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# Quasistatic mechanical behaviour of stainless steel hollow sphere foam: Macroscopic properties and damage mechanisms followed by X-ray tomography

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#### 1. Introduction

Metallic hollow sphere foams are a new class of cellular materials which exhibit a double open/closed porosity and a very regular cellular structure. In [1] Sanders has computed the elastic properties of bodycentered and face-centered cubic packings and he has shown that the elastic moduli surpassed the values given by the classical Gibson and Ashby models of open and closed-cell foams. Hollow sphere foams exhibit thus a great potential for improved properties for low-density metal structures. Experimental characterisation of the mechanical behaviour of random hollow sphere structures has been investigated by Andersen et al. [2]. Lim et al. [3] and Friedl et al. [4]. None of these studies have come to give the evolution of the macroscopic properties up to densification relating to structural parameters of the foam. Macroscopic mechanical properties are extracted from the compression tests and scaling law based on the foams initial density are identified. Qualitative explanation of the mechanical behaviour is provided by the analysis of damage mechanisms at the mesoscale observed by in situ X-ray tomography.

#### 2. Material and experiments

#### 2.1. Material

In this paper hollow spheres foams made of 314 stainless steel are investigated by compression tests. The hollow spheres are manufactured by PLANSEE via a powder metallurgy process [2]. They are

### ABSTRACT

Random packings of stainless steel hollow spheres are characterised with static X-ray tomography. Compression tests were performed on the foams and size effects were investigated. Relevant parameters of the macroscopic mechanical behaviour are extracted and scaling law based on the foams initial density are given and used to predict the energy absorbed at densification. In situ X-ray tomography compressive test were carried out in order to analyse damage mechanisms at the mesoscale.

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randomly packed, shaped and finally sintered. Four different foams were used, with three densities and two spheres diameters.

#### 2.2. Macroscopic tests and mechanical properties

Compression tests are carried out on the four foams. For each foam, three sample sizes are investigated: cubic samples of 10 mm, 20 mm and 30 mm side size. Tests are realized on a displacement-controlled universal machine (ADAMEL DY35), with a LVDT Tesla sensor, and a 20 kN stress cell. The crosshead velocity is set to 0.05 mm/s and numerous unloading sequences are performed all along the compression to get Young's modulus as a function of strain. A systematic extraction of classical parameters is carried out on the stress–strain curves (Fig. 1). The procedures of extraction of these parameters require conventions which are described in Table 1.

#### 2.3. Tomography and image analysis

Static tomography are realised at ESRF (Grenoble, France) and at INSA Lyon (France) with a voxel size close to 8  $\mu$ m. Compressive tests are realized on cubic samples (15 mm side size) inside an X-ray tomograph thanks to a dedicated device developed at INSA Lyon [5] with a voxel size close to 16  $\mu$ m. Further 3D image analysis allows to get the mean values and standard deviation of shell thicknesses, and sphere radii, the coordination number of the sphere and the neck size.

#### 3. Material structure

Four foams are used in this study. Three of the foams are made of spheres of 2.6 mm of mean diameter, with mean shell thickness of 48 µm,

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Fig. 1. Parameters extracted from the stress-strain curve.

72  $\mu$ m and 95  $\mu$ m. Mean neck size is almost identical, ranging from 390  $\mu$ m to 420  $\mu$ m. Therefore densities are respectively of 0.47 g/cm<sup>3</sup>, 0.62 g/cm<sup>3</sup> and 0.77 g/cm<sup>3</sup>. The last foam has a density of 0.76 g/cm<sup>3</sup>, a mean sphere diameter of 1.7 mm, mean shell thickness of 50  $\mu$ m and mean neck size of 280  $\mu$ m. The mean coordination number of all the foams ranges from 7.6 to 8.2.

#### 4. Mechanical behaviour

#### 4.1. Sample size effect

The stress–strain curves responses to compressive loading does not show any major influence of sample size (Fig. 2a). Even for relatively small sample size normalised to the sphere diameter (L/d=3.3), macroscopic behaviour is reproducible. Provided the cube side size is superior or equal to 20 mm  $(L/d \ge 6.6)$ , the scatter is very small, which is consistent with numerical simulations [6] or experiments [3].

#### 4.2. Sphere size effect

Comparison between responses of foams with same density but with different sphere diameter does not reveal any influence of sphere size (Fig. 2b). Since both foams have the same t/R ratio (shell thickness over sphere radius ratio) and the same density, it seems that density (or t/R ratio) can be roughly used to describe the foams behaviour at constant homogenized neck size.

#### 4.3. Scaling laws

A natural consequence of the parametric study is the ability to describe the behaviour of a foam. The key parameter choosen is the classical one for foams: the initial density  $\rho_0$ . Therefore scaling laws (Eq. (1)) are used to fit the various macroscopic parameters ( $\sigma_{25\%}$ , H,

Table 1	
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Procedure	10	extraction	10	parameters.

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Parameter	Sign	Particular procedure
Stress at $\epsilon = 0.25$	$\sigma_{25\%}$	
Stress at $\epsilon = 0.50$	$\sigma_{50\%}$	
Mean plateau hardening modulus	Н	Slope of the stress-strain curve
		for $0.2 \le \epsilon \le 0.8$
Unloading modulus	$E(\epsilon_i)$	Slope of the unloading stress-strain
		curve for $0.2 * \sigma(\epsilon_i) < \sigma < \sigma(\epsilon_i)$
Initial unloading modulus	Einit	Maximum of <i>E</i> for $\epsilon < 0.05$
Mean "plateau" unloading modulus	Emean	Mean value of <i>E</i> for $0.2 < \epsilon < 0.8$
Stress at densification	$\sigma_{\rm dens}$	Stress for $\sigma(\epsilon) = 1.05^{*} \text{H}^{*}(\epsilon - 0.5)$
Strain at densification	€dens	Strain for $\sigma = \sigma_{dens}$
Energy absorbed at densification	Wdens	$\int_{0}^{\epsilon \text{ dens}} \sigma(\epsilon) d\epsilon$



**Fig. 2.** Compression response for: (a) several sample size of the  $0.47 \text{ g/cm}^3$  foam, (b) several sphere diameter with same foam density.

 $W_{dens}$ ) defined in Table 1 and presented in Fig. 3a,b,d. Only responses of the samples larger or equal to 20 mm are analysed.

 $Property(\rho_0) = K(\rho_0^n) \tag{1}$ 

#### 5. Damaging

#### 5.1. Macroscopic damaging

Stress at 25% of strain,  $\sigma_{25\%}$  is commonly used as main indicator of plateau level. Its dependence on density is found to follow a power law with *n* equal to 1.86. The mean Plateau hardening modulus is also well described by a power law with a larger value of equal to 2.10.

#### 5.2. Prediction of energy absorbed at densification

While focusing on the densification phenomenon, it seems that the strain at densification is independent of foam initial density (Fig. 3c). Its mean value is of 1.08. It is not surprising because it is a geometric transformation and the t/R ratio is small.

A minimal model (Eq. (2)) is used to describe curves up to densification whatever the initial density  $p_0$ , provided it is in the experiment range (0.4 g/cm<sup>3</sup> to 0.8 g/cm<sup>3</sup>).

$$\sigma(\epsilon) = \sigma_{25\%}(\rho_0) + H(\rho_0) \cdot (\epsilon - 0.25) \text{ for } \epsilon < \epsilon_{\text{dens}}$$
(2)

The energy absorbed at densification is estimated with this model (Eq. (2)) and with the scaling power laws (Eq. (1)) of  $\sigma_{25\%}$  and of H. Prediction is compared to experiments on Fig. 3d.



**Fig. 3.** Evolution with foam initial density of: (a) characteristic strains, (b) hardening modulus, (c) strain of densification, (d) energy absorbed at densification.

The offset is due to the area overestimated by omitting the initial loading up to the plateau. With addition of another parameter (such as initial loading slope  $E_{load}$ ) in the model this offset would be limited, however the simplest model give enough information to predict the foam absorption capacity, and is very easy to identify.

Another macroscopic parameter, the Young's modulus with strain (Fig. 4a), gives information on the material behaviour. The unloading modulus value decreases during the first stages of strain. Then it is more or less constant up to initiation of densification where it increases again. The initial decrease indicates damage in the material. Because of the scatter of initial unloading modulus, the characteristic value studied to define the stiffness of the material is the mean unloading modulus for strain between 0.2 and 0.8. This modulus is representative of the material stiffness during a great part of its deformation. Mean unloading modulus over the plateau  $E_{mean}$  show a small experimental scatter (Fig. 4b). Its value is related to the foam density by a power law with n = 1.64. This value is close to what is obtained by numerical simulation of the initial Young's modulus [1] on various hollow sphere packings: on SC packing (n = 1.36), on BCC packing (n = 1.67) and on FCC packing (n = 1.33).

#### 5.3. In situ compressive tests

Qualitative observations are based on 3D analysis, however 2D slices of the sample at several macroscopic strain give an overview of the phenomena involves. On Fig. 5, a 2D slice of the sample and 3D isolated spheres are followed simultaneously from initial state up to densification through four strain steps.

First step of deformation shows the initiation of damage by inter penetration of spheres (Fig. 5b). Then, with larger deformation (between Fig. 5b and c), new contacts are created. Uniform and progressive crushing of the spheres can be shown on Fig. 5c. At



**Fig. 4.** Parameters extracted from the unloading modulus versus strain curve (a) and evolution of characteristic stiffness moduli with foam initial density (b).



Fig. 5. Tomography observations at several stage of the compression: (a)  $\epsilon$  = 0, (b)  $\epsilon$  = 0.1, (c)  $\epsilon$  = 0.5, (d)  $\epsilon$  = 1.0.

densification, sphere shells auto penetrate and open porosity seems to have been completely filed up (Fig. 5d).

#### 5.4. Multiscale relations

Simultaneous observations of the macroscopic response and of the local damage mechanisms show a good correspondence between the

phenomena at both scales. The initial decrease of macroscopic stiffness is explained by the initiation of buckling at mesoscale which induces a softening of the contact sphere/sphere and therefore of the whole structure.

During "plateau" compression, two antagonist phenomena occur: a softening by crushing of spheres and hardening by creation of new contacts between spheres. It leads to a stiffness "plateau". Since it is likely that new contacts occurs as a consequence of a local buckling event, the compensation effect is not surprising. Auto penetrations of spheres and occlusion of open porosity lead to a important stiffening of the structure, and imply transition from a shell bending deformation mechanism to a bulk material compression mechanism. It explains the transition between "plateau" and densification domain.

#### 6. Conclusions

The static tomography and 3D image analysis gives a accurate knowledge of the material structure. Since sample size effects are shown to be negligible, hollow spheres foams can be considered as an homogeneous material when L/d ratio (size of sample/size of sphere) is larger than 7. It should be important in case of integration in small structure such as sandwich plates.

The parametric study of the behaviour of the foam as function of its initial density allows to describe the behaviour of the foam up to densification with simple power law relationship. While strain at densification is found to be independent of the initial density of the foam, the classical power laws led to exponent close to 2 for other macroscopic parameters. The integration of these laws in a simple behaviour model describes accurately the energy absorbed at densification by the foams.

In situ observations during compressive tests indicates that up to densification there is sphere indentation and new sphere/sphere contacts which explains the macroscopic behaviour.

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