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Damping capacity and compressive characteristic in some aluminum foams ①

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Abstract: The compressive behavior, energy absorption and damping capacity of Al-28% Zn alloy foam, Al-10% Mg alloy foam and commercial pure aluminum foam with open cell were investigated. The Al-28 % Zn alloy foam exhibits the typical deformation behavior of brittle foam in static compression, and a much higher energy absorption capacity than the Al-10% Mg alloy foam and pure aluminum foam to the densification strain. Over a large plastic strain range, the energy absorption efficiency of the Al-28 % Zn alloy foam keeps nearly constant and above 80%. The experiments on the internal friction of the three foams are also conducted on a multifunction internal friction apparatus (MFIFA). The Al-28% Zn alloy foam exhibits a high damping capacity which is three to four times larger than those of the pure aluminum foam and Al-28% Mg alloy foam around room temperature. The mechanism for the high damping capacity of the foamed Al-28% Zn alloy may be associated with the viscous sliding at the interface between the soft phase α and the brittle rich Zn phase η in its base metal during vibration.

Key words: damping capacity; compressive behavior; energy absorbing capacity; aluminum foam
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1 INTRODUCTION

Metallic foams, especially aluminum alloy foams are super-light metals exhibiting unique properties such as high energy absorption and high damping capacity. So, they are believed to have great potential for applications in many aspects, for example, the application in energy absorption and vibration damping. Therefore, their mechanical properties have attracted a considerable attention in recent years. A number of works on the compressive behavior of foamed aluminum and its alloy have revealed that the deformation behavior of aluminum foams is characterized by a large deformation at a nearly constant nominal stress. As a result, a large amount of energy is absorbed at a relatively low flow stress in compression. Moreover, it has been reported that aluminum foam also exhibits a significantly improved damping capacity compared with its matrix metal for a quantity of macroscopic pores existing in the base metal[1, 2], which has potential applications in attenuation of noise and mechanical vibration.

However, it should be recognized that the properties of the base metals play a very important role in both the energy absorption and damping capacity of metallic foams. From the limit works reported on the damping behavior of metallic foams, it is known that the difference existing in damping capacity of the foams made of different kinds of alloys is significant[2, 3]. The Zn-Al eutectoid alloy foam exhibits the highest damping capacity among the foams reported. According to the past works on metallic foams[4-6], the strength and the energy absorption capacity of metallic foams are directly proportional to the strength of their matrix. Therefore, from the point of view above, a good combination of the damping capacity and the energy absorption property could be achieved by proper selection of base material for the metallic foam. The Zn-Al eutectoid alloy and the foams made of this alloy have been proved to have a high damping capacity[3, 7], while the excessively heavy weight of this alloy foam is a disadvantage in application for structural materials. But the results obtained with this material promote the idea of this study that the damping capacity of aluminum alloy foams should be improved efficiently by addition of a appreciable amount of Zn in the matrix without much rise in its weight, and its strength as well as energy absorption capacity can also be increased from the solid solution strengthening effect of Zn in the matrix.

The aim of the present work is to investigate the damping behavior, the compressive properties and energy absorption capacity of the foamed aluminum alloy with a comparatively high content of Zn (w(Zn)

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= 28%). For the purpose of comparison, the damping capacity and compressive properties of common foamed Al-10% Mg alloy and pure aluminum are also investigated.

2 EXPERIMENTAL

The foams used in the experiments were made of commercial pure Al, Al-10% Mg and Al-28% Zn alloy. All the foams were prepared by infiltrating process and had the morphology of open cell. The infiltrating process was to penetrate the aluminum alloy melt by pressure around the salt granules which were compacted in a mold and heated previously to 600 - 700 ℃. After the melt solidified, a composite of aluminum or its alloy with granules was obtained and a block of foamed aluminum or aluminum alloy with three dimensional open cells was prepared by leaching out the salt granules in the composite using water. The foams made of pure aluminum, Al-10% Mg alloy and Al-28% Zn alloy for experiments had the same morphology and the average pore size ranging from 1 - 1.5 mm, and the densities of 1.05 - 1.08, 0.88 - 0.90 and 1.23 - 1.24 $g \cdot cm^{-3}$ respectively. Although there are some differences existing among the densities of these foams made from the different base metals, their relative densities are approximately identical (about 0.39 - 0.4). The rectangular specimens with the dimensions of $2.5 \times 3 \times 70\ mm^3$ for damping experiments and the columnar specimens with 25 mm in diameter by 20 mm in height for compressive experiments were all cut by electric spark manufacturing process from each foam block prepared.

In this paper, the damping capacity of the foams is characterized by internal friction (IF) and evaluated with the inverse quality factor Q^{-1}. All damping experiments were performed on a MFIFA through forced vibration and carried out at the frequencies of 0.1 - 3 Hz with the same strain amplitude of 1×10^{-5}, and over the temperature range from 25 ℃ to 300 ℃ at a changing temperature rate of 2 ℃/min.

The compressive experiments on the foams were conducted by employing MTS 810 material testing machine at the strain rate of $10^{-3} \cdot s^{-1}$. The compressive curve of the foam in each single experiment was obtained with three same samples.

3 RESULTS AND DISCUSSION

3.1 Damping capacity of foams

Fig. 1 shows the Q^{-1}-temperature curves of as-cast foamed Al-28% Zn alloy at the low frequencies of 0.1, 0.3, 1.0 and 3.0 Hz respectively over the temperature range from room temperature to 300 ℃ with heating rate of 2 ℃/min. Several interesting phenomena are observed in the Q^{-1}-temperature curves of foamed Al-28% Zn alloy. First, like that of the foamed Zn-Al eutectoid alloy[3], the curves of the foamed Al-28% Zn alloy rise rapidly when the temperature is above 150 ℃. The mechanism for this phenomenon is possibly due to the grain boundary sliding of the thermally activated relaxation process occurring in many polycrystalline[8]. Secondly, an inverse frequency dependence is found in the internal friction of the foamed Al-28% Zn alloy, its damping capacity decreases with increasing of frequency in the range of 0.1-3 Hz over the experimental temperature range. The similar phenomenon has been reported for the damping behavior of the foamed Zn-Al eutectoid alloy[3].

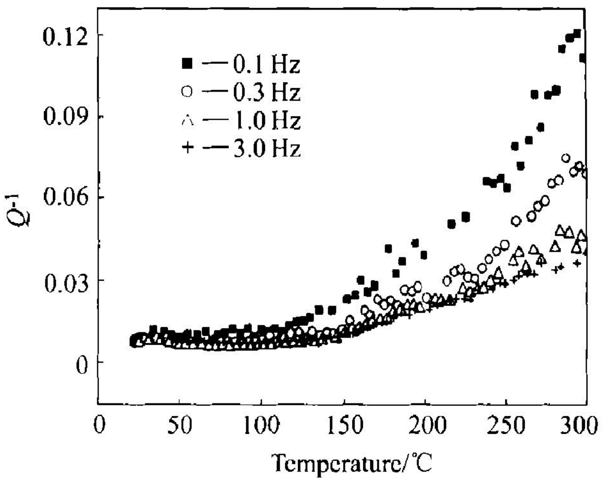

Fig. 1 Q^{-1} as a function of temperature for foamed Al-28% Zn alloy in as-cast state at different low frequencies

The Q^{-1} as a function of temperature measured at the frequencies of 1 Hz and 3 Hz in the three investigated foams of the same relative density in the as-cast state is shown in Fig. 2 and Fig. 3 respectively. One can observe that the foamed Al-28% Zn alloy presents the highest damping capacity among the foams investigated at each measuring frequency over the whole temperature range. The Q^{-1} of the foamed Al-28% Zn alloy is between 7.5×10^{-3} - 9.7×10^{-3} in the experimental frequency range at room temperature, which is about three times larger than that (1.9×10^{-3} - 3×10^{-3}) of the foamed Al-10% Mg alloy and four times higher than that (1×10^{-3} - 2.8×10^{-3}) of the aluminum foam measured at the same conditions. Moreover, when the temperature is above 150 ℃, the difference between the Q^{-1} of the foamed Al-28% Zn alloy and those of the other two foams further increases with increasing the temperature, for a rapid increase in the Q^{-1} of the foamed Al-28% Zn alloy but only a slight increase existing in those of the foamed pure aluminum and the Al-10%

Mg alloy with increasing the temperature. Because the structural parameters of the three foams used in the study are identical, the difference between the intrinsic damping capacity of their base metals should account for the difference in the damping behaviors of the foams. The damping capacity of Al-28% Zn alloy is much higher than those of pure Al and Al-10% Mg alloy. And this may be interpreted by the increase of its damping capacity caused by the interaction between dislocations and solute Zn atoms. Particularly, a large amount of brittle and hard rich Zn phase η is formed in the microstructure of the Al-28% Zn alloy under the non-equilibrium casting condition, as a result, the energy is dissipated and the damping capacity is improved by the viscous sliding at the interface between the soft phase α and the brittle rich Zn phase η during vibration[9]. Additionally, it is found in Fig. 2 and Fig. 3 that the damping capacity of the foamed Al-10% Mg alloy is higher than that of the aluminum foam although their structural parameters are identical. This result also may be interpreted by the increase of the damping capacity in the matrix of the foamed Al-10% Mg alloy caused by the interaction between dislocations and solute Mg atoms[10].

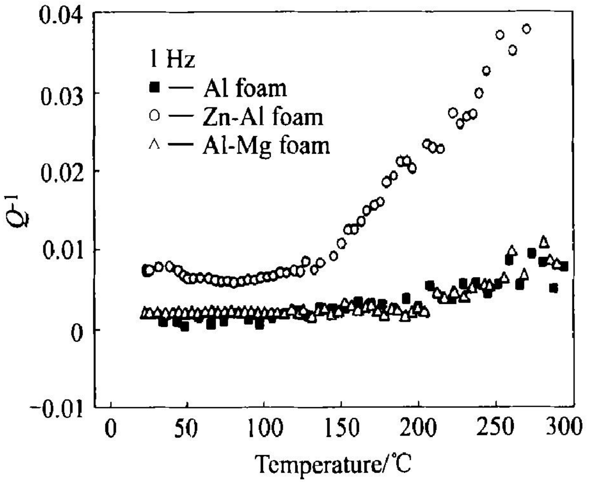

Fig. 2 Internal friction spectra of three foams in as-cast at 1 Hz

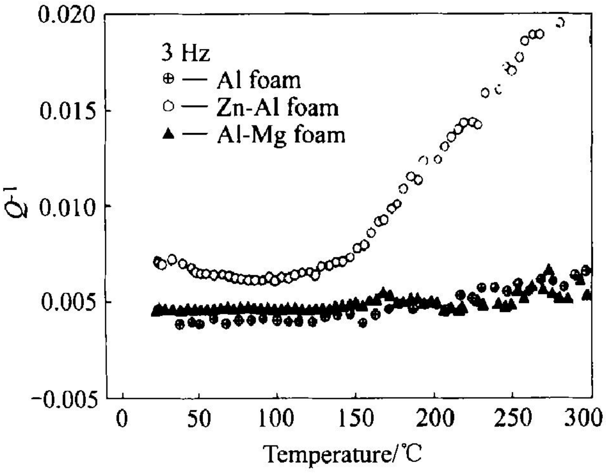

Fig. 3 Internal friction spectra of three foams in as-cast state at 3 Hz

3.2 Compressive behavior

The typical compressive stress-strain curves of the three foams investigated with the same relative density and structural parameter are shown in Fig. 4. As seen in Fig. 4, although all of the curves of the foams are characterized by three distinct

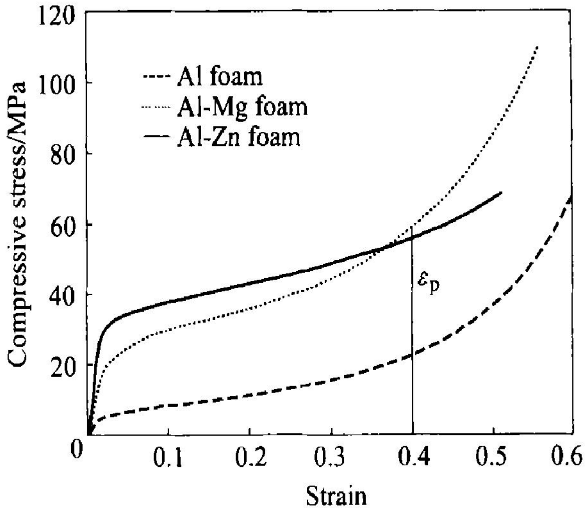

Fig. 4 Compressive stress-strain curves of three foams

regions, i. e., the linear elasticity region, the plastic collapse region or brittle crushing region and the densification region, the differences between the shape of the curves are significant. The foamed pure aluminum has the lowest plastic collapse strength and flow stress in the plateau region among the foams investigated. The compressive stress-strain curve of the foamed pure aluminum presents the typical deformation of plastic foams as reported in Ref. [11], which turns softly, not abruptly from the linear elasticity region to the plateau region and rises slowly with increasing strain, and after a large plastic deformation it begins to rise steeply. As shown in Fig. 4, for the solid-solution strengthening effect of solute Mg atoms in the matrix, the plastic collapse strength and flow stress of the foamed Al-10% Mg alloy are much higher than those of the foamed pure aluminum. The compressive stress-strain curve of the foamed Al-10% Mg alloy rises more rapidly in both the linear elasticity and plateau regions as compared with that of the foamed pure aluminum. However, a significantly different behavior from those of the foamed pure aluminum and Al-10% Mg alloy is observed in the compression of the foamed Al-28% Zn alloy. The foamed Al-28% Zn alloy presented a typical stress-strain response of brittle metallic foam during compression. The compressive stress-strain curve of this foam rises most steeply in the shortest linear elasticity region (about less than 0.03) among the three curves, however nearly keeps horizontal in the plateau region which is approximately as long as that in the curve of the foamed pure aluminum. Additionally, the plateau region on the curve of the foamed Al-28% Zn alloy is above that both of the foamed aluminum and Al-10% Mg. It is indicated that the foamed Al-28% Zn alloy has the highest elastic modulus and plastic collapse strength among the foams investigated. The reason for the high elastic modulus and strength of this foam are the solid solution-strengthening effect of solute Zn atoms and the existence of large amount of brittle rich Zn phase in the matrix of the foam. However, unlike the compressive stress-strain curves of closed cell brittle foams with lower density[6, 12], no serrated flow is observed in the plateau region of the compressive stress-strain curve of the foamed Al-28% Zn alloy investigated in this study. These may result from that the density of the open-cell foams prepared by infiltrating process in the present study is comparatively higher, and the deforming mechanism of open-cell foam is much different from that of closed-cell foams.

3.3 Energy absorption capacity

When a metallic foam is compressed, the work is done by the force to it, or in other words, the compressive energy is absorbed. The energy absorbed per unit volume in the deformation of the foam is simply equal to the area under the stress-strain curve corresponding to the given strain ε. The capacity of energy absorption of a metallic foam should be evaluated by the energy absorbed (C) at the strain ε_D where its densification begins, and the formula is expressed as

$$C = \int_0^{\varepsilon_D} \sigma(\varepsilon)\,d\varepsilon \qquad (1)$$

where ε_D is the maximum strain before densification, σ is the compressive stress as the function of strain ε. Generally, ε_D is read at the point in stress-strain curve where the stress begins to rise steeply, and determined by the equation[4]

$$\varepsilon_D = 1 - 1.4\left(\frac{\rho^*}{\rho_s}\right) \qquad (2)$$

where ρ^*/ρ_s is the relative density of the foam. According to Eqn. (2), ε_D of the three foams investigated is approximately 40% for their same relative density. It is known from Eqn. (1) that the higher the stress σ, the more the energy absorbed in the compression of the foams. Fig. 5 shows the plots of the energy absorbed vs strain for the three foams investigated. The foamed Al-28% Zn alloy has the highest collapse strength, as a result, it absorbs the most energy among the three foams to any given strain before densification. While at the densification strain ε_D (40%), according to Eqn. (1), the energy absorbed by the foamed Al-28% Zn alloy, Al-10% Mg alloy and Al foam is 16.1, 14 and 4.7 MJ/m^3 respectively. So

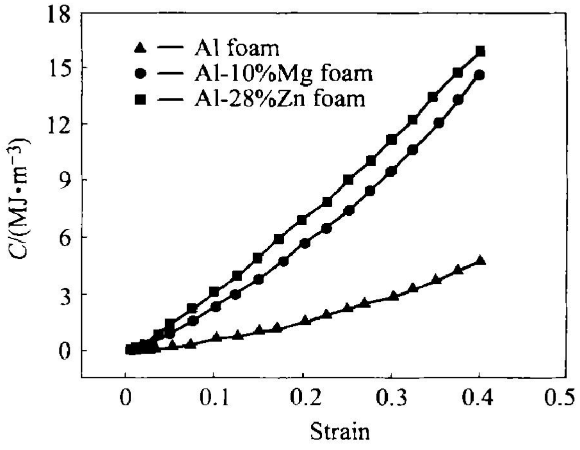

Fig. 5 Variation of energy absorption as a function of strain for three foams

the foamed Al-28% Zn alloy has the biggest capacity to absorb compressive energy among the three foams investigated.

For a given energy absorbed to the densification strain ε_D, the peak stress corresponding to the strain ε_D is another important criteria to evaluate the energy absorption ability of a material[4]. As shown in Fig. 4, the peak stress on the curve of the foamed Al-28% Zn alloy is smaller than that of the foamed Al-10% Mg alloy up to the same densification strain. Furthermore, it is expected from the curves in Fig. 4 that after onset of densification, for the same energy-absorption, the foamed Al-28% Zn alloy will generate the lowest peak stress among the foams investigated.

3.4 Energy absorption efficiency

Another parameter to characterize energy absorption in foam is the energy absorption efficiency (E)[11], which is represented as

$$E = \frac{\int_0^{\varepsilon_D} \sigma(\varepsilon)\,d\varepsilon}{\sigma_D \cdot \varepsilon} \qquad (3)$$

where σ_D is a given peak stress, ε is the strain corresponding to σ_D, and $\sigma_D \cdot \varepsilon$ represents the idealized energy absorbed by foam at the given peak stress σ_D and strain ε. Clearly, the best foam is the one that absorbs the most energy for a given peak stress and strain. The energy absorption efficiency (E) of a foam is determined by the shape of its stress-strain curve. Fig. 6 shows a plot of the energy absorption efficiency vs strain for each foam in this study. The foamed Al-28% Zn alloy exhibits a much higher E than those of the foamed Al-10% Mg alloy and commercial pure aluminum over almost the all strain range. Especially, the energy absorption efficiency of the foamed Al-28% Zn alloy keeps above 80% over a wide range of strain, while that of the foamed Al - 10% Mg alloy and aluminum only exhibit the peak

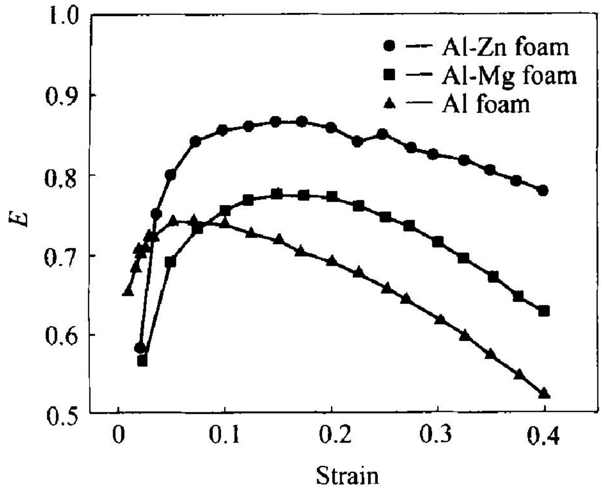

Fig. 6 Plots of energy absorption efficiency vs strain for three foams

value up to a certain strain and then descend gradually.

5 CONCLUSIONS

1) The damping capacity of the foamed Al-28% Zn alloy, Al-10% Mg alloy and commercial pure aluminum with the same relative density have been investigated by MFIFA at low frequencies from 0. 1 Hz to 3 Hz over the temperature range from room temperature to 300 ℃. It is found that the variation of the frequency notably affects the damping capacity of the foamed Al-28% Zn alloy. The foamed Al-28% Zn alloy exhibits the damping capacity three to four times higher than those of the foamed Al-10% Mg alloy and commercial pure aluminum foam around room temperature.

2) The static compressive behavior and the energy absorption characteristics of the foamed Al-28% Zn alloy, Al-10% Mg alloy and commercial pure aluminum were studied as well. Resulting from the solid-solution strengthening effect of solute Zn atoms combined with the existence of the brittle and hard rich Zn phase, the foamed Al-28% Zn alloy exhibit the typical deformation behavior of brittle metallic foam in compression, and a higher plateau collapse strength than those of the foamed Al-10% Mg alloy and commercial pure aluminum.

3) The foamed Al-28% Zn alloy exhibits the highest energy absorption capacity at the same densification strain, and the lowest peak stress for the same given energy absorbed after densification among the three foams investigated. Especially, the energy absorption efficiency of the foamed Al-28% Zn alloy is much higher than those of the other two foams, and kept above 80% over a wide range of strain under compression.

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