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Mechanical Behaviour of Metallic Hollow Spheres Foam**

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Hollow spheres foams are a special class of cellular solids which exhibit a mixed open/closed porosity.^[1] The main advantage of this material, beside this dual porosity which allows a combination of mechanical and acoustic properties, is the regularity of its structure, which should ensure a good reproducibility of mechanical properties of the foam, that can be directly related to geometrical features and constitutive material properties. Such studies have been carried out by Lim et al.^[2] for random packing and by Sanders^[3,4] and Gasser^[5] for regular packing (simple cubic, body-centered cubic and face-centered cubic). They have computed the elastic moduli and initial yield strength of hollow spheres foams and gave scaling laws relating these two properties to the geometrical parameters of the structure of the material. Gao et al.^[6] have also performed finite element simulations on regular packing to investigate the mechanical behaviour at large plastic deformation and to estimate the energy absorption capacity of such materials. Besides, phenomenological models for the mechanical behaviour of metallic foams have been developed by Deshpande and Fleck^[7] but have not been applied yet to hollow spheres foams.

The mechanical behaviour of cellular solids depends upon the cell material properties and the cells' structure/architecture (open or closed cell, cell size, etc.).^[1] In this work we focus on the effect of the architecture for a given constitutive material. The aim is, first, to analyze experimentally and numerically the plastic behaviour of random packing of hollow spheres and thus to determine the deformation mechanisms of these foams as function of geometrical features such as spheres diameter, spheres thickness and necks size. In a second step a phenomenological model which takes into account the deformation mechanisms in order to predict the macroscopic mechanical behaviour is proposed.

Materials and Methods

Materials

Samples of 314 stainless steel hollow spheres were provided by PLANSEE (Austria). These hollow spheres foams are manufactured by a powder metallurgy based process.^[8,9] Three specimens of different densities are available, Named A, B and C. Their densities are respectively 0.47, 0.62 and 0.77 kg/dm³ leading to relative densities of 0.063, 0.083 and 0.103 with respect to the density of the sphere wall material taken to be 7.5 kg/dm³.

The cells' structure is described by two dimensionless geometrical parameters (Fig. 1):

- thickness-to-radius ratio (t/R) of the spheres.
- bond angle (θ) of the necks.

Experimental Procedures

In order to investigate the relationships between structure and mechanical behaviour, the samples have been characterized by X-ray microtomography and mechanically tested by *in-situ* compression test and macroscopic compression tests.

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Fig. 1. Tomographical views of hollow spheres and geometrical parameters.

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X-ray Microtomography

This technique is very attractive because it provides nondestructively the 3-dimensional structure of the material. The analysis have been carried out in ESRF (Grenoble, France) and INSA Lyon (France) on cubic samples of 5, 10 and 15 mm side length scaned with a spatial resolution (voxel size) of 8 μ m and 16 μ m.

3D images analysis allows to get information on the structure of the samples such as relative density and geometrical parameters. A 3D granulometry method, as commonly used in powders analysis, gives the size distribution of thicknesses (t) and diameters (D) of the cells. Morphological operations, used to separate each cell, allow to access to bond angle values (θ) which characterize the relative size of the necks.

In Situ Compression Tests

A tension/compression device, specifically designed to be used in the X-ray beamline, allows to perform *in-situ* uniaxial compression test with a constant crosshead velocity of 1 mm/min^[10] leading to an initial strain-rate of $1.1 \cdot 10^{-3}$ s⁻¹ with cubic samples of 15 mm side length. The compression of the sample is interrupted at various strain levels in order to acquire a tomographic scan at each step. The force-displacement curve is also registered during the tests. These experiments enable to follow locally the cells deformation and then to identify the plasticity and crush mechanisms active inside the foam.

Macroscopic Compression Behaviour

Compression tests were achieved for the three Specimens A, B and C on cubic samples of 20 mm side length. A 20 kN stress cell was used on a displacement-controlled universal testing machine (Adamel DY34) with a LVDT Tesla sensor to access the macroscopic strain. The crosshead speed was 0.05 mm/s for all specimens, resulting in an initial strain rate of $2.5 \cdot 10^{-3}$ s⁻¹. During compression, a large number of un-



Fig. 2. FE model and mesh with 2D axisymetric elements.

loading sequences were performed in order to measure the unloading modulus at different strain stages.

Numerical Computations

In order to establish a relation between geometrical parameters and deformation mechanisms, numerical simulations of the compression of a pair of connected spheres have been computed with ZeBuLoN FE program.^[11] The geometry is modelled with 2D axisymetric elements (see Fig. 2). The behaviour of the cell wall constitutive material is assumed to be elastic-plastic with a power-law strain hardening. Numerical values are characteristic of steel with Young Modulus E = 207 GPa, Yield strength $\sigma_{ys} = 185$ MPa and strain hardening coefficient n = 0.24.

The model takes into account large strain and non-penetration (contact law). Calculations were designed to evaluate the effect of the shell relative thickness t/R and the bond angle θ on the mechanical response of the cells.

Experimental Results

Structural Characterization

Parameters investigated by images analysis are: relative density, outside diameter of spheres D, wall thickness t and average neck size d. The adimensionless parameters t/R and bond angle θ (sin θ = d/D as shown on Fig. 1) are calculated.

Table 1 summarizes the results of structural characterization of the three Specimens A, B and C. Relative density measurements are in good agreement with values announced by the manufacturer which confirm the validity of 3D images analysis. For all the samples, the spheres diameter is constant equal to 2.6 mm and the shell thickness is varying from 48 µm for specimen A to 95 µm for Specimen C, leading to three relative densities from 0.067 to 0.104. As for the neck angles all samples show the same range of values between approximately $[0^{\circ} - 30^{\circ}]$, which indicate that they were compacted with the same process parameters during their manufacture.

Macroscopic Behaviour

The responses of macroscopic compressive tests are very reproducible. Among all these tests, Figure 3 shows stress (plain lines) and unloading moduli (symbols) versus true strain for the three families of samples. The macroscopic behaviour is very similar for the three wall thicknesses excepted

Table 1. Structural parameters obtained by 3D images analysis.

	Relative density	Diameter (mm)	Thickness (µm)	Neck size (µm)	t/R	θ (°)
А	0.067	2.6	48	420	0.037	$0-30.8^{\circ}$
В	0.088	2.6	72	401	0.055	$0-31.9^{\circ}$
С	0.104	2.6	95	389	0.073	0 – 29.7°





Fig. 3. Compressive macroscopic behaviour.

in regard to levels of stresses and moduli, which are larger for thicker walls. If the increases of stress and moduli for high strains are known to be associated to densification phenomena, the early and large decrease of unloading moduli remained to be explained.

Plasticity and Deformation Mechanisms

Two-dimensional sections showing a couple of spheres extracted from the X-ray tomography in-situ compression tests are presented on Figure 4 at various strain levels. Plastic hinge at necks vicinity followed by indentation of spheres appear to be the main deformation mechanisms for all samples. One can see that the first step of deformation is localized at the neck with flattening of the contact area (Fig. 4(b)) due to the formation of a plastic hinge. With increasing macroscopic strain, spheres are indented by their neighbours (Fig. 4(c)) which lead to the crush of the cells (Fig. 4(d)). All the spheres involved in a deformation mechanism (plastic hinge at neck or indentation) constitute the "damaged phase" (Fig. 4.(b), 4(c)) while completely crushed cells (Fig. 4(d)) constitute the "densified phase".

A quantitative analysis of the deformation progress was carried out, with a criterion of a given relative variation of distance between the centers of connected spheres. Over a



Fig. 4. Deformation mechanisms observed, constituting the "healthy phase" (a) and the "damaged phase" with plastic hinge at necks (b) and indentation (c). Crushed spheres (d) constitute the "densified phase".

critical variation of distance the neck is considered as damaged. Whatever the critical variation arbitrary choosen as the damaging limit, the number of damaged necks as a function of strain can be described by a Weibull type law. The Weibull exponent m which gives the best fit is around 0.75 (see Eq. 1).

$$P(\varepsilon) = 1 - e^{-\left(\frac{\varepsilon}{\varepsilon_u}\right)^m}$$
(1)

A similar equation is used for the proportion of densified phase. In this case the Weibull exponent m remains equal to 0.75. Only the mean strain ε_u is different for damaging law and densification law.

Numerical Modelling

Two approaches have been investigated. First, at the mesoscale for low strain ($\varepsilon < 10\%$), the observed local behaviours will be analysed. Then at the macroscale, using a phenomenological model, we will propose a description of the macroscopic behaviour over a wide range of strain in coherence with the previously observed local mechanisms.

At Mesoscale: FEM Calculations of a pair of Connected Spheres

Finite Element Model

Calculations were designed to evaluate the effect of the shell relative thickness t/R and the bond angle θ on the mechanical response of the cells in compression. A parametric study was conducted with t/R varying from 0.01 to 0.2 and θ from 5° to 30°.

Results

In all cases the deformation of the structure is due to the development of a plastic hinge around the neck leading to the flattening of the contact area before indentation occurs (Fig. 5). This is consistent with the previous tomographic observations. We find the same deformation mechanisms, namely plastic hinge followed by indentation.

Figure 6(a) shows macroscopic stress-strain curves for

t/R = 0.05 and 2 different values of θ = 10° and 30°. Two kind of behaviour are observed:

A. Sharp stress increase followed by a softening;

B. Sharp stress increase followed by a "plateau"

without softening.

This stage corresponds to the formation of the plastic hinge (flattening of the contact area). The following stress increase observed on the curves matches to the indentation of the sphere.

The parametric study allows to draw a map (see Fig. 6(b)) showing which kind of behaviour (stress softening or not) is observed according to the geometric parameters t/R and θ . We can notice that, for a given θ , the smaller t/R the larger the softening.



Fig. 5. Deformed shape of the cell (t/R = 0.04, θ = 10 °) at various strain stages, exhibiting the local deformation mechanisms.

At Macroscale: 3 Phase Model

Architecture and Calibration of the Model

Relying on the previous observations, a simple approach is proposed to develop a phenomenological descrition of the stress strain behaviour, along the lines of "damage plasticity". The integration of damaging and densification in a "uniaxial" simulating model was done by considering the foam as a multi-phase material corresponding to different stages in the damage process. It consists in a healthy phase (He), a damaged phase (Da) corresponding to the formation of plastic hinges or indentations, and a densified phase (De). Each phase is described by an elastic-plastic behaviour with a linear work hardening H. Healthy phase and damaged phase are assumed to be loaded "in parallel" while the densified phase is loaded "in series" (see Fig. 7). The transition from a phase to an other is driven by a probabilistic law of evolution with strain, such as Equation 1.

The Young's modulus of the healthy phase (E_{He}) was taken equal to the initial unloading modulus, and the others parameters were adjusted to fit the experimental results obtained for the highest density foam (Specimen C).



Fig. 6. (a) compression curves of the pair of spheres showing two different behaviours of plastic hinge. (b) map of plastic hinge behaviour according to the geometry $(t/R, \theta)$ of the cells.



Fig. 7. the three phases model.

Extrapolation to Other Densities

The input parameters of the model depend on the material initial relative density. Inspired by the classical laws of Gibson and Ashby for cellular solids,^[1] this dependence was described by a simple power law. Young's moduli of the three phases and hardening moduli followed Equation 2.

$$\frac{E}{E_C} = \frac{H}{H_C} = \left(\frac{\rho}{\rho_C}\right)^{1.8} \tag{2}$$

The other parameter of the model, namely the mean strain ε_u of Equation 1, is also expected to depend on the initial relative density. Hence it were described by a linear dependence (Eq. 3).

$$\frac{\varepsilon_u}{\varepsilon_{u_c}} = \frac{1.37 - \rho_C}{1.37 - \rho} \tag{3}$$

Figure 8(a) and 8(b) show the comparison between responses of the model and experimental results for two densities corresponding to Specimens A and B, for both the stressstrain curve (Fig. 8(a)) and unloading modulus evolution with strain (Fig. 8(b)). Stresses are well predicted up to strain of 1.2 and unloading moduli up to densification.

Conclusion

The plastic behaviour of hollow spheres foams has been investigated by X-ray tomography in-situ compression tests which allowed to identify the main deformation mechanisms within the material. Two mechanisms are observed: firstly a plastic hinge at necks vicinity, followed by an indentation of

the spheres. FEM calculations of the compression of a pair of connected spheres enabled to distinguish two kind of behaviour of the initial plastic hinge depending on the geometrical parameters of the spheres. A parametric study allowed to plot mechanisms map showing the behaviour achieved for various (t/R, θ) couples for a given constitutive material of the spheres.

The macroscopic behaviour the hollow spheres foams is modelled as a three phases material: healthy, damaged and densified phases, whose volume fractions evolve with strain. The model, once calibrated on one kind of hollow sphere foam, allows to predict the behaviour of foams of other initial density in uniaxial compressive loading up to





Fig. 8. (a) Macroscopic compression stress versus true strain , (b) Unloading moduli versus true strain.

densification. It describes correctly the stress-strain curve and the evolution of the unloading modulus with strain.

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