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Elasto-plastic constitutive model of aluminum alloy foam subjected to impact loading

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Abstract: A multi-parameter nonlinear elasto-plastic constitutive model which can fully capture the three typical features of stress—strain response, linearity, plasticity-like stress plateau and densification phases was developed. The functional expression of each parameter was determined using uniaxial compression tests for aluminum alloy foams. The parameters of the model can be systematically varied to describe the effect of relative density which may be responsible for the changes in yield stress and hardening-like or softening-like behavior at various strain rates. A comparison between model predictions and experimental results of the aluminum alloy foams was provided to validate the model. It was proved to be useful in the selection of the optimal-density and energy absorption foam for a specific application at impact events.

Key words: elasto-plastic; constitutive model; metallic foam; strain rate effect; energy absorption

1 Introduction

Cellular materials, such as metallic foams, can dissipate considerable energy by large plastic deformation under quasi-static or dynamic loading[1−4]. Their cellular microstructures offer the ability to undergo large plastic deformation at nearly constant stress, and thus the materials can absorb a large amount of kinetic energy before collapsing to a more stable configuration or fracture. With this excellent feature and other advantages[1−4] including low density, high specific strength, high specific stiffness and high energy absorption ability, metallic foams are very suitable as inside structural material for protective structures and shock absorbers. Now they have been increasingly used in a wide range of protective applications[4−7]. A full mathematical description of the mechanical properties of metallic foams at various strain rates is significant for the corresponding impact events. However, the current metallic foam models[8−13] are mostly presented on the base of empirically obtained stress—strain curves under quasi-static test, which could only represent a narrow range of behaviors. The mechanical behavior of metallic foams can be modified in a wide range to meet specific requirements by choosing the cell wall materials, type, size and statistical distribution of the individual cells. However, this advantage combined effect of material properties and structure on the stress—strain behavior of foams complicates the description and prediction of their properties in terms of these parameters. Only a few models, such as the Gibson model[1], are based on the deformation mechanism and therefore could account for the effects of the characteristic parameters, such as density and cell size. These models are too complex to be applied in industry since the Gibson density dependency laws or the proposition of other laws[2−4] must be characterized by analyzing the foam structure.

A number of researchers[8−13] implemented simplified structural analysis by some nonlinear empirical constitutive models in finite element method (FEM) codes. Basically, these models can be expressed by the following equation,

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$$\sigma = H(T)G(\rho)M(\dot{\varepsilon})f(\varepsilon) \tag{1}$$

where H, G and M are the functions of temperature T, initial density ρ and strain rate $\dot{\varepsilon}$, respectively; $f(\varepsilon)$ is called the shape function and is used to describe the fundamental stress—strain response. Obviously, all the functions above play the role of scaling of the shape function.

It is important to obtain mechanical properties of metal foams from a single constitutive model which is capable of describing the stress—strain behavior at a wide range of specific foams densities and strain rates. Such data are essential in realistic numerical simulations for the safety design of structures.

In this investigation, a more comprehensive formulation of elasto-plastic constitutive model which can describe the entire dynamic compression behavior of aluminum alloy foams including three typical deformation stages was developed based on experimental results. Relative density and strain rate are two most important parameters determining the mechanical properties of aluminum alloy foams, and the dependency of the model parameters on them was analyzed. The dynamic compressive behavior of aluminum alloy foams can be characterized by using a single constitutive equation at various strain rates. It was noted that this model reduces the complexity related to cell morphologies. Moreover, more precise parameters of the foams in its optimal design, especially in evaluating the optimal density in the specific strain rate, can be obtained through this constitutive model.

2 Experimental

The open-cell aluminum alloy foams were made by infiltration casting process. The composition of the cell wall material is Al-3%Mg-8%Si-1.2%Fe (mass fraction). Specimens were cut into cylinders with sizes of d35 mm×30 mm for quasi-static tests and d35 mm×10 mm for dynamic tests, respectively, using an electrical discharge machine from blocks of the foam material. With this choice of dimensions, the specimens have at least 6−8 cells in all directions. Prior to tests, each specimen was weighted and measured in order to calculate its effective density.

Aluminum alloy foams with approximate relative density (defined as the density of the foam ρ^* divided by the density of the cell wall material ρ_s) ranging from 0.25 to 0.40 were investigated. The average cell sizes of these foams are approximately 0.9 and 1.6 mm, respectively. For comparison, a universal material testing system (MTS810.25) was used to perform the quasi-static compressive tests at a strain rate of 1×10^{-3} s^{-1}. For foam with each relative density, at least three repetitions of the compression test were performed. Figure 1 shows the typical SEM photographs of foam microstructures.

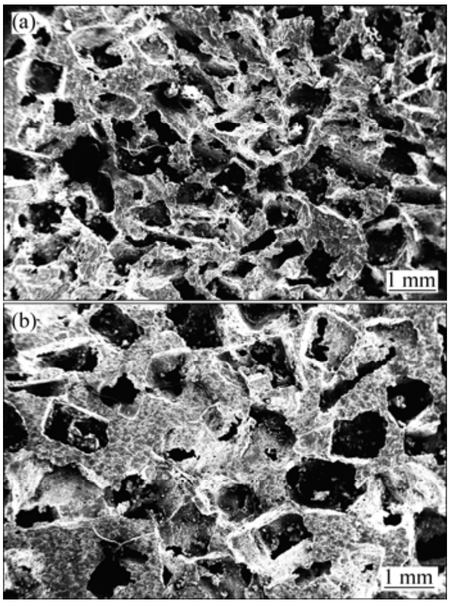

Fig.1 SEM images of aluminum foams with different open-cell sizes: (a) 0.9 mm; (b) 1.6 mm

3 Dynamic measuring techniques and optimized data processing

High strain-rate tests were conducted on the cylindrical samples described above using a split Hopkinson pressure bar apparatus[14−15], as shown in Fig.2. The striker, incident and transmitter bars were made of aluminum with yield stress equal to 200 MPa. They have an identical diameter of 37 mm and different lengths of 800, 2 000 and 2 000 mm, respectively. The end surfaces of the bars were lubricated to reduce the frictional restraint. The axial impact of striker bar and incident bar generates a compressive pulse, which is partially reflected when reaching the interface between the incident bar and specimen. The other portion of the wave is transmitted through the transmitter bar. The incident pulse and reflect wave in the incident bar were

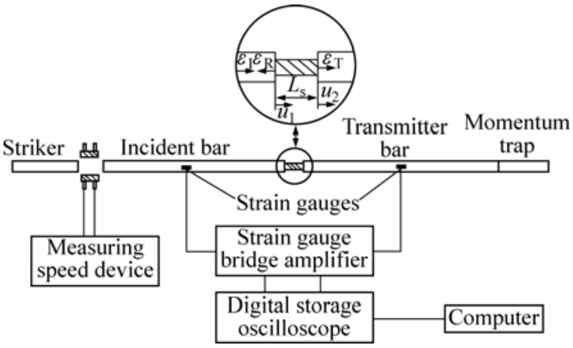

Fig.2 Schematic diagram of split Hopkinson pressure bar apparatus