Cellular Metals: New Materials, New Applications, New Science

D.L. Weaire[1], J. Banhart[2] and S.J. Cox[1]

[1] Trinity College Dublin, Ireland.
[2] Fraunhofer Institut für Fertigungstechnik und Angewandte Materialforschung, Bremen, Germany.

Abstract

The technology of metallic foams is beginning to reach the market of industrial applications. We sketch the underlying science and describe simulations of the effects of drainage under gravity in the fabrication process.

1 Introduction

In the last few years metallic foams have attracted the interest of the worldwide research community. They are by no means new materials, but they have reached a stage of development at which they can begin to be taken seriously as future industrial materials. To qualify as such, efficient and well controlled fabrication processes are needed, and a range of these now exists, from investment casting of open cell foams to foaming of large slabs by injection of gas into liquid metal. Intermediate between these is the powder metallurgy process of the Fraunhofer Institute in Bremen [1, 2], described in figure 1. In this, a blowing agent releases gas close to the melting point of the material, which can be relatively pure aluminium. In the alternative method of sparging to create large samples, special alloys and additives are needed to maintain a high viscosity, indeed a semi-solid state.

All of these methods have been steadily refined, and some startling progress was reported at the recent MetFoam conference in Bremen. The proceedings [3] provide a comprehensive and up-to-date overview of the field. A high degree of homogeneity can now be routinely achieved, satisfying one of the engineer's main requirements. Nevertheless, many questions remain regarding the nature of the material and the physical and chemical principles that govern its formation.

For example, in the case of aluminium, which is the main constituent of most commercial metallic foam, an important rôle has often been attributed to the surface oxide layer. This is supposed to act as a surfactant, stabilising the films between the gas bubbles, but this has not been investigated in detail.

Even the very structure of the foam, while critical in many of its applications (such as sandwich panels for construction and crash boxes for energy absorption), has been only rather loosely characterised. Roughly speaking, it may be said to be analogous to that of a typical aqueous liquid foam, with the same main elements: **bubbles**, separated by **thin films** connected to **Plateau borders** which meet at **junctions** [4]. Indeed, much of the theory of liquid foams has direct relevance - for example, the Lemlich formula for conductivity [4, 5]. But a foamed metal, while it may begin in the liquid state with such an ideal structure, typically exhibits considerable departures from it in its final state. Cells may undergo severe distortion in cooling, with cracking of solidified films. The mechanical properties of the material are generally thought to be optimal when such effects are minimised and the material retains the structure of the liquid foam to the greatest possible extent.

In the worst cases, the foam actually collapses before it is solidified. Figure 2 compares a well formed foam with a sample that has been over-heated. This occurs because gravity-induced drainage has reduced film thicknesses to the point of instability.

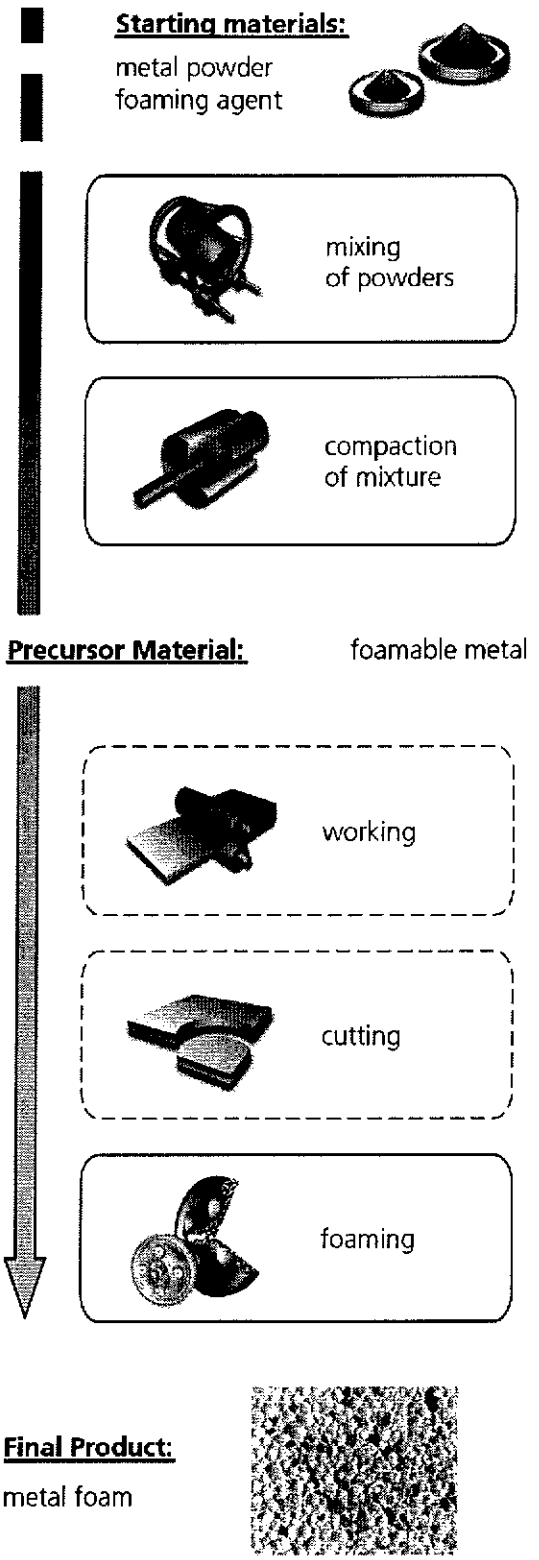

Fig. 1: The powder metallurgical process of metallic foam production.

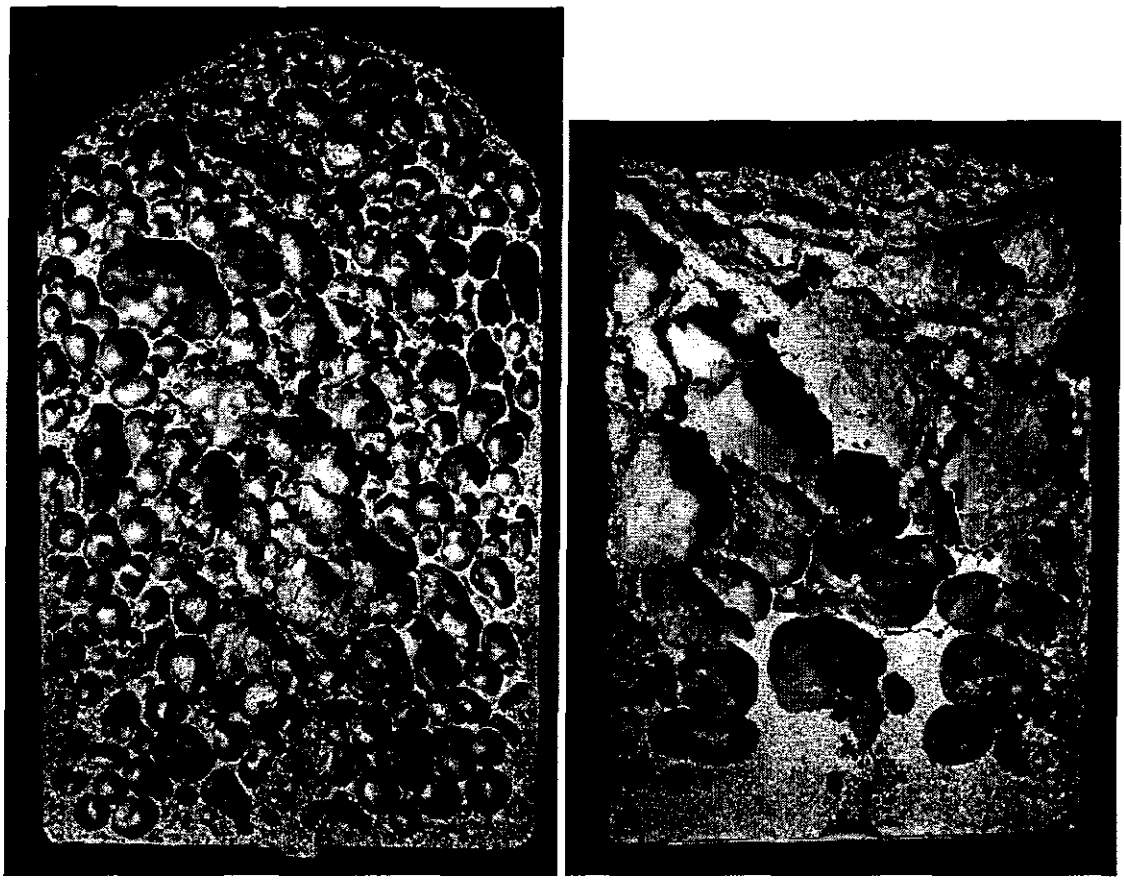

Fig. 2: The photographs show cross-sections through samples of foamed aluminium, which have been formed in a mould. The sample on the left is well-formed, while the one on the right has been kept in the furnace for a longer time leading to structural collapse. Both pictures are reproduced from [1].

While foamed semi-solid materials may not be prone to this, samples made with powder metallurgy may be seriously affected, and this poses a limitation on their size. We have studied the combined effects of the drainage and solidification processes, in simple terms, by using elements of the standard theory of liquid foams in a computational simulation [6] to model this "race against time". In this paper we shall describe the model in basic terms, briefly review its application to a hypothetical one-dimensional experiment, and describe the implications for large, truly three-dimensional foams.

2 Mathematical Model

We model the process of solidification and drainage, assuming that the bubble melt has been fully expanded. The mathematical representation is based upon the now well-known foam drainage equation, which has been extensively tested and verified for aqueous foams [7, 8, 9]. This nonlinear partial differential equation describes the variation of the liquid fraction of a foam (here we prefer the term *relative density*, since the foam solidifies) with position and time. In the present model this is combined with the equations of heat conduction, so as to describe the motion of the freezing fronts. For more details see [6], which treats a one-dimensional foam, and includes effects such as bubble growth.

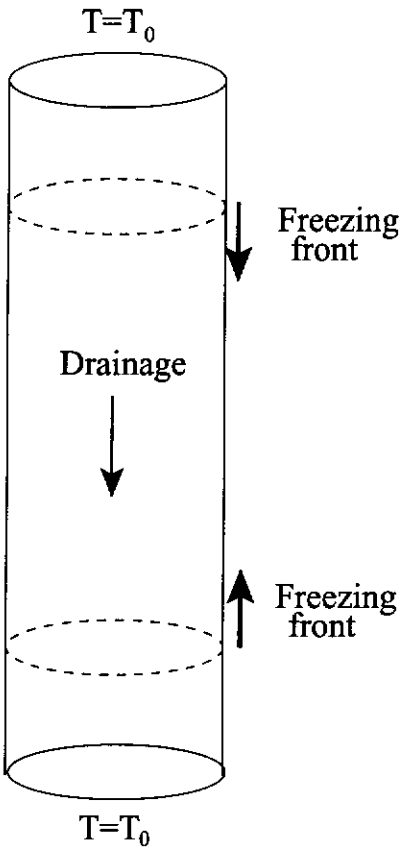

Fig. 3: This sketch of a one-dimensional foam which is cooled from both ends shows that the central region in which drainage occurs shrinks as the freezing fronts move inwards.

These two systems of partial differential equations are non-dimensionalised and solved simultaneously, using a finite difference representation. Boundary conditions must be specified for both the liquid and the temperature. For our purposes it is helpful to think of an experiment in which the foam is cooled from all of its external faces, so that the boundary temperature is everywhere equal to a constant value which is less than the melting temperature. Since this rapidly induces freezing, we apply the condition that there is no liquid flow at any of the boundaries. The initial conditions are that the profile of relative density is initially uniform - i.e. the foam has the same wetness throughout, and that the temperature is constant (and greater than the melting temperature) everywhere in the bulk.

3 A One-dimensional Sample

We consider first a one-dimensional experiment, in which a foam is expanded and insulated at the sides. Then the freezing proceeds simultaneously from top and bottom. Drainage occurs in a shrinking region at the centre of the foam, as illustrated in figure 3.

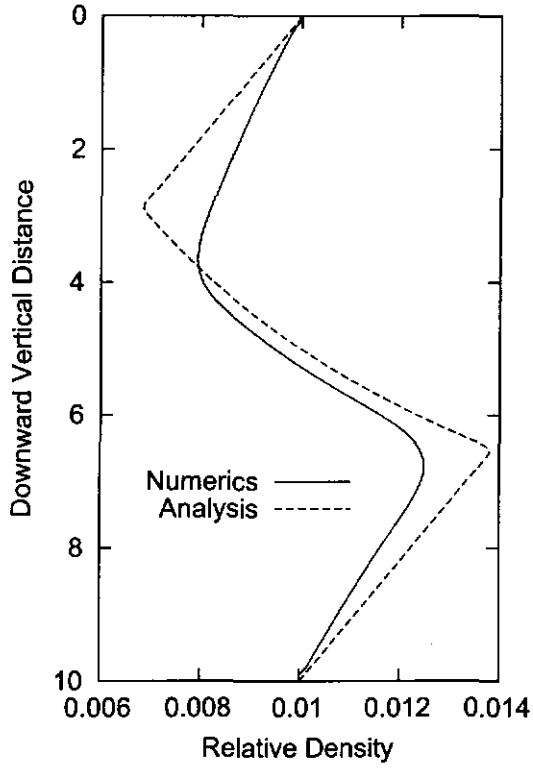

Fig. 4: The final, solidified, profile of relative density in a one-dimensional sample of metallic foam. The numerically obtained profile is compared with a theoretical curve based upon conservation of heat and energy. Both show a decrease in density close to the top of the sample and an increase in density towards the base.

3.1 Numerical results

We solve the coupled foam drainage and solidification equations numerically to determine the profile of density in the solidified sample. Initially the relative density is uniform. Then some of the liquid drains from the top, so that there is a decrease in density; this part of the foam is then frozen. A similar process occurs at the base of the foam, where liquid now accumulates. In this way the profile is built up, with increasing density at the base and decreasing density at the top. As the freezing fronts approach the centre of the sample, the density interpolates smoothly between the two ends, giving the profile shown in figure 4. It has the form of a (smoothed) saw-tooth shape.

3.2 Theory

For the one-dimensional case we have also developed a theoretical analysis [6], based upon conservation of liquid and of energy. This leads to a prediction of the distribution of relative density in the solidified foam. As shown in figure 4, it shows good agreement with the numerical calculations. Moreover, the theory gives a measure of the degree of inhomogeneity in the foam, i.e. how far the relative density departs from its initial value. We are then led to a criterion for obtaining uniform samples of foam in the form of a relationship between the material and physical parameters which describe the foam.

This *homogeneity criterion* is

$$\frac{L_f \rho^2 g L \Phi_l^0}{\kappa \Theta_{crit} \eta} \ll 1 \qquad (1)$$

where L_f, ρ, κ, Θ_{crit} and η are the latent heat of freezing, density, thermal conductivity, melting temperature and viscosity of the liquid metal, L is the length of the foam, Φ_l^0 is the initial relative density, and g is the acceleration due to gravity.

Note in particular that (1) exhibits linearity in the factors of gravitational acceleration and length. Thus doubling the length of a sample would lead to twice the degree of inhomogeneity, which may pose severe limitations on the fabrication of large samples. This effect may be reduced by a corresponding increase in the viscosity of the metal, or by fabrication in a microgravity environment [10].

4 Three-dimensional simulations

The extension of the one-dimensional case to a three-dimensional foam is relatively straightforward. We consider a similar scenario in which the foam is cooled from each of its edges, leaving a shrinking body of draining, liquid foam in the centre of the sample.

For example, figure 5 shows the distribution of relative density in a cylindrical sample of metallic foam. Liquid has drained from the top to the bottom of the sample, close to the centre-line. However the most of the foam has retained its initial relative density.

Figure 6 shows the distribution of relative density in a cube of metallic foam. The profiles are similar in nature to those in the cylinder of figure 5. Particular note should be taken of the triangular regions of homogeneous foam.

In general, the volume of uniform foam can be increased by changing the aspect ratio of the sample; i.e. by aligning the long side of the foam with the direction of gravity.

5 Outlook

A great deal of effort is being expended in applying the technology of metallic foams in the automobile industry and elsewhere. More basic studies are now under way in many laboratories. Our own contribution seeks to guide and interpret experimental studies of drainage, and hence delineate the limitations imposed by it, through criteria such as equation (1). Beyond this, and coupled to it, lies the important problem of coalescence, which is poorly understood even for aqueous foams [4]. Exciting opportunities also exist in the field of microgravity research [10], where the reduced effect of gravity will make these foams easier to fabricate and enable the foam to be retained in the liquid state for appropriate analysis.

Acknowledgements

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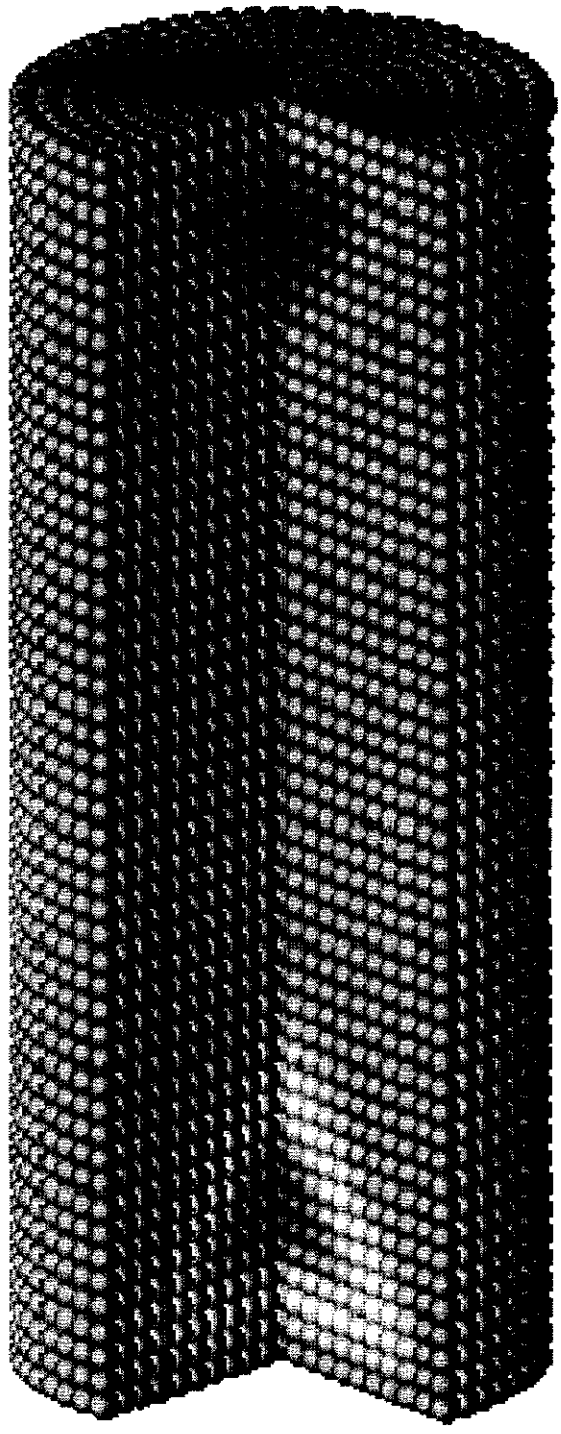

Fig. 5: A cylinder of metallic foam which has been cooled from all sides, and from which a quarter segment has been removed. The coloured spheres denote relative density: the blue areas close to the centre of the top of the sample have low density, while liquid has collected and frozen in the red areas close to the bottom of the sample.

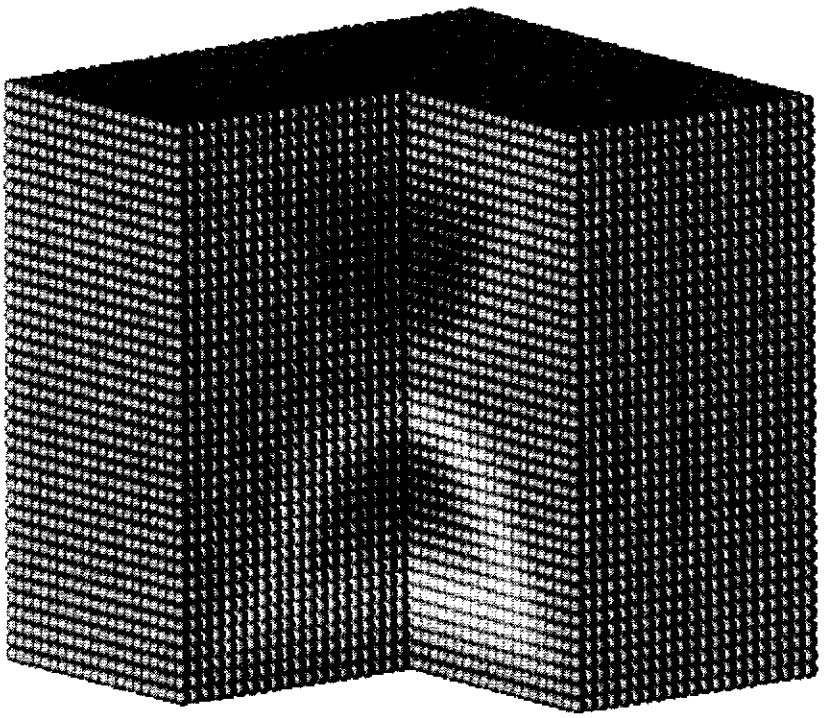

Fig. 6: A cube of solidified foam from which a quarter segment has been removed to show the distribution of relative density. The coloured spheres denote density, as in figure 5.

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