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Compression behavior and constitutive model establishment of fly ash cenosphere/polyurethane aluminum alloy syntactic foam

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Abstract: The aluminum matrix syntactic foam was fabricated by pressure infiltration technique, and the filling material is syntactic foam material with fly ash cenosphere as the main component and polyurethane foam as the binder. Split Hopkinson pressure bar (SHPB) dynamic compression and quasi-static tests were carried out to examine the compressive response of syntactic foam in this study. Then the dynamic constitutive model was established. Results show that the compressive stress-strain curve of syntactic aluminum foam is similar to that of other metallic foam materials: both kinds of aluminum matrix syntactic foams have strain rate effect, and the syntactic foam has higher compressive strength and energy absorption than the same density aluminum foams. However, due to the different sizes of cenospheres, the dynamic compression results of two kinds of syntactic foams are different, and the energy absorption effect of syntactic foam with small size under dynamic impact is the best. In the range of strain rate and density studied experimentally, the curves of constitutive model fit well with the curves of experimental data.

Key words: fly ash cenosphere; polyurethane; composite foam aluminum; strain rate effect; mechanical property; constitutive model

0 Introduction

Since aluminum foam has low density, high porosity and large specific surface area due to its unique porous structure, it offers potential for energy absorption, sound absorption, denoise, etc. Hence, the aluminum foam has been widely used in aerospace, national defense, automotive protection and other fields. At present, there has been a lot of research on aluminum foam materials, mainly including the influence of relative density, pore size and other factors on the mechanical properties of aluminum foam[1-3]. With the development of material research, a novel composite material was fabricated by mixing polymer into aluminum, which was called interpenetrating phases composite (IPC), and the viscoelasticity of polymer is used to improve the mechanical properties of foam materials[4-5]. Li et al.[6] investigated the compressive behaviour of aluminium composite, and the results show that the quasi-static stress-strain (σ-ε) curves of the aluminum composite are similar to those of aluminum foams. Lin et al.[7] pointed out that the length and height of plateau region of aluminum foam with silicone rubber is increased and the energy absorption ability is improved. This finding has indicated that foam composites have a stable absorption capacity in a much larger strain range than their foam counterparts. Subsequently, studies have shown that aluminum foam filled with polymeric reduces the compressibility of foam composites, and the compression plateau region is not obvious, hence, it will reach its densification stage much more quickly under a high applied stress level effect of energy absorption. To enhance the compressibility of composite foam, Jhaver et al. pointed out that a new type of material can be made by adding hollow particles into the polymer and then filling it into foam metal, which is called multi-interleaving phase composite material[8-11]. The mechanical testing & simulation (MTS) compression experiment has found that the plateau stress is 42% higher than that of the resin foam of the same composition, and the energy absorption is 50% higher. Periasamy et al.[12-13]

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studied the effect of microsphere volume fraction on aluminum foam composite, and the energy absorbed by microspheres decreases with the increase of microsphere ratio. Zou et al. [14] examined high strain rate energy absorption on syntactic foam. Goel et al. [15] studied the strain rate effect of aluminum matrix syntactic foam. All these studies show that the addition of cenosphere into the filling materials can effectively improve the compressibility and impact response of the material so as to improve the energy absorption efficiency. It has become an important means to improve the energy absorption efficiency of foam materials to use the foam filled with polymeric containing hollow particles.

The major attraction of multi-interpenetrating phases composite(MIPC) is that each constituent can contribute its most desirable attributes by its contiguous morphology. Therefore, it endows MIPC with improved combinations of mechanical and other properties. However, the structure of this new syntactic foam is more complex, in order to use syntactic foams in the advanced applications such as high speed collision and impact, blast resistance, aeronautical, and space structures, it is crucial to understand their behavior under high rate of loading.

In the research of constitutive model, aluminum foam material has been relatively mature. Most researchers have modified and improved the empirical constitutive model proposed by Sherwood and Frost[16]. Hu et al. [17-18] modified the temperature term and obtained the empirical constitutive equation of aluminum foam; Jeong et al. [19] established the constitutive model of polyurethane foam; Liu et al. [20] modified the density term and established the constitutive model of polyurethane foam. For aluminum foam composite, Zhang et al. [21] established the constitutive model of density and strain rate of polyurethane filled aluminum foam. Based on the empirical constitutive model, the constitutive model of density and strain rate sensitive terms is established.

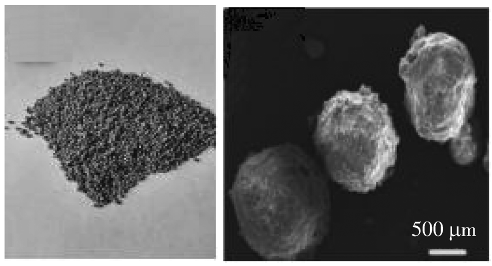
At present, the hollow particle materials used to improve buffer protection are mainly glass microspheres, while it costs more. Fly ash is the main component of industrial by-product coal ash after pulverized coal combustion in power plants, which is considered as a pollutant. However, due to its good mechanical properties such as low density, high specific stiffness and high specific strength, it has been gradually developed and applied in construction and other fields. Therefore, fly ash particles are selected as the main filler in this study. the filling material is a syntactic foam material with fly ash cenosphere as the main component and polyurethane foam as the binder.

Based on this, we mainly study the mechanical properties of aluminum foam under axial compression, analyze its energy absorption characteristics as well as the strain rate effect of aluminum foam under different strain rates by SHPB experiment, The constitutive model of aluminum foam is fitted with experimental results.

1 Material and sample preparation

The matrix material used in the experiment is aluminum foam with 6 mm pore diameter spherical holes, and the wire cutting technology is used to cut the aluminum foam sheet, as shown in Fig. 1.

Fig. 1 Aluminum foamed sample



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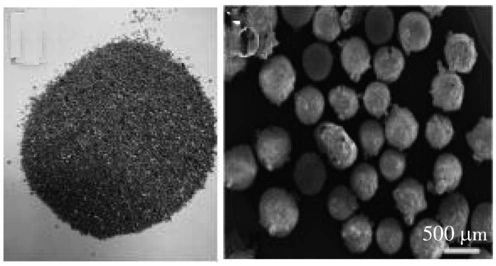


(b)

Fig. 2 Fly ashcenospheres with large cenospheres (a) and little cenospheres (b)

The selected aluminum foam cells are evenly distributed. A series of studies have been conducted on the mechanical properties and behaviors of aluminum foam in the early stage. It is found that the mechanical properties of aluminum foam are good and the energy absorption effect is significant when axial compression is performed. The matrix aluminum foam size is Ø25 mm × 20 mm and the density is 0.95 g/cm^3. Fly ash (Fig. 2) cenosphere as the main filler, according to the diameter of fly ash, they are divided into large (LG) particles (800 μm – 1 000 μm) and little particles (LT) (400 μm – 600 μm). Polyurethane was prepared by mixing white and black materials in the same proportion, The device principle is shown in Fig. 3, the process is as follows, and the prepared sample is shown in Fig. 4(a).

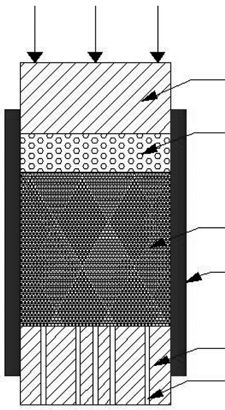


Fig. 3 Schematic diagram of sample preparation

a) Put aluminum foam samples in the homemade mold, then insert a plug with exhaust hole at below end of mold.

b) Fill fly ash into sample from the other end of mold and vibrate mold until fly ash just covers the upper end of the sample.

c) Select appropriate black and white material under sample volume, fill in mold after using blender mixing evenly rapidly, pressure piston into end of mold.

d) Fix the mold with fixture, and make it foaming, then foam will be a good sample for grinding, porosity in 40%–50% of the sample.

Quasi-static compression tests were performed at ambient temperature using Universal Testing Machine at a strain rate of 0.001/s. For each set three samples were tested, the density range 1.0 g/cm^3–1.33 g/cm^3. The load-displacement data were recorded during the testing and converted to stress-strain curves using standard methodology. For each set three samples were tested, the final data were gotten by the average.

2 Test results of quasi-static compression experiment

The stress-strain curves of composite aluminum foam at different densities were obtained through static compression test. The compressed composite aluminum foam is shown in Fig. 4.

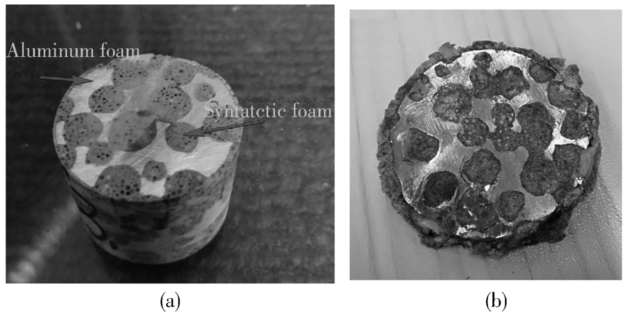
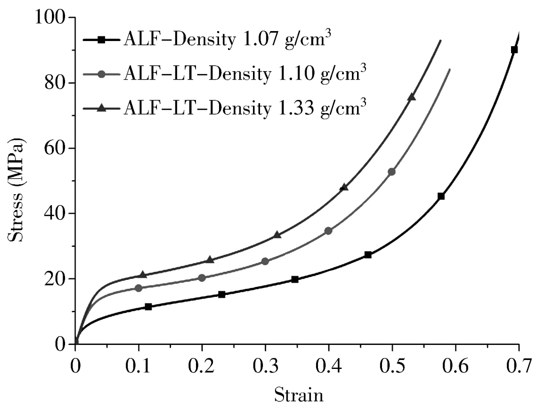
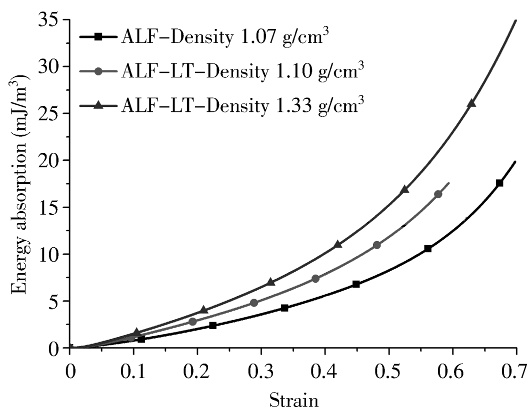


Fig. 4 Comparison before and after compression of composite aluminum foam

In Fig. 5(a), the stress-strain curves of little cenosphere composite aluminum foam (ALF-LT) at different densities are compared, and a matrix aluminum foam (ALF) curve with similar density is added. It can be found that the compressive stress-strain curve of syntactic aluminum foam is the similar as that of other metallic foam materials, which includes three typical processes: elastic stage, stress plateau stage and densification stage. This is due to the material before filling is porous, and the material after filling is still porous as the existence of cenosphere, therefore the form of stress-strain curve after compression remains unchanged. In order to quantitatively analyze the energy absorption effect of foam materials, we use the energy absorption per unit volume formula proposed by Miltz[22] to calculate the energy absorbed by aluminum foam under axial compression in different strains. The densification strain is defined according to the strain at the tangent intersection of the curve of the platform segment and the curve of the compaction segment[23]. The densification strain of little cenosphere composite aluminum foam increases from 0.478 to 0.449, and the energy increases from 7.329 mJ/m^3 to 13.393 mJ/m^3 when the densification strain is reached. To take the corresponding stress at the strain of 0.05 as approximate yield strength [24], the yield strength increases by 76% after filling under the same density, and the flow stress increases by 50% under 20% strain. Comparing the energy absorption diagram (Fig. 5(b)), it can be found that there exists a significant increase. For aluminum foam material, different forms of destruction in hole wall appear in the plastic platform stage, leading to collapse and closure of cell pores and absorbing a large amount of energy. The filled composite foamed aluminum still has a large number of pores, which retains the advantages of the porous material. In platform stage, the different forms of damage to the foamed aluminum cell pore wall appear, which causes the hollow microspheres in the filler to break and close, and absorb part of the energy simultaneously, thus the foam aluminum cell collapses finally. The filled composite foam material greatly improves the compressive strength and energy absorption of the aluminum foam, strengthens the mechanical properties of the foamed aluminum, and improves the utilization value of the foamed aluminum as a buffer energy absorbing material as a whole, therefore, it has great application prospects.



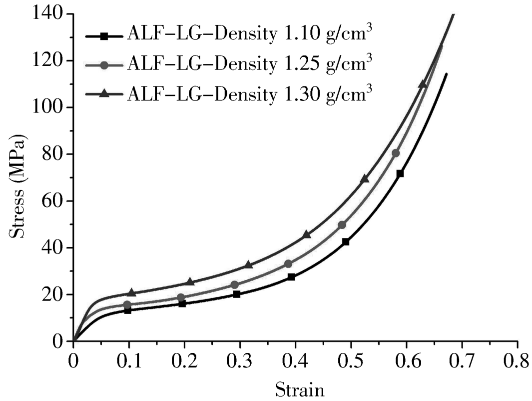
(a)



(b)

Fig. 5 Stress-strain curve(a) and energy absorption curve (b) of aluminum foams filled with little fly ash and unfilled aluminum foams

In order to analyze the effect of density on the mechanical properties of composite foamed aluminum, multiple sets of quasi-static compression experiments were carried out on composite foamed aluminum of a certain density range with the same particle size, and the average value of each group was taken to reduce the experimental error. Through the quasi-static compression results of small particle composite aluminum foam (ALF-LT) and large particle composite aluminum foam (ALF-LG) as shown in Figs. 6 and 7, it can be seen that the yield strength increases by 60% with the increase of density. At densification strain, the absorbed energy is increased by 50%, which shows favorable mechanical properties. In composite aluminum foam, not only the matrix aluminum foam cell hole collapse to absorb energy, but also filled material hollow core ball will crack, which greatly improves the energy absorption effect of compound aluminum foam. The greater the density of compound aluminum foam, the more filling quantity of fly ash polyurethane, so the strength and energy absorption effect are better.



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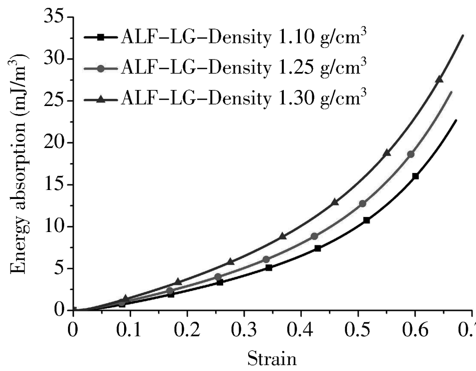
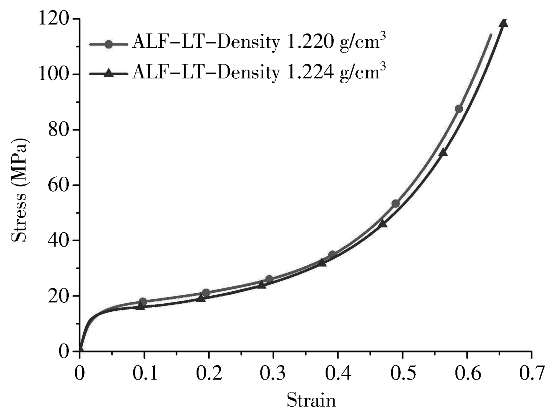


(b)

Fig. 6 Stress-strain curve(a) and energy absorption curve (b) of aluminum foams filled with large fly ash and unfilled aluminum foams



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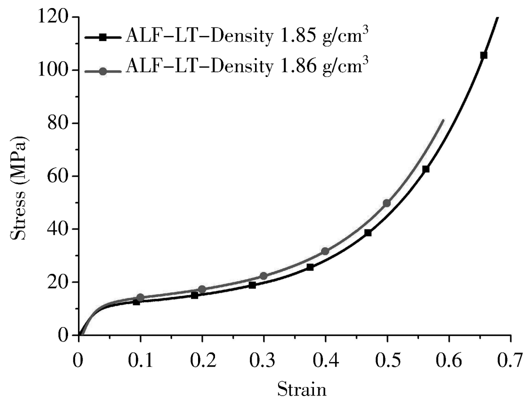


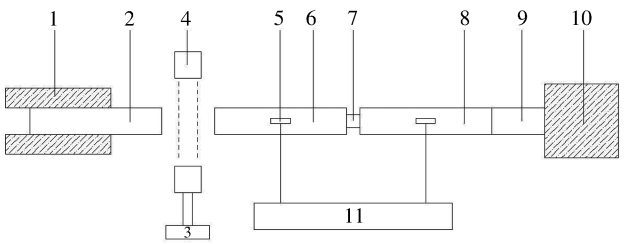
(b)

Fig. 7 Stress-strain curves of different microspheres with the same density

In order to study the effect of the size of the floating bead on the energy absorption of the composite foam aluminum in the given particle size range, the static pressure results of multiple groups of similarly sized particles are compared. Only some data are listed in this paper. The curves in Fig. 7 are almost coincident, and within this particle size range, the particle size has little effect on static compression.

3 Test results of dynamic compression experiment by SHPB

The high strain rate tests were conducted using the split Hopkinson pressure bar (SHPB), as shown in Fig. 8.



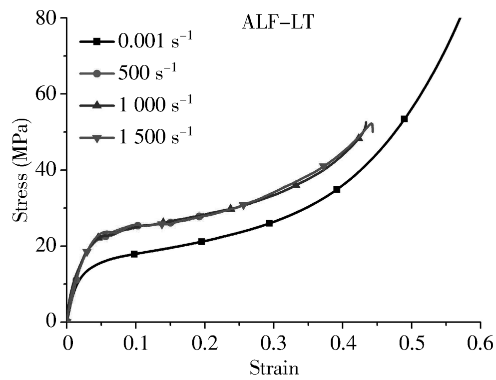
1—Air gun; 2—Striker; 3, 4—Light electric tachometer; 5—Strain gages; 6—Incident bar; 7—Sample; 8—Transmitter bar; 9—Absorbing bar; 10—Damper; 11—High dynamic strain indicator

Fig. 8 Schematic diagram of SHPB

A standard SHPB consists of a striker, an incident bar (input) and a transmitter bar (output), with the specimen sandwiched between the incident and transmitter bars. The diameter of the bar is 50 mm, the striker bar, incident bar and the transmitter bar are 1.0 m, 2.5 m and 2.5 m length, respectively. Considering that the transmitted wave signal of foam material is weak, the transmitted wave is measured by the semiconductor strain-gauges. The striker bar is suddenly released with high pressure air in order to generate the necessary compressive pulse, which propagates down the input bar towards the specimen. and acquires the stress-strain curve by high dynamic strain indicator.

In order to adjust the loading wave style, the rubber disk with thickness about 2 mm—4 mm and diameter 10 mm is selected as waveform shaper and pasted on center of incident bar's front end by vaseline. The adjusted wave style is on longer original rectangle wave, instead of trapezium wave with longer rising edge, in which loading wave can reach balance. The thickness of sample is 20 mm, and two ends keep even and smooth as far as possible. The selected composite aluminum foam density of large particles and little particles is 1.20±0.03 g/cm^3, the wave forms collected are processed by the two-wave method, and the stress-strain curves of composite aluminum foam under several strain rates are obtained. The plateau stress σ_{pl} of the material is calculated by equation[25]. For composite foam, the ε_0 is generally 5%, and the ε_d is the densification strain.

According to the stress-strain curve, when the strain rate is small, the sample has not became dense due to the low velocity of the impact bar, thus the stress-strain curve only obtains the elastic stage and part of the plateau section. When the strain rate increases, the impact velocity increases.



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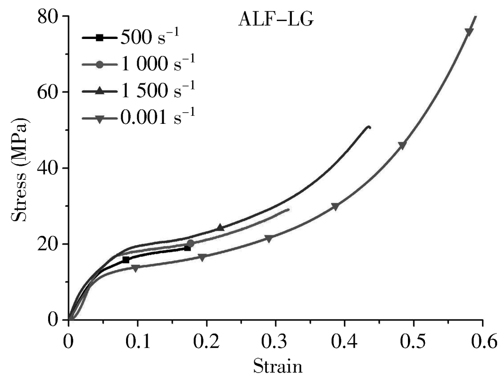

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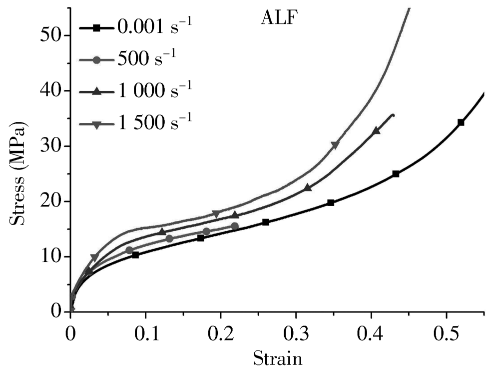


(c)

Fig. 9 Stress-strain curves of little cenosphere composite aluminum foam (a), large cenosphere composite aluminum foam (b) and aluminum foam(c) under different strain rates

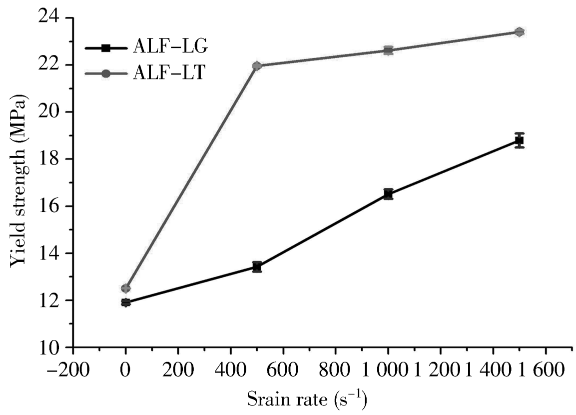
In Fig. 9 (a), the curve of little cenosphere composite aluminum foam under dynamic impact is significantly higher than the quasi-static compression curve, and the yield strength and platform stress are higher than the quasi-static one under the same density (Fig. 9), which shows obvious strain rate effect. The dynamic compression results of large cenosphere also have obvious strain rate effect (Fig. 9(b)). However, the results of little cenosphere composite aluminum foam under impact are different from those of large cenosphere. The strain rate sensitivity parameter Σ is computed by using the following Eq. (1), where σ is the compressive strength, σ^* is the quasi-static flow stress at 5% strain, $\dot{\varepsilon}$ is the strain rate, wherein, subscripts 'd' and 'q' define dynamic and quasi-static conditions, respectively. The results are reported in Table 1.

$$\sum=\frac{\sigma_d-\sigma_q}{\sigma^*}\left[\frac{1}{\ln(\varepsilon_d^*/\varepsilon_q^*)}\right]. \tag{1}$$

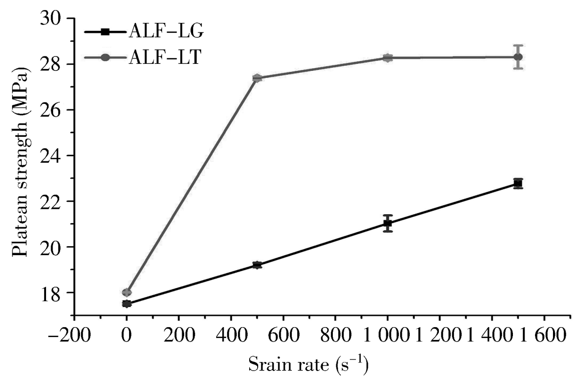
Table 1 Strain rate sensitivity parameter of composite aluminum foam

$\dot{\varepsilon}$ (s^{-1})	ALF/Σ	ALF-LT/Σ	ALF-LG/Σ
500	0.008 93	0.017 00	0.009 98
1 000	0.017 33	0.018 16	0.021 28
1 500	0.028 37	0.016 75	0.026 69

The strain rate sensitivity parameter of little-cenosphere composite aluminum foam is about 0.17, and there is obvious strain rate effect in the range of 0.001 s^{-1} − 500 s^{-1} strain rate, while there is no obvious strain rate effect in the range of 500 s^{-1} − 1 500 s^{-1}. The aluminum foam parameter of large-cenosphere increases with the increase of strain rate, which is close to that of the aluminum foam matrix. The large cenosphere composite aluminum foam has obvious strain rate effect in the range of strain rate studied. Yield strength and platform stress increase with the increase of relative density. At the same density and strain rate (500 s^{-1} − 1 500 s^{-1}), the yield strength of little-cenosphere composite aluminum foam is higher than that of large-cenosphere composite aluminum foam, as shown in Fig. 10. Compared with the compression results in quasi-static condition, at the compaction strain under the strain rate 1 500 s^{-1}, the energy absorption of small particles composite aluminum foam increases by 44%, while that of large particles only increases by 20%. From the results with the same density under the strain rate of 1 500 s^{-1} (see Fig. 11) comparing the matrix aluminum foam at densification strain, it can be seen that the little cenosphere of composite aluminum foam absorb energy increases by 70%, and the large cenosphere composite aluminum foam absorb energy increases by 45%. Therefore, for the little-cenosphere composite aluminum foam within the scope of the research of the strain rate, energy absorption effect is better.



(a)



(b)

Fig. 10 Yield strength (a) and plateau stress (b) of two kinds of composite aluminum foam under dynamic impact

The strain rate effect of composite aluminum foam is not only determined by the strain rate effect of aluminum base, but also related to the strain rate effect of the filled composite foam material. The aluminum foam substrate material used in experiment exist strain rate effect, the research by Geol[26] shows that this composite foam filled with fly ash in a certain range of strain rate has obvious strain rate effect. Two kinds of particle size composite aluminum foams show different strain rate effects under the high speed impact, which means that microsphere size influences impact result of composite aluminum foam under the dynamic impact. Two kinds of compound aluminum foam have the strain rate effect, and a stronger absorbing energy under high speed impact.

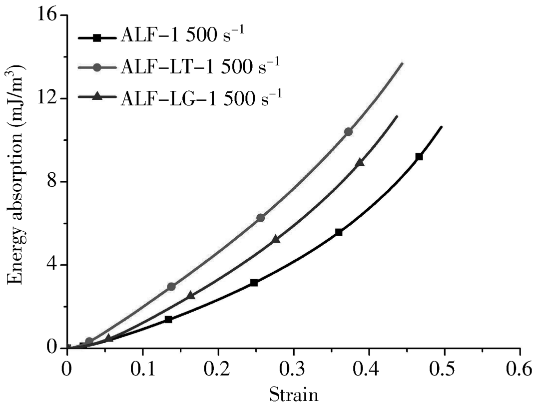


Fig. 11 Energy absorbed per unit volume of composite aluminum foam and aluminum foam

4 Dynamic constitutive model of composite aluminum foam

4.1 Selection of constitutive model

Johnson-cook constitutive model has been widely used to describe the mechanical properties of metal materials. For foam materials, Sherwood and Frost[16] concluded the empirical constitutive equation as

$$\sigma = H(T)G(\rho)M(\varepsilon,\dot{\varepsilon})f(\varepsilon), \tag{2}$$

where H, G and M are the functions of temperature T, initial density ρ and strain rate ε, respectively; $f(\varepsilon)$ is called the shape function, Sherwood and Frost express in the form of power series

$$f(\varepsilon) = \sum_{i=1}^{n} A_i \varepsilon^i. \tag{3}$$

Eq. (4) is the temperature term, where T is the ambient temperature of the experimental sample, T_r is the experimental room temperature, T_m is the melting point of the material, namely

$$H(T) = 1 - \frac{T - T_r}{T_m - T_r}. \tag{4}$$

In addition, $G(p)$ is the density term, wherein ρ_0 usually selects the minimum density in the experimental sample.

$$G(\rho) = D\left(\frac{\rho}{\rho_0} - 1\right) + 1. \tag{5}$$

In Ref. [21], the empirical constitutive model of polyurethane aluminum foam is obtained by using this empirical formula. In our work, the empirical constitutive model is used to determine the constitutive equation of composite aluminum foam. The shape function uses the sixth-order polynomial[21], and the strain rate enhancement term[17] is

$$M(\varepsilon,\dot{\varepsilon}) = 1 + C\ln\frac{\varepsilon}{\dot{\varepsilon}_0}, \tag{6}$$

where $\dot{\varepsilon}_0$ is the strain rate, and C is the strain rate sensitivity parameter, which can be obtained by fitting the experimental data. In general, $\dot{\varepsilon}_0$ is the quasi-static strain rate, $\dot{\varepsilon}_0 = 0.001\ \mathrm{s}^{-1}$.

The temperature and density in the above constitutive model are all single terms, here we do not consider the temperature term, that is, $H(T)=1$. Then the dynamic constitutive model is established as

$$\sigma = \left[D\left(\frac{\rho}{\rho_0} - 1\right) + 1\right]\left[1 + C\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right]\sum_{i=1}^{n} A_i \varepsilon^i. \tag{7}$$

4.2 Calculating parameters

Firstly, little cenosphere composite aluminum foam is fitted with $p_0 = 1.10\ \mathrm{g/cm^3}$, $\dot{\varepsilon}_0 = 0.001\ \mathrm{s}^{-1}$. The sixth-degree polynomial fitting for the shape function $f(\varepsilon)$ is performed, $R^2 = 0.9989$, and the parameters of the shape function are shown in Table 2.

Table 2 Shape function parameters of little cenosphere composite aluminum foam (MPa)

A1	A2	A3	A4	A5	A6
512.1.6	−5 244	26 200	65 700	81 810	39 030

When the strain rate is $0.001\ \mathrm{s}^{-1}$, the density term is fitted, here $M(\varepsilon,\dot{\varepsilon})=1$, and the fitted result is $D=4.947$. Different strain rate sensitivity coefficients C can be fitted according to different strain rates, C is calculated by Eq. (8), and the correlation coefficient R^2 is 0.984 7.

$$C = 3.704\times10^{-11}\dot{\varepsilon}^3 - 1.37\times10^{-7}\dot{\varepsilon}^2 + 0.000\,156\,7\dot{\varepsilon} - 0.028\,67. \tag{8}$$

For the large cenosphere composite aluminum foam, the values of each parameter are obtained by the same method as mentioned above, and the parameters of the shape function are shown in Table 3, with $R^2=0.9997$.

Table 3 Shape function parameters of large cenosphere composite aluminum foam(MPa)

A1	A2	A3	A4	A5	A6
328.6	−3.55	14 010	−32 000	36 400	−15 630

When ρ_0 is 1.10 g/cm^3, the value of D is 5.25, C is calculated by Eq. (9), and R^2 is 0.984 7.

$$C=-6.429\times10^{-8}\dot{\varepsilon}^2+0.000\,190\,4\dot{\varepsilon}-0.105\,3. \tag{9}$$

Finally, the parameters in Eqs. (8) and (9) of the two kinds of composite aluminum foam are substituted into the constitutive Eq. (7). After putting in the parameter, the stress-strain curves under different strain rates are fitted through the constitutive equation. The fitting results are shown in Figs. 12 and 13. It can be seen that the little cenosphere composite aluminum foam has a good coincidence degree, and the large cenosphere composite aluminum foam has a good elastic section fitting under the strain rate of 1 500 s^{-1}, but the plateau stress is slightly lower than the experimental results.

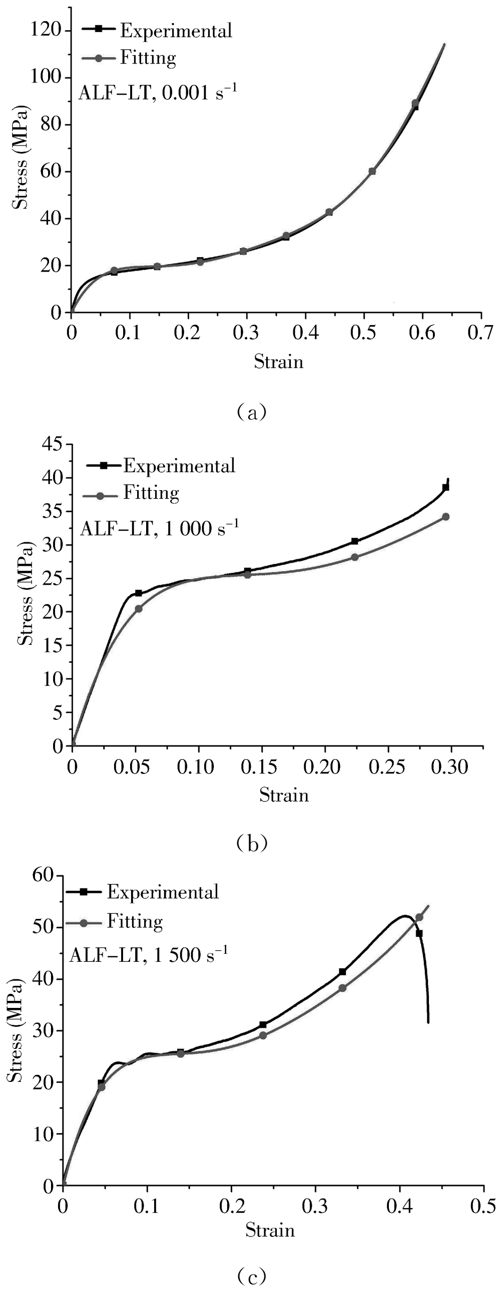


Fig. 12 Fitting curves of constitutive model of little cenosphere composite aluminum foam at different strain rates compared with experimental curves

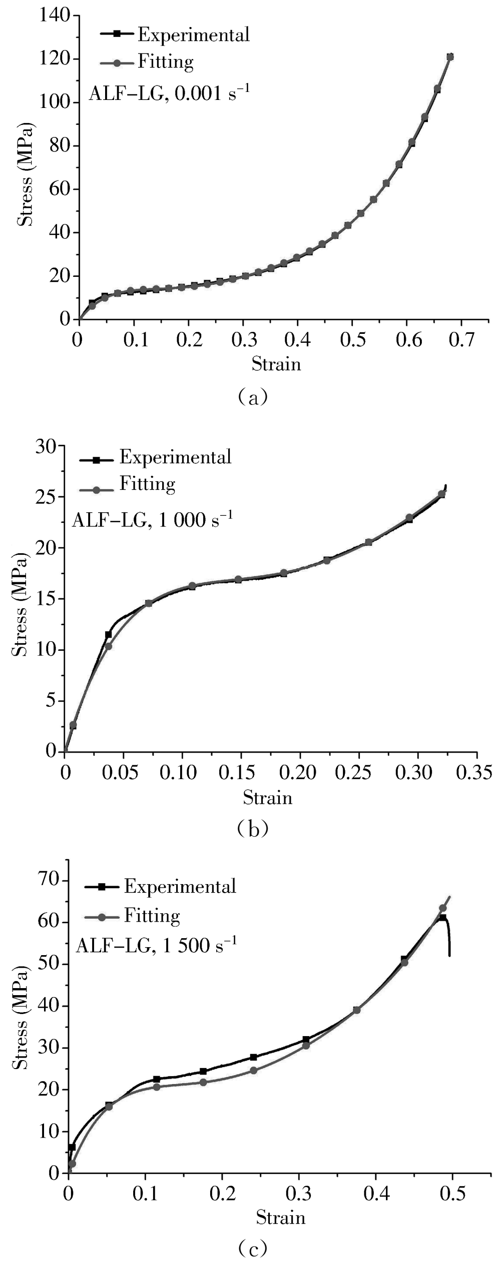


Fig. 13 Fitting curves of constitutive model of large cenosphere composite aluminum foam at different strain rates compared with experimental curves

5 Conclusions

Through the quasi-static and dynamic mechanical properties analyses of composite aluminum foam, the following conclusions are drawn:

1) A new type of composite aluminum foam with better mechanical properties and energy absorption was obtained by filling the spherical open-hole aluminum foam with a polymer material containing hollow microspheres. Under quasi-static compression, the effect of energy absorption is increased by 85% when the densification strain is reached, which is of great significance for the development of energy absorbing materials.

2) The mechanical properties of fly ash/ polyurethane composite aluminum foam are affected by the density. The density increases from 1.0 g/cm^3 to 1.30 g/cm^3, yielding strength increases by 60%, and energy absorption increases by 50% with the increase of density.

3) Syntactic foam can not only improve the mechanical properties of aluminum foam, but also affect its dynamic compression results, mainly related to the size of fly ash floating beads. Fly ash/ polyurethane composite aluminum foams have strain rate effects, and the dynamic yield strength under shock and plateau stress is higher than quasi-static one. Composite aluminum foam in small particles has strain rate and strain rate effect within a certain range, and for larger particles composite aluminum foam, with the increase of strain rate and strain of 0.2, absorbed energy increases by 50%.

4) The dynamic constitutive model of composite aluminum foam is obtained without considering the temperature term.

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粉煤灰漂珠/聚氨酯复合泡沫铝材料压缩性能与本构关系研究

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摘　要： 采用压力渗透法制备出了铝基复合泡沫材料，填充材料是以粉煤灰漂珠为主要组分、硬质聚氨酯泡沫为粘结剂的复合泡沫材料。通过准静态实验和分离式霍普金森压杆(Split Hopkinson pressure bar, SHPB)动态压缩的方法研究了复合泡沫铝的压缩力学响应，然后建立了动态本构关系。研究表明，复合泡沫铝的压缩应力-应变曲线与其它泡沫材料的应力-应变曲线类似，文中的两种铝基复合泡沫具有应变率效应，复合泡沫铝较密度相近未填充前的泡沫铝基具有更高的压缩强度与能量吸收能力。但由于漂珠尺寸的不同，导致两种复合泡沫铝的动态压缩结果不尽相同，且小颗粒复合泡沫铝在动态冲击下吸能效果最好。在本研究实验的应变率和密度范围内，本文建立的本构模型曲线与实验曲线吻合较好。

关键词： 粉煤灰漂珠；聚氨酯；复合泡沫铝；应变率效应；力学性能；本构模型

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