Effect of Cell Size on the Dynamic Compressive Properties of Open-Celled Aluminum Foams

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In the present paper, open-celled AA6101–T6 aluminum foams, Duocel, with virtually the same relative density of 0.09 were tested at both a dynamic strain rate of $1.2 \times 10^3 \, s^{-1}$ and quasi-static strain rate of $1 \times 10^{-3} \, s^{-1}$ in compression at room temperature. These Duocel foams have different cell sizes (10, 20, and 40 pp) but similar cell morphology and microstructure. The mechanical strength and energy absorption of these foams were characterized as a function of strain rate and cell morphology. Experimental results indicated that the mechanical responses of Duocel foams were independent of the cell size and strain rate. Similar tests were also conducted with fully dense AA6101–T6 aluminum alloy and the results were compared with those obtained from the foam materials.

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1. Introduction

Cellular solids are a special class of material with an interconnected network (two dimensional; honeycomb or three dimensional; foam), which differ from solids with isolated pores.¹ They exist not only in nature world (e.g., wood, cork, sponge, cancellous bone and so on) but also in man-made goods such as disposable coffee cups and packing materials. Advanced foaming techniques and processes have now resulted in the production of cellular materials from polymers,² metals³—⁶ and ceramics.⁷, ⁸ These materials have widespread applications taking the advantage of the mechanical, chemical, electrical and acoustic properties that can be offered by their cellular structures. Recent interests are focusing on developing lightweight metallic (e.g., aluminum and magnesium) foams for automotive, train, and aerospace applications. Many studies have been reported on the mechanical properties of aluminum foams and significant progress has been made.⁹—¹⁹ For example, Yamada et al.⁵, ²⁰ demonstrated that low-density aluminum and magnesium-based alloy foams can be fabricated with an improved stress plateau. In fact, a design guide for metallic foam has recently been published,²¹ in which the implementation of these materials in various structural applications was also discussed.

Metallic foams also have a major advantage over solid materials for their ability to absorb impact energy during the crashing of a vehicle either against another vehicle or a human body. To absorb effectively the impact energy, a foam material is required to exhibit an extended stress plateau. To measure the energy of absorption during impact, the relationship between the compressive stress and strain under dynamic loading must be characterized. However, only limited data are available for the strain rate dependence of the mechanical strength of cellular materials, including polymers and metals. For example, Rinde and Hoge²² 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 Ashby²³ also examined a flexible polyurethane foam at strain rates ranging from $2 \times 10^{-3}$ to $20 \, s^{-1}$ and found that the plateau strength exhibited a remarkable strain rate dependence when this polyurethane foam was filled with a viscous water-glycerin mixture. In the case of metallic foams, Lankford and Dannemann²⁴ reported that the strain rate dependence of mechanical strength was negligible for a low density open-celled AA6101–T6 aluminum foam. Deshpande and Fleck²⁵ 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. reported that open-celled AZ91 Mg,²⁶ open-celled SG91A Al,²⁷ and close-celled aluminum Alulight,²⁸ all exhibited a higher strain rate sensitivity of the plateau stress than the polystyrene foam by Rinde and Hoge.²² Dannemann and Lankford²⁹ also demonstrated the strain rate dependence of plateau stress for Alporas at high strain rates ranging from $4 \times 10^2$ to $2.5 \times 10^3 \, s^{-1}$. Thus, despite the fact that cellular metals are attractive materials for energy absorption, only limited data are available for dynamic strain rates ($> 10^3 \, s^{-1}$).

The deformation behavior of metallic foams can vary significantly by changing the intrinsic cell structures, such as imperfections (wavy distortions of cell walls),³⁰, ³¹ microstructure of cell edge materials and cell morphology. For example, Thornton and Magee³² reported the effect of heat treatment on the mechanical property of as-cast and heat-treated 7075 aluminum foams with a relative density of approximately 0.1 in compression at a static strain rate. Kanahashi et al.³³, ³⁴ recently demonstrated that the deformation behavior of open-celled AZ91 Mg and SG91A Al foams with the same structure at both quasi-static³⁵, ³⁶ and dynamic strain rates was strongly affected by heat treatment. These results suggest that heat treatment can improve the microstructure of the solid materials (or cell edge materials) and, thus, the dynamic re-
sponse of metallic foams. Some studies have also been carried out to address the mechanical properties of metallic foams as a function of cell morphology. For example, at a quasi-static strain rate, Nieh et al.\textsuperscript{37} observed the effect of cell size and shape on the compressive behavior of open-celled AA6101–T6 aluminum foams with different relative density and showed that the former appeared to have a negligible effect on the strength of foam, whereas the latter had certain influences on the strength of foam. Yamada et al.\textsuperscript{38} also observed similar results in open-celled nickel foams. It is noted that, these studies were all carried out at static strain rates. The deformation behavior of metallic foams as a function of cell morphology at dynamic strain rates has not been investigated. In the present study, open-celled aluminum foams with different cell sizes but a similar relative density were examined at a dynamic strain rate of over $10^3\text{s}^{-1}$ at room temperature in order to estimate the effect of cell size on the compressive mechanical property and the energy absorption capability.

2. Experimental Procedure

The aluminum alloy used in the present study is AA6101 (Al–0.6 mass%Mg–0.5 mass%Si), which is heat-treatable and exhibits high strength and good corrosion resistance. AA6101–T6 aluminum foams, Duocel\textsuperscript{TM} (herein, Duocel foam), with open-cell structure were fabricated by Energy Research and Generation, Inc., by using a directional solidification of metal from a super-heated liquidus state in an environment of overpressures and high vacuum. These foams have a cell size of 10, 20 and 40 pore per inch (ppi) (hereafter, denoted as Foam A, B and C, respectively). The intercellular spacings of these foams are 5.0, 4.2 and 3.0 mm, respectively. The morphology and microstructure of foams were examined using SEM and optical metallography. These foams have practically the same relative density, $\rho/\rho_0$, of 0.09, where $\rho$ and $\rho_0$ are the density of the foam and the cell edge material, respectively. Specifically, the relative densities are 0.094, 0.088, and 0.089 for Foam A, B, and C, respectively. Compressive specimens with a dimension of $11 \times 11 \times 7.6\text{mm}^3$ were directly machined from the as-received materials. The compressive axis was parallel to the solidification direction. Both end surfaces of a test specimen were lubricated with a thin layer of molybdenum disulfide grease to minimize the friction effect prior to testing.

Dynamic compression test was performed at a strain rate of $1.2 \times 10^3\text{s}^{-1}$ at room temperature using the split Hopkinson pressure bar (SHPB) method.\textsuperscript{39} This method has found a wide acceptance as the device to perform experiments at high strain rates ($10^2$ to $10^4\text{s}^{-1}$). The stress $\sigma$-strain $\varepsilon$-strain rate $\dot{\varepsilon}$ relationship for the material during the dynamic test can be calculated from the strain pulse data, which is detected by strain gages attached on the surface of two stress bars, based on following eqs. (1)–(3) derived from the one-dimensional wave propagation theory:

$$
\sigma = E(A/A_s)\varepsilon_t \tag{1}
$$

$$
\varepsilon = -2(C_0/l_s)\int_{0}^{t} \varepsilon t dt \tag{2}
$$

$$
\dot{\varepsilon} = -2(C_0/l_s)\varepsilon_t \tag{3}
$$

where $\varepsilon_t$ and $\varepsilon_r$ is the transmitted and the reflected strain pulse detected by strain gauges, $E$ is the Young’s modulus of the stress bars, $A$ and $A_s$ is the cross sectional area of the stress bars and the specimen, $C_0$ is the elastic wave velocity in the stress bars and $l_s$ is the original gauge length of the specimen.

It is, however, a quiet low impedance ratio between the foam material and the metallic stress bars, which means that the strength of the foam material is much smaller than that of the metallic bars. It has been pointed out the technical difficulty and inaccuracy to detect the strain pulse traveling into the stress bars.\textsuperscript{40} In order to verify an accurate measurement in calculated strain and strain rate for foam materials, the direct measurement was performed with a non-contact optical displacement transducer (ZIMMER model 200X), which can simultaneously measure the displacement of two objects traveling at high speed. The measured strain rate and strain of the foam specimen were derived from the relative displacement of the maker fixed on both ends of stress bars that the foam specimen sandwiches. Figure 1 shows the direct comparison of the strain measured by ZIMMER with the one calculated from eq. (2) using strain pulse data as a function of time for Duocel Foam C. Although the measured strain has an undulated variation, it changes almost proportionally with the time. The accuracy in the calculated strain could be verified because the calculated strain from strain pulse data showed a good agreement with the result of the measured strain by the non-contact optical displacement transducer.

Compressive test was also performed at a quasi-static strain rate of $1 \times 10^{-3}\text{s}^{-1}$ using an Instron type testing machine.

3. Results and Discussion

3.1 Cell morphology and microstructure

The morphologies of the presently studied AA6101–T6 aluminum foams are shown in Figs. 2(a) (Foam A), (b) (Foam B), and (c) (Foam C). They all have an open-celled structure without wavy distortion of the cell ligament or wall often observed in closed-celled structures. The cell geometry is remarkably uniform and duodecahedronally shaped. Nieh et al.\textsuperscript{37} previously reported that the cell shape of Duocel foams...
was anisotropic, elongated in the solidification direction. As shown in Fig. 2, the cell shape also appears to be slightly elliptical with the major axis of the elliptical cells parallel to the solidification direction. The aspect ratio of these elliptical cells, which is the ratio of the major axis to the minor axis, was subsequently measured. There are slight differences among the three foams (1.33, 1.28, and 1.33 for Foam A, B, and C, respectively), but for practical purposes the ratio are essentially the same (≈1.3). The microstructures of the three foams are presented in Fig. 3, which are typical cast microstructures containing coarse inclusions. These inclusions are probably Fe–Si–Al particles commonly observed in 6000-series aluminum alloys. No internal voids were observed within cell ligaments. Based upon the above observations, it is concluded that the three kinds of Duocel foams have practically the same density value, cell aspect ratio and microstructure.

3.2 Mechanical property under dynamic loading

For cellular materials, it has been shown that the most important variable determining the mechanical properties of them is relative density, $\rho/\rho_s$. To study the effect of cell size on the mechanical property of Duocel foams, it is necessary to use materials with a nearly constant relative density. The
relationship between the relative stress, $\sigma_{pl}/\sigma_{ys}$, and the relative density, $\rho/\rho_s$, was analyzed 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 $\sigma_{pl}$ and $\sigma_{ys}$ are the plastic-collapse stress of the foam and the yield stress 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:

$$\sigma_{pl}/\sigma_{ys} = C(\rho/\rho_s)^{3/2}$$  \hspace{1cm} (4)

where $C$ is a constant related to the cell geometry. The value of $C$ in eq. (4) is about 0.3 using data obtained from many open-cellular polymer and metallic foams.\(^3\) Therefore, the engineering stress for all foams in the present study at the dynamic strain rate can be normalized by eq. (4), which expresses as the normalized engineering stress, $\sigma_N$, equal to engineering stress/relative density\(^{3/2}\).

Normalized engineering stress-engineering strain curves for the three open-celled AA6101–T6 aluminum foams at a dynamic strain rate of $1.2 \times 10^3$ s\(^{-1}\) and a quasi-static strain rate of $1 \times 10^{-3}$ s\(^{-1}\) in compression are shown in Figs. 4(a), (b) and (c). Deformation curves at both the dynamic and quasi-static strain rates for all Duocel foams exhibit similar features, namely, an initial regime of linear elasticity, followed by a plateau and, then, densification. It is noted that a significant drop in flow stress at an early stage of deformation, especially at the high strain rate, which is associated with the buckling of cell columns, was often observed in cellular solids, such as open-celled AZ91 Mg,\(^{20,26}\) SG91A Al,\(^{27}\) and their heat-treated foams.\(^{33-36}\) However, this stress drop was not discernible in the present Duocel foams deformed either at the dynamic or quasi-static strain rate. Apparently, the occurrence of a drop in flow stress in a foam material is not only determined by the cell structure but also by the alloy used to make the foam.\(^{34}\) It is of interest to note in Fig. 4 that, despite of six orders of magnitude difference in strain rate, the curves at both the dynamic and quasi-static strain rates are practically the same. It appears that there is no strain rate effect on stress for the Duocel foams in the present study.

The plateau stress is an important parameter, as it usually determines the allowable stress during the impact of the foam against an object. Strain rate dependence of the normalized plateau stress, $\sigma_{Np}$, for the present aluminum foams is shown in Fig. 5. The value of $\sigma_{Np}$ is defined as the stress at an engineering strain of 0.2. Also included in Fig. 5 are results obtained from previous experiments\(^{24,25,29}\) on the Duocel foams at high strain rates ranging from $1.2 \times 10^3$ to $3.2 \times 10^3$ s\(^{-1}\) and a quasi-static strain rate. It is readily observed that $\sigma_{Np}$ for all Duocel foams at the dynamic strain rates are consistent, and essentially the same as that observed at the quasi-static strain rate. This result indicates that $\sigma_{Np}$ of Duocel foams is independent of strain rate.

It is noted that two factors may contribute to the dependence of stress on strain rate of a cellular solid: cell morphology and the alloy used to synthesize the cell structure. To characterize the stress dependence on strain rate of the cell alloy, fully dense AA6101–T6 aluminum alloy were also tested at the dynamic and quasi-static strain rate of $1.7 \times 10^3$ s\(^{-1}\) and $1 \times 10^{-3}$ s\(^{-1}\). The engineering stress-engineering strain curves for the alloy are shown in Fig. 6. It is readily noted that flow stress of the fully dense specimen shows strain rate dependence. In a manner similar to that observed in the foam materials, there is no yield drop. The yield stresses, which is defined as the 0.5% offset proof stress, at the dynamic and quasi-static strain rates were measured to be 215 and 190 MPa, respectively. This corresponds to a 13% increase in the yield stress caused by a six orders of magnitude increase in strain rate. Therefore, even though there exists a strain rate dependence of stress in the AA6101–T6 aluminum
alloy, however, this dependence vanishes in the Duocel foams synthesized from the alloy. This suggests the absence of strain rate effect in Duocel foams is associated with the cellular structure not the microstructure of the cell edge material. Apparently, when the relative density of a foam material is low, the intrinsic properties of the cell edge material are overwhelmed by the extrinsic properties of the cell structure during compression.

Fig. 5 Strain rate dependence of the normalized plateau stress for different open-celled AA6101–T6 aluminum foams with a relative density of about 0.09.

Fig. 6 Compressive engineering stress-engineering strain curves for the fully dense AA6101–T6 aluminum foam fabricated by casting at a dynamic strain rate of \(1.7 \times 10^3 \text{s}^{-1}\) and quasi-static strain rate of \(1 \times 10^{-3} \text{s}^{-1}\).

Relationship between the normalized plateau stress and cell size for the present aluminum foams is shown in Fig. 7. Also included are data of Duocel foams with a cell size of 40 ppi from previous studies. It can be readily observed in this figure that the cell size (from 10 to 40 ppi) appears to have insignificant effect on \(\sigma_{\text{lim}}\), even at the dynamic strain rate of \(\sim 10^3 \text{s}^{-1}\). This is very similar to the observations of Nieh et al. and Yamada et al. both reported a cell size effect at quasi-static strain rates in Duocel and nickel foams, respectively.

### 3.3 Energy absorption

The selection and design of cellular materials for energy absorbers such as bumpers for automobiles and motorcycles 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, namely,

\[ W = \int_{0}^{\varepsilon_{\text{lim}}} \sigma(\varepsilon) d\varepsilon \quad (5) \]

where \(\varepsilon_{\text{lim}}\) is the limit of plateau strain up to the onset of densification. To assess the effect of strain rate on the absorbed energy for different foams, the absorption energy normalized by (relative density)\(^{3/2}\), \(W_{\text{N}}\), was used. The average \(W_{\text{N}}\) for each of the open-celled AA6101–T6 aluminum foams at the dynamic and quasi-static strain rates in compression are summarized in Table 1. The calculation of \(W_{\text{N}}\) was made at an engineering strain of 0.5. The average values of \(W_{\text{N}}\) are noted to be practically the same, despite of different cell sizes and strain rates.

### Table 1

<table>
<thead>
<tr>
<th>Strain rate, (\dot{\varepsilon}/\text{s}^{-1})</th>
<th>Normalized absorption energy, (W_{\text{N}}/\text{MJ/m}^3)</th>
</tr>
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<tbody>
<tr>
<td>1.2 (\times) 10(^3) (Dynamic)</td>
<td>36.6</td>
</tr>
<tr>
<td>1 (\times) 10(^{-3}) (Quasi-static)</td>
<td>37.2</td>
</tr>
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4. Summary

The compressive deformation behavior of open-celled AA6101–T6 aluminum foams (Duocel) with virtually the same relative density of 0.09 was studied. These foams had different cell sizes and morphology but similar microstructure. They were tested under both static (1.0 \(\times\) 10\(^{-3}\) \text{s}^{-1}) and dynamic strain rates (1.2 \(\times\) 10\(^3\) \text{s}^{-1}). It was found that the plateau stress of these Duocel foams exhibited negligible strain rate dependence. This is in contrast to fully dense AA6101–T6 aluminum alloy, of which the yield stress is strain rate dependent. Also, within the cell size range (10–40 ppi) used in the present investigation, mechanical re-
sponses of Duocel foams appear to be independent of the cell size. Therefore, from application viewpoints, intensive efforts to modify the cell morphology are probably not an effective way to improve the impact properties of Duocel foams.

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