Foam Structure Effect on the Compression Behavior of Foamed Aluminum Alloy

C. C. YANG and H. NAKAE

Industrial Technology Research Institute Materials Research Laboratories, Bldg.52, 195-5 Chung Hsing Rd., Section 4 Chutung, Hsingchu, 31015 Taiwan, Republic of China
Department of Materials Science and Engineering, Waseda University, Nishi-Waseda, 2-chome Shinjuku-ku Tokyo, Japan

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The effect of the foam structure on the compression behavior of an Al–Si–Mg alloy foam, which was produced by a liquid metal method was experimentally investigated. The compressive stress–strain behavior is discussed due to the deformation of a cell within the foam. It is found that the foam with an 81.3% porosity has both a higher energy absorption capacity and a higher efficiency. The compressive strength decrease as the porosity increases. Experimental result showed that the low compressive strength is attributed to cells imperfection due to the higher porosity.

KEY WORDS: compressive behavior; aluminum foam; cell wall; energy absorption.

1. Introduction

The technology of aluminum foams production has been extensively reviewed.1–4) These foams are composite materials of gaseous and solid phases which exhibit a porosity of 70–90% and yet still retain significant levels of strength and stiffness. The unique properties of aluminum foams make them desirable for a wide variety of applications, including lightweight construction, and sound and heat insulation. Aluminum foams also have a potential application as energy absorbing materials during the crash of a vehicle due to their special compressive characteristics which shows a constant deformation stress at a higher percent strain during the entire deformation process.5,6) Many methods, including liquid metal and powder metallurgy, are available for manufacturing the close-cell aluminum foams.1,3) In addition, a refined process to control the porosity and minimize cell structure imperfections was also developed.7)

To date, the mechanical properties of the aluminum foams have been measured in a number of studies,8–10) and these data have been discussed in terms of theoretical models.11,12) These studies have shown that the measured values of Young’s modulus and strength are below those of the ideal closed cell foam structure due to morphological defects, such as a non-uniform foam density, cell wall curvature and cell wall corrugations. It was suggested that optimization of the foam structures is important for improving the mechanical properties, and, particularly the enhancement of energy absorption. To effectively absorb the impacting energy, the material is required to exhibit a high energy absorption capacity. Normally, the energy absorption efficiency, the ratio of the actual amount of energy absorbed to the total energy acting on a system is moderate. By changing the alloy composition and its porosity, it is possible to alter the energy absorption capacity. On the other hand, Gibson and Ashby13) have developed models to describe the mechanics of deformation. They pointed out the influence of cell fluid and membrane stresses in the cell faces on the strength of the closed cell foam. For an appropriate morphology of foams to be used in the design of the energy absorbing material structure, the deformation behavior of various aluminum alloy foams under compressive load must be considered. The compressive characteristics are only slightly known, however, the effect of the porosity on the mechanical properties of the aluminum alloy foams has not been clarified in detail. In this study, the compressive strength of aluminum alloy foams is examined in order to investigate the effects of the foam structure on the strength of the Al–Si–Mg alloy foams.

2. Experimental Procedure

The foam was made of an Al–Si–Mg alloy (nominal composition: Al–7 wt% Si–0.45 wt% Mg) using a melting foaming process. It was processed by blowing oxygen at 25 l/min into 100 kg of molten aluminum and stirring to increase the viscosity. After the viscosity of the aluminum alloy melt increased, 1.0 wt% titanium hydride powder was added as a foaming agent. The melt is then rapidly stirred for dispersing the powder, which results in the formation of pores in the castings. After cooling, the obtained foamed block showed a characteristic density gradient through the thickness due to its unidirectional solidification in the mold. Rectangular specimens for the compression tests with a typical dimension of 30 mm thick, 20 mm wide and 25 mm length were cut from the block. The apparent density of the
individual specimens was calculated from a measurement of its weight and volume for each configuration. From the values of the apparent density of the foams, we can calculate the porosity of the foam according to the expression \( 1 - \frac{\rho_F}{\rho_S} \), where \( \rho_F \) and \( \rho_S \) are, respectively, the apparent density of aluminum foam and that of solid aluminum. Compressive tests were carried out at room temperature using an Instron type machine in displacement control at a strain rate of 0.5 mm/min until the specimens completely densified. The load and displacement were converted into the nominal stress and the nominal strain by conventional methods. The structures of the specimens were observed using an optical microscope and scanning electron. In order to evaluate the effect of the cell morphology on the energy absorption, the edge length \( L \) and the thickness \( t_{1/2} (1/2L) \) of the cell walls, as in Fig. 1, were measured and calculated the mean value using more than 50 walls for the 70% and 84% porosity samples.

3. Results and Discussion

Figure 2 shows the compressive stress–strain curves of three foams with different porosities. For the case of the 92.5% porosity, a series of macrographs taken at various strains for the deformation of a cell within the foam are shown in Fig. 3. The curves exhibit differences among the three foams. The stress increases as the porosity decreases. The 92.5% porosity cell has a long plateau area with a constant strain and hardly shows a higher maximum stress. The reason is that the higher the porosity, the larger cell may exist in the foam. All specimens, independent of their porosity show three deformation stages. The peak stress (compressive strength denoted by the arrows) at the peak strain is followed by a plateau region where the stress remains almost at a constant level and accompanied by a minor fluctuation in the stress due to the buckling of cell walls throughout the entire deformation range. However, the length of plateau region is smaller than those of other closed-cell aluminum alloy,\(^{14}\) which is possible related to that the effect of specimen height and cellular structure, which leads to the contribution of cell face to the deformation of foamed aluminum.\(^ {15}\) In other words, the plateau region increases in size with increasing strain until it is wholly collapsed. This demonstrate the difference in both plateaus. After the plateau region, the foam completely collapsed results in the rapid increase in stress due to the cell walls contacting to each other. As shown in the micro- graphs of Fig. 3(C) the cell walls that plastically collapsed have already been initiated at the strain of about 20%.

From the compression test data, the energy absorption during the deformation can be calculated. The definition of the energy absorption efficiency \( A \) is given in Ref. 16) by Eq. (1)
Where \( W \) and \( W_0 \) are, respectively, the actually absorbed energy after a compression strain \( \varepsilon \) (at the end of the plateau region) and that of an ideal absorber which shows a rectangular change in the stress–strain curve. For these Al–Si–Mg alloy foams, the \( W \) can be calculated by integrating the area under the stress–strain curve of Fig. 2. The energy absorption per unit volume of the Al–Si–Mg alloy foams with porosities of 72.4%, 81.3% and 92.5% are listed in Table 1. It can be seen in Table 1 that the foam with an 81.3% porosity has a higher energy absorption value as a result of the high peak stress and the plateau (Fig. 2).

The relationship between the compressive strength and porosity of the Al–Si–Mg alloy foams is shown in Fig. 4. With an increase in the porosity, the strength exponentially decreases. The slope of the strength line drastically changes at the porosity of about 80%. This clear discontinuity is associated with the cells imperfection within the higher porosity due to the processing conditions.

The cell morphology changes with porosities are shown in Figs. 5(a) through 5(c). It can be observed that a cell shape and size is uniform in the foam with 70% porosity. However, many of the cells in the 84% porosity foams have many irregularities in shape and size. In addition to, a few cells are open in the case of 88% porosity foam.

The measured results for the length and thickness of the cell walls are summarized in Figs. 6(a) and 6(b), respectively. It shows that the distribution of the wall thickness and edge length of cell is greatly changed by the porosity. In the foam with 70% porosity are smaller than those in the foam with 84% porosity. This because 70% porosity foam as if its cells are small which leads to the approachable values between the thickness and length of cell walls. It is note that the foam with 70% porosity exhibits a more uniform

**Table 1. Energy absorption properties of Al–Si–Mg foams.**

| Porosity (%) | Amount of absorbed energy (MJ/m³) | Efficiency of energy absorption (%) |
|-------------|---------------------------------|-----------------------------------|
| 72.4        | 0.82 (at strain of 16.5%)       | 68.9                              |
| 81.3        | 1.12 (at strain of 34.7%)       | 76.7                              |
| 92.5        | 0.82 (at strain of 59.2%)       | 66.5                              |

Fig. 4. Effect of porosity of the foamed aluminum on compressive strength.

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A(\varepsilon)=\frac{W}{W_0}=\int_0^\varepsilon \sigma(\varepsilon) \, d\varepsilon \cdot \varepsilon(\varepsilon)\ldots\ldots\ldots\ldots\ldots(1)
\]

Fig. 5. Section of foamed aluminum (a) 70% vol. porosity (b) 84% vol. porosity (c) 88% vol. porosity.

Fig. 6. Distribution of wall thickness and edge length of cells (a) 70% porosity (b) 84% porosity.
cell wall compared with that 84% porosity one. The average values of the measured edge length and wall thickness are summarized in Table 2. The aspect ratio of the wall thickness to the edge length in the cell walls (i.e., \( t_{1/2}/L \)) for the foams with 84% porosity is slightly smaller than that of the 70% porosity foams.

In the case of the 84% porosity sample, the foams have large cells with an irregular shape that results in a decrease in the aspect ratio of \( t_{1/2}/L \) (see Table 2). The presence of large cells result from the growth and coalescence of bubbles during the foaming process of the aluminum melt which cause high defective cell walls. From the results of Fig. 6 and Table 2, note that the contribution of the membrane stresses of cell walls in the foam with 84% porosity is insufficient which easily induces a stress concentration and therefore causes the decrease in the compressive strength. These experimental results indicate that non-uniform cell walls are susceptible to compressive deformation and influence the energy absorption efficiency of Al–Si–Mg alloy foams. It can also be found that the aspect ratio of \( t_{1/2}/L \) in the present study exhibits higher value than as compared to that of other data previously reported.\(^{14}\) This reveals some relationship between the porosity of foam and cell morphology, since the samples in this study have a low porosity with thicker cell wall, which leading to much higher value of \( t_{1/2}/L \), thus different results were obtained in the present study.

### Table 2. The average value of thickness and edge in the cell wall for the foams with 70% and 84% porosities.

| Porosity (%) | Measured edge length (mm) | Measured thickness at \( t_{1/2} \) (mm) | Aspect ratio \( t_{1/2}/L \) |
|--------------|---------------------------|--------------------------------------|--------------------------|
| 70           | 2.91                      | 1.62                                 | 0.557                    |
| 84           | 3.04                      | 1.63                                 | 0.537                    |

### 4. Conclusions

The effects of the foam structure on the compression behavior of an Al–Si–Mg alloy foam were experimentally investigated. From the compressive test at a stain rate of 0.5 mm/min, the plastic yield followed by a long plateau region leads to materials with a high degree of energy absorption. As a result, the value of the energy absorption per unit volume (\( W \)) up to a strain of 34.7% for the porosity of 81.3% is 1.12 MJ/m\(^3\). The strength will decrease as the porosity increases. There is a turning point at the porosity of about 80%. These experimental results indicated that the foam with about an 81% porosity has a high energy absorption characteristic, which suggested that the 81% porosity in the Al–Si–Mg alloy foams is suitable for energy absorbing applications.

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