Research Paper

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Rotation Effects of Unstable Flow in Porous Structures

Engineering

KEYWORDS : process of deformation, porous structure, rotary modes, fracture process, nonuniform rotation, strong heterogeneity, destruction.

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ABSTRACT

We consider the process of deformation and buckling of flow during compression of the porous structure on the basis of aluminum with a high concentration of pores. Analyzed rotary modes plastic flow and their relationship with the beginning of the fracture process. Allocated for this reference points - the joints and then determined their trajectory in the process of loading . Was established the important role of nonuniform rotation associated with strong heterogeneity of the porous structure. Nonuniform rotation in the vicinity of large central pores leads to a collapse of the two neighboring pores and subsequent destruction.

INTRODUCTION

Foam metals are used in a car and pace industries, engineering, constructing and medicine. There are two basic methods of obtaining foam metals – powder and foundry. Powder technology provides a more uniform distribution of the foaming reagent in a powder and leads to high level of isotropy for materials.

RELATED WORK

Typical porous structure, obtained by powder technology presents in Fig.1

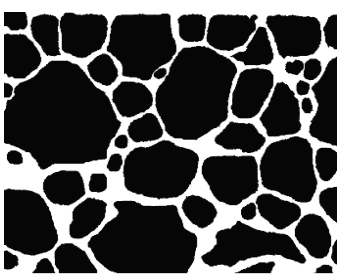


Fig.1. The porous structure of the aluminum foam. The volume fraction of pores is $N_0 = 0.3$, the average size ~1500 μm.

Characteristic diagram of the deformation of the porous structure of the aluminum foam is presented in Fig. 2

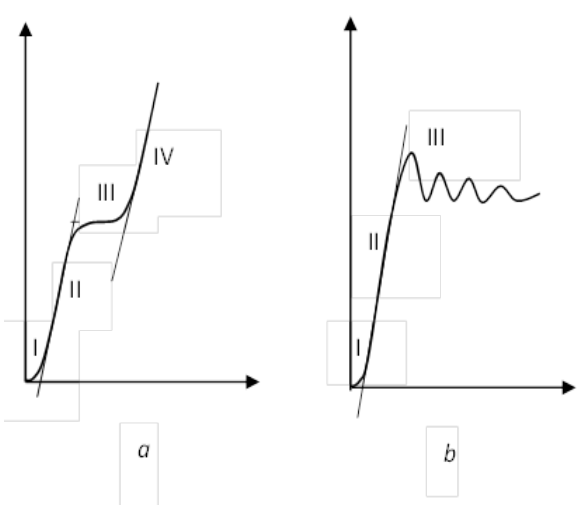


Fig. 2. The Compression stress (σ)–strain (ε) curves of a highly porous materials: a - for plastic materials; b - for brittle materials with a porosity of less than $N_0 = 0.9$ [1].

For ductile materials can be divided into four main stages of deformation patterns: initial nonlinear phase I, line section II, the plateau region III and region steep hardening IV, followed by the collapse of most of the pores and the destruction of the material. In brittle materials - the fourth stage is usually not observed – collapsing then the destruction of the walls superimposed on the plateau. The average stress plateau varies in the range of $3-0$ MPa and tends to grow with increasing average density of the material. The length of the site plateau can reach 100%.

Among all of the possibilities of application of porous structures we will consider three main areas: porous structure, as a material for the manufacture of rigid structural panels, as a material for conventional and high-energy damping.

The possibility of using porous structures as a structural material for the manufacture of panels is based on the following simple estimates. Maximum stress at double-seat bending is inversely proportional to the moment resistance of the beam $\sigma_{max} = \frac{M}{b^2}$ – where M is the applied moment, b, h - the width and the thickness of the beam. With constant mass of the structure per unit length, the stress is inversely proportional to the square of the thickness of the beam, i.e., a quadratic density-dependent $\sigma_{max} \approx \rho_0^2$.

Material works in field I stress–strain curves (Fig. 2a, b). The stress plateau usually depends on the density as exponential $\sigma_s \approx \rho_0^\beta$, with a rate β usually lies in the interval $1 < \beta < 1{,}5$ [2], i.e. existence of areas of density, in which the beams on the basis of metal foam tougher than monolithic structures is possible.

For the energy damping stage I-III chart plastic deformation of porous materials are suitable (Fig. 2a). Specific work – area under the curve depends on the density N_0 measures and the heterogeneity of the structure (for a given basis).

In the range of densities material aluminum foam specific power absorption is $0.5 - 3.0$ MJ/m³ and decreases substantially with an increase in the degree of heterogeneity of the material at a given density.

If this material is used as a car bumper, when the mass of the car is 1000 kg and a speed of 18 m/s (60km/h), the energy of a frontal impact may be irreversiblyscatteredby metal foam structure with a total volume $5-0$ Dm³, with a mass just $5-5$ kg, what is quite practical to use on a complex of parameters of cost-effectiveness.

High-energy damping, i.e., absorption and scattering of high-energy flow with the energy density $150-200$ MJ/m² was considered in [3]. Area of work material is the entire diagram deformation. The sources of such effects - means the cumulative destruction of armored vehicles. Calculations show that a pure

foam material is not effective enough: protection thickness against a standard weapon of destruction has to exceed one meter.

However, the combined decision is possible. Foam is placed right after a high-modular composite $Al - SiC$ and is used as the intermediate environment - its purpose is to "stretch" in time the return influence of elements of the gradient reinforced dynamic protection [4]. One of advantages of similar "sandwich" - technological compatibility of materials: the porous structure simply foams on the basis of the gradient reinforced composite.

The density of metal foam affects their strength properties; in particular, its reduction reduces the current flow stress medium. However, a number of experiments [1, 2 and 5, 6] indicate a significant influence of structural heterogeneity (statistical pore size, topology, joints, wall thickness, etc.) on the mechanical properties.

In other words, at the same porosity and, accordingly, the specific mass shift from "good" homogeneous and isotropic structure to "bad" is highly heterogeneous, can decrease the voltage plateau by 15-20 percent, almost twice the deformation at the third site and, consequently, manyfold (!) the work to fracture – damping capacity of the structure.

PROBLEM DEFINITION

An important problem is to establish the relationship between the structure and porosity (including its heterogeneity) and final mechanical properties. The complexity of the mathematical description of the flow of the porous structure lies in the considerable heterogeneity of the material: pore size, wall thickness may vary greatly within a medium porosity; a local chart of deformation at the scale of the average pore size is very different from the average deformation.

Buckling with relatively uniform pore structure under compression starts in the frame with the lowest strength (Fig. 3) is an area located in the center, inside the red perimeter (3*b*). Strength structures in adjacent areas of the sample are sufficient to transfer the load to the central portion without breaking.

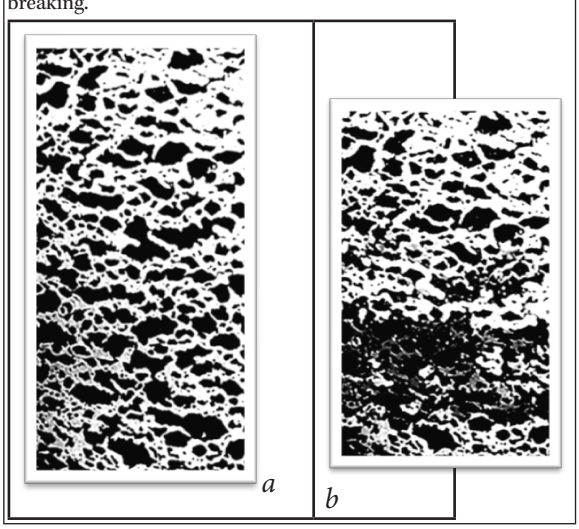


Fig. 3. Changes of the relatively homogeneous porous aluminum structure under compression: *a* - initial state; *b* - after compression with a degree of deformation ε= 18,26% - in the red perimeter - the area of destruction (the area adjacent to the destruction of the top and bottom of the structure transfers the strain without destruction).

Deformation less uniform structure is more complicated (Fig. 4) - as it is non-uniform as in the scale of the pores themselves, but at the next scale level - in the pore walls, thus accompanied not only by pore collapse and destruction of their walls, but also by rotation.

One of variants of such a description is provided in [7]. We use numerical - analytical approach: figure deformation represented

$$\sigma_{ij}(\mathbf{r}, \varepsilon_{mn}) = \frac{\rho(\mathbf{r})}{\rho_0(1+\theta)\left(\mathbf{h}(s)e_{ij} + \frac{1}{3}\mathbf{K}(\theta)\theta\right)}$$

$$\sigma_{ij}(\mathbf{r}, \varepsilon_{mn}) = \frac{\rho(\mathbf{r})}{\rho_0(1+\theta)\left(\mathbf{h}(s)e_{ij} + \frac{1}{3}\mathbf{K}(\theta)\theta\right)}$$

where $\rho(\mathbf{r}), \rho_0 \rho(\mathbf{r}), \rho_0$ - are local and average density of the material, s, $\theta\ \theta$ - the first invariant of the deviatory strain tensor, $\mathbf{h}(\mathbf{s}),$ $\mathbf{K}(\theta)\mathbf{h}(\mathbf{s}),$ $\mathbf{K}(\theta)$ intersecting modules hardening for the deviator and hydrostatic compression.

The value $\rho(\mathbf{r})\rho(\mathbf{r})$ of assumed random with a given law of distribution, equilibrium equations to compress the cube solved numerically for various statistics . $\rho(\mathbf{r})\rho(\mathbf{r})$.

The essential feature of the model in a nonlinear is dependence on the modulus $\mathbf{K}(\theta)\mathbf{K}(\theta)$ from the process of deformation (due to structure compacted during compression) and the renormalization of the stress-strain depending on the local density at each point r.

It was shown that for a given average density of the material measure heterogeneous structure significantly affects the diagram and power consumption of deformation.

However, there is a problem with a large quantity of local deformations, and so it is impossible to limit ourselves to the strain tensor. This leads to the need to consider the full tensor distortion and, consequently, to consider separately its asymmetric part - the pseudo-rotation or rotational deformation mode.

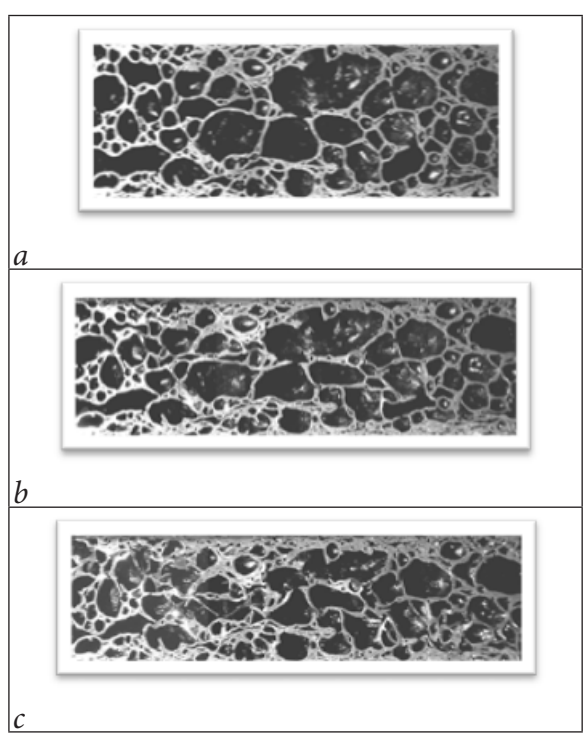


Fig. 4. Change of the relatively inhomogeneous porous structure based on aluminum under compression: *a* - initial state; *b* - after compression with a degree of deformation of ε=7,6%; *c* - after

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compression with a degree of deformation ε = 25%.

This rotation modes flow of porous structures and determine, according to the authors, the macro-instability and destruction (for porous structures loss of bearing capacity) of porous materials

RESEARCH METHODOLOGY

To construct a theory of deformation of highly porous structures it is necessary to establish the presence and contribution of rotational modes in deformation of porous structures, the mechanism of the effect of the loss of rotational modes of flow stability and destruction of material.

For this purpose, we considered the process of deformation and buckling of the flow through the porous structure of aluminum with a high concentration of pores [8]. The compression tests were performed on the samples from compressive foamed Al-6,3%Mg alloy (analog ASTM - 518.0) at room temperature with stops at a certain deformation and photographing sample surface - Fig. 5.

The binarization images of the surface of the sample was performed using the Adobe Photoshop software. On this images triple junctions (cells) were fixated, and for each degree of deformation their position - coordinates were determined - Fig. 5.

On the basis of these data the quantitative analysis of rotational modes of plastic flow and their relation with the start of the destruction process was made.

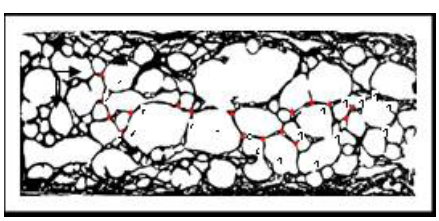


Fig.5. Scheme of identifying characteristic points.

To assess rotational modes used rotation vector ϖ, which characterizes the rotation of the elementary volume (cell), which is calculated by the equation:

$\omega(n,\varepsilon_{\hat{e}})=\frac{1}{2}\cdot(\hat{A}_{12}(n,\varepsilon_{\hat{e}})-\hat{A}_{21}(n,\varepsilon_{\hat{e}}))$, where n is the number of characteristic points - triple junction; $\varepsilon_{\hat{e}}$ is the average strain.

The magnitude $\hat{A}_{i,j}$ is a distortion at characteristic points for all degrees of deformation determined from the relationship:, $A_i=\frac{\delta_i(n+1,\varepsilon_{\hat{e}})-A_i(n,\varepsilon_{\hat{e}})}{\delta_i(n+1)-x_i(n)}$ where $A_i(n+1,\varepsilon_{\hat{e}})$ is the offset point (n+1) for the average deformation $\varepsilon_{\hat{e}}$; $A_i(n,\varepsilon_{\hat{e}})$ is offset points n for the average deformation $\varepsilon_{\hat{e}}$; $\delta_i(n+1), \delta_i(n)$ are coordinates of points (n+1) and n is in the initial state when $\varepsilon=0$.

During the deformation of the porous structure under compression process of collapse of large and average size pores is observed during non-uniform rotation in the vicinity of large central pore.

Figure 6 shows the evolution of the localization of the flow in the vicinity of large pores with different degrees of deformation.

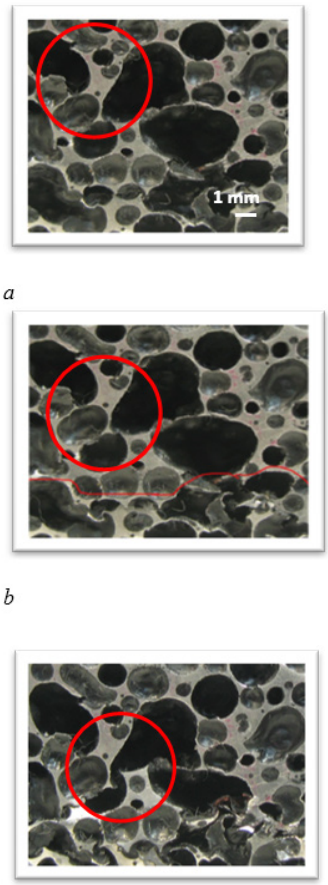


Fig.6 The structure of aluminum foam at moderate strains: a - 18%, b - 23%, c- 27%.

The concentration of large pores (3-5 times larger than the average size) is small (~10^{-2}); their statistics lies on the so-called "tail of the distribution" - areas where statistical methods are not very effective - are not met limiting inequality and the theorem of probability theory. These areas are determined ultimately by the moment buckling and fracture of the porous structure. The presence of small quantities of large pores reduces ultimate strain by 10-15% and power consumption of the structures by 25-35%.

The analysis of the dependence of the modulus of the vector rotation ϖ on the average strain for the points that characterize the situation of certain small and large pores and separately a) to the end of the sample, b) to the opposite side of the sample and the average absolute value of the average rotation strain showed: in the initial stage of loading the greatest contribution to rotational modes of plastic deformation of porous structures is made by large pores; there is non-uniform rotation, which is a measure of the full tensor bending - torsion $\chi_{ij}=-\frac{1}{2}e_{ijk}\varpi_k$; in the area where χ_{ij} is maximum plastic flow of material becomes unstable and destroyed [6,7].

DISCUSSION

The destruction is determined not by the average properties of the defect structure, but a small number of "bad places" – areas of generation of microcracks, therefore, the construction of a rational theory of unstable plastic flow and destruction on the basis of only the classical statistical models is impossible.

The generation of microcracks is due to the non-uniform rotation in the vicinity of large pores provoking their own "collapse" and a similar interaction with adjacent pores, i.e., local destruc-

tion.

The measure of inhomogeneous rotation is complete tensor bending - torsion. In the area of the maximum values of its components material flow becomes unstable and structure becomes destroyed.

For a given average density of the material measure heterogeneous structure significantly affects the diagram and power consumption of deformation.

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