

ENERGY ABSORPTION PROPERTIES OF METAL FOAMS

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Abstract - The application of cellular materials, especially metal foams within light-weight structures for energy absorption arouses high interest. In this paper a model is suggested to describe the energy absorption capacity of metal foams, which takes into account the cell-size distribution. In the case of uniform cell-size distribution an analytical expression was found. To check the validity of the model Alporas foams were investigated with compression tests.

1. INTRODUCTION

In the past years several applications have been found for different cellular materials: polymer and glass foams are applied for thermal insulation exploiting their low thermal conductivity, or for packaging, since they show good energy absorption properties, ceramic foams can be used as filters, etc [1]. Recently, a new class of cellular materials, metal foams emerged. These materials exhibit novel mechanical, thermal, electrical and acoustic properties: these are light and stiff, have potential for heat and sound insulation like polymer foams, moreover they are good flame arresters [2-5]. The increasing number of publications and the growing applications show that metal foams have come to the fore, although, so far only a few applications have been found in everyday-life.

One of the main applications of metal foam is in the automotive and space industry. Metal foams can be used as bumpers e.g. for suburban railcars, trams or cars [4]. The reason for this is that they are excellent energy absorbers due to their special deformation mechanism, the formation of deformation bands. Therefore metal foams (as well as other cellular materials) exhibit a characteristic compressive stress-strain curve which can be divided to three stages. At small strains (<1-2%) foams deform elastically; there is then a plateau of deformation (up to 60-80% strain), where the stress is almost constant. Finally, as the deformation reaches the densification strain, foams densify: the cell-walls crush together. Due to this long plateau foams are suitable for absorbing energy without exceeding a given stress limit.

To characterize the energy absorption features of aluminum foams the compressive properties, like the plateau stress and the densification strain must be determined as a function of the properties of the foam.

2. EXPERIMENTAL

Alporas foams of different relative densities were investigated here. This foam is manufactured by a batch casting process. First calcium is stirred into the molten aluminum to increase the viscosity. Then titanium hydride is dispersed in the melt in

order to form bubbles. These bubbles are stabilized by the added calcium. After the melt expanded and filled up the mold, the foam is cooled with a powerful blower until it solidifies.

Compression tests were performed on Alporas foams with three different relative densities (Table 1). An MTS hydraulic machine was used for quasi-static compression tests at strain rate of 10^{-3} s^{-1} . The dimensions of the samples were $30 \times 30 \times 25 \text{ mm}^3$.

Name	Ap0.8	Ap1.1	Ap2.08
Relative density	6%	9%	17%

Table 1

3. RESULTS

3.1. Plateau stress

Gibson and Ashby modeled foams with a structure consisting of cubes of solid struts and plates in which the struts meet at their midpoints [1] (Fig. 1). According to this model the plateau stress depends only on the size of the cells (l) and the thickness of the cell-edge (t_e) and cell-wall (t_w):

$$\frac{\sigma_{pl}^*}{\sigma_{y,s}} = B_1 \left(\frac{t_e}{l} \right)^3 + B_2 \left(\frac{t_w}{l} \right) \quad (1)$$

where σ_{pl}^* is the plateau stress of the foam and $\sigma_{y,s}$ is the yield stress of the solid it is made of, and B_1 and B_2 are constants.

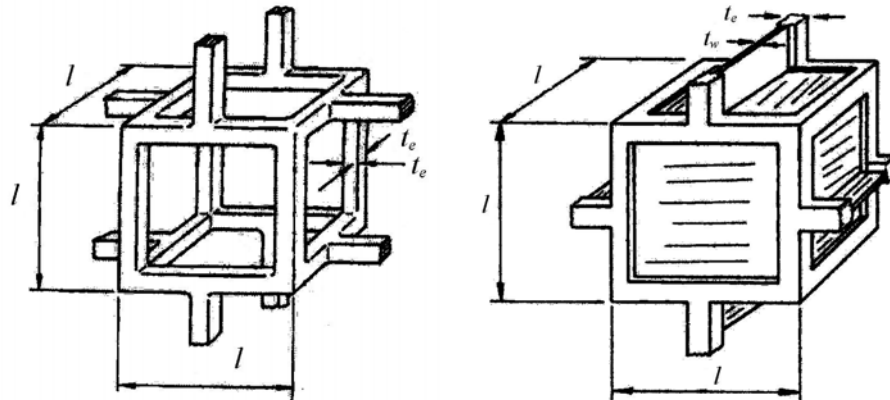


Fig.1 The open- and closed-cell structure according to the Gibson-Ashby model [1]

This gives a good estimation; however, it is inadequate for precise design. The model supposes identical cube cells, thus neither the distribution of the cell-size, cell-edge and cell-wall thickness nor the different imperfections (broken cell-walls, cell-edge and wall curvature etc.) are taken into account. Compression tests show that the constant plateau stress can be taken only as a first approximation; actually the plateau stress increases slowly with increasing deformation. The reason for this increment in the plateau stress can be the cell-size and the cell-wall/cell-edge thickness distribution.

Let us consider an open-cell foam as a cubic array of struts of different length, each strut having square cross section of size t . For the sake of simplicity let the cell-size distribution of the foam be uniform (i.e. all cell-size the same number of cells can be found in the foam from all cell sizes). Let us suppose further that the plateau stress is governed by the stress caused by the cell collapse at that moment, and first the largest and finally the smallest cell will collapse. Then the following connection can be given between the strain (ε) and the size of cell which is about to collapse (l):

$$\varepsilon(l) = \frac{\int_l^{l_2} l'^3 dl' - \int_l^{l_2} 3t_e^2 l' dl'}{\int_{l_1}^{l_2} l'^3 dl'} = \frac{(l^2 - l_2^2)(l^2 + l_2^2 - 6t_e^2)}{l_1^4 - l_2^4}, \quad (2)$$

where l_1 and l_2 are the size of the smallest and the largest cell, respectively [6]. The second term in the numerator is the volume of the totally compressed part of the foam at ε deformation, while the first term in the numerator is the original volume of that part of the foam in which the cells are already collapsed at ε deformation. (The changes in the cross section during compression are neglected.) From Eq. 2 l can be expressed as the function of ε :

$$l(\varepsilon) = \sqrt{3t_e^2 + \sqrt{l_2^4 - 6l_2^2 t_e^2 + 9t_e^4 + (l_1^4 - l_2^4)\varepsilon}}. \quad (3)$$

The average relative density of the undeformed foam can be calculated as

$$\rho_{rel} = \frac{\int_{l_1}^{l_2} 3t_e^2 l dl}{\int_{l_1}^{l_2} l^3 dl} = \frac{6t_e^2}{l_1^2 + l_2^2}. \quad (4)$$

This gives for the average cell-edge thickness:

$$t_e = \sqrt{\frac{(l_1^2 + l_2^2)\rho_{rel}}{6}}. \quad (5)$$

Substituting Eq. 3 and 5 into Eq. 1 using $B_2 = 0$ (open-cell foam) the following expression is obtained for the plateau stress at ε deformation:

$$\sigma_{pl}^*(\varepsilon) = \frac{B_1 \sigma_{y,s}}{3\sqrt{3}} \frac{1}{\left(1 + \frac{1}{\rho_{rel}(1+k^2)} \sqrt{4(1-k^4)\varepsilon + (\rho_{rel} + k^2(-2 + \rho_{rel}))^2}\right)^{3/2}}, \quad (6)$$

where $k = l_2/l_1$. In this simple case the plateau stress is an increasing function of the strain and depends also on characteristic parameters of the foam, ρ_{rel} , k and $B_1 \sigma_{y,s}$, this latter being a fitting parameter in the present description.

Since the energy absorption capacity per unit volume can be calculated as

$W_{vol}(\varepsilon) = \int_0^\varepsilon \sigma(\varepsilon') d\varepsilon'$, Eq. 6 allows for the evaluation of the absorbed energy as a function of strain:

$$W_{vol}(\varepsilon) = \frac{B_1 \sigma_{y,s} \rho_{rel} \sqrt{\Phi}}{3\sqrt{3}(k^2 - 1)} \left(\frac{2\Phi + \Psi}{\sqrt{\Phi + \Psi}} - \frac{2\Phi + \sqrt{4\varepsilon(1 - k^4) + \Psi^2}}{\sqrt{\Phi + \sqrt{4\varepsilon(1 - k^4) + \Psi^2}}} \right) \quad (7)$$

where

$$\Phi = (1 + k^2) \rho_{rel} \quad \text{and} \quad \Psi = k^2 (\rho_{rel} - 2) + \rho_{rel}. \quad (8)$$

It must be emphasized that in this treatment W_{vol} can be obtained as an analytical function containing the relative density (ρ_{rel}), the quotient of the largest and the smallest cell-size (k), and $B_1 \sigma_{y,s}$. Since the ρ_{rel} , $\sigma_{y,s}$ and k parameters of a given foam are known or can be measured, only one parameter remains to fit: B_1 .

3.2 Densification strain

The essence of crack protection and protective packaging is to absorb as much energy as possible while keeping the protected object below the force limit, which would cause damages or injuries. Since after reaching the densification strain, ε_D the stress rises steeply, the absorbed energy can be calculated practically by integrating the stress in the plateau regime from zero to ε_D . Thus, it is important to determine the densification strain for the energy absorption applications.

The first estimation for the densification strain was given by Gibson and Ashby [1]. They have found that the densification strain is a linear function of the relative density both for closed- and open-cell foams:

$$\varepsilon_D = 1 - 1.4 \rho_{rel}, \quad (9)$$

A coefficient of correction is proportional to the cube of the relative density was introduced later by Ashby in [2] in order to improve the quality of the fitting:

$$\varepsilon_D = (0.9 \div 1) (1 - 1.4 \rho_{rel} + 0.4 \rho_{rel}^3) \quad (10)$$

Chan and Xie suggested an analytical model for the densification strain [6]. They define it as the intersection of the slopes of the stress-strain curves in the plateau and the densification regime. According to their calculations the expression for the densification strain of closed-cell foams is similar to Eq. 9:

$$\varepsilon_D = 1 - \alpha_c \rho_{rel}. \quad (11)$$

The α_c factor indicates that the foam cannot be totally compressed, in practice, a certain amount of pores remains in the crushed material.

Eq. 11 changes to Eq 12 in the case of open-cell foams:

$$\varepsilon_D = 1 - \alpha_o (\rho_{rel})^{1/2}, \quad (12)$$

where α_o is a constant, depending on the foam structure and the cell-edge material.

The difference between Eq. 11 and Eq. 12 indicates that the amount of the pores in the crushed foam depends also on the cell-structure, and this modifies the expression for the densification strain. The compression tests performed by Chan and Xie show, that α_c is approximately 1.4 ($\alpha_c \approx 1.4-1.7$), so Eq. 9 describes well the densification strain of closed-cell foams. In the case of open-cell foams Eq. 9 and 10 were found to give good results only when the fitting regime is not too wide ($\Delta \rho_{rel} < 10\%$). When the fitting regime is greater than approximately 20%, Eq. 12 seems to give a better fit.

4. DISCUSSION

The calculations in 3.1 can be modified to closed-cell foams of low relative density. Also the cell-size distribution of the foam can be taken into account in the calculation of $\varepsilon(l)$ (Eq. 2) and the average relative density (Eq. 4). The cell-size distribution can be determined from 2D slices or 3D tomographic images [4]. Using the measured cell-size distribution (determined from the 2D slices) the energy absorption capacity can be determined with three fitting parameters: $B'_1 = B_1\sigma_{y,s}$, $B'_2 = B_2\sigma_{y,s}$ and t_w . Choosing $t_w \approx 100\mu\text{m}$ for Ap0.8 and Ap1.1, and $t_w \approx 150\mu\text{m}$ for Ap2.08 [8] only B'_1 and B'_2 must be fitted.

The fitted curves and the energy absorption capacity according to the Gibson-Ashby model are shown in Fig. 2. Since the plateau stress in the Gibson-Ashby model is constant, W_{vol} is a linear function of strain. As Fig. 2 shows the Gibson-Ashby model describes the energy absorption properties quite well for low relative density foams. As the relative density increases the Gibson-Ashby model gives good values only for smaller and smaller strains while the calculations, which take the cell-size distribution into account, give good estimations even up to high strain. The difference between the two models is marked mostly in the case of the highest density foam, Ap2.08.

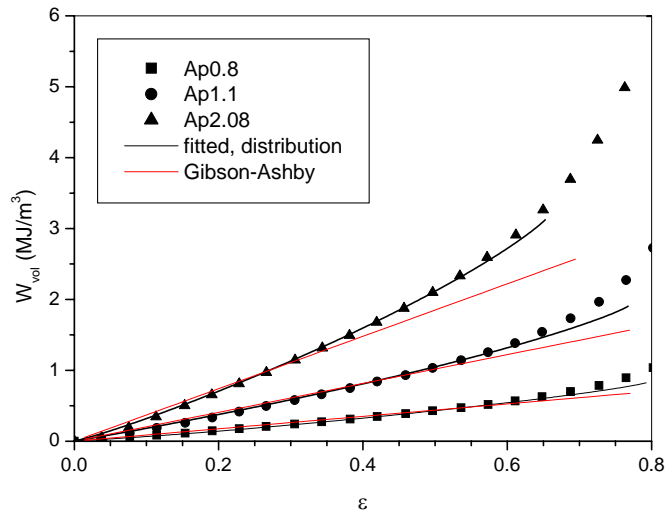


Fig. 2 The energy absorption capacity as a function of strain. The symbols belong to the measured curves, the red continuous lines are the linear fits according to the Gibson-Ashby model and the black continuous lines are the calculated curves using the measured cell-size distribution.

5. CONCLUSION

One of the main features of the model taking into account also the cell-size distribution is that it gives better description for the energy absorption capacity compared to the inevitably more simple Gibson-Ashby model. The two models give similar results for low relative density foams, however for the investigated higher density foams the difference gets larger.

The description presented here has another advantage: in the case of uniform cell-size distribution the expressions for the plateau stress and the energy absorption capacity remain analytical (in the physically relevant regime). Therefore for this case an exact analytical description can be given for the shape of the energy absorption function. The analytical description allows also for analyzing the influence of different structural and materials features of the foam.

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