Materials Transactions, Vol. 42, No. 10 (2001) pp. 2087 to 2092

Improvement of Crashworthiness in Ultra Lightweight Metallic Foam by Heat-Treatment for Microstructural Modification of Base Material

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It is very important to understand the strain rate dependence of the plateau stress or the impact energy for the applications to a suitable design of automotive components. Limited data are, however, available for the mechanical response of metallic foams under dynamic loading in comparison with polymer foams. In this study, the mechanical response and absorbed energy of an open-celled SG91A aluminum foam with the low relative density of 0.03–0.065 is evaluated at a dynamic strain rate in $\sim 10^3\,\mathrm{s}^{-1}$ order in compression by the split Hopkinson pressure bar apparatus. In order to investigate the effect of microstructure in the solid material, solution treatment and aging are performed and then examined at the same dynamic strain rate. As a result, mechanical strength and absorption energy for as-received and heat treated SG91A aluminum foams showed the strain rate dependence. This dependency was clearly decreased by the heat treatment. This mechanical response directly affects the energy absorption: the strain rate dependence of absorption energy is weakened with enhancing the ductility in solid materials by the heat treatment. Therefore, it is possible to control the absorption energy of the metallic foam by the modification of its microstructure, which affects the ductility in the solid material.

(Received June 15, 2001; Accepted August 8, 2001)

Keywords: *aluminum foam, open-cell, heat treatment, stress yielding, strain rate dependence, absorption energy, ductility*

1. Introduction

Recently, one of the highest interests in applications for automotive, locomotive and aerospace is how to utilize lightweight metallic foams (*e.g.*, Aluminum and Magnesium) aiming for weight reduction and improvement in comfort from the viewpoint of the environmental protection.1) It has been investigated on some mechanical properties of the metallic foams extensively.2–13) Lightweight metallic materials are highly superior to structural use because of their low densities in comparison with ferrous alloys. Yamada *et al.*14,15) have demonstrated the performance of aluminum and magnesium-based alloy foams for the reduction of their density and extended stress plateau. Metallic foams also have a potential for absorbing impact energy during the crashing of a vehicle either against another vehicle or human body, because of their unique deformation behavior in compression. To absorb the impact energy effectively, a foam material is required to exhibit an extended stress plateau. In order to evaluate the impact energy absorption of metallic foams, the relationship between the compressive stress and strain under dynamic loading must be characterized. The compressive stress-strain behavior at the dynamic strain rate is often characterized by using the split Hopkinson pressure bar (SHPB) method.16) The SHPB method has been widely used for characterizing the dynamic response of structural materials in a high strain rate range. Despite the fact that cellular materials are attractive materials for energy absorption, only limited data are available for the strain rate dependence of the strength of foam materials, including polymers and metals. For example, Rinde and Hoge17) studied the compressive strength of rigid polystyrene foams at room temperature as a function of strain rate and showed that the strength increased only slightly with strain rate. Tyler and Ashby18) examined a flexible polyurethane foam at strain rates ranging from 2×10^{-3} to $20\,\mathrm{s}^{-1}$ and found that the plateau strength exhibited a remarkable strain rate dependence when the foam was filled with a viscous water-glycerin mixture. In the case of metallic foams, Lankford and Dannemann19) reported that the strain rate dependence of mechanical strength was negligible for a low density open-celled AA6101-T6 Al. Deshpande and Fleck20) also showed that close-celled foam, Alulight, did not exhibit the strain rate dependence of plateau stress. On the other hand, Mukai *et al.* and Kanahashi *et al.* recently reported that all of an open-celled AZ91,21) an open-celled SG91A22) and a close-celled aluminum, the trade name "ALPORAS",23) exhibited a higher strain rate sensitivity of the plateau stress than the polystyrene foam. Dannemann and Lankford24) also demonstrated the strain rate dependence of plateau stress in ALPORAS at high strain rates ranging from 4×10^2 to $2.5 \times 10^3\,\mathrm{s}^{-1}$.

Moreover, Thornton and Magee25) examined as-cast, solution-treated and aged 7075 aluminum alloy foams with a relative density of approximately 0.1 at a static strain rate and reported the effect of the heat treatment on the mechanical property of their foams in compression, as summarized in Table 1. It is suggested that the heat treatment to be improved the microstructure of the metallic material is possible to control the dynamic response of their foams. The dynamic response of the metallic foams at the dynamic strain rate, however, has never been estimated from the viewpoint of the microstructural modification in the metallic foams. In the

Table 1 The effect of heat treatment on the dynamic response at the static strain rate in compression for 7075 aluminum ally foams with a relative density of approximately 0.1.[25)]

7075 foam	Peak stress (MPa)	Plateau stress (MPa)	Plateau strain	0.1% flow stress (MPa)*
As-cast	3.24	2.08	0.65	342
Solution-treated	3.73	4.73	0.52	275
Aged	3.29	1.97	0.72	502

*The value of 7075 aluminum bulk materials which Thornton and Magee[25)] reported.

present study, the aluminum foam produced by casting was examined at a dynamic strain rate of over $10^3\ \mathrm{s}^{-1}$ in compression by SHPB method. In order to investigate the effect of microstructure in the solid material on the strain rate sensitivity of the metallic foam, solution treatment and aging were performed to the foam specimens and then examined at a dynamic strain rate at room temperature. The relationship between the dynamic response of all foams and the mechanical properties in the solid material has been discussed. It has been proposed to the possibility of controlling the strain rate sensitivity in open-celled aluminum foam material.

2. Experimental Procedure

The material used in the present study is SG91A (Al–9 mass% Si–0.45 mass% Mg–0.5 mass% Fe–0.45 mass% Mn) aluminum alloy, which is popular aluminum alloy with a good castability and exhibits good wear and corrosion resistance. An open-celled SG91A (herein, SG91A as-cast foam) with an ultra-low density were fabricated by reciprocating cast using the polyurethane form. Detailed procedures have been reported previously.[15)] The morphology of the SG91A as-cast foam was characterized with a conventional scanning electron microscope (SEM), as shown in Fig. 1. The foam has an open-celled structure without the wavy distortion of the cell column or wall like a closed-celled structure, and the most of column surface appears to be rough. The average column spacing and thickness of the SG91A as-cast foam are 4.5 and 0.35 mm, respectively. The relative density (ρ/ρ_s) of the foam is 0.03–0.065, where ρ and ρ_s are the density of the foam and the solid material, respectively.

Specimens with a dimension of $16 \times 16 \times 11\ \mathrm{mm}^3$ were machined from the as-cast foam. In order to investigate the effect of microstructure in the solid material on the strain rate dependency, heat treatments were also performed to as-cast foam specimens at 798 K for 36 ks as solution treatment (herein, T4 foam) and then at 433 K for 32.4 ks as aging treatment (herein, T6 foam). Compressive test at a dynamic strain rate of $1.4 \times 10^3\ \mathrm{s}^{-1}$ at room temperature was performed by SHPB method. To examine the rectangular-sectioned specimen ($16 \times 16\ \mathrm{mm}^2$), a special rectangular Maraging steel attachment with a dimension of $18 \times 18\ \mathrm{mm}^2$ was fixed at the contact end of the bars. The both ends of the specimen surface were lubricated prior to compressive testing with a thin layer of molybdenum disulfide grease to minimize the friction effect.

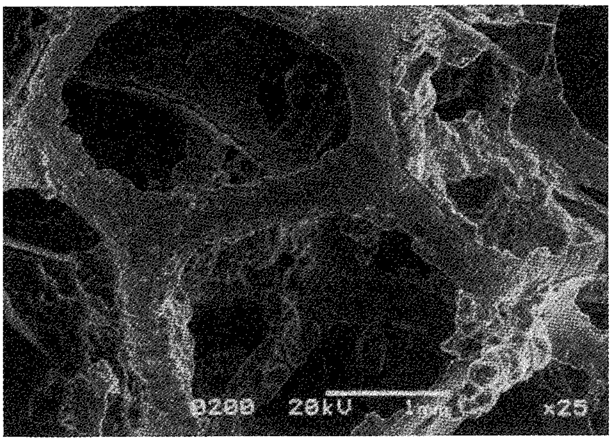

Fig. 1 Scanning electron microsgraph of open-celled SG91A as-cast foam.

3. Results and Discussion

3.1 Compressive behavior under dynamic loading

The cellular materials exhibit different mechanical properties in compression for a tiny change of its relative density with homogeneous cellular structure. Gibson and Ashby[1)] analyzed the relationship between the relative stress, $\sigma_{\mathrm{pl}}/\sigma_{\mathrm{ys}}$, 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 in a cubic cell model, where σ_{pl} is the plastic-collapse stress (peak stress), σ_{ys}, is the yield stress of the cell edge material, ρ is the density of the cellular material, and ρ_s is the density of the cell edge material, respectively. Accordingly, the relative stress is related to the relative density for an open-celled material through the following equation:[1)]

$$\sigma_{\mathrm{pl}}/\sigma_{\mathrm{ys}} = C(\rho/\rho_s)^{3/2} \tag{1}$$

where C is a constant related to the cell geometry. Gibson and Ashby[1)] reported that the data obtained from many open-cellular polymer and metallic foams is adequately described by eq. (1) with the value of C equal to 0.3. Therefore, the nominal stress for all foams in the present study at the dynamic strain rate can be normalized by eq. (1), which expresses as the normalized nominal stress, σ_{N}, equal to nominal stress/(relative density)$^{3/2}$.

Normalized nominal stress-nominal strain curves for an open-celled SG91A (a) as-cast foam,[22)] (b) T4 foam and (c) T6 foam at a dynamic strain rate of $1.4 \times 10^3\ \mathrm{s}^{-1}$ are shown in Fig. 2. Included are the data of the same foams examined at a quasi-static strain rate of $1 \times 10^{-3}\ \mathrm{s}^{-1}$ [14,26)] for the direct comparison. Compressive deformation behavior for all SG91A foams progressed in the same deformation mechanisms in the conventional cellular materials, which are the regime of linear elasticity, plateau and then densification. It is noted that the drop of peak stress at an early stage of deformation by buckling of cellular columns is readily observed for all foams at the dynamic strain rate. The normalized peak stress, σ_{N} [peak stress], reaches 3 times in maximum higher than the normalized plateau stress, σ_{N} [plateau stress], defined as the stress at the strain of 0.2 in average value. The optical micrograph of an open-celled SG91A (a) as-cast foam, (b) T4 foam and (c) aged foam is shown in Fig. 3. The microstructure of Al–Si

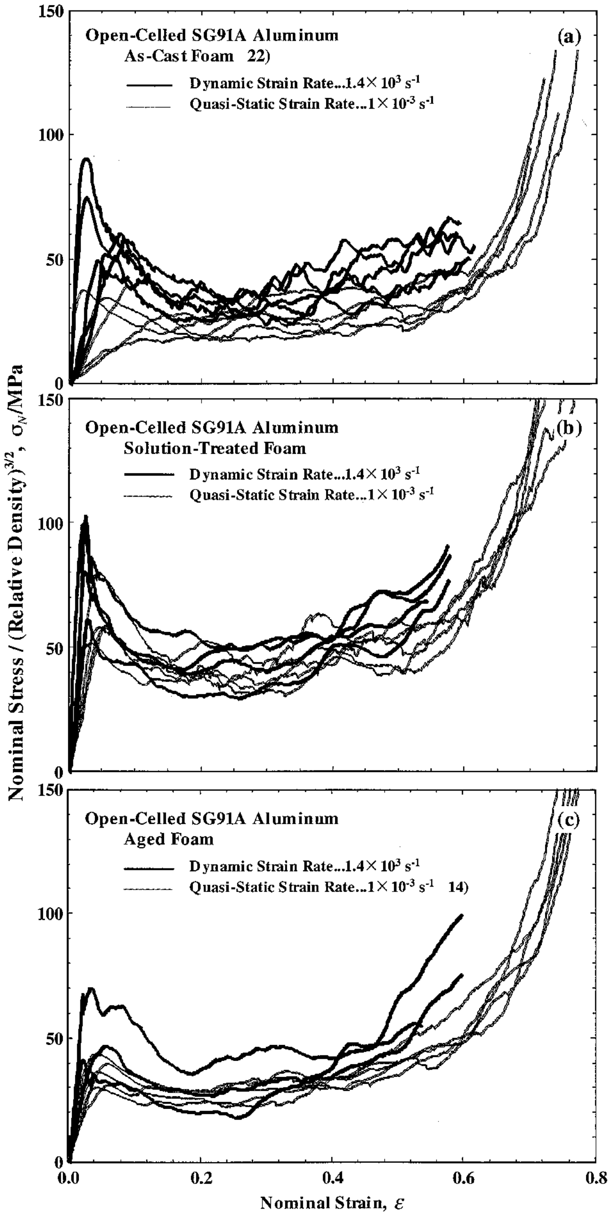

Fig. 2 Normalized nominal stress-nominal strain curves for open-celled SG91A (a) as-cast foam, (b) T4 foam and (c) aged foam at a dynamic strain rate of $1.4 \times 10^3\,\mathrm{s}^{-1}$. Included are the data the same foams at a quasi-static strain rate of $1 \times 10^{-3}\,\mathrm{s}^{-1}$.

cast alloy such as SG91A generally consists of a network of Si particle, which is formed in the interdendritic aluminum-silicon eutectic. The mechanical property in Al–Si system alloy system depends heavily on an extent of the dedrite cell size and an eutectic Si particle size and shape. It is obvious in this figure that the heat treatment makes changes to rounder eutectic Si particles by the diffusion for T4 foam and to smaller eutectic Si particles and dedrite cell size for T6 foam than these for as-cast foam. Therefore, it can be expected that microstructural evolution in SG91A foams brings about some changes in the deformation behaviors as shown in Fig. 2.

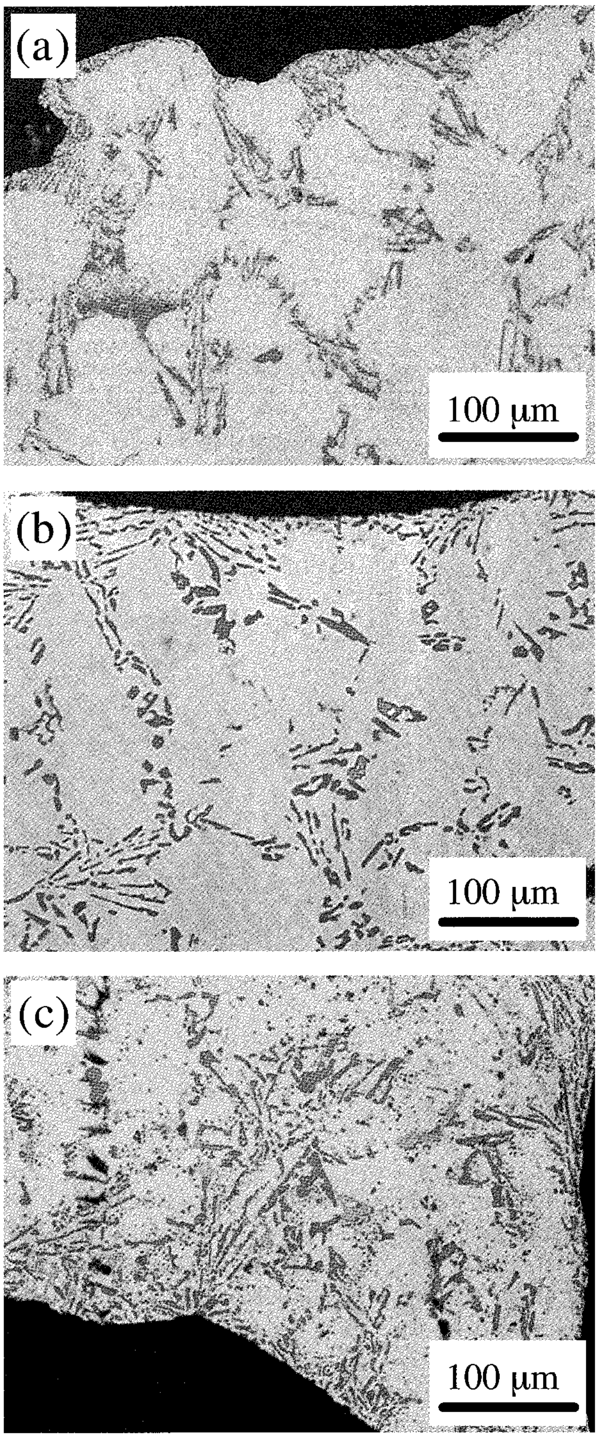

Fig. 3 The optical microstructure of cell column in an open-celled SG91A (a) as-cast foam, (b) T4 foam and (c) T6 foam.

In order to characterize the strain rate dependence of compressive stress in the solid materials, the fully dense SG91A as-cast, T4 and T6 alloys were examined at a dynamic strain rate of $1.6 \times 10^3\,\mathrm{s}^{-1}$ and a quasi-static strain rate of $1 \times 10^{-3}\,\mathrm{s}^{-1}$. The nominal stress-nominal strain relations are shown in Fig. 4. The flow stress of all fully dense specimens obviously exhibits the strain rate dependence. The values of yield stress defined as 0.5% offset proof stress at the dynamic and quasi-static strain rates were measured to be 220 and 190 MPa for SG91A as-cast alloy,[22] 245 and 190 MPa for T4 alloy and 380 and 320 MPa for T6 alloy, respectively.

3.2 Strain rate sensitivity in open cellular foams

The variations of the dynamic-static ratio of σ_N[peak stress] and σ_N[plateau stress], r_σ for SG91A as-cast foam, T4 foam

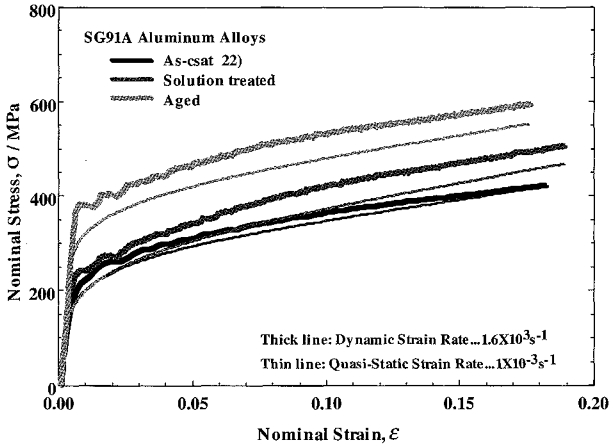

Fig. 4 Nominal stress-nominal strain curves for the fully dense SG91A as-cast, T4 and T6 alloys at a dynamic strain rate of $1.6 \times 10^3\,\mathrm{s}^{-1}$ and a quasi-static strain rate of $1 \times 10^{-3}\,\mathrm{s}^{-1}$.

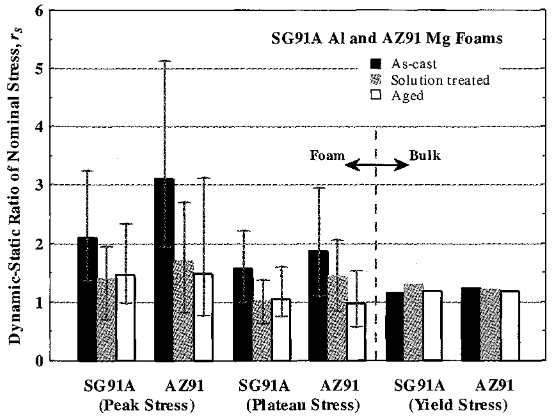

Fig. 5 The variation of the dynamic-static ratio of peak stress and plateau stress normalized by (relative density)$^{3/2}$ for open-celled SG91A and AZ91[25] as-cast foams, T4 foams and T6 foams. Included are the data of the fully dense each alloy.

and T6 foam are shown in Fig. 5, where the ratios are calculated from the nominal stress at the dynamic strain rate divided by that at the quasi-static strain rate. Included are the data for AZ91 magnesium alloy as-cast foam, T4 foam and T6 foam with the same cellular structure[27,28] and fully dense SG91A and AZ91 as-cast and two heat treated alloys examined at the similar dynamic and quasi-static strain rates. As can be seen in this figure, the average value of r_σ in peak stress and plateau stress for both foams decreases to ~ 1 by the heat treatment. The values of the dynamic-static ratio of yield stress for fully dense SG91A and AZ91 alloys are, however, almost constant in comparison to those for SG91A and AZ91 foams. It is found that the strain rate dependence of mechanical strength for all SG91A and AZ91 foams is not correlated with that for solid materials. The dynamic-static ratio equal to 1 means that the strain rate dependence of mechanical strength is negligible. The ideal deformation behavior of cellular materials for the component of energy absorption is not only to exhibit no peak stress at an early stage of deformation but also to transfer smoothly from the linear elasticity to the extended plateau region. Thus, the allowable stress of the protected object which avoid the damage should be not determined by the peak stress but the plateau stress with a large strain during the impact of the foam for the design of effective energy absorbers. Therefore, it is noted that the heat treatment is one of the effective ways to control the deformation behavior of SG91A and AZ91 foams at the dynamic strain rate.

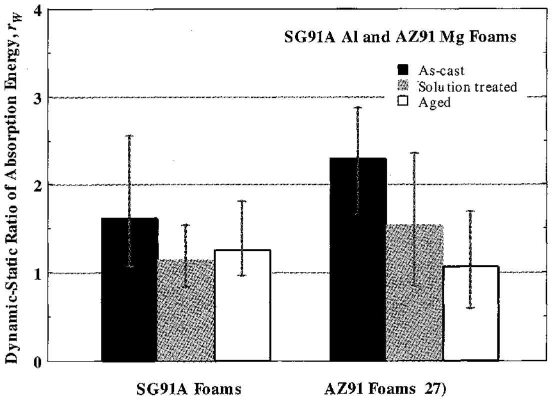

Fig. 6 The variation of the dynamic-static ratio of absorption energy normalized by (relative density)$^{3/2}$ for open-celled SG91A and AZ91[25] as-cast foam, T4 foam and T6 foam.

The selection and design of cellular materials for energy absorbers such as the bumper for automobiles or motor cycles should be based on the energy absorption at the actual strain rate. The absorption energy per unit volume, W, can be estimated from the integrated area of the stress-strain curve,[1] namely;

$$W = \int_0^{\varepsilon_{\mathrm{lim}}} \sigma(\varepsilon)d\varepsilon \qquad (2)$$

where $\varepsilon_{\mathrm{lim}}$ is the limit of plateau strain up to the onset of densification. The following calculation of W was taken with a nominal strain of 0.5 for all SG91A foams. Furthermore, in order to assess the effect of strain rate on the absorption energy of different material and relative density of foams, the absorption energy normalized by (relative density)$^{3/2}$, W_N, might be used, because the important parameter σ in eq. (2) varies directly according to eq. (1). The variations of the dynamic-static ratio of absorption energy normalized by (relative density)$^{3/2}$, r_W for open-celled SG91A and AZ91 as-cast foam,[27] T4 foam and T6 foam[28] are shown in Fig. 6. It can be seen that the values of r_W decreases to ~ 1 by the heat treatment as well as that of peak stress and plateau stress shown in Fig. 5.

The values of r_W for both SG91A and AZ91 foams as a function of the value of elongation-to-failure of the solid material,[29] ε_f, is plotted in Fig. 7, where the value of elongation-to-failure is used as an index of the ductility in the solid material. Included in this figure is the data of another open-celled AA6101-T6 Al foam, Duocel, reported by Lankford and Dannemann.[19] It can be seen that r_W for lightweight metallic foams has a tendency to decrease in approximately 1 with increasing the value of ε_f in the solid materials. It is suggested from this figure that the microstructural ductility in the solid materials is greatly concerned on compressive deformation behavior and strain rate dependence of the mechanical strength for SG91A and AZ91 foams.

The open-celled foam has the structure that cell columns form the three-dimensional network at the simplest level. The

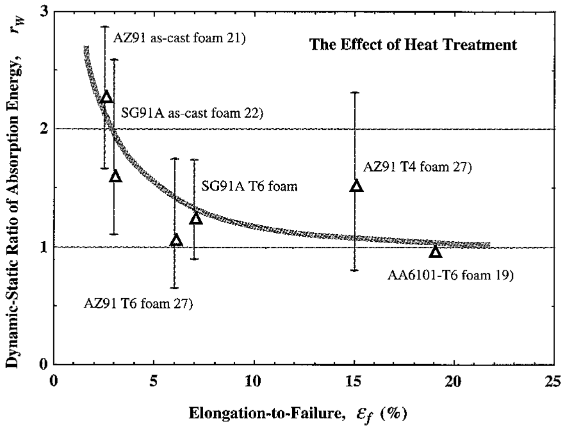

Fig. 7 The dynamic-static ratio of absorption energy normalized by (relative density)$^{3/2}$ for all SG91A and AZ91 foams as a function of the typical value of elongation-to-failure in the solid material.

cell columns should play main roles of the deformation by buckling and the transition of a compressive load to neighbor or another columns in principle. In general, a buckling of metallic columns is a phenomenon that causes to apply in a direction perpendicular to the loading direction, because the cross sectional area is as small as compared with their length. The metallic columns in compression is unlikely to be able to carry stress high enough to cause yielding and then buckling instability can occur at stress well below the yield. In case of the open-celled foam, the mechanical strength of each cell column is not constant owing to the distribution of diameter and length of each cell column. The deformation of the open-celled foam should occur at the cell columns with low stiffness, which is the weak cell column. Yamada *et al.*[30] certainly reported the compressive deformation behavior of open-celled SG91A as-cast foam and Al_2O_3 foam with the almost same cellular structure at a quasi-static strain rate of $1 \times 10^{-3}\,s^{-1}$ and showed that the deformation behavior in stress-strain curves for these foams was changed by the extremely different plastic deformability in the solid materials. Accordingly, it is possibly considered that the deformation mechanism for open-cell foams classifies roughly into two types by the ductile property in foam materials; the *ductile column-buckling* for the open-cell foams consisting of ductile materials and *the brittle column-buckling* for that consisting of brittle materials. For the open-celled foams consisting of brittle materials, the weak cell column buckles and immediately ruptures because it cannot resist to the compressive load owing to reaching at the buckling limit of its strength. It is considered that peak stress at the early stage of deformation in foams and many fluctuations of stress up to densification results in the rupture of the weak cell columns. On the other hand, for the open-celled foams consisting of ductile materials, weak cell columns buckles as well as that of brittle materials at first. However it dose not rupture owing to bending deformation caused to ductile property in itself and carries smoothly the load to neighbor or another cell columns prior to failure. And then neighbor or another cell columns start to buckle, which repeats this event. It is also considered peak stress and many any fluctuations of stress through the compressive deformation cannot be appeared such as Duocel foam reported by Lankford and Dannemann,[19] which bending deformation resulting from ductility in the solid materials might act the minimizing mechanism of the buckling limit in the solid materials.

The mechanical strength for open-celled metallic foams depend on their relative density, the kind of solid materials[1] and cell geometry.[13] It is very important to relate the mechanical strength and their deformation behavior in order to obtain a high performance as the effective energy absorber for the actual use. In this study, we focus on changing the deformation behavior for cell columns of open-celled metallic foams by the heat-treatment for microstructural modification at dynamic and quasi-static strain rates. As a result, two different deformation mechanisms might be conserved for open-celled foams consisting of the solid materials with a different ductility at least in the order of a strain rate examined in this study, because of the similar deformation behavior shown in Fig. 2 at dynamic and quasi-static strain rates. As shown in Fig. 7, the strain rate dependence of the absorption energy as well as the mechanical strength of metallic foams also decreases with increasing the ductility of solid materials. The ideal deformation behavior for the energy absorbers has no peak stress at a transition from linear elasticity to plateau region in a stress-strain curve and an extended plateau region at any strain rates. The values of r_σ and r_W equal/close to 1 means no/slightly strain rate dependence of mechanical response. As considered in this point of view, the open-celled metallic foams for the more effective energy absorber should be made of ductile materials that the cell columns deforms by both buckling and bending. Therefore, it is possible to control toward the ideal deformation behavior of the metallic foams by heat treatment that affects the ductility of the solid materials with improving its microstructure.

4. Summary

In order to investigate the effect of heat treatment for microstructural modification in the solid material on the strain rate sensitivity in the mechanical strength and absorption energy of open-celled SG91A as-cast, solution treated (T4) and aged (T6) foams with an ultra low relative density of 0.03–0.065 were evaluated in compression at a dynamic strain rate of $1.4 \times 10^3\,s^{-1}$. As a result, mechanical strength and absorption energy for all SG91A foams showed the strain rate dependence. This dependency clearly decreased by heat treatment. It is expected that the metallic foam consisted of a ductile solid material exhibits a slight strain rate dependence of the absorption energy because of its deformation mechanism on the column structured each cellular material in compression. Therefore, it is possible to control the absorption energy of metallic foams by the improvement of its microstructure, which affects the ductility of the solid materials as the result in heat treatment.

Acknowledgments

This work was performed in part under the financial support from the U. S. Army Research Office-Far East (Grant No. N62649-99-1-0006).

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