Influences of Inertia and Material Property on the Dynamic Behavior of Cellular Metals

J.L. Yu*, Y.-D. Liu, Z.-J. Zheng, J.-R. Li, and T.X. Yu

Abstract Cellular metals are widely used in light-weight structures and energy absorption devices. Although many experimental studies on the dynamic behavior and rate sensitivity of cellular metals have been reported in the literature, there are some conflicting conclusions on the rate effect of metallic foams. In this paper, some numerical tests are presented to explore the effects of inertia, strain hardening and strain-rate hardening of the cell wall material on the behavior of Voronoi honeycomb samples under dynamic compression. Three deformation modes are found and corresponding nominal stress-strain curves and the plateau stress of the "specimens" are obtained. The results reveal that inertia plays an important role in Shock Mode and Transitional Mode but it does not affect the compressive stress-strain curve of the honeycomb. The strain-rate sensitivity of the honeycombs is less significant than that of the cell-wall material and becomes negligible under high impact velocities. The strain-hardening effect of the cell-wall material is of less importance.

1 Introduction

As a new-class of multifunctional materials, cellular metals, have attracted considerable research interest due to its excellent physical, chemical and mechanical properties. Potential applications of cellular metals include light weight cores for sandwich structures to increase the impact resistance, and improve the energy absorbing capacity. Much effort, including both experimental investigation and numerical analysis, has been made on the dynamic behavior of metallic foams, but

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there are some conflicting conclusions in the rate effect on the deformation behavior of metallic foams in the literature.

Considerable amount of experimental studies has been carried out on the strain rate sensitivity of metallic foams. Mukai et al. (1999) and Dannemann and Lankford (2000) observed a strain rate effect for the closed-cell aluminum foam Alporas (Al-Ca-Ti). In contrast, another closed-cell foam Alulight (Al-Mg-Si) formed by powder processing technique does not exhibit a strain rate effect (Deshpande and Fleck, 2000). Hall et al. (2000) also derived that the strain rate effect is not significant for a closed-cell 6,101 aluminum foam. Analogous confusions exist in open-cell aluminum foams. Duocel (Al 6101-T6) is regarded as a strain-rate insensitive foam (Danneman and Lankford, 2000; Deshpande and Fleck, 2000; Lee et al., 2006). On the other hand, Kanahashi et al. (2000) reported a strong strain rate sensitivity of an open-cell aluminum foam (SG91A). Nevertheless, Wang et al. (2006) found that the yield strength of another open-cell aluminum foam with similar chemical compositions of SG91A (Al-Mg-Si-Fe) are almost insensitive to the strain rate.

In order to clarify the inconsistencies in the literature mentioned above, Tan et al. (2005a) carried out an extensive experimental study on the crushing behavior of closed-cell Hydro/Cymat aluminum foam (Al-Si-Mg). They found that the plastic collapse stress increases with the impact velocity, which is attributed to micro-inertial effects. When the impact velocity exceeds a critical value the deformation of the foam is of 'shock-type' due to inertia effects. Below the critical velocity, the dynamic plateau stresses are insensitive to the impact velocity. Meanwhile, a one-dimensional "steady-shock" model based on a rate-independent, rigid, perfectly-plastic, locking (r-p-p-l) idealization of the quasi-static stress-strain curves for aluminum foams was proposed (Tan et al., 2005b) to provide a first-order understanding of the dynamic compaction process.

Regular honeycombs (Ruan et al., 2003) and 2D Voronoi honeycombs (Zheng et al., 2005) were used to investigate the mechanism of dynamic crushing of cellular metals numerically. The influences of cell wall thickness and the irregularity of honeycombs, as well as the impact velocity, on the deformation mode and the plateau stress were investigated. However, the influence of the material properties of cell wall on the dynamic response of foams has not been studied.

In this paper, we employ 2D Voronoi honeycomb in our numerical simulations. The density and plastic hardening properties of the cell wall material are factitiously changed to investigate the effects of inertia, strain hardening and strain-rate hardening on the crushing behavior of Voronoi honeycombs.

2 Finite Element Models

The Voronoi technique is employed to generate 2D Voronoi honeycombs. The irregularity of a Voronoi honeycomb with N cells in a square area A_0 is defined as (Zheng et al., 2005)

$$k = 1 - \delta / \sqrt{2A_0/\sqrt{3}N}, \tag{1}$$

where δ is the minimum distance between any two nuclei. The relative density of a Voronoi honeycomb is specified by

$$\bar{\rho} = \rho^*/\rho_s = \frac{1}{A_0}\sum h_i l_i, \tag{2}$$

where ρ^* is the density of honeycomb, ρ_s the density of its cell wall material, l_i the ith cell wall length and h_i the corresponding thickness.

In the present study, five random sample patterns are constructed in an area of $100 \times 100\,\text{mm}^2$ with 200 nuclei. The irregularity of the samples is taken to be 0.45. The cell wall thickness is identical for one sample and three values of thickness, i.e. 0.26, 0.36 and 0.48 mm corresponding to the relative densities of 0.073, 0.1 and 0.135, are investigated.

ABAQUS/EXPLICIT is employed to analyze the uniaxial compression behavior of Voronoi honeycombs under different impact velocities. In the finite element models, each edge of the cell wall is divided into a few shell elements of type S4R with five integration points. Three kinds of cell wall materials are considered. The first one is elastic-perfectly plastic with the Young's modulus, yield stress and Possion's ratio being 66 GPa, 175 MPa and 0.3, respectively. The second one is elastic-plastic material with linear strain-hardening. The third one is elastic-perfectly plastic material with strain-rate hardening. The stress-strain relation in the plastic stage for the last two materials are defined as

$$\sigma = \sigma_y + B\varepsilon_p \tag{3}$$

and

$$\sigma = \sigma_y\left[1 + C\ln\left(\dot{\varepsilon}_p/\dot{\varepsilon}_0\right)\right], \tag{4}$$

respectively, where ε_p is the equivalent plastic strain, σ_y the yield strength of the cell wall material, $\dot{\varepsilon}_p/\dot{\varepsilon}_0$ the relative equivalent strain rate, and B and C are material parameters. In this study we take $B = 175\,\text{MPa}$, $C = 0.05$ and $\dot{\varepsilon}_0 = 0.1$.

For quantitative comparison and analysis, the plateau stress is specified by

$$\sigma_p = \frac{1}{\varepsilon_D - \varepsilon_y}\int_{\varepsilon_y}^{\varepsilon_D} \sigma d\varepsilon, \tag{5}$$

where the densification strain ε_D is defined as (Tan et al., 2005a)

$$\frac{d}{d\varepsilon}\left(\frac{1}{\sigma}\int_0^{\varepsilon} \sigma d\varepsilon\right)\bigg|_{\varepsilon=\varepsilon_D} = 0, \tag{6}$$

and ε_y is the yield strain, which is taken as 0.02 in this study.

3 Results and Discussions

3.1 *Inertia Effect*

The influence of inertia on the crushing behavior of honeycombs is analyzed by changing the density of cell wall material. Elastic-perfectly plastic material property is assigned and four values of the density of cell wall material, i.e. 2.7×10^3, 0.9×10^3, 0.3×10^3 and $0.1 \times 10^3\,\mathrm{kg/m^3}$ are chosen artificially. Zheng et al. (2005) have found that the deformation of Voronoi honeycombs is complicated but it can be catalogued into three modes. A Quasi-static Homogeneous Mode occurs under low impact velocities, in which the crash bands are randomly located and the deformation is macroscopically homogeneous. If the impact velocity is very high, a Shock Mode occurs and cells crush sequentially in a planar manner from the impact end. A Transitional Mode occurs in between, in which the crash bends are more concentrated near the impact end. In the present study, it is found that when the cell wall material density is $2.7 \times 10^3\,\mathrm{kg/m^3}$, the critical velocities between the corresponding modes are about 40 and 90 m/s, respectively, regardless of the cell wall thickness (or the relative density of honeycomb).

Under the Homogeneous Mode, the calculated stress-strain curves under different impact velocities for Voronoi honeycombs with the same sample pattern and relative density (i.e., the cell wall thickness is fixed) almost remain identical, regardless of different densities of cell wall material, as shown in Fig. 1. It is evident that the inertia effect is negligible when the deformations of the honeycombs are macroscopically homogeneous.

The plateau stresses on the impact surface and the support surface under different velocities for the cell wall material density of $2.7 \times 10^3\,\mathrm{kg/m^3}$ are shown in Figs. 2 and 3, where Regions I, II and III correspond to the Homogeneous, Transitional and Shock Modes, respectively. It is found that under the Homogeneous

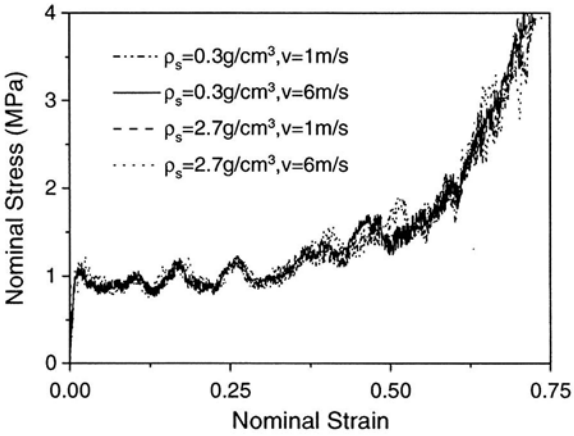

Fig. 1 Stress–strain curves under Homogeneous Mode

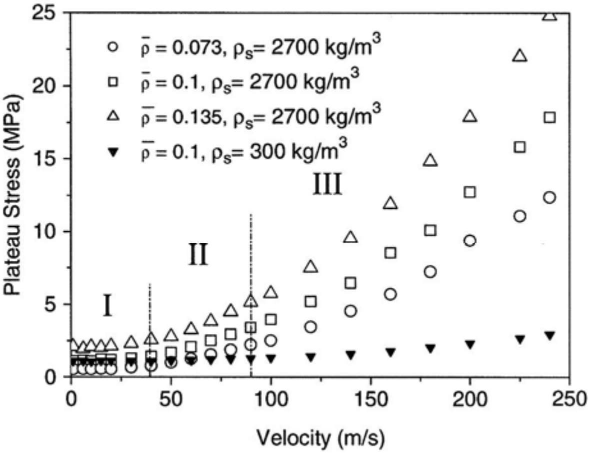

Fig. 2 The plateau stress on the impact surface under different impact velocities

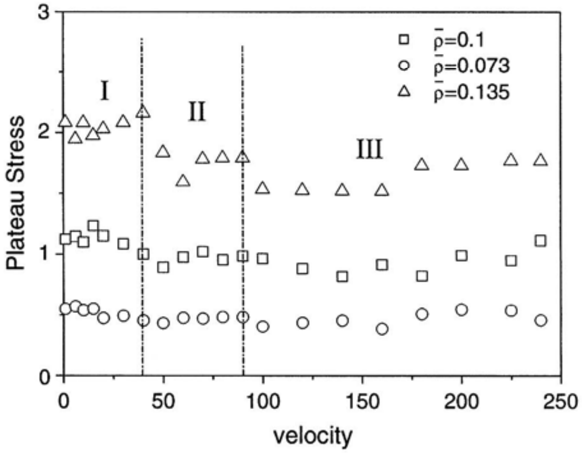

Fig. 3 The plateau stress on the support surface under different impact velocities

Mode, the plateau stresses on the impact surface and the support surface are almost the same, indicating an early achievement of internal force equilibrium. Also, the plateau stress increases remarkably with the increase of the relative densities. Thus, the plateau stress mainly depends on the relative density (the cell wall thickness), in agreement with experimental results reported in the literature.

On the other hand, under the Transitional Mode and Shock Mode, the plateau stress on the impact surface increases rapidly with the increase of impact velocity but the plateau stress on the support surface exhibits little velocity dependence. This is in accordance with the inhomogeneous deformation of the sample. The enhancement of the plateau stress on the impact surface can be explained as follows. The macroscopic strain along the impact direction is not uniform. The layer near the impact surface has the maximum macroscopic strain whilst the stress and strain there are located in the densification portion of the nominal stress–strain curve. The difference in macroscopic strain distribution between the two modes is that under the Shock Mode it is shock-like while under the Transitional Mode it changes gradually.

The plateau stresses on the impact surface under different velocities for the cell wall material density of $0.3 \times 10^3\,\mathrm{kg/m^3}$ is also shown in Fig. 2 for comparison. It seems that with the reduction of inertia, the force equilibrium and uniform deformation become much easier and the critical velocities for modes transition increase dramatically.

3.2 *Influence of the Cell-Wall Material Properties*

To investigate the effect of the cell-wall material properties on the crushing behavior, we select the linear strain-hardening and strain-rate hardening elastic-plastic materials to study the responses of the Voronoi honeycombs under various velocities. The density of cell wall material is $2.7 \times 10^3\,\mathrm{kg/m^3}$ and the relative density is $\bar{\rho} = 0.1$.

In comparison with the elastic-perfectly plastic material, the relative increase in the plateau stress caused by the linear strain-hardening effect can be specified by

$$\lambda_1 = (\sigma_1 - \sigma_0)/\sigma_0, \tag{7}$$

where σ_0 and σ_1 are the plateau stresses of the elastic-perfectly plastic material and the strain-hardening material, respectively. Note that the relative increase in the flow stress of the solid material is proportional to the plastic strain.

Similarly, the relative increase in the plateau stress caused by the strain-rate hardening effect, compared to elastic-perfectly plastic material, can be defined as

$$\eta_1 = (\sigma_2 - \sigma_0)/\sigma_0, \tag{8}$$

where σ_2 is the plateau stress of the strain-rate hardening material. According to Eq. (4), the relative increase in the flow stress of the solid material is described by

$$\eta_2 = (\sigma - \sigma_y)/\sigma_y = C\ln(\dot{\varepsilon}_p/\dot{\varepsilon}_0). \tag{9}$$

The variation of the averaged relative increase in the plateau stress on the impact surface of five random samples and their mean square deviations with the impact velocity for honeycombs made of strain-hardening material is shown in Fig. 4. It is found that λ_1 takes a small value over the whole range of the impact velocities studied, so the strain-hardening of cell wall material has minor influence on the plateau stress under both quasi-static and dynamic cases. The effect might be well submerged into experimental scatter for irregular cellular metals.

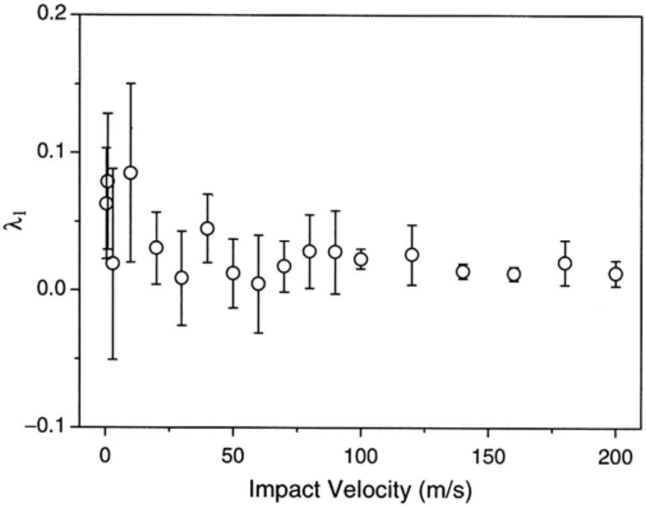

Fig. 4 The relative increase in the plateau stress of honeycombs made of strain-hardening material under different impact velocities

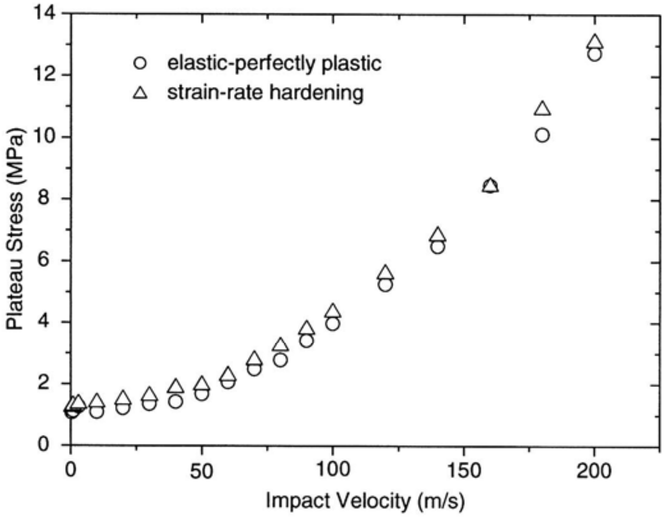

Fig. 5 The plateau stresses on the impact surface under different impact velocities

A comparison of plateau stress on the impact surface of a honeycomb sample made of elastic-perfectly plastic and strain-rate hardening materials is shown in Fig. 5. The variation of the relative increase in the plateau stress with the nominal strain rates for honeycombs made of strain-hardening material is shown in Fig. 6.

It is found from Fig. 5 that the increase in the plateau stress due to the strain-rate sensitivity of cell wall material is small and almost independent of the impact

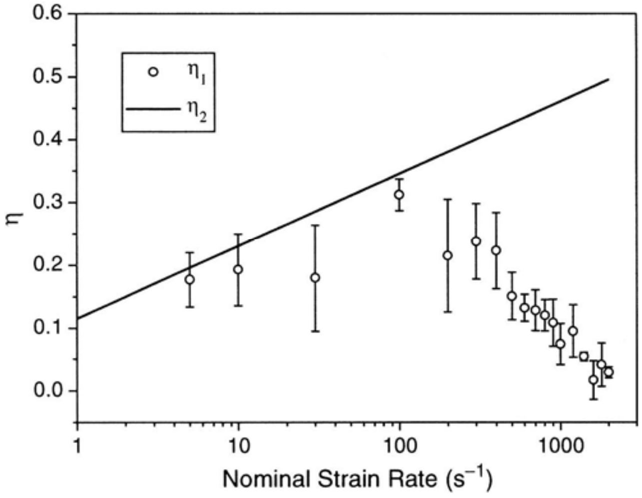

Fig. 6 The relative increase in the plateau stress of honeycombs made of strain-rate hardening material under different nominal strain-rates

velocity. The relative increase in the plateau stress is always less than the relative increase in the flow stress of the corresponding solid material. About 20% increase in the plateau stress is found under the Quasi-static Homogeneous Mode when the strain rate is smaller than $400\,s^{-1}$ for the parameters used in this paper, as shown in Fig. 6. It is interesting to note that under the Transitional Mode and Shock Mode, the strain-rate effect seemingly decreases fast with the impact velocity. This can be attributed to the enhancement of the plateau stress due to the inertia effect.

From the numerical results we also found that the critical velocities of deformation modes are almost independent of the strain hardening and strain-rate hardening of the cell-wall material. The possible explanation is that the plastic strain in most parts of the honeycomb is small except along the plastic hinge lines.

4 Concluding Remarks

The present numerical results indicate that inertia is a dominant factor which affects the dynamic response of cellular metals. The strain-rate sensitivity of cell-wall material leads to an increase in plateau stress but it can not explain the strong rate dependence observed in some metallic foams. More elaborative experiments and punctilious analysis are required to solve the existing puzzle.

Some possible mechanisms responsible to the rate sensitivity of metallic foams need to be further explored, e.g., cell morphology, cell wall material distribution, ductile-brittle transition of the cell wall material, strain-rate sensitivity of its failure strain, and micro-structural characters associated with their manufacture.

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