been made to foam metals, but methods suffered from relatively high costs and produced only a poor quality foam material. In the last ten years there have been improvements, so that nowadays various methods for making metallic foams are available. Some start with the molten metal, others with metal powders (*see* Production Methods for Metallic Foams by Banhart and Baumeister). In particular, a powder method for foaming metals was invented a few years ago at the Fraunhofer-Institute in Bremen. It allows us to foam many metals and alloys based on, for example, aluminium, zinc, tin, lead, and gold.

The porous structure of a foam is evident when a metallic foam is cut apart. This can be seen on the photograph *at the top of this page*. The top image is a sandwich consisting of a foamed aluminium layer and two metallic face sheets. A photograph of the porous foam, enlarged by ten, was used for the cover of this issue. Magnification by one hundred reveals features such as the intersection of three cell membranes—a so-called Plateau border—*as shown above* and even the typical

solidification texture of the alloy.

The foaming process is rather complicated because at no time during foaming is a thermodynamic equilibrium reached. The expanding foam is a complex mixture of gaseous, liquid and solid phases. (*see box* Recipe for metallic foams). The various stages of foam evolution are shown in *figure* 1.

The first stage is pore formation: above the decomposition temperature of the blowing agent the evolving gas accumulates in tiny voids in the precursor material, forming a pore as pressure increases. If the solid precursor material is made by compacting powder, there will always be a sufficient number of residual pores or oxide filaments which can act as centres of (heterogeneous) nucleation.

Increasing the temperature further increases the gas pressure and reduces the strength of the metal, which practically vanishes at the melting point: pore growth begins and the pores are inflated by the evolving gas. Growth may not be isotropic because of textures in the solid which originate from the nature of the precursor material. A liquid foam is essentially unstable so that the foaming process ends with collapse and a partial destruction of the structure.

In *figure* 2 some of the stages of foaming are shown. Each stage was prepared
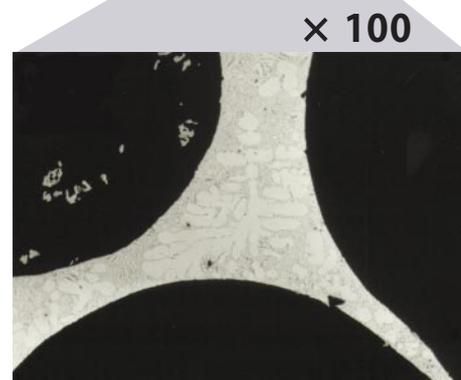
Left Table 1 Dispersions of one phase in a second one where each phase can be in one of the three states of matter. Systems considered in the present paper are in bold

Below Fig 1 Stages of foaming. The numbers correspond to those in figure 3

Fig 1

stage / process

	heterogeneous nucleation
1 formation	
2,3 growth	inflation
4 collapse	drainage
	coarsening

	when a gas	is dispersed in a gas	
when a liquid	gas mixture		is dispersed in a liquid
when a solid	fog	**foam**	is dispersed in a solid
	smoke	emulsion	**solid foam cellular solid**
	suspension slurry	gel	
	embedded particles		
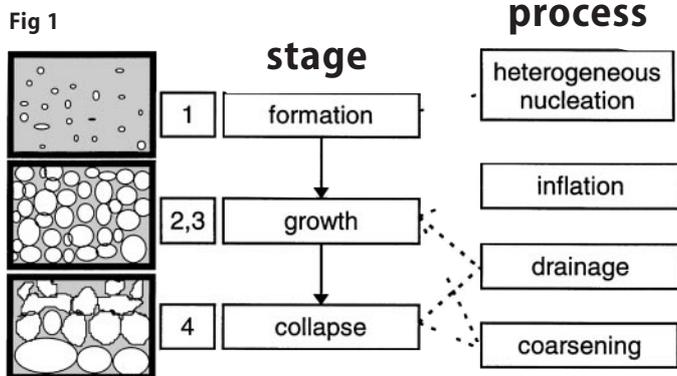
by interrupting the foaming process after a given time. The micrograph on the left represents an early stage of foaming. One sees tiny pores all over the sample. The image in the middle shows greatly enlarged pores which together take up most of the space. Finally, a foam with a very coarse pore structure and some signs of collapse is shown on the right.

In order to gain more insight into the foaming process time-resolved expansion curves of foams were measured. *Figure* 3 shows the volume and temperature of an aluminium foam as a function of time. The foam is made as follows: at the beginning a piece of foamable precursor material is put into a pre-heated furnace at 780°C. The material warms up, and at first the volume remains constant apart from the usual thermal expansion at temperatures up to the melting point (T_m = 650°C)

Recipe for metallic foams

1 Mix a metal powder with a blowing agent. For example, mix 99.5% aluminium powder with 0.5% titanium hydride powder.
2 Hot press, or extrude, the powder mixture. This should give an almost perfectly dense "precursor" material.
3 Heat the precursor to the melting point of the metal. As the metal begins to melt the blowing agent will release gas (hydrogen in the example given above).
4 Wait while the melt slowly expands. Because the process takes place in the liquid state, the pores and the outer surface will close due to surface tension.
5 Lower the temperature of the foam. Freezing the foam structure will give a solid metallic foam.

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of the alloy (*stage* 1). However, as soon as the sample starts to melt its volume increases owing to the internal pressure of the gas. During melting the temperature remains nearly constant (*stage* 2). Once all the metal is molten, the temperature begins to increase again and approaches the furnace temperature (780°C). The volume expansion speeds up and the volume finally reaches its maximum value of almost six times the original volume V_o (*stage* 3). After this, the formation of gas comes to an end and the unstable foam partially collapses (*stage* 4).

The causes of foam decay are two processes called drainage and coarsening. Drainage is the downward flow of liquid out of the foam through the cell membranes and is caused by gravity. Coarsening is the growth of some bubbles at the expense of others. One cause of this can be the diffusion of gas from one cell to another: pores with different diameters have different internal pressures because pressure is proportional to the inverse of the pore radius, so a smaller pore with a higher pressure disappears after giving its gas to a larger pore. In addition, the membranes between two adjacent cells can rupture spontaneously.

Figure 4 is a photograph of a foam sample which has undergone decay. As a result of drainage there is a thick layer of metal at the bottom. And due to coarsening, there are very large and irregular pores in the middle. Collapsed sections can be seen at the top. One can see exactly the same processes if one pours beer into a glass too quickly: first the entire glass will be filled with very fine froth. Then drainage causes an accumulation of
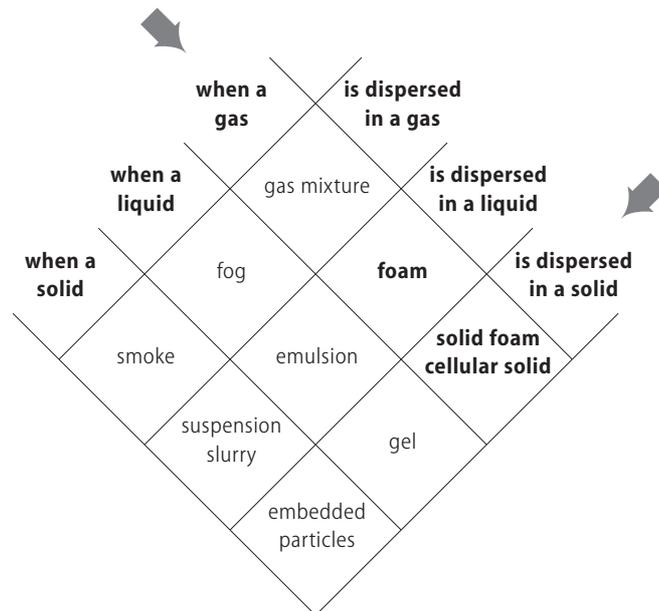
beer at the bottom of the glass and the foam gets coarser over time. This demonstrates that some of the phenomena observed are quite universal. However, with beer the flow of liquid out of the foam is necessary in order to obtain some drinkable beer, whereas drainage is unfavourable when making metallic foams. One tries to avoid it by keeping temperatures as low as possible, so keeping viscosity high, or by adding viscosity enhancing substances.

The image on the right of *figure* 2 shows the cell imperfections which can in principle occur in a foam. One can see remnants of ruptured cell walls, a variety of pore sizes and shapes, cell walls with an unfavourable curvature and other undesired deviations from what would be a perfect foam. One aim of current research is to find out how such imperfections can be avoided or at least minimized.

The most prominent property of foamed metal is its low density. Density values of aluminium foams range from 0.1 to 0.4 gcm^{-3} (solid aluminium is 2.7 gcm^{-3}) when using liquid metal methods (*see box* Alternative Recipes), whereas the powder method yields foams with densities ranging from 0.3 gcm^{-3} to 1 gcm^{-3}. The pores are predominantly closed and foams usually develop a closed outer skin hiding their porous structure.

The mechanical properties depend strongly on the apparent density of the foamed metal. Quantities such as Young's modulus, compression or tensile strength, for example, increase rapidly with increasing density. An example of density dependence is given in *figure* 5, where the deformation strain of an aluminium foam is shown as a function
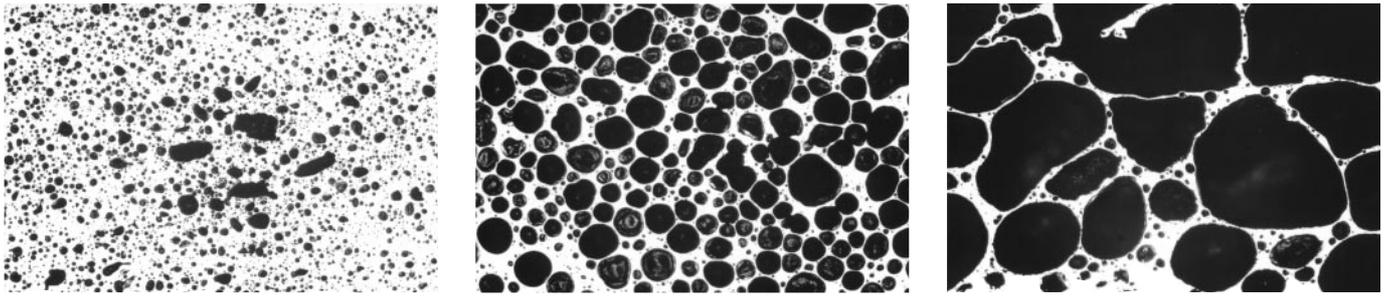
Fig 2 Zinc foam samples foamed at 600°C for 6, 7 and 8 minutes *left to right*—the black dots and circles are pores

of applied stress for different densities.

This deformation behaviour is typical of all kinds of foams not only metallic ones: there is a linear increase of stress at the beginning of the deformation and a plateau regime of nearly constant stress for deformations up to 60% followed by strong compaction for even higher deformations. As well as density, mechanical properties are also influenced by the choice of the matrix alloy. By foaming age-hardenable alloys the strength properties can be optimized. Due to the special form of the compressive stress-strain curve, foamed materials are capable of absorbing large amounts of energy at relatively low stress levels. Metallic foams behave exactly like conventional foams, for example polyethylene foams, with the only difference that their strength is about 30 times higher at the same level of porosity.

So far the foaming process and some properties of metallic foams have been described. For real applications the foam has to be processed and integrated into technical systems. Making parts is therefore important. Foaming precursor material in a furnace results in a shapeless piece of foam unless one restricts spatial expansion. This is done by foaming inside closed moulds. In this way, almost any shape can be made. Foam and conventional metallic parts can be joined during the foaming process. Metallic profiles, for example, can be filled with metallic foam. By bonding metallic face sheets to a sheet of foamable material and, after an optional deformation step, foaming, 3D-shaped sandwich structures, such as the one shown on *page 17* can be made.

There are many possible engineering applications for metallic foams ranging from lightweight construction, sound and heat insulation to energy absorption applications. In the past few years there has been an increase in interest especially for metallic foams made of aluminium or aluminium alloys. The demands of passenger safety, in automobiles for example, or aspects of materials recycling, have recently encouraged manufacturers to consider using metallic foams, whereas just a few years ago the same material would have been ruled out for technical or financial reasons. Up to now, aluminium foams have been applied only on a small scale in demonstration and testing. There are a number of companies in Europe that are now developing production facilities for aluminium foams. Various ideas are currently under investigation.

Possible applications for metal, especially aluminium, foams exist in the automotive industry, aviation and space industries and building and constructing industries, for example.

Measures taken to improve the safety of automobiles usually lead to a high vehicle weight, which increases fuel consumption. Light, stiff structures made of aluminium foam, preferably in the form of sandwich panels, could help to reduce weight. Examples are bonnets, boot lids, front or rear walls, where a high stiffness is needed in order to prevent these parts from vibrating or to avoid torsional deformation. The German company Karmann (Osnabrück) is currently testing 3D-shaped sandwich panels for use in convertible cars, where stiffness problems frequently occur.

A further important application for metallic foams is energy absorption. Using suitable elements of aluminium foam it is possible to induce a controlled, programmed deformation of the crashed zone in cars or trains with maximum energy consumption. Possible applications exist in side and front impact protection,

Fig 4 Aluminium foam sample which has suffered heavy drainage and partial collapse after overheating
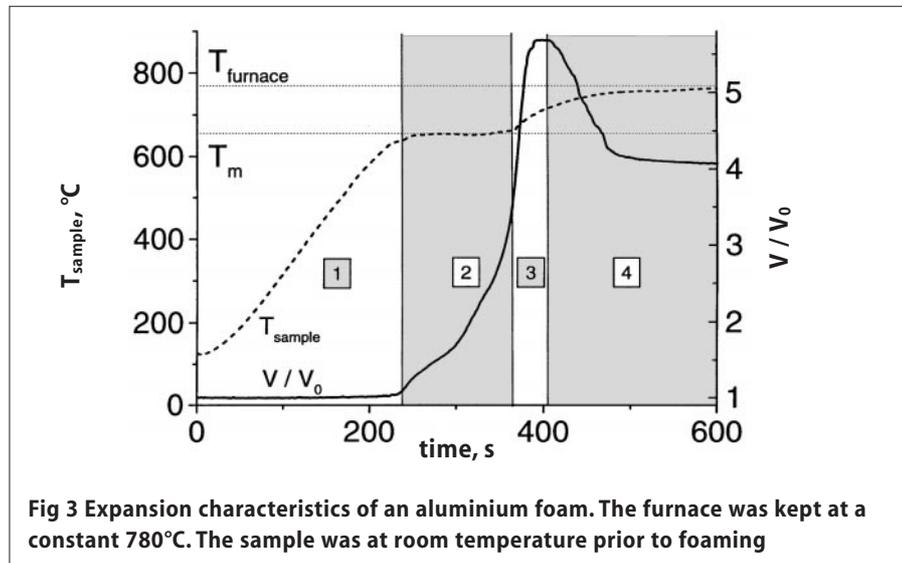
Fig 3 Expansion characteristics of an aluminium foam. The furnace was kept at a constant 780°C. The sample was at room temperature prior to foaming
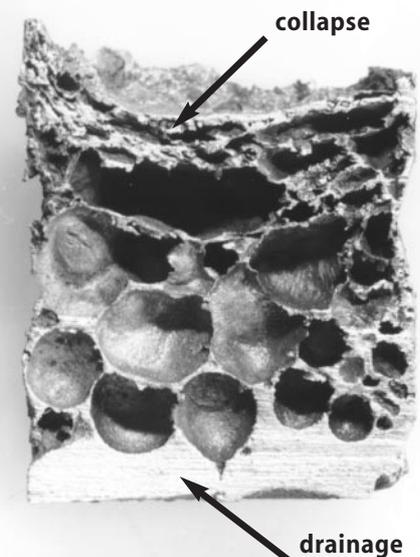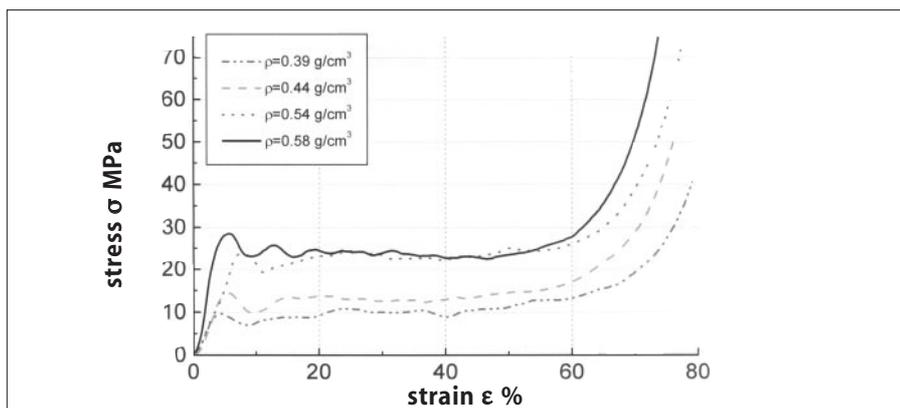
Fig 5 Deformation behaviour of various aluminium foams. Deformation strain versus applied stress is shown

especially in the new generation of compact city cars (such as the new Smart car *below*) where the realisation of such energy absorbers is a difficult task because of the limited space available.

Metallic foams are useful because of their high energy absorption capacity per volume and per mass unit. Taking the values given in *figure* 5 for a foam of density 0,58 gcm^{-3} gives an absorption capacity of 24 kJ per kg of foam, or equivalently 14 MJm^{-3}. This is much more than the energy absorption capacity of high strength polymer foams made, for example, from polymethacrylimid, particularly for the energy per volume ratio. Another advantage is the isotropy of energy absorption which is important in many crash situations.

An interesting property of foams is their influence on the deformation behaviour and failure mode of aluminium and steel profiles and other hollow parts when they are filled with foam. A foam filling generally leads to higher deformation forces when profiles are bent, to higher energy absorption, when profiles are axially crushed. This property could be used in bumpers, the underride protections on lorries, the pillars next to car doors, or other elements which are in danger of buckling or being compressed or have to absorb a large amount of energy.

In the aerospace indus-

try the replacement of expensive honeycomb structures by foamed aluminium sheets or aluminium foam sandwich panels could lead to reduced costs. An important advantage is the isotropy of the properties of such panels and the absence of any kind of adhesive bonding. The latter gives rise to a more benign behaviour in the case of fires where it is essential that the structure maintains its integrity.

Aluminium foams or foam panels could be very helpful in reducing the energy consumption of elevators. Because of the high frequency of accelerations and decelerations lightweight construction is an important issue.

The properties of the foamable precursor material can also be used: in order to fasten plugs in concrete walls a piece of foamable aluminium is inserted into the borehole before the plugs are inserted. The foamable precursor material is then heated up locally thus enabling its expansion. The foam generated this way will fill the gap between concrete and plugs and lead to a very strong connection provided the density of the foam is not too low.

As already mentioned, metals other than aluminium can be foamed. Lead

foams could serve as supports for the active mass in lead-acid batteries thus making the construction of very light electrodes possible. Foams based on gold or silver offer new design opportunities and could be used for jewellery or decoration.

The research field of metallic foams, however, is still rather young and some questions still have to be answered. Nevertheless, manufacturing processes are now advanced enough to open a way towards industrial application. For physicists the work generates a fascinating perspective, working at the direct interface of fundamental and application oriented research.

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Further reading
Cellular Solids by L.J. Gibson, M.F. Ashby (Oxford University Press 1997) • Production Methods for Metallic Foams by J. Banhart, J. Baumeister *MRS Symp. Proc.* **521** (1998)

Alternative recipes
Foaming metallic melts directly

*M*etallic foams can also be prepared by adding a blowing agent to a bath of molten metal after properly adjusting the viscosity of the melt. For aluminium this can be done for example by adding calcium metal. The blowing agent is usually a powdered metal hydride which releases hydrogen when it comes into contact with the molten metal. If a sufficient amount of hydride is added, the entire metal bath starts to bubble and to expand. The result is a block of foam which can be cut into sheets for further processing.

An alternative way to foam aluminium is to add some (10-15%) silicon carbide particles to a melt. Provided the powder and the mixing procedure are appropriate, the manipulated melt has an enhanced viscosity and can be foamed by introducing gas with a rotating nozzle. The resulting foam will accumulate on top of the liquid and can be drawn off by a conveyor belt. Foam slabs of considerable size (*eg* 0.1 × 1 × 10 metres) can be produced this way. However, there are still problems with drainage effects and the homogeneity of such foams.