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Compressive deformation behavior and energy absorption characteristic of aluminum foam with elastic filler①

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Abstract: An open-cell aluminum foam filled with silicate rubber (AFFSR) was fabricated by infiltration of the liquid silicate rubber into the open-cell aluminum foam. The experiments were carried out to investigate the compressive behavior and energy absorption characteristics of the material. It is found that the stress—strain response of the AFFSR exhibits five regions including two plateau regimes, which is quite different from the stress—strain curves of many unfilled metallic foams that usually exhibit three distinct regions. The plastic deformation of the AFFSR is prolonged because of the filled silicate rubber, compared with the aluminum foam without such a filler. The AFFSR also exhibits a higher energy capacity than the aluminum foam without filler. Additionally, for the prolonged plateau region in the stress—strain curve, the energy absorption efficiency of the AFFSR maintains a high level (above 0.6) over a wide strain range from 3% to 60%.

Key words: open cell aluminum foam; silicate rubber; compressive property; energy absorption capacity

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1 INTRODUCTION

Aluminum foams are ultra-light materials which possess high strength, stiffness, and energy absorption capacity. They have great potential for use in applications which require superior impact energy absorption, such as cores for sandwich plates and shell structures which will lead to significant reductions in the mass of components, coupled with high strength and stiffness. Currently, there is a high interest in using metallic foams, particularly aluminum foams for automotive, railway, and aerospace applications where mass saving, impact protection, and improvements in comfort and safety are required. During the past two decades, considerable attention has been devoted to the synthesis and properties of aluminum foams. A series of technologies, including casting, powder metallurgy, and metallic depositions have been developed for manufacturing open and closed cell aluminum foams[1-4]. Meanwhile, a lot of experimental and theoretical studies have been carried out both on the static and dynamic mechanical properties of aluminum foams[5-10].

Actually, metallic foams are themselves composite materials consisting of gaseous and solid phases[11]. Most past works have concentrated on the micro-mechanical mechanisms for deformation of the matrix in compression, and the effects of parameters such as the fraction of solid (relative density), pore size, cell shape and morphology on the properties of the aluminum foams[8-12]. The contributions of the gaseous phase to the properties of the foams have rarely been considered because they have negligible effects on the gross properties of the materials. However, if the gaseous phase in the pores is substituted by another stiffer or damping phase, the response of the foams can be very different, e.g. a open-cell foam filled with an incompressible viscosity liquid will behave quite differently. The cell fluids will have a distinct contribution to strength of the open-cell foam. When the foam is compressed, the contained viscosity fluid is squeezed out, thus extra work is required to force it through the interconnected porosity of the foam. The faster the foam is deformed, the more the work will be required; thus the pore fluid introduces a strongly strain-rate dependent contribution to strength[13]. Gibson and Ashby have previously analyzed the contributions of cell fluids to the strength and energy absorption of open-cell foams[14]. From their work, it is expected that when a soft solid material, e.g. rubber, is filled into an open-cell foam, it will create significant effects on the mechanical prop-

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erties of the foam. Although rubber materials have long been used as cushions, vibration reducers, and impact energy absorber, their structural applications generally have been limited because of their low strength. However, if a rubber material is filled into a metallic foam, e. g. an aluminum foam, a structural material with high stiffness and strength combined with high energy absorption may be obtained. Therefore, the objective of this work is to prepare open-cell aluminum foams filled with silicate rubber (AFFSR), and to investigate the compressive behavior as well as the energy absorption characteristics of these materials.

There is very little reported research on aluminum foams containing polymer. Kwon et al[15] prepared open-cell aluminum foams with an elastic filler and investigated their compressive properties. They found that the relative strength and stiffness were notably improved.

2 EXPERIMENTAL

2.1 Preparation of AFFSR specimens

In order to prepare the AFFSR samples, an open-cell aluminum foam was fabricated. The aluminum foams used in this study were made of commercial pure aluminum and fabricated by the filtrating process. The main procedures for the foams included the preparation of a preform composed of NaCl particulates with specific particle sizes, followed by the penetration of the aluminum melt into the preform through the application of high pressure air. As a final step, the dissolution of the NaCl particulates from the ingots after the aluminum melt solidified, resulted in an aluminum foam with a three dimensional open cell structure. The pore size of the aluminum foam can be controlled by adjusting the particle size of the salt granules. The average pore size of the aluminum foam prepared for this work was 2 mm. A scanning electron micrograph of the open-cell aluminum foam is shown in Fig. 1. The cylindrical AFFSR specimens for compressive experiments with a diameter of 35 mm and a height of 20 mm were prepared by filling the open-cell aluminum foam samples with silicate rubber. The cylindrical aluminum foam samples were first prepared by electrodischarge machining from the aluminum foam blocks. The density of individual samples was calculated by weighing the samples on a balance and measuring their dimensions. The average value of the density of the aluminum foam samples was 1.137 g/cm^3 (corresponding to a relative density of 0.421, and a porosity of 0.579), and variations in density from sample to sample were less than 0.5%. The AFFSR specimens were prepared by the infiltration process, i. e. filling the liquid silicate rubber into the open spaces of the aluminum foam samples under pressure, and heating the samples to 80 − 100 ℃ to cure the silicate rubber. The volume fraction of the silicate rubber in the AFFSR specimen is equal to the porosity of the aluminum foam, i. e, approximately 0.579. A representative scanning electron micrograph of the AFFSR is shown in Fig. 2. The white phase in the figure is silicate rubber and the grey one is aluminum.

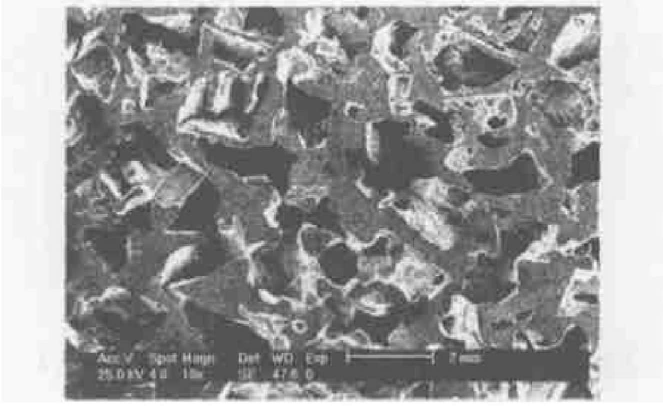

Fig. 1 SEM image of open-cell aluminum foam

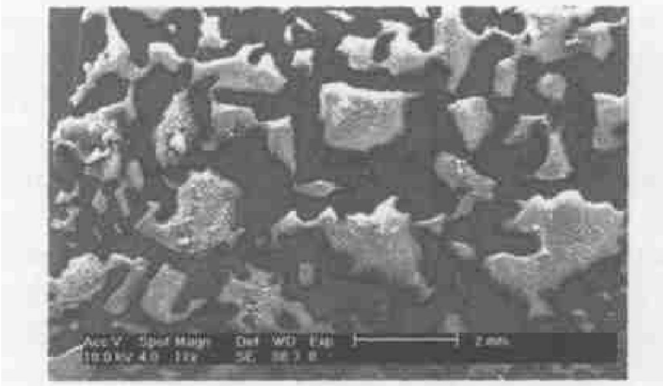

Fig. 2 SEM image of AFFSR

2.2 Static compression tests

The static compression tests were conducted on a MTS 810 material testing machine. The crosshead movement was monitored by a computer. All compression tests on the specimens were conducted at a strain rate of 10^{-3} s^{-1}. At least three specimens were tested under the same compressive conditions. For comparison, the same open-cell aluminum foam and bulk silicate rubber were also investigated by similar compressive tests. The bulk silicate rubber specimens were 30 mm in diameter and 25 mm in height.

3 RESULTS AND DISCUSSION

3.1 Compressive deformation behavior

The stress—strain curve obtained on the bulk silicate rubber is shown in Fig. 3. As seen from the figure, the stress—strain response of the silicate rubber exhibits the typical behavior of an elastomer. The stress increases with increasing the strain linearly up to a strain of 35%, and no yield point is observed in the curve. The stress level of the rubber is very low (below 1.5 MPa) to a strain of 35%, and is less than 3 MPa to a strain of 50%.

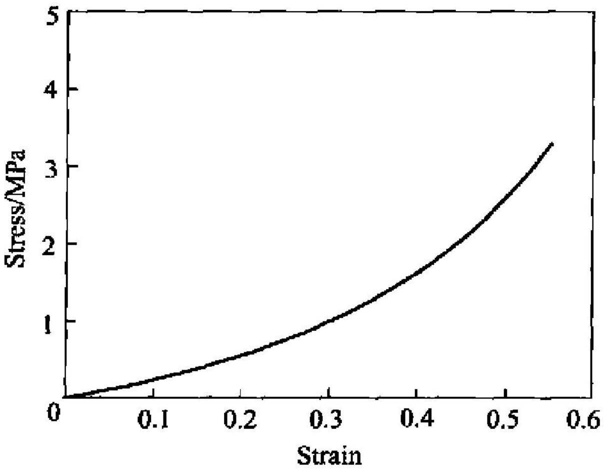

Fig. 3 Compressive stress—strain curve of bulk silicate rubber

A typical stress—strain curve on the AFFSR is shown in Fig. 4. For comparison, a stress—strain curve of the same aluminum foam without a filler is included in the figure. As can be seen, the stress—strain curve of the aluminum foam without a filler is characterized by typical characteristics of three distinct regions: a linear elastic regime, and a plateau regime followed by a densification regime, these are usually observed in the stress—strain response of other aluminum foams[4-6]. However, a much different stress—strain response is observed in the compression of the AFFSR. It seems that five regions, including two plateau regions, can be identified, i.e. a linear elastic region at very low stress and strain (less than 2%), the first plateau region with a slight increase in stress to a strain of about 0.09, the following region with gradually increasing flow stress to a strain of about 0.32, and the second plateau region between a strain range from 32% to approximate 60% where the stress dependence is low, and a final region where the stress again rises gradually. No distinct densification region showing a rapid rise in stress is observed on the stress—strain curve of the AFFSR. Obviously, the compressive behavior, particularly the plastic deformation of the aluminum foam is affected significantly by the filled silicate rubber. However, the distinct effects of the rubber only emerge when a considerable degree of plastic deformation occurs. At the early stage of deformation (less than a strain of 9%), the stress of the AFFSR is slightly higher than that of the aluminum foam. If we define the stress at 0.02 offset strain as the yield strength ($\sigma_{0.02}$), the yield strength of the AFFSR and the aluminum foam are 4.06 MPa and 3.97 MPa respectively. It is noted that the stiffness and yield strength of the aluminum foam are not significantly enhanced by the silicate rubber. After a considerable deformation (larger than 9%), the flow stress of the AFFSR begins to rise more rapidly and is higher than that of the aluminum foam until the strain reaches about 30%. However, after the strain exceeds 32%, the flow stress of the AFFSR is nearly constant to a strain of about 60%, i.e. the second plateau region. Clearly, the plastic deformation of the AFFSR is much prolonged by the filled silicate rubber compared with that of the aluminum foam. The filled silicate rubber prevents the aluminum foam from densification during compression. In contrast, for the unfilled aluminum foam, when the strain exceeds about 32%, due to cell wall bucking and pore cells collapse, the flow stress of the foam rises more and more rapidly as a result of the increase in its density. When the applied strain reaches a limiting compressive strain, known as the densification strain, ε_d, the densification occurs. The onset of densification is given by[14]:

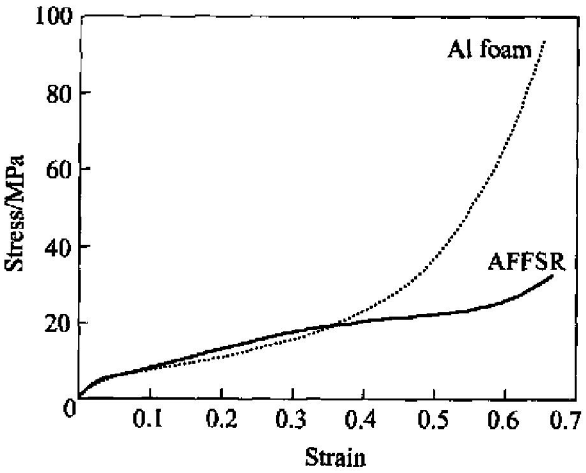

Fig. 4 Compressive stress—strain curves of AFFSR and open-cell aluminum foam

$$\varepsilon_d = 1 - \alpha\left(\frac{\rho^*}{\rho_s}\right) \tag{1}$$

where ρ^* and ρ_s are the density of aluminum foam and commercial aluminum respectively, and the material constant α is between 1.4 and 2 for the currently metallic foams[16]. According to Eqn. (1), the densification strain, ε_d, of the present aluminum foam is 41.1% if α is chosen to be 1.4. A SEM micrograph of the densification structure of the aluminum foam without filler at a strain of 40% is shown in Fig. 5, in which much of the pore space in the foam has been squeezed to shut. Therefore, the stress—strain curve of the aluminum foam rises steeply after the strain exceeds about 40% (as can be seen in Fig. 4).

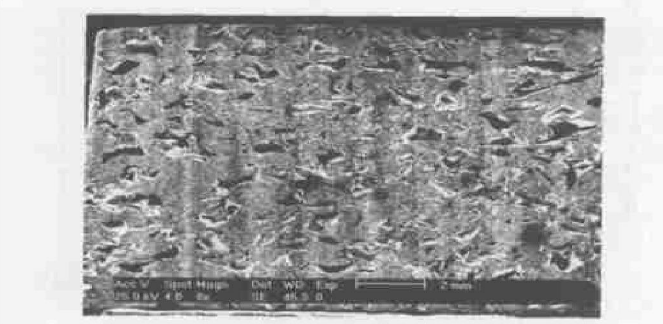

Fig. 5 SEM image of open-cell aluminum foam after a strain of 40%

To the authors' knowledge, there is no mechanical model for open-cell metal foams containing rubber. Although the deformation mechanism for the AFFSR remains unclear, its deformation behavior can be interpreted partially according to existing explanations for the deformation mechanism of open-cell foams and the properties of the rubber. Because in the early stage of compression, the plastic deformation of open cell foams proceeds mainly by cell walls yielding axially, and bending[14], which do not result in a notable reduction in the volume of the cell. The silicate rubber contained in the cells deforms with its volume conserved. The elastic modulus as well as the strength of the silicone rubber are very low (as shown in Fig. 3) compared with those of the aluminum foam, so their contributions to the overall properties such as the elasticity and the strength of the composite material can be neglected. However, after a considerable deformation (a strain of about 9%), as the bending of the cell beams proceeds and the collapse occurs due to buckling and yielding, the volume of the cell will decrease notably. On the other hand, the incompressible property of the rubber will resist cell-beam bending and plastic collapse, which results in an increase in the applied stress to maintain further deformation. As the stress and strain further increase, the volume of the cell is partially conserved by cell-wall stretching which compensates for reductions in cell volume resulting from cell wall bulking, and the volume also partially decreases by squeezing a part of the silicate rubber out of the cell. Meanwhile, the rubber constrained in the cells introduces a strong tension in the cell beams in the direction perpendicular to the compressive stress, and the cells deform by stretching along the tensile direction. When the tensile stress in the cell beams is increased to a critical value, the fracture of the aluminum frame will occur in the radial direction of the specimen. After the ruptures occur in the beams of the most of the cells, a considerable part of the rubber is no longer constrained and the resistance to deformation decreases to a great degree, and the applied stress required for deformation no longer increases at this point. Since the pore cells of the aluminum foam have stretched greatly in the direction perpendicular to the compressive stress, this AFFSR behaves like a multi-layer material constructed of many alternating mixed layers of aluminum and silicate rubber in the compression direction. For this reason, the densification of the aluminum frame is prevented, and the material undergoes a large plastic deformation at a nearly constant stress. The final rise in the stress—strain curve at a strain of about 60% (as shown in Fig. 4) may be associated with the contact of some of the opposing fractured cell beams by cutting through the silicate rubber between them which has become very thin as a result of stretching. The above explanations are confirmed by examining the radial and microstructure of the AFFSR specimen after compression. Compared with the compressed aluminum foam specimen, much more radial expansion was observed in the AFFSR specimen after compression. A SEM image of transverse section of the AFFSR specimen after compression is shown in Fig. 6. Many fractures are observed in the aluminum frame (as indicated by arrows in the figure). Unlike the densification structure of the compressed aluminum foam without filler (as shown in Fig. 5), the opposing beams of the aluminum foam cells in the AFFSR remain untouched and are still separated by the silicate rubber after a deformation of about 65%.

Fig. 6 SEM image of transverse section of AFFSR after a strain of 65%

3.2 Energy absorption capacity

When the foam is loaded, work is done by the compressive applied forces and energy is absorbed by the foam during plastic deformation. The energy absorbed by per unit volume (W) in deforming the foam to a strain ε is simply the area under the stress—strain curve up to a certain strain ε and can be written as:

$$W = \int_0^{\varepsilon} \sigma(\varepsilon) \mathrm{d}\varepsilon \quad (2)$$

where $\sigma(\varepsilon)$ is the stress as a function of the strain. It is known from Eqn. (2) that the energy absorbed to a certain strain is determined by the shape or $\sigma(\varepsilon)$ function of a stress—strain curve. As seen from Figs. 3 and 4, the stress to deform the bulk silicate rubber is very low compared with that of the aluminum foam at any given strain, therefore, limited energy absorption capacity is available. The energy absorption capacity of a foam is usually evaluated by the absorbed energy measured up to the onset of the densification strain, ε_d[8,14]. From Eqn. (2), the energy absorbed by the unfilled aluminum foam to its densification strain (0.41) is 4.98 MJ/m^3, while that absorbed by the AFFSR to the same strain is 5.40 MJ/m^3. However, the peak stress generated in the aluminum foam without filler (24.32 MPa) corresponding to the densification strain is higher than that in the AFFSR (20.79 MPa) for the same strain. The optimum choice of foam in practice is the one which absorbs the most energy without the stress rising above the chosen limit peak stress. For this reason, the peak stress generated in a foam, for a given amount of energy absorbed, is also an important consideration in engineering design[14]. Using Eqn. (2), in combination with the stress—strain curves in Fig. 4, the curves of W vs stress for both the AFFSR and the aluminum foam without filler can be obtained and are shown in Fig. 7. As it can be seen in the figure, in the stress range from about 9 MPa to 18 MPa, for the same absorbed energy, the peak stress generated in the AFFSR is slightly larger than that in the unfilled aluminum foam. It is a direct result of the fact that in this stress range, the stress—strain curve of the AFFSR is above that of the aluminum foam without filler. However, after the stress exceeds about 18 MPa, the stress—strain curve of the AFFSR exhibits a long plateau regime (Fig. 4) which allows a large energy absorption to occur at near-constant stress, and so as a result, the energy absorption-stress curve rises steeply as the stress increases. Whereas, for a rapid rise in the stress—strain curve of the aluminum foam after the onset of densification, a much higher peak stress is generated in the foam in absorbing the same energy.

The results above suggest that the AFFSR has a higher energy absorption capacity than the aluminum foam without filler. This may result from the fact that more mechanisms are at work in absorbing energy in the AFFSR, for example, the elastic, plastic deformation and fracture of cell walls of the aluminum frame, and the compression and flow of the silicate rubber within the cells.

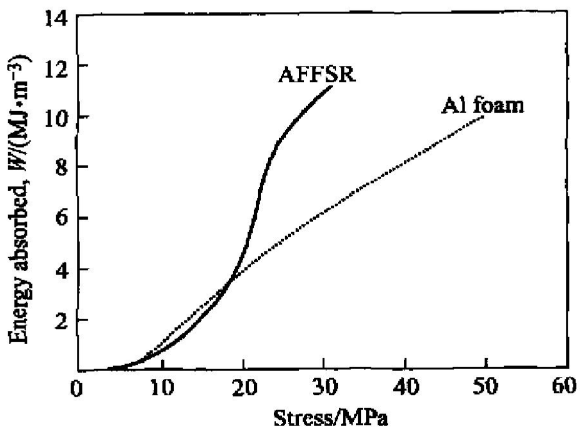

Fig. 7 Variation in energy absorbed with stress for AFFSR and open-cell aluminum foam

3.3 Energy absorption efficiency

The energy absorption property of a foam is further characterized by the efficiency[17], E, which is known as the ratio of the real energy absorbed to the ideal energy absorbed for a given strain, ε, and the corresponding peak stress, σ_p, and is given by

$$E = \frac{\int_0^{\varepsilon} \sigma(\varepsilon) \mathrm{d}\varepsilon}{\sigma_p \cdot \varepsilon} \quad (3)$$

where $\sigma_p \cdot \varepsilon$ is the ideal energy absorption, i. e. the energy is absorbed at a constant stress σ_p over the strain range ε. Clearly, E is also relevant to the shape of a stress—strain curve. The E—strain curves of the AFFSR and the aluminum foam are calculated from Eqn. (3) and shown in Fig. 8. The E—strain curve of the AFFSR exhibits a saddle shape which is quite different from that of the other foams in past work[18]. The drop of the curve in the strain range from 9% to 32% is related to the relatively rapid rise in the stress—strain curve of the material in this region. Additionally, the E—strain curve of the AFFSR maintains a high level (above 60%) over a wide strain range from 3% to 62%. By contraction, the E—strain curve of the unfilled aluminum foam keeps above the same level only in the strain from 3% to 28%, and decreases rapidly

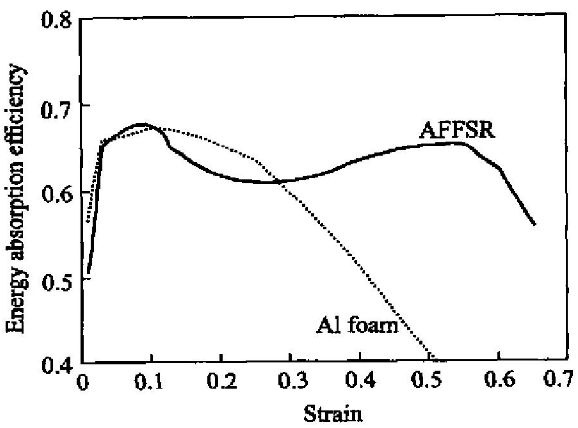

Fig. 8 Variation in energy absorption efficiency with strain for AFFSR and open-cell aluminum foam

after the strain exceeds about 28%. The energy absorption efficiency E of the unfilled aluminum foam measured to the onset of its densification strain (41.1%) is only 0.5, which is quite below that of the AFFSR for the same strain. Therefore, the results of either the energy absorbing capacity or the energy absorption efficiency suggest that the AFFSR may have greater potential than aluminum foam for energy absorbing applications.

4 CONCLUSIONS

1) An aluminum foam containing silicate rubber (AFFSR) was fabricated by infiltration of silicate rubber into the open-cell aluminum foam.

2) Compressive experiments have been conducted on the AFFSR, the bulk silicate rubber, and the aluminum foam without filler. The experimental results reveal that the AFFSR has a unique compressive stress—strain response which is quite different from those of many metallic foams that usually exhibit three distinct regions. It is believed that cell wall buckling, stretching and fracturing perpendicular to the compressive stress dominate the deformation and failure of the AFFSR under compression. This proposal has been confirmed by the SEM images of the compressed samples.

3) The AFFSR exhibits a higher energy absorbing capacity than the aluminum foam without filler, yielding a much lower peak stress for the same energy absorbed. Additionally, the energy absorption efficiency of the AFFSR maintains a high level (above 0.6) over a wide strain range from 3% to 60%. All of the experimental results and analyses suggest that the AFFSR may have a greater potential than aluminum foam for energy absorbing applications.

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