Energy Absorption of Light-Weight Metallic Foams under Dynamic Loading

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Abstract

The energy absorption of a closed-celled magnesium and an open-celled magnesium has been evaluated under a dynamic loading (> 1×10^3 s^{-1}) in compression. It was found that the two light-metallic foams at the dynamic strain rate exhibited a 50 ~ 100% increase in plateau stress as compared to that at a quasi-static strain rate. As a result, the two foams under dynamic loading also showed higher absorption energy values than that under quasi-static loading. The experimental results suggest that it is important to understand the exact dynamic response and actual strain rate sensitivity of a material in order to determine its appropriateness for a specific application.

1 Introduction

There is currently a high interest in using light-weight metallic foams (e.g., Al and Mg) for automotive, railway and aerospace applications where weight reduction and improvement in comfort are needed [1]. Metallic foams also have a potential for impact energy absorption during the crashing of a vehicle either against another vehicle or human body. Limited data, however, exist for the strain rate dependence of the mechanical strength of cellular materials. For example, Rinde and Hoge studied the strain rate dependence of the compressive strength of rigid polystyrene foams at room temperature and showed that the strength increases only slightly with strain rate [2]. Lankford and Dannemann also reported that the strain rate dependence was negligible for a low-density open-celled aluminum [3]. Tyler and Ashby examined a flexible polyurethane foam at strain rates ranging from 2×10^{-3} to 20 s^{-1} and found that the plateau stress of the foam filled with air was independent of the strain rate [1]. However, the stress exhibited a strong strain rate dependence when the foam was filled with a viscous water-glycerin mixture. Apparently, there is no universal agreement on the strain rate dependence of plateau stress. Up to date, despite the fact that cellular metals have been appreciated for energy absorption, only limited mechanical property data are available, especially at dynamic strain rates $>10^3$ s^{-1} [3-5]. In the present study, a closed-celled aluminum and an open-celled magnesium foam are examined at dynamic strain rates ~ 10^3 s^{-1}. A Split-Hopkinson pressure bar(SHPB) apparatus was used to measure the stress-strain response at the dynamic strain rates of $8x10^2$ ~ $2.5x10^3$ s^{-1}.

2 Materials

The aluminum foams used in the present study are commercial ALPORAS (Shinko Wire Co. Ltd., Japan), which were produced by a melting process. The chemical composition of the foam is Al-1.42Ca-1.42Ti-0.28Fe-0.007Mg (by mass%). Typical structure of the closed-celled foam has been reported elsewhere [6]. The average diameter of the cells was measured to be 2.6 mm, and the relative density ($\rho\ \rho_s$) of the foam was about 0.1, in terms of the density of the foam (ρ) and of the solid (ρ_s).
The other foam is an AZ91 (Mg-9wt.%Al-1wt.%Zn-0.2wt.%Mn) Mg alloy. An open-celled AZ91 (herein, AZ91 foam) was fabricated by casting using a polyurethane form. Detailed procedures and morphology of the foam have been reported previously [7]. The average column spacing and thickness were 4.5 and 0.3 mm, respectively. The relative density of AZ91 foam is ~ 0.03.

3 Dynamic Compressive Behavior of Aluminum and Magnesium Foams

Although the SHPB apparatus has an advantage of applying a constant loading during deformation, the test is, sometimes, limited by the size of the sample. A previous study suggested that, to evaluate reliably the mechanical properties of cellular materials, the height of a specimen should be ten or twenty times larger than the cell diameter in order to minimize variation in data measurement [8]. Thus, it was decided to determine the minimum height of foam specimens for compression test at a quasi-static strain rate [4].
Aluminum foam samples with dimensions of 9x9x3 and 9x9x6 mm^3 were selected for testing. The relative density of both samples is essentially identical. Typical stress-strain curves for these foams at a quasi-static strain rate of $1x10^{-3}$ s^{-1} are shown in Fig. 1. (The datum for a large specimen (30x30x20 mm^3) of the same material is included for comparison.) The sample shows an elastic region at the initial stage followed by a plateau region (with nearly constant flow stress). After the plateau region, the flow stress rapidly increases because of densification. This stress-strain characteristic is consistent with that observed in other closed-celled aluminum [9]. The smaller sample of 9x9x3 mm^3 shows higher constant stress and smaller plateau strain comparing with that of 9x9x6 mm^3. This is somewhat surprising since, in principle, the reduced constraint of the cell walls on the sample surface is expected to decrease the strength as the samples get smaller. It is unclear why small samples are stronger than the large ones. This may be associated with the surface to volume ratio, namely, the 3mm height specimen has a higher surface to volume ratio than those with a height over 6mm. It is noted in Fig. 1 that the shape of the curves from the 9x9x6 mm^3 specimen is similar to that from the large 30x30x20 mm^3 specimen, specifically, the plateau stress and strain are virtually identical for these two specimens. From the experimental results, the dimension of compressive specimen was determined to 9x9x6 mm^3.
A number of stress-strain curves for ALPORAS at a dynamic strain rate of $2.5x10^3$ s^{-1} are shown in Fig. 2. In comparison to the data at a quasi-static strain rate (Fig. 1) the flow stress at dynamic strain rate exhibits essentially a higher value than that at the quasi-static strain rate.

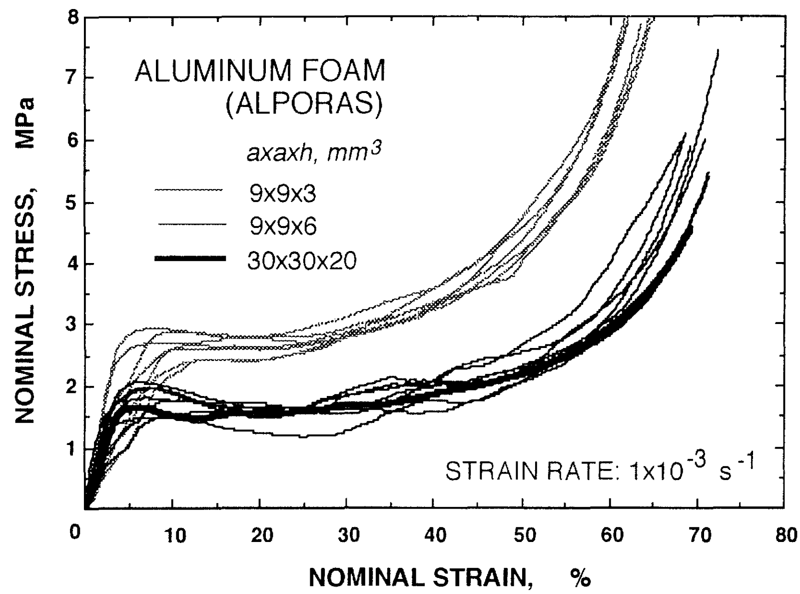

Fig. 1 Nominal stress-strain curves for ALPORAS at a quasi-static strain rate of $1x10^{-3}$ s^{-1}.

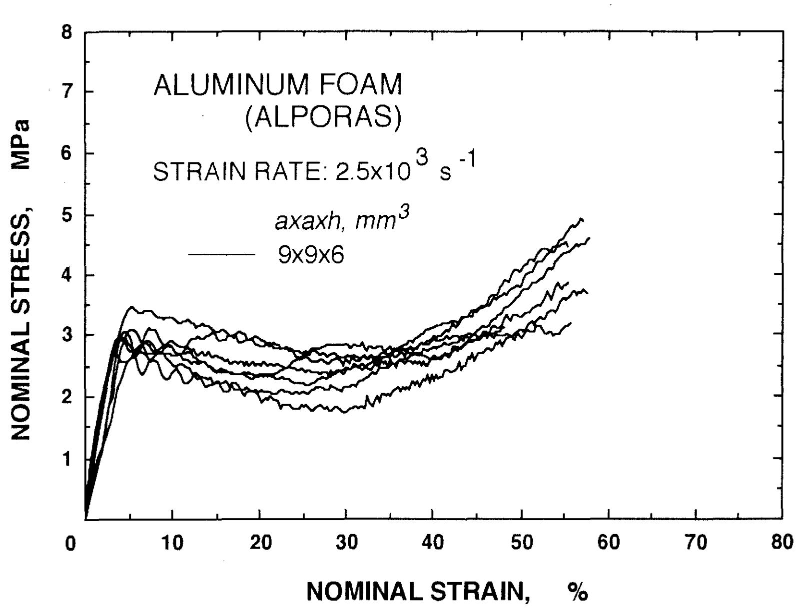

Fig. 2 Nominal stress-strain curves for ALPORAS at a dynamic strain rate of $2.5x10^3$ s^{-1}.

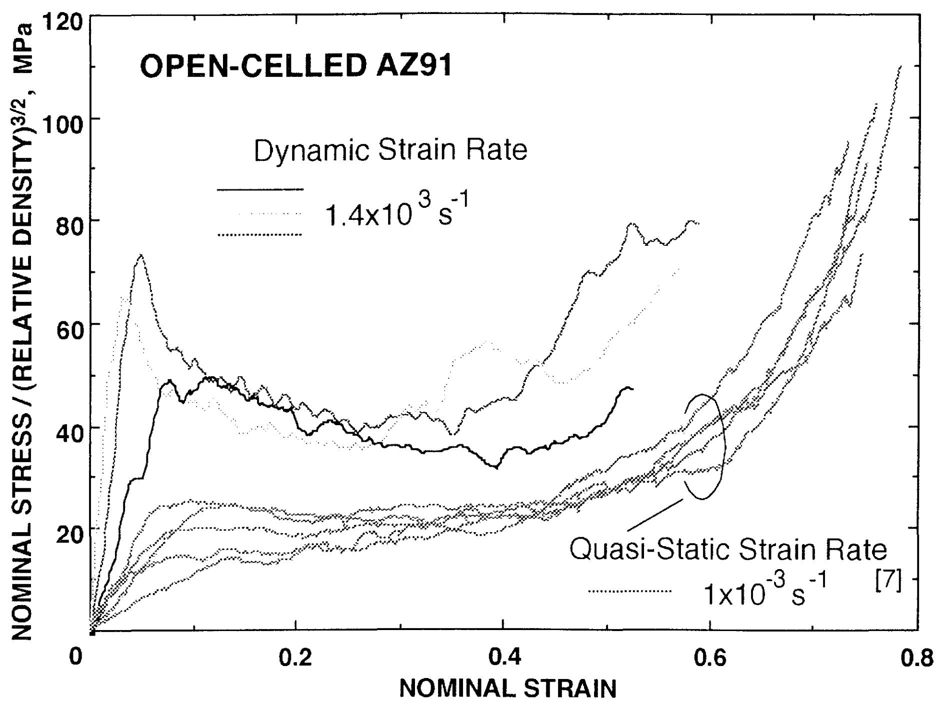

Fig. 3 Nominal stress normalized by (relative density)$^{3/2}$ for AZ91 foam at a dynamic strain rate of $1.4\text{x}10^3$ s^{-1}. Data obtained at a quasi-static strain rate of $1\text{x}10^{-3}$ s^{-1} are also included [7].

Gibson and Ashby [1] analyzed the relationship between the relative stress, σ_{pl}/σ_{ys}, and the relative density, ρ ρ_s, assuming that plastic collapse occurs when the moment exerted by the compressive force exceeds the fully plastic moment of the cell edges, where σ_{pl} is the plastic-collapse stress, σ_{ys} is the yield stress of the cell wall (edge) material, ρ is the density of the cellular material and ρ_s is the density of the cell wall (edge) material, respectively. The relationship between the relative stress and the relative density for open-celled material was given by [1],

$$\frac{\sigma_{pl}}{\sigma_{ys}} = C\left(\frac{\rho}{\rho_s}\right)^{3\ 2} \qquad (1)$$

where C is a constant. Following this relationship, normalized stress-strain curve for AZ91 foam at a dynamic strain rate is plotted in Fig. 3. For a direct comparison, data obtained from the same foam tested at a quasi-static strain rate of $1\text{x}10^{-3}$ s^{-1} [7] are also included. In comparison to the data measured at a quasi-static strain rate, several different features are readily observed for both metallic foams: (1) the yield stress at the dynamic strain rate is higher than that at the quasi-static strain rate, (2) plateau strain (ε_{pl}) at the dynamic strain rate is slightly smaller than that at the quasi-static strain rate, and (3) a gradual stress drop with strain occurs at the dynamic strain rate.

The normalized plateau stress for ALPORAS and AZ91 foams as a function of strain rate is plotted in Fig. 4. To make a direct comparison, data from a rigid polystyrene [2] with a relative density of about 0.1 are also included. Despite some data variations, the strength of both ALPORAS and AZ91 foams clearly shows a strong strain rate dependence. In contrast, the polystyrene exhibits only a slight dependence. Specifically, the compressive strength of AZ91 foam nearly doubles with six orders of magnitude increase in strain rate. It was found that the compressive yield stress of the bulk ALPORAS exhibited a significant strain rate sensitivity. A possible reason for the significant strain rate sensitivity in the foamed state is due to the strain rate sensitivity of the compressive stress in the solid.

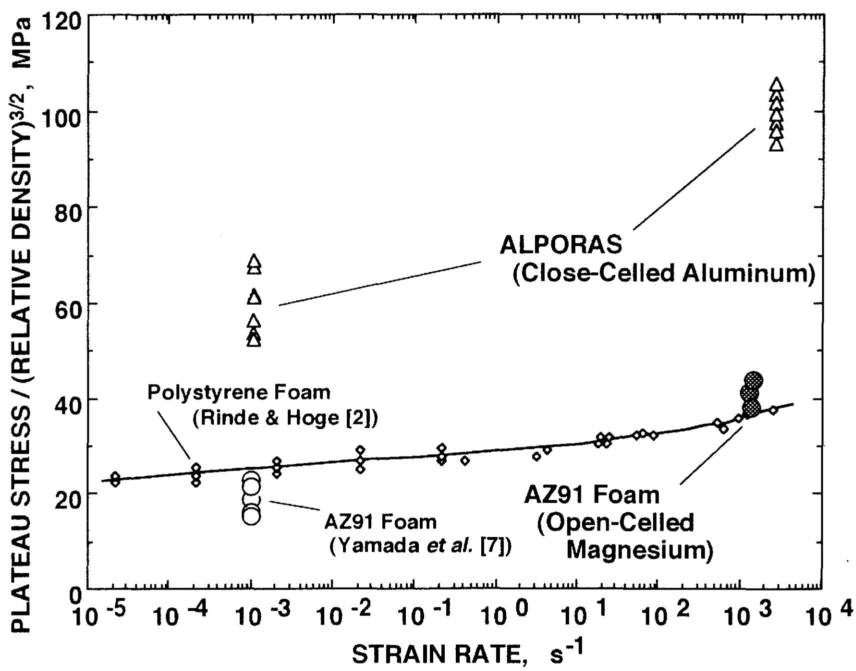

Fig.4 Strain rate dependence of plateau stress per (relative density)$^{3/2}$ in AZ91 foam and ALPORAS. Included is the data for a polystyrene by Rinde & Hoge [2].

4 Energy Absorption

The absorption energy per unit volume (W) for ALPORAS and AZ91 foams can be evaluated by integrating the area under the stress-strain curve [1], i.e.

$$W = \int_0^{\varepsilon} \sigma(\varepsilon) d\varepsilon \tag{1}$$

The value of absorption energy per unit volume at the dynamic strain rate is found to be about twice higher than that at the quasi-static strain rate due to a higher plateau stress. The average values of W for ALPORAS at a strain of 0.55 for the quasi-static ($1x10^{-3}$ s^{-1}) and the dynamic strain rate ($2.5x10^3$ s^{-1}) have been evaluated to be 1.00 and 1.51 MJ/m^3, respectively [4]. The average values of W for AZ91 foam at a strain of 0.5 at the quasi-static strain rate of $1x10^{-3}$ s^{-1} and the dynamic strain rate of $1.4x10^3$ s^{-1} have also been reported to be 49 and 111 KJ/m^3, respectively [5]. In both foams the average value of W (at a strain of ~ 0.5) at the dynamic strain rate is about 50 ~ 100% higher than that at the quasi-static strain rate, although the amplitude of W in both foams were different. The experimental results obtained in this study indicate that there exists a significant difference in mechanical strength and absorption energy between testing at a quasi-static and a dynamic strain rate. Since the selection of cellular materials is based on energy absorption for applications such as cycle helmet inner liner and the bumpers for automobiles or motor cycles, it is important to know the actual strain rate sensitivity for a specific application in order to properly select materials.

5 Summary

The dynamic response of a closed-celled aluminum and an open-celled magnesium foam was investigated in compression at dynamic strain rates over 1×10^3 s^{-1}. It was found that the plateau stress of both foams exhibited a strong strain rate sensitivity. Also, the absorption energy per unit volume (W) of the two foams at dynamic strain rates was twice higher than those obtained at the quasi-static strain rate (1×10^{-3} s^{-1}), although the specific value of W is material-dependent. The present results suggest that it is important to know the actual strain rate sensitivity for a specific application in order to properly select the ultra-lightweight metallic foam.

Acknowledgment

The author (KH) expresses his thanks to the financial support of the Priority Area from the Ministry of Education, Science and Culture, Japan (10148225). The work of one of the authors (TGN) was performed under the auspices of the U.S. Department of Energy by LLNL (contract No. W-7405-Eng-48).

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