C. R. Physique 15 (2014) 696–704

Contents lists available at ScienceDirect

Comptes Rendus Physique

www.sciencedirect.com

Liquid and solid foams / Mousses liquides et solides

Structural properties of solid foams

Propriétés structurales des mousses solides

Pierre Lhuissier [a,b]

[a] *Univ. Grenoble Alpes, SIMAP, F 38000 Grenoble, France*
[b] *CNRS, SIMAP, F 38000 Grenoble, France*

ARTICLE INFO

Article history:
Available online 29 September 2014

Keywords:
Foams
Structural properties
Scaling laws

Mots-clés :
Mousses
Propriétés structurales
Lois d'échelle

ABSTRACT

The low density of foams is responsible for their high specific mechanical properties. Classical models describing the structural properties of solid foams are functions of the foam density. The exponent of the scaling law used to describe the evolution of the properties with density is a key parameter in order to optimise the foam for a given application. This exponent is generally assumed to correspond to particular local deformation mechanisms. Nevertheless, the underlying models are based on ideal foams. A finer description of the foam, taking into account the real architecture, the structural heterogeneities, and the constitutive material heterogeneity and defects, is required to explain and predict the behaviour of real foams.

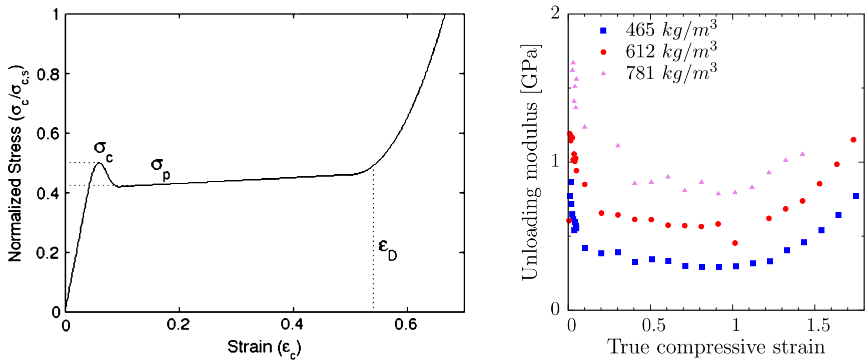
RÉSUMÉ

La faible densité d'une mousse est responsable de ses hautes propriétés mécaniques spécifiques. Les modèles classiques décrivant les propriétés structurales des mousses solides sont fonctions de la densité de celles-ci. L'exposant de la loi d'échelle utilisée pour décrire l'évolution des propriétés en fonction de la densité constitue un paramètre clé pour l'optimisation de la mousse en vue d'une application donnée. Cet exposant est généralement supposé correspondre à des mécanismes de déformation particuliers. Néanmoins, les modèles sous-jacents envisagent des mousses idéales. Une description plus fine de la mousse, tenant compte de son architecture réelle, de ses hétérogénéités structurales, ainsi que de l'hétérogénéité et des défauts du matériau constitutif, est nécessaire pour expliquer et prédire le comportement des mousses réelles.

1. Introduction

The use of lattice structures allowed the development of metallic structures. A suitable organisation of beams and truss bars placed the matter only where needed while removing the inefficient one. By proceeding this way, engineers increased the moments of inertia of the structures while reducing the weight, and thus opened a huge field of application to metallic structures. The same considerations should be applied at a lower-dimensional scale: the scale of the material. By removing part of the matter or introducing a very low density phase inside the material, one can produce a new material whose combinations of properties are better in a sense than the bulk material.

http://dx.doi.org/10.1016/j.crhy.2014.09.003
1631-0705/



(a) (b)

Fig. 1. (a) Typical stress–strain curve for metal foam in compression (from [1]). (b) Typical evolution of unloading stiffness with compressive strain for a metal foam in compression (from [2]). Stiffness level increases with foam density.

Depending on the processing route chosen, foams present an architecture that can be beneficial for the macroscopic mechanical behaviour. The parallel between foams and lattice structures can be carried out quite far in the description of the architecture and the characterisation of the mechanical behaviour.

In Section 2, the mechanical properties of foams and the classical models used to predict these properties will be presented. Scaling laws and indexes of performances will be introduced.

Then, Section 3, we will see to which extent these models and predictions remain valid for real foams.

2. Structural properties

In the following, *microstructure* will refer to the metallurgical characterisation of the constitutive material (grains size, precipitates...), *mesostructure* will be related to the organisation of the matter inside the foam (truss bars, necks, shells, cells...) and will also be referred to as *architecture* of the foam. The *macroscopic* properties are the ones of a piece of foam with a size large enough compared to the elementary architectural element (cell, truss bar...). The *macroscopic* properties are the ones of the equivalent homogeneous medium.

Beside forefront thermophysicochemical properties due to their very high specific surface, foams present interesting structural properties. Theses properties inherit from the low content of matter in the foam, which leads roughly to low density and high deformability.

2.1. Stress–strain curves

The stress–strain curve of a foam enduring compression is very characteristic and is easily recognised (Fig. 1a). It is divided into three stages. First appears a pseudo-elastic domain, characterised by a relatively low stiffness (compared to that of the constitutive material), which ends for a yield stress σ_c also relatively moderated compared to the constitutive material. Next is a long plateau with almost constant stress level σ_p that can be lower than the yield stress σ_c, or with a moderate strain hardening. The length of the plateau region can reach a true strain larger than 1. Finally a densification domain appears. It is characterised by a steep hardening.

The evolution of the stiffness of a foam with compressive strain is also characteristic (Fig. 1b). The stiffness (measured by small unloading steps during compression) decreases with strain in the pseudo-elastic domain. This decrease is not necessarily due to damaging. Geometrical effects when involving thin shells can induce such evolution of stiffness while involving only elastic deformation in the mesostructure. Nevertheless, one must keep in mind that even for very small macroscopic strains, in a domain where the foam is considered macroscopically in the elastic domain, buckling and even fracture of some cells can occur. With increasing strain, stiffness is almost constant along the plateau domain. Finally, stiffness increases with strain in the densification domain.

2.2. Creeping

The creep behaviour of metallic foams is similar to the one of the constitutive material, especially when enduring tension. When submitted to compression, the interpretation is more difficult. Geometrical instabilities and evolution of topology (during densification) can either hide on the macroscopic response local secondary and ternary creeping regimes or lead to an earlier failure [3].

Inhomogeneities and defects are highly detrimental to the creep resistance of foams, by promoting geometrical instabilities for compressive loading, and by leading to enhanced creep rates for tensile loading. When the size of the grains' substructure is of the same order as the stress, foams creep in the dislocation invariant-substructure regime with a lower creeping rate than the bulk material submitted to the same effective applied stress (a stress the material in a single truss endures) would have done [4].

The creep behaviour of foam is highly sensitive to the relative density. Mueller et al. [5] proposed a model describing the creep rate $\dot{\varepsilon}_c$ of a foam of relative density ρ^* and relative stiffness E^* with a constitutive material that follows a Norton law (exponent n, activation energy Q), when submitted to a stress σ_c:

$$\dot{\varepsilon_c} = \frac{K{\sigma_c}^n}{{E^*}^{\frac{n+1}{2}}{\rho^*}^{\frac{n-1}{2}}} e^{-\frac{Q}{RT}} \tag{1}$$

2.3. Fatigue

Foam resistance to fatigue is dependent on foam density, but the scale varies roughly linearly with the yield stress. Low-density foams often present rachetting (accumulation of strain) for cyclic loading. For compressive–compressive loading, localisation bands appear, which correspond to important local damaging. Fatigue resistance increases strongly with foam density and with foam homogeneity. Nevertheless, the processing parameters are often as important as the foam density [6]. In the case of pre-notched samples, the crack growth was shown to follow the Paris law, with a high exponent in the range between 6 to 25 [7]. An extensive literature on this property may be found in [8] and in [9].

2.4. Density

The key property of foam is clearly its relative density ρ^*. This parameter describes the volume fraction of the foam that really consists in solid matter. It characterises one of the most interesting foam properties: its lightness. Actually, this lightness, allied with the effective properties of the foam, is responsible for some forefront specific properties.

Most of the models describing the structural properties of foams are expressed as functions of the relative density, often as a combination of power laws of the relative density. As a consequence, the specific properties are easily expressed. These power laws generally reflect a high sensitivity of the studied properties to the relative density. Heterogeneities in mechanical fields (stress, strain...) are often consequences of relative density heterogeneities.

2.5. Local deformation mechanisms and scaling laws

The architecture of the foam plays a major role in the activation of some local deformation mechanisms.

Depending on architecture and on mechanical loading, cell edges and faces can endure tension–compression or bending. The stiffness of the foam is highly linked to the local deformation mechanism of the cell edges. Thus foams are classically classified into two categories, depending on the fact that bending or tension–compression is the dominant local deformation mechanism.

Classical open-cell foams obtained by foaming or replication processes can be modeled with a simple architecture. The cubic model for an open cell-foam proposed by Gibson and Ashby [10] as the simplest model for such a foam has been widely approved (Fig. 2a). Cell edges are truss bar of length l and cross section of side t. The cells are connected by truss bar at the middle of some of their members. The relative density ρ^* is proportional to the square ratio t/l. When t is small compared to l (i.e. when $\rho^* < 10\%$), the members mainly deform by bending (Fig. 2b). The second moment of inertia of the members I is proportional to the power 4 of t. The relative Young modulus E^* scales as I/l^4, and thus can be expressed as a function of the relative density by:

$$E^* = C_1 {\rho^*}^2 \tag{2}$$

where C_1 is a constant embedding all the geometric constants.

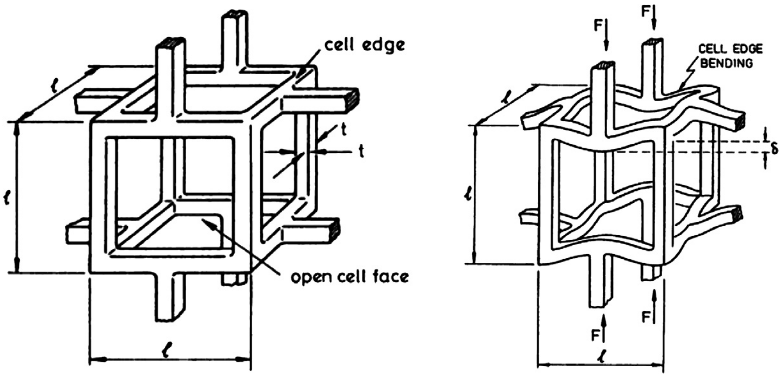
Even if this model is simple, it represents quite well the dependence of the stiffness on the relative density, provided the dominant deformation mechanism at the scale of the cell edges is bending.

Since the bending stiffness of a bar is generally much lower than the stiffness in tension or compression, an important increase of the foam stiffness is expected for a foam for which the dominant local deformation mechanism is tension–compression. Hence, a triangulated foam structure with cells joined at their corner presents a higher stiffness. For an optimised structure, the octet truss structure (Fig. 3a) at low density, the stiffness is linear with density [11]:

$$E_1^* = \frac{\rho^*}{9} \tag{3}$$

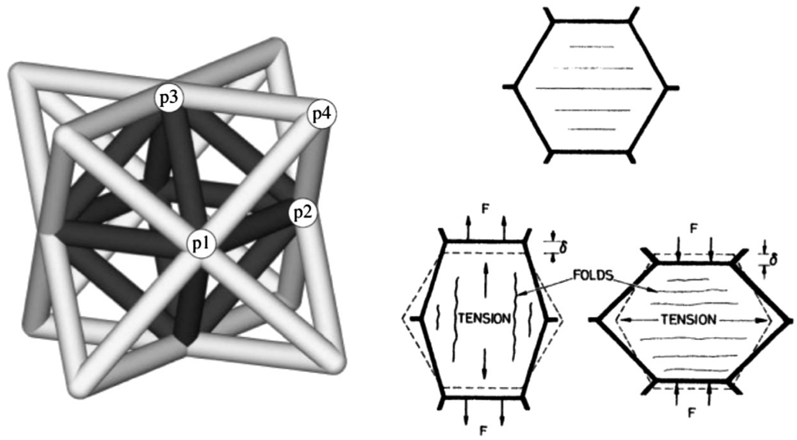
A closed-cell foam often presents a compromise between bending controlled open cell foams and stretching-controlled open cell foams. While cell edges endure bending, cell walls are stretched (Fig. 3b). Thus, depending on the fraction ϕ of matter contained in the cell walls, the stiffness can be expressed as:

$$E^* = C_1 \phi^2 {\rho^*}^2 + C_2 (1 - \phi) \rho^* \tag{4}$$



(a) (b)

Fig. 2. Models of open-cell foam deformation mechanisms (from [10]). (a) A cubic model for an open-cell foam showing the edge length, l, and the edge thickness, t. (b) Cell edge bending during linear elastic deformation.



(a) (b)

Fig. 3. (a) Octet truss structure (from [11]). (b) Stretching of cell walls during closed-cell foam compression and tension (from [10]).

Thus once aware of the dominant deformation mechanism at the scale of the foam architecture, the material density is a relevant parameter to extend, at first order, the properties of a given foam. This extrapolation is consistent with a small variation of the thickness of the cell wall and truss bars.

In a manner similar to the case of stiffness, simple models have been developed to predict yield stress as a function of foam density. In the case of bending-controlled deformation mechanisms, the normalised yield stress scale with the power 3/2 of relative density. For stretch-dominated foams, the yield stress depends linearly on the yield stress. Thus, depending on the fraction ϕ of matter contained in cell walls, the yield stress can be expressed as:

$$\sigma^* = C_1' \phi^{\frac{3}{2}} \rho^{*\frac{3}{2}} + C_2'(1-\phi)\rho^* \tag{5}$$

2.6. Size effect

Compressive properties of foams (both stiffness and stress) are representative when the sample size is 6 or 7 times the cell size [12]. But when looking at the shear behaviour, the size of the representative volume element can be two or three times smaller. But more than the difference in the representative size for the above-mentioned loadings, the variation with sample size does not follow the same trend. While stress and stiffness increase with sample size for compressive loading, both decrease with size for shear loading. Fig. 4 sums up these trends.

An interesting property of foams, due to their cellular structure is notch strengthening. A double-notched specimen fails at a net section stress larger than in the case of an un-notched specimen. Three explanations have been proposed for this behaviour: a triaxiality effect (either for foam with apparent plastic Poisson ratio higher than 0.3 for a non-hardening foam [15] or for foams with more important hardening [16]), a volume effect (the larger the volume, the higher the probability of containing defects), and a similarity of the deformation pattern in the double notched specimen with the deformation pattern for indentation for which a size effect has been found (see Fig. 4). Fig. 5 summarises the influence of notch ge-

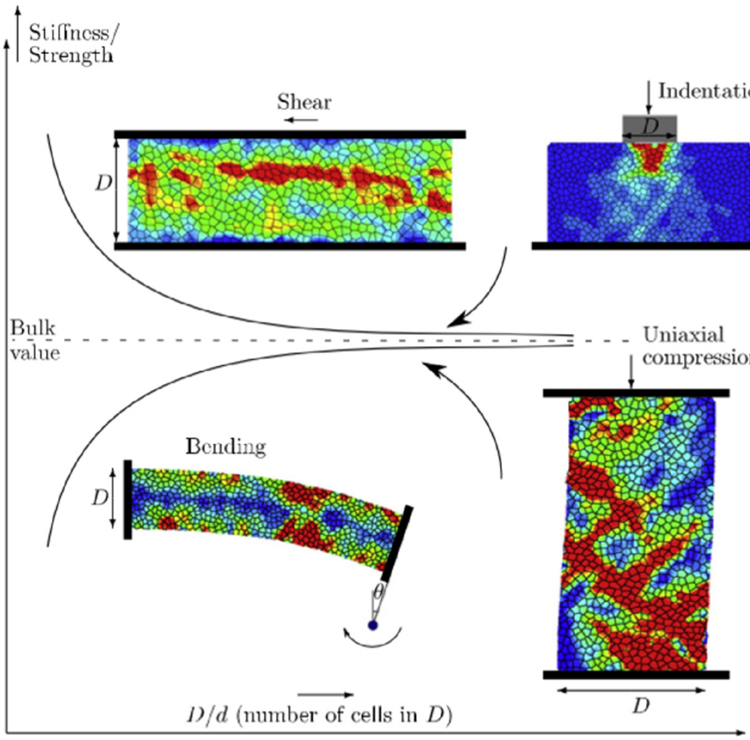


Fig. 4. Evolution of stiffness and of strength with sample size depending on loading conditions (from [13]). Deformation patterns and trends are obtained with 2D Voronoi simulations.

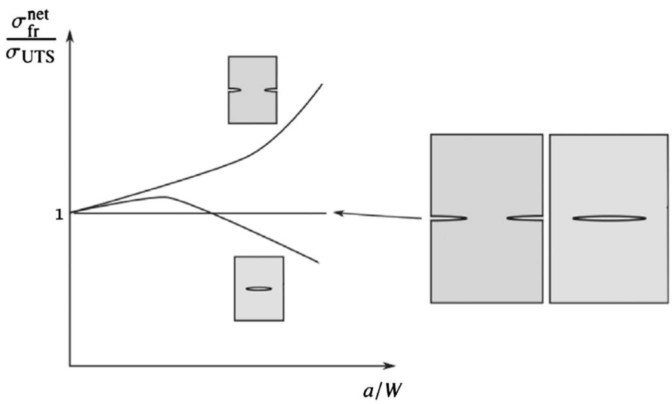


Fig. 5. Influence of notch geometry and of the scale effect on the effects of a notch in two-dimensional foams (from [14]).

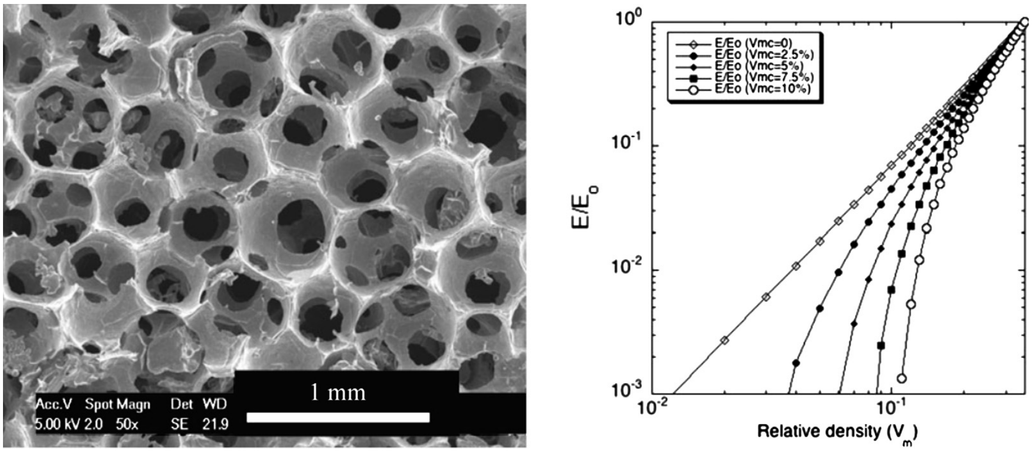
ometry and of the scale effect on the effects of a notch in two-dimensional foams. Double-notched specimens present notch-strengthening, while central crack panels present slight notch-weakening. As the sample size (compared with that of the cell) is increased, foams tend to approach the continuum limit of notch insensitivity for both notch geometries [14].

2.7. Structural performances

The underlying reason for models based on foam density is the will to simply optimise foams for structural applications. For example, in the case of a monolithic panel with constrained bending stiffness, the performance index P_{panel} that minimises weight is:

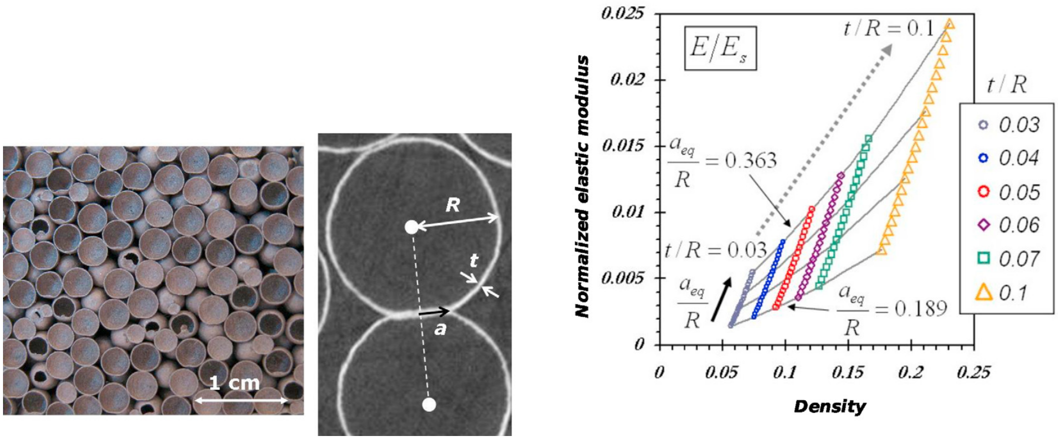
$$P_{panel} = \frac{E}{\rho^3} \tag{6}$$

The higher the index P is, the lighter the panel is. In the case of a monolithic beam with constrained bending stiffness, the performance index P_{beam} that minimises weight is:



(a) (b)

Fig. 6. Replicated foam with 400 μm pores with a spherical shape (a) and evolution of the relative stiffness of such a foam with relative density for several packing configurations (b) (from [17]).



(a) (b)

Fig. 7. (Color online.) (a) Hollow sphere stacking. (b) Evolution of foam stiffness as a function of the density when neck size or shell thickness are varied (from [18]).

$$P_{\text{beam}} = \frac{E}{\rho^2} \tag{7}$$

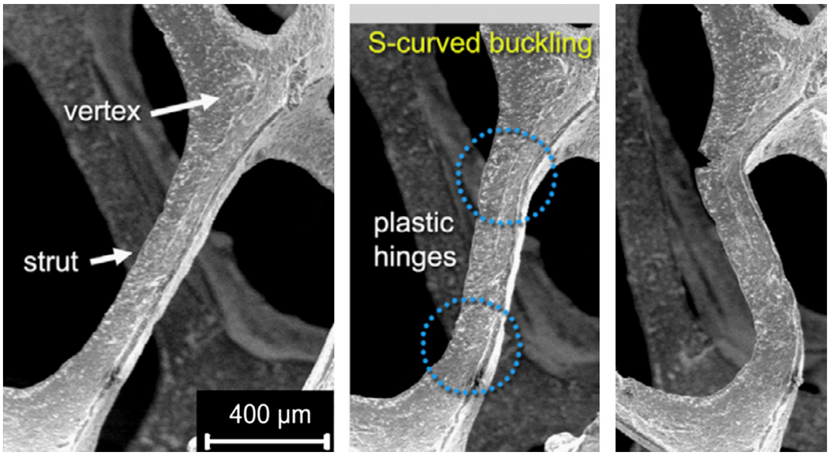
Thus, one must keep in mind that the specific property to consider is highly dependent on the set of requirements. This specific property is generally not linear with the density. The specific tension/compression stiffness of a foam E/ρ is often poorer than that of the constitutive material. But when considering specific properties with higher exponents of density (such as for bending), then the performances of the foam overtake those of the constitutive material.

3. Real foams

Generally, as presented in the previous section, the material's density is assumed to be a relevant parameter to extend, at first order, the properties of a given foam.

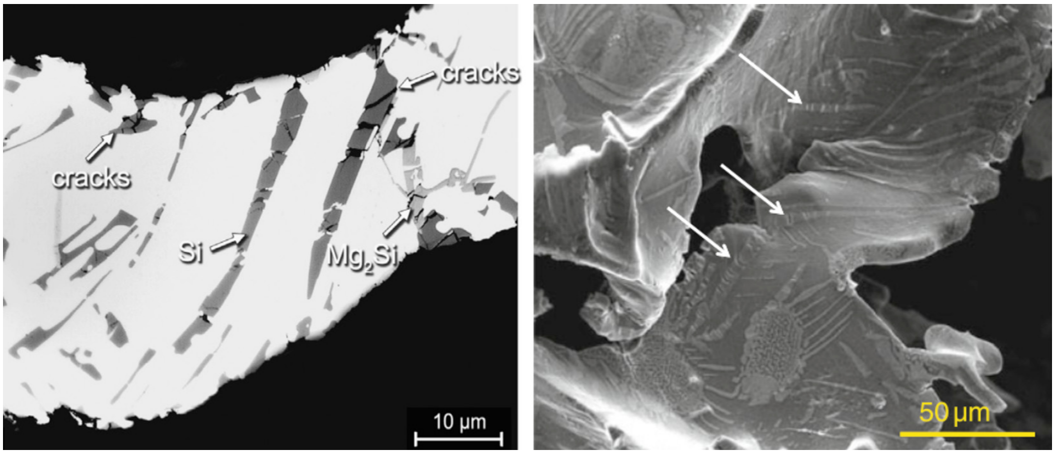
Nevertheless, there are numerous degrees of freedom in a foam architecture. Thus a finer understanding of the effect of each parameter on the mechanical properties is often more relevant to obtain an optimised foam. For example, in the case of replicated foams, the relative stiffness of the foam for a given foam density is a function of the packing configuration [17]. The evolution of the foam stiffness with the density also depends on the packing configuration (see Fig. 6). The exponent of the scaling law can be larger than two for low-density replicated foams.

Another example, where a finer description of the foam's architecture is required is the case of hollow spheres stackings. The foam is obtained by sintered random stacking of hollow spheres. There are two relevant architectural parameters: the



(a) (b) (c)

Fig. 8. (Color online.) SEM observation of in situ buckling of a strut (from [19]). Near the vertices plastic hinges are formed and the strut shows a typical S-curved distortion.



(a) (b)

Fig. 9. (a) SEM observation of microcracks within brittle Si and Mg_2Si phases within the strut of an aluminium A356 foam (from [19]). (b) SEM observations of microcracking of the θ-phase (white arrows) and buckling in a deformed foam of Al-4.5 wt% Cu (from [20]).

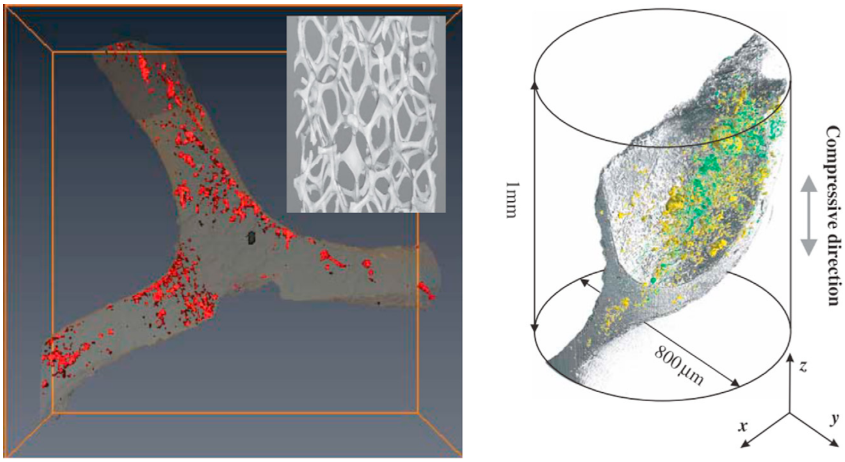
shell's thickness t and the neck's radius a when normalised by the sphere radius R. Fig. 7 presents the foam architecture and the evolution of the stiffness with density, depending on the way the architecture is modified.

If the shell's thickness is modified and if the neck's size is kept constant, the exponent of the scaling law range between 1.28 and 1.42. But if one keeps the shell's thickness constant and increases the neck's size (and thus also slightly the mean coordination number), the exponent ranges between 4.44 and 4.87. Thus, for a required increase in stiffness, the increase of the neck's size will save weight compared to an increase of the thickness of the shell.

Up to now, we considered that foams present a linear elastic domain, but, due to the architecture, this if often not the case. Either the material almost directly presents some local damaging, or elasticity is not linear. Foam architectures generally promote a non-linear local deformation mechanism such an S-curved buckling (Fig. 8). The macroscopic yield stress (5) is then not governed by the same deformation mechanism and is thus no more valid.

A finer knowledge of the strut shape, homogeneity, loading and defects is mandatory to predict these local deformation mechanisms. Large connected brittle phases such as that presented in Fig. 9 prevent smooth deformation and promote stress concentration. The effects of composition heterogeneities and strain localisation are even combined and lead to microcracks in the strut, and by the way often reduce the local bending stiffness.

It remains difficult to decouple the effects of materials' heterogeneities and of architecture heterogeneities on the local deformation mechanisms. The three-dimensional nature of foams architecture makes this even more complex. Fine characterisations, in three-dimensions, of the local heterogeneities, and of the deformations, at several scales, of a foam during macroscopic straining have great potential to discriminate the contributions of architecture and of materials' heterogeneities.



(a) (b)

Fig. 10. In situ local X-ray microtomography observation of pores and intermetallics during compression tests in an open cell aluminium foam (from [21]) (a) and in a closed-cell aluminium foam (from [22] (b)).

Fig. 10 presents examples of three-dimensional characterisations of open and closed cells foams during mechanical loading. Such observations are used to feed numerical models or at least to measure local strain fields.

4. Conclusions

The structural properties of foams can be expressed as a power law of their density. Much attention has been paid to the value of the exponent of these scaling laws. Simple relations have been found between local deformation mechanisms (bending or stretching) and the exponent. These simple laws are now very popular. They are helpful in estimating roughly the evolution of the properties with density. Such laws can be directly incorporated in the expression of the index of performance of a structure when weight is considered. Nevertheless, before using them, one must be aware of the simple assumptions underlying these models. A finer descriptions of the foam, taking into account the foam's architecture, allows us to explain the variation of the exponent, which depends mainly on the elaboration parameters. The effects of structural heterogeneities have been widely studied in two dimensions, but few investigations have been performed in three dimensions. The effects of microstructural heterogeneities (pores, intermetallics...) are an active subject of investigation. Hence, a step forward toward the characterisation and the prediction of the mechanical behaviour of real foams has been carried out during the last ten years. This finer understanding of foam behaviour is clearly the way to overtake the skepticism about the use of foams as structural parts in industrial applications.

References

[1] B. Smith, S. Szyniszewski, J. Hajjar, B. Schafer, S. Arwade, Steel foam for structures: a review of applications, manufacturing and material properties, J. Constr. Steel Res. 71 (2012) 1–10.
[2] P. Lhuissier, Random hollow spheres stackings: structure, behaviour and integration into sandwich structures, Ph.D. thesis, Institut polytechnique de Grenoble, Grenoble University, France, 2009.
[3] E. Andrews, J.-S. Huang, L. Gibson, Creep behavior of a closed-cell aluminum foam, Acta Mater. 47 (10) (1999) 2927–2935.
[4] S. Soubielle, F. Diologent, L. Salvo, A. Mortensen, Creep of replicated microcellular aluminium, Acta Mater. 59 (2) (2011) 440–450.
[5] R. Mueller, S. Soubielle, R. Goodall, F. Diologent, A. Mortensen, On the steady-state creep of microcellular metals, Scr. Mater. 57 (1) (2007) 33–36.
[6] O. Caty, E. Maire, T. Douillard, P. Bertino, R. Dejaeger, R. Bouchet, Experimental determination of the macroscopic fatigue properties of metal hollow sphere structures, Mater. Lett. 63 (13–14) (2009) 1131–1134.
[7] C. Motz, O. Friedl, R. Pippan, Fatigue crack propagation in cellular metals, Int. J. Fatigue 27 (10–12) (2005) 1571–1581.
[8] M.F. Ashby, A. Evans, N.A. Fleck, L.J. Gibson, J.W. Hutchinson, H.N. Wadley, Metal foams: a design guide, Mater. Des. 23 (1) (2002) 119.
[9] R. Goodall, A. Mortensen, Porous metals, D. Laughlin, K. Hono (Eds.), Physical Metallurgy, vol. 7, fifth edition, Elsevier, 2014, pp. 2399–2595.
[10] L. Gibson, M. Ashby, Cellular Solids, Structure and Properties, second edition, Cambridge University Press, Cambridge, 1997.
[11] V. Deshpande, N. Fleck, M. Ashby, Effective properties of the octet-truss lattice material, J. Mech. Phys. Solids 49 (2001) 1747–1769.
[12] E. Andrews, G. Gioux, P. Onck, L. Gibson, Size effects in ductile cellular solids. Part II: Experimental results, Int. J. Mech. Sci. 43 (2001) 701–713.
[13] C. Tekoglu, L. Gibson, T. Pardoen, P. Onck, Size effects in foams: experiments and modeling, Prog. Mater. Sci. 56 (2) (2011) 109–138.
[14] K. Mangipudi, P. Onck, Notch sensitivity of ductile metallic foams: a computational study, Acta Mater. 59 (19) (2011) 7356–7367.
[15] P. Onck, Application of a continuum constitutive model to metallic foam DEN-specimens in compression, Int. J. Mech. Sci. 43 (12) (2001) 2947–2959.
[16] E. Combaz, A. Rossoll, A. Mortensen, Hole and notch sensitivity of aluminium replicated foam, Acta Mater. 59 (2) (2011) 572–581.
[17] A. Mortensen, Y. Conde, A. Rossoll, C. San Marchi, Scaling of conductivity and Young's modulus in replicated microcellular materials, J. Mater. Sci. 48 (23) (2013) 8140–8146.
[18] A. Fallet, P. Lhuissier, L. Salvo, C. Martin, A. Wiegmann, M. Kabel, Multifunctional optimization of random hollow sphere stackings, Scr. Mater. 68 (1) (2012) 35–38.

[19] P. Schüler, S.F. Fischer, A. Bührig-Polaczek, C. Fleck, Deformation and failure behaviour of open cell Al foams under quasistatic and impact loading, Mater. Sci. Eng. A 587 (2013) 250–261.
[20] Y. Conde, R. Doglione, A. Mortensen, Influence of microstructural heterogeneity on the scaling between flow stress and relative density in microcellular Al–4.5 %Cu, J. Mater. Sci. 49 (6) (2014) 2403–2414.
[21] T. Zhang, É. Maire, J. Adrien, P.R. Onck, L. Salvo, Local tomography study of the fracture of an ERG metal foam, Adv. Eng. Mater. 15 (8) (2013) 767–772.
[22] T. Ohgaki, H. Toda, M. Kobayashi, K. Uesugi, M. Niinomi, T. Akahori, T. Kobayash, K. Makii, Y. Aruga, In situ observations of compressive behaviour of aluminium foams by local tomography using high-resolution X-rays, Philos. Mag. 86 (28) (2006) 4417–4438.