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Effects of heat treatment on dynamic compressive properties and energy absorption characteristics of open-cell aluminum alloy foams

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Abstract: The effects of heat treatment on the dynamic compressive properties and energy absorption characteristics of open cell aluminum alloy foams (Al-Mg-Si alloy foam and Al-Cu-Mg alloy foam) produced by infiltrating process were studied. Two kinds of heat treatment were exploited: age-hardening and solution heat treating plus age-hardening (T6). The split Hopkinson pressure bar (SHPB) was used for high strain rate compression test. The results show that both age-hardened and T6-strengthened foams exhibit improved compression strength and shortened plateau region compared with that of foams in as-fabricated state under high strain rate compression, and the energy absorption capacity is also influenced significantly by heat treatment. It is worthy to note that omitting the solution treating can also improve the strength and energy absorbed much.

Key words: aluminum foam; heat treatment; dynamic property; energy absorption characteristics

1 Introduction

In the past few years, there has been a considerable increase in using metal foams for lightmass structural components and energy absorption parts for their wide plateau in the compressive stress-strain curve[1−3]. It has been shown that, e.g. the compression strength is connected to the density of a foam, thus allowing to adjust this property within a certain range. However, because density cannot always be varied freely and in order to gain more control over the properties of metallic foams, adjustment of other variables seems desirable, namely of alloy composition, foam morphology (size and shape of cells) and the metallurgical state of the matrix metal[4−10]. There have been some results on the heat treatment of metal foams published in the past, almost all of them focused on the properties of foams under quasi-static loading or cyclic loading[11−14]. However, there have been no prior efforts to examine the effects of heat treatment on the dynamic behavior of open cell aluminum foams. The purpose of this study is to evaluate the influence of heat treatment on the dynamic compressive properties and energy absorption characteristics of two kinds of open-cell aluminum alloy foams. This will be beneficial to the multi-functional applications of aluminum alloy foams in industry.

2 Experimental

2.1 Sample preparation

Cellular solids can be produced by various methods. Two kinds of open-cell aluminum foams produced by infiltrating process were used in this study. The compositions (analyzed using ICP-AES) of these foams are listed in Table 1. Fig.1 shows the microstructures of these foams observed using LEO438VP SEM. All test samples were electro-discharge machined from blocks of aluminum alloy foams. Heat treatments of samples were carried out in two different ways. One was followed a conventional precipitation hardening cycle which consisted of three steps, namely solution heat treatment, quenching and ageing. The other consisted of only one step of ageing. In our study the foams were solution heat treated at 515 ℃ for 30 min and quenched in water at room temperature. Warm ageing was chosen and done at 160 ℃ for 16 h.

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Table 1 Chemical analysis of foamed aluminum alloys (mass fraction, %)

Alloy	Mg	Si	Cu	Fe	Mn	Ca
Al-Mg-Si alloy	0.48	1.77	0.17	0.34	0.23	0.35
Al-Cu-Mg alloy	0.12	0.67	0.45	0.29	0.05	0.02

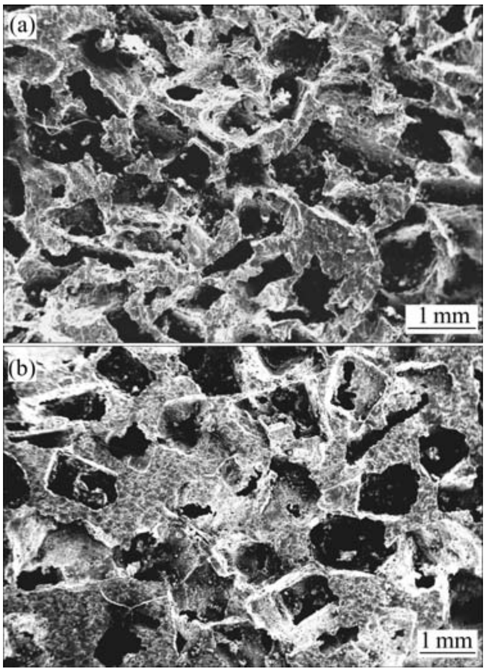

Fig.1 Microstructures of aluminum alloy foams used in this study in as-fabricated condition: (a) Al-Mg-Si alloy foam; (b) Al-Cu-Mg alloy foam

2.2 Compression test

The split Hopkinson pressure bar(SHPB) was used for dynamic compression test of aluminum alloy foams for strain rates above several hundred per second. The samples were 35 mm in diameter and 6 mm in height for dynamic compressive tests. Using thin specimen was to obtain high strain rate. The apparatus was mainly composed of a gas gun, a striker bar, an incident pressure bar, a transmitter bar, a momentum trap and the data acquisition system (Fig.2). The diameters of the striker, incident and transmitter bars were 37 mm, and their lengths were 800 mm, 2000 mm and 2000 mm, respectively. The striker bar, accelerated by the gas gun, hit the incident bar and generated a compressive pulse. As the wave reached the end of the incident bar, a portion of the incident pulse was reflected back and a portion was transmitted through the specimen to the transmitter bar. The reflected wave traveled back as a tensile wave. The incident stress wave generated in the incident bar was recorded by the resistance strain gauge attached at the incident bar. A semiconductor strain gauge attached at the transmitter bar recorded the portion of wave that has transmitted the specimen, and at the same time, a strain gauge attached at the incident bar recorded the reflect wave. All the bars were made of aluminum alloy.

3 Results and discussion

The compressive stress-strain curves of aluminum foams under high strain rate exhibits universal three deformation regions: an initial linear-elastic response; an extended plateau region with a nearly constant flow stress, sometimes an upper and lower yield point can be observed; and a final densification as collapsed cells are compacted together. These deformation characteristics are similar to those of other aluminum alloy foams in as-fabricated condition.

3.1 Effects of heat treatments on strength and densification strain

Definition of compression strength is somewhat ambiguous for metal foams. As one observes a different stress-strain behavior depending on the type of alloy used, varying definitions for strength can be adequate[15]. For determining strength values from the stress-strain curves measured in this work, the following approach was chosen: strength is taken as the stress at 10% total deformation.

From the stress-strain curves that obtained in experiments, it is difficult to identify the densification strain that clearly delimitates the constant stress plateau regime and the densification regime. In this paper, the densification strain is defined as the intersection of the tangents to the stress plateau regime and densification regime, as suggested by PAUL and RAMAMURTY [16].

Fig.3 shows the compressive stress-strain curves for Al-Mg-Si alloy foam and Al-Cu-Mg alloy foam under high strain rates in three different conditions, i.e. as-fabricated, solution heat-treated plus warm aged and only warm aged. In our study, heat treatment processes significantly affect the stress-strain curves under high strain rate compression. Compared with the curves obtained in as-fabricated condition, the curves obtained in heat-treated conditions become smooth without obvious stress peak. It can be seen from Figs.3(a) and (b) that for both aluminum alloy foams two kinds of heat treatment increase the plateau strength and decrease the length of plateau region compared with those in as fabricated condition, and specimens after solution heat treatment plus warm ageing assume the highest strength value and the lowest plateau length. The compression strengths and densification strains for both foams under high strain rate compression are listed in Table 2. It is obvious that the effects of heat treatment on the com-

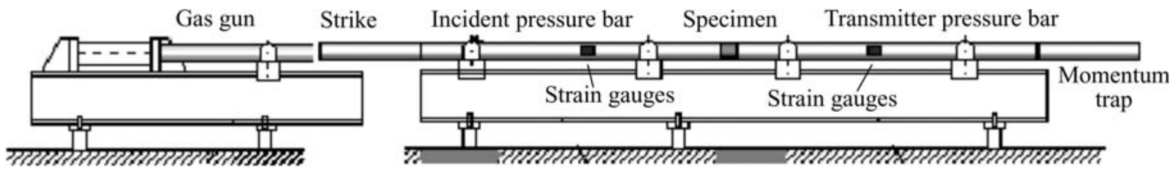

Fig.2 Schematic of split Hopkinson pressure bar

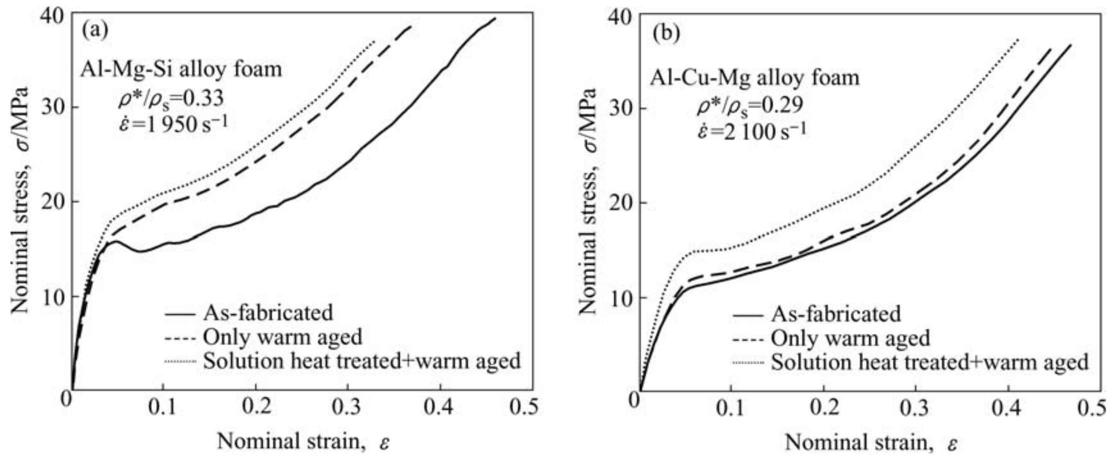

Fig.3 Compressive stress-strain responses of heat-treated aluminum foams under high strain rate

Table 2 Compressive strength and densification strain of foams under high strain rate compression in three different conditions

Material	ρ^*/ρ_s	$\dot{\varepsilon}$ /s^{-1}	Heat-treament	σ_{pl}/MPa	ε_d	$\Delta\sigma_{pl}/\sigma_{pl}$	$\Delta\varepsilon_d/\varepsilon_d$
Al-Mg-Si alloy	0.33	1 950	F	15.58	0.27		
			A	19.73	0.25	26.64%	7.41%
			T6	20.88	0.23	34.02%	14.81%
Al-Cu-Mg alloy	0.29	2 100	F	12.09	0.32		
			A	12.62	0.31	4.30%	3.13%
			T6	15.33	0.28	26.69%	12.50%

F—As-fabricated; A—Only warm aged; T6—Solution treated plus warm aged

pressive strength and densification strain of Al-Mg-Si alloy foam are more significant than those on the Al-Cu-Mg alloy foam.

From the chemical analysis we can see that there are much more Si and Mg in Al-Mg-Si alloy foam (1.77%Si and 0.48 %Mg) than those in Al-Cu-Mg alloy foam (0.67 % Si and 0.12 % Mg). The age-hardening effect in Al-Mg-Si alloys is primarily based on the occurrence of the Mg_2Si phase in which the mass ratio of Mg to Si is 1.73 ∶ 1. The 0.48 % Mg found in the material therefore corresponds to 0.28 % Si in the Mg_2Si phase and 1.49% excess Si. The age-hardening effect in Al-Cu-Mg alloys is primarily based on the occurrence of the Mg_2Si and Al_2CuMg phase in which the mass ratio of Cu to Mg is 2.61 ∶ 1. The 0.12 % Mg found in the material therefore corresponds to 0.07 % Si in the Mg_2Si phase and 0.6% excess Si. But in Al-Mg-Si alloy foam investigated in this study there is more Mn than in Al-Cu-Mg alloy foam, and the existence of Mn is beneficial to refining the microstructure and can improve the strength of aluminum alloy by means of precipitation hardening.

It is worthy to note that omitting the solution heat treatment during precipitation hardening, i.e. only warm aged, the compressive strength of Al-Mg-Si alloy foam studied here is improved by 26.64 % under high strain rate compression compared with that obtained in as-fabricated conditions. This happens because a supersaturated solution of precipitate-forming elements might already be achieved during cooling after foaming. Omitting the solution heat treatment during precipitation hardening not only can be of economical benefits but also can avoid the danger of damaging the foamed structure during quenching in water.

3.2 Effects of heat treatment on energy absorption characteristics

When a metallic foam is compressed, the work is done by the force to it, or in other words, the compressive energy is absorbed. From the stress-strain curves the energy absorption capacity W and the energy absorption efficiency I can be calculated using the definition:

$$W=\int_0^{\varepsilon_m}\sigma(\varepsilon)\mathrm{d}\varepsilon \qquad (1)$$

$$I=\frac{1}{\sigma_m\varepsilon_m}\int_0^{\varepsilon_m}\sigma\mathrm{d}\varepsilon \qquad (2)$$

where ε_m is the given strain, σ_m is the corresponding compressive stress, σ is the compressive stress as a function of strain ε.

Fig.4 shows the energy absorption efficiency of foams varying with the strain in three conditions under high strain rate compression. From the I—ε curves obtained in this study, we can see that the energy absorption efficiency first increases then falls as the strain increases, that is to say, there exists a peak value of I and the corresponding stress is about the plastic plateau stress. The peak width of I—ε corresponds to the plateau regime in compression stress-strain curves.

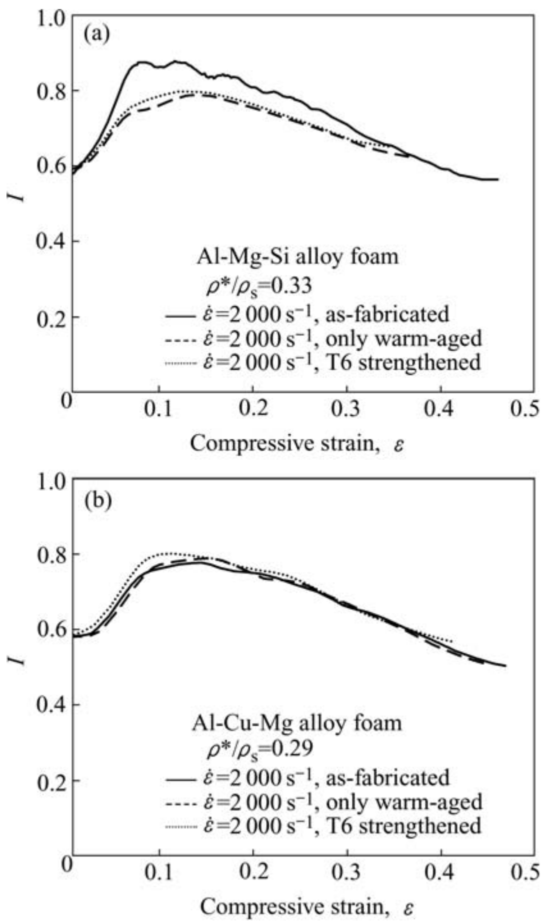

Fig.4 Effects of heat-treatment on energy absorption efficiency

To compare the effects of A and T6 heat treatments on the energy absorption characteristics of foams, we calculated the energy absorbed by two foams when the strain is up to 0.3 under high strain rate compression (see Table 3). Table 3 show that after heat treatment, the peak values of energy absorption efficiency of Al-Mg-Si alloy foams decrease, but those of Al-Cu-Mg alloy foams do not change much, and the effects of heat-treatment on energy absorption capacity of foams are similar to those on foam strength. The peak values of energy absorption efficiencies of foams are close to or larger than 80 %.

Table 3 Effects of heat treatment on energy absorption capacity and energy absorption efficiency of foams under high strain rate compression

Material	ρ^*/ρ_s	$\dot{\varepsilon}$/s^{-1}	Heat-treament
Al-Mg-Si alloy	0.33	1 950	F
			A
			T6
Al-Cu-Mg alloy	0.29	2 100	F
			A
			T6

Material	W/(MJ • m^{-3})	I_{max}/%	$\Delta W/W_F$
Al-Mg-Si alloy	5.14	87.78	
	6.45	78.72	25.49%
	6.93	79.87	34.82%
Al-Cu-Mg alloy	4.01	77.75	
	4.22	78.92	5.24%
	5.20	80.07	29.68%

F—As fabricated; A—Only warm aged; T6—Solution treated plus warm aged

So we can conclude that open cell aluminum alloy foam is also a good material for energy absorber, and heat treatment is a very effective way to improve the energy absorption capacity of metal foams in constructing an energy absorber.

4 Conclusions

High strain rate (about $2.1\times10^3 s^{-1}$) compressive properties and energy absorption characteristics of open cell Al-Mg-Si and Al-Cu-Mg aluminum alloy foams produced by infiltrating process in as-fabricated (F), age-hardened (A) and solution heat treated plus age-hardened (T6) conditions have been studied using split Hopkinson pressure bar (SHPB).

1) After A and T6 heat treatments, the stress-strain curves under high strain rate compression become smooth compared with those in as-fabricated condition.

2) Both A and T6 heat treatment can increase the foam strength, the strengthening effect of Al-Mg-Si alloy foam under high strain rate compression is more significant than that of Al-Cu-Mg alloy foam.

3) After heat-treatment, the peak values of energy absorption efficiency of Al-Mg-Si alloy foams investigated in this study decrease, but those of Al-Cu-Mg alloy foams do not change much. And the effects of heat-treatment on energy absorption capacity of foams

are similar to those on foam strength. This is especially important when aluminum foams are used as energy absorbers.

4) It is encouraging that ageing directly after foaming without solution heat treatment also yields a considerable strengthening effect. Omitting the solution heat treatment during precipitation hardening not only can be of economical benefits but also can avoid the danger of damaging the foamed structure during quenching in water.

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