Energy Absorption in Closed-Cell Al–Zn–Mg–Ca–Ti Foam

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Cellular metallic foams have interesting potential for impact energy absorption. In this study, modification of solid in a closed-cell Al–Ca–Ti foam was carried out, adding the strengthening elements of Zn and Mg for enhancement of energy absorption. Samples with dimensions of 100 × 100 × 100 mm³ were examined at a dynamic strain rate corresponding to the crashing speed of automobiles. The compression behavior of the Al–7Zn–0.5Mg–1.5Ca–1.5Ti (by mass%) foam was found to be different from that of the original Al–1.5Ca–1.5Ti (by mass%) foam. Plateau stress could be effectively enhanced with the combined effect of strengthening solid alloy and increasing the aspect ratio of cell wall thickness against cell edge length. Plateau stress of the modified foam was independent of strain rate, while the stress in Al–Ca–Ti foam exhibited a certain strain rate sensitivity. Plateau strain, designated as the strain where the compressive stress reached 1.5 times higher value than the yield stress, was also enhanced by the present modification. As a result, absorption energy was also effectively enhanced but was independent of strain rate as a result of the present modification.

(Received February 1, 2002; Accepted June 5, 2002)

Keywords: closed-cell foam, alloying, crashing speed, strain rate sensitivity, plateau stress, energy absorption

1. Introduction

In recent years, there has been great interest in using lightweight metallic foams for automotive, railway and aerospace applications where weight reduction and improvement in comfort are required.¹ The metallic foams have the potential to absorb impact energy during the crashing of a vehicle either into another vehicle or a pedestrian.

It is well known that the strength of a metallic foam is dependent on its structure, the strength of the matrix material and relative density as already noted in some papers on the subject. Many researchers attempted to characterize the mechanical properties relating to the geometric structure, e.g., solid distribution,² cell face curvature and corrugations,³–⁶ aspect ratio of cell wall thickness against the edge length.⁷ Other attempts demonstrated to increase the plateau stress by adding strengthening elements in aluminum matrix.⁸,⁹ These reported results suggest controlling the geometric structure or alloying the aluminum matrix effectively increase the plateau stress and enhancement of energy absorption under a quasi-static loading. The information of actual deformation behavior is important in case of applying foams as energy absorber, since the previous research results showed the strain rate sensitivity of plateau stress varied with the structure of foams.¹⁰–¹³ In this study, the dynamic compression behavior of a closed-cell aluminum alloy foam was examined to adapt the foam for energy absorbers corresponding to the actual crashing speed of automobiles.

2. Characteristics of Modified Foam

A closed-cell foam with the chemical composition of Al–7Zn–0.5Mg–1.5Ca–1.5Ti (by mass%), denoted as Type ZM, was fabricated by a batch casting process, taking the surface tension, melting point and volume of gaseous hydrogen bubbles into consideration, along with our previous investigation.⁹ The size of the fabricated foam block was 600 × 600 × 300 mm³. Specimens with the dimensions of 100 × 100 × 100 mm³ were machined from the block. For comparison, a closed-cell foam with the original composition of Al–1.5Ca–1.5Ti (by mass%), denoted as Type CT, was also prepared with a similar cell-size and density to Type ZM.Appearances of the cell structure are shown in Figs. 1(a) and (b) for Type ZM and Type CT, respectively.

The relative density and structural-characteristics of both foams are summarized in Table 1. The average diameter of the cells was also measured according to the method prescribed by ASTM for the measurement of grain diameter in polycrystalline materials.¹⁴ In order to characterize the structures of two foams, an optical microscope was used and measured the apparent edge length (denoted as L) and the thickness of cell walls for any 200 edges. The schematic illustration for the measurement is shown in Fig. 2. The edge length was measured as the distance from the center point of a node to the neighbor point. As shown in this figure, the thickness, denoted as t₁/4 and t₁/2, was estimated for two points at 1/4L and 1/2L, respectively. The aspect ratio of the wall thickness against the edge length is estimated. The measured edge length of the Type ZM is smaller than that of Type CT, while the thickness at 1/2L of Type ZM is larger than that of Type CT.

The effect of adding Zn and Mg to the strengthening of solid was examined by a micro-indentor. The average measured hardness values are also shown in Table 1.

3. Compression Behavior

The compression test was carried out by a drop-weight impact apparatus. A 290 kg weight containing the weight of the frame was dropped from 11 m and impacted the specimen at a dynamic strain rate of 1.38 × 10² s⁻¹ corresponding to the crashing speed of automobiles (≈ 50 km/h). The transmitted load through the sample was measured by a load-cell unit,
Table 1  Structural characteristics and hardness for the present Al–7Zn–0.5Mg–1.5Ca–1.5Ti and Al–1.5Ca–1.5Ti (by mass%) closed-cell foams.

<table>
<thead>
<tr>
<th>Foams Type</th>
<th>Type ZM, Al–7Zn–0.5Mg–1.5Ca–1.5Ti (by mass%)</th>
<th>Type CT, Al–1.5Ca–1.5Ti (by mass%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative Density, ( \rho/\rho_s )</td>
<td>0.0617</td>
<td>0.0613</td>
</tr>
<tr>
<td>Cell Diameter/mm</td>
<td>4.04</td>
<td>4.18</td>
</tr>
<tr>
<td>Measured edge length, ( L/mm )</td>
<td>2.033</td>
<td>2.341</td>
</tr>
<tr>
<td>Measured thickness of cell wall at ( 1/4L ), ( t_{1/4}/mm )</td>
<td>0.087</td>
<td>0.083</td>
</tr>
<tr>
<td>at ( 1/2L ), ( t_{1/2}/mm )</td>
<td>0.093</td>
<td>0.101</td>
</tr>
<tr>
<td>Aspect ratio, ( t_{1/2}/L )</td>
<td>0.0427</td>
<td>0.0353</td>
</tr>
<tr>
<td>Hardness/Hv</td>
<td>90.6</td>
<td>42.2</td>
</tr>
</tbody>
</table>

and the displacement was also done by laser ranging. In order to estimate the strain rate effect, all foams were also subjected to a compression test by an Instron machine at a static strain rate of \( 1 \times 10^{-3} \) s\(^{-1}\).

Engineering stress-strain curves for Type ZM and Type CT are shown in Fig. 3 at two strain rates of \( 1 \times 10^{-3} \) and \( 1.38 \times 10^{2} \) s\(^{-1}\). Curves at the dynamic strain rate are undulated for both foams, which relate to the measuring procedure of transverse stress wave. In the current study, the plateau stress was estimated by an average value for the engineering strain from 0.2 to 0.5. The gradient of the curve at the dynamic strain rate is similar to that at the static strain rate. One of the interesting facts worth noting is that the strain rate dependence of the stress depends on the solid material; Type CT shows a rate dependence of the plateau stress obviously, while Type ZM shows a rate independence. The same trend of strain rate sensitivity of the plateau stress was also found in the small sample of the closed-cell Al–Ca–Ti foam.\(^{11–13}\) The shape of the curve is different for two foams; Type CT shows slight strain hardening, while Type ZM exhibits an almost constant value. Thus, the strain hardening behavior of closed-cell foams is noted to be affected by the solid material.
The value of plateau stress of Type ZM is higher than that of Type CT. The limit of plateau region of compressive stress can be determined as a strain at which densification starts. Since the plateau stress in a metallic foam often increases slightly, it is difficult to determine the strain. In the present study, we designated the plateau strain as a strain where the compressive stress reached 1.5 times higher value than the yield stress. The value of plateau strain for Type ZM (= 0.73) is also found to be higher than that of Type CT (= 0.58).

As it is well established that the hardness of the material is proportional to the yield stress, the ratio of yield stress in the solid for Type ZM against Type CT is calculated to be 2.14 from the values of hardness as shown in Table 1. On the other hand, the ratio of the measured collapse stress for Type ZM (= 2.04 MPa) against Type CT (= 0.85 MPa) is calculated to be 2.4 at the static strain rate. Thus, the measured collapse stress of Type ZM is higher than that as expected from the strengthening of the solid. The additional strengthening effect is expected to be as below.

The structure of a closed-cell metal foam is often compared to a tetrakaidecahedra. For relative densities less than or equal to 0.2, the relationship between the relative density (\( \rho / \rho_s \)) cell wall thickness (t) and edge length (l) of a tetrakaidecahedral foam with uniform wall thickness is approximated by the following equation:

\[
\frac{\rho}{\rho_s} = 1.185\frac{l}{t} - 0.4622\left(\frac{t}{l}\right)^2 \tag{1}
\]

where \( \rho \) is the density of the cellular material and \( \rho_s \) is the density of the cell wall (solid) material. In the case of substituting the values of \( l/t \) and \( L \) in Table 1 to the above equation, the relative densities of Type ZM and Type CT are calculated to be 0.0497 and 0.0413, respectively. On the other hand, the measured values of relative density for both foams are 0.0617 and 0.0613, respectively. Therefore, the mass of 81% for Type ZM and 67% for Type CT formed tetrakaidecahedral foam with uniform wall thickness. Thus, the resistant strength against the plastic stretching of the cell faces (denoted as membrane stress) in Type ZM is noted to be higher than that in Type CT. This prediction can also be expected due to the higher aspect ratio of the wall thickness against the edge length for Type ZM. It is summarized that the enhancement of the plateau stress in Type ZM is attributed to be the combination effect for strengthening of solid and increasing the membrane stress.

4. Energy Absorption

The absorption energy can be calculated from the integration of a load-displacement relation. The variations of absorption energy in the present foams are shown in Fig. 4 as a function of engineering strain. The absorption energy of each foam monotonically increases with strain, while the gradient varies with the kind of solid alloy. The deviation between the absorption energy at dynamic and static strain rate increases for Type CT, while that for Type ZM it is slight. This trend in the deviation corresponds to the strain rate sensitivity of the plateau stress for the present foams. It can be summarized that the absorption energy of the Al–7Zn–0.5Mg–1.5Ca–1.5Ti foam is found to be roughly 60% higher than that of Al–1.5Ca–1.5Ti foam at an initial dynamic strain rate of 1.38 × 10^2 s\(^{-1}\) (= ~ 50 km/h).
14) ASTM Designation E 112–82.