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Compressive properties and energy absorption characteristics of open-cell nickel foams

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Abstract: Open-cell nickel foams with different relative densities and pre-stretching degrees were subjected to room temperature quasi-static compressive tests to explore their compressive properties. The compressive properties of the nickel foams including yield strength, elastic modulus, energy absorption density and energy absorption efficiency were calculated accurately. The results show that the compressive properties of yield strength, elastic modulus and energy absorption density increase with the increase of relative density of nickel foams. The compressive properties are sensitive to the pre-stretching degree, and the values of yield strength, elastic modulus and energy absorption density decrease with the increase of pre-stretching degree. However, the energy absorption efficiency at the densification strain state exhibits the independence of relative density and pre-stretching degree. The value of energy absorption efficiency reaches its peak when the strain is at the end of the collapse plateau region.
Key words: nickel foam; compressive property; relative density; pre-stretching degree

1 Introduction

Metal foams are cellular materials that exhibit a unique combination of physical properties owning mainly to their structures [1]. They can be used as not only structural materials but also functional materials because of their excellent mechanical and functional properties, such as high specific strength, sound absorption capacity, high flame resistance and excellent vibration reduction capacity [2−5]. Metal foams are widely used in electromagnetic, thermal insulation, railway or aerospace industries and crash energy absorption during device crash [6−8]. Nickel foams, constituted by open cells with a porosity exceeding 90% (volume fraction), are one of the most useful metal foams and usually used in nickel−cadmium-type (Ni−Cd) or metallic nickel−hydride (Ni−MH) batteries. The nickel foams need to support the positive electrode in the battery, so that they required good mechanical and electrical properties [9].

In order to make sure the flat surface of the nickel foams, the original polyurethane foams always need to stretch to a certain extent during the progress of production before they are produced into nickel foams. By specific method, a certain tension is applied at the ends of the product during the production process. However, the research work on the relationship between pre-stretching degree of the original polyurethane foams and the compressive characteristics of the nickel foams is seldom reported. Therefore, experiments were designed to explore the relationship between such two parameters.

In order to simulate the mechanical response of the metal foams, GIBSON and ASHBY [10] considered the cell of the foams as a simple cube or hexagon. They expressed the plastic yield strength σ_{pl}^* as the following equation [10]:

$$\frac{\sigma_{pl}^*}{\sigma_{ys}} \approx 0.3\left(\frac{\rho^*}{\rho_0}\right)^{3/2} \tag{1}$$

where σ_{ys} (MPa) stands for the yield strength of full dense material, ρ^* and ρ_0 stand for the densities of solid and foam structure, respectively. It can be learnt from this equation that relative density is one of the most important structural characteristics of metal foams [11,12]. In order to explore the relationship between the relative density and the yield strength, and at

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the same time verify whether the equation is suitable for the compressive properties of the nickel foams, some experiments were designed in this paper. And the effects of different parameters, such as the density and pre-stretching degree, were also analyzed.

2 Experimental

The specimens used in this experiment were open-cell nickel foams, which were electro-deposited on the surface of the polyurethane foams at first. Then, a suitable heat treatment was used to burn the polymer foams. As a result, the structure of nickel foams was similar to the structure of the origin polyurethane foams [13].

Quasi-static compression tests were performed on a MTS 810 universal testing machine at ambient temperature. All the tests were conducted under displacement control at an initial strain rate of 4.629×10^{-3} s^{-1}. The specimens were cut into four squares with 30 mm in length and 1.8 mm in thickness. The specimen is shown in Fig. 1. The pore size ranges from 100 to 300 μm, and the average pore size is about 260 μm. The microstructure and cell morphology characteristic were investigated by scanning electron microscope (JEOL JSM−7800F).

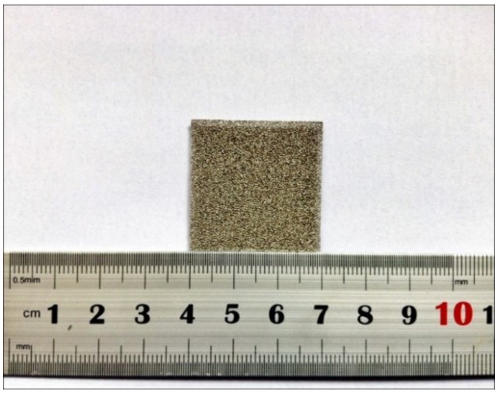

Fig. 1 Morphology of specimen

The relationship between the relative density and compressive properties was investigated in this paper, so nickel foams with different relative densities were prepared. The relative densities of nickel foams studied in this paper were 1.56%, 1.75%, 1.99%, 2.18%, 2.62%, 2.81% and 3.12%, respectively. In order to investigate the effects of the pre-stretching degree, nickel foams with different pre-stretching degrees were also produced. The nickel foams with densities of 1.56%, 1.75%, 1.99%, 2.18% and 2.62% were studied in this part of experiment. The pre-stretching degrees of them were 1%, 3%, 5% and 8%. The original polyurethane foams were stretched in different degrees before they were produced into nickel foams during the process of production.

3 Results and discussion

3.1 Compressive behavior of nickel foams

The morphologies of open-cell nickel foams before and after compression can be seen in Fig. 2. Figure 2(a) shows the original morphology of the nickel and Fig. 2(b) shows the morphology of the nickel foam after compression.

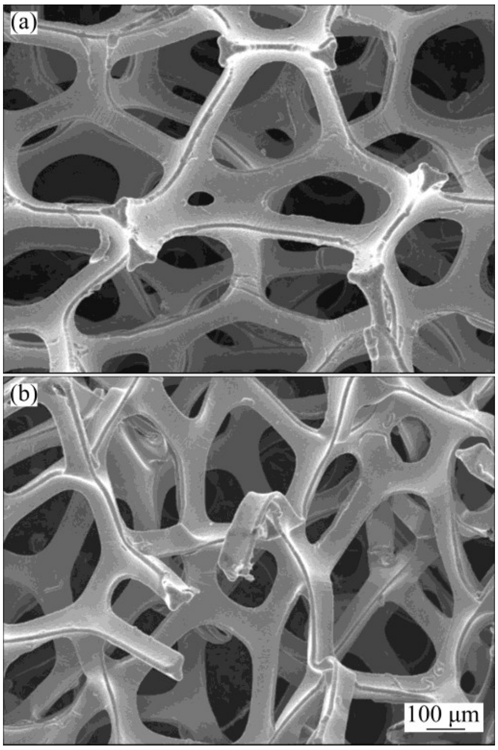

Fig. 2 Morphologies of open-cell nickel foams before and after compression: (a) Nickel foam before compression; (b) Nickel foam after compression

The compressive stress−strain curves of open-cell nickel foams with different relative densities are shown in Fig. 3.

As shown in Fig. 3, the compressive stress−strain curves of nickel foams exhibit three distinct states. The first state is the linear elastic deformation state and then the collapse plateau state, and the densification state [14,15].

In the linear elastic deformation state, the compressive stress increases quickly with the increase of strain. However, the linear elastic region appears only with a small strain degree less than 0.1. At this state, the main deformation of open-cell nickel foams is the bending of the cell walls or ligaments. At the linear deformation stage, the bending of the ligaments is slight and the ligaments will almost restore to the original state after the unloading of the pressure. So, the bending of the ligaments at this stage can hardly be observed. But after the linear deformation stage, the bending of the ligaments can be observed and the morphology is similar to the situations in Fig. 3.

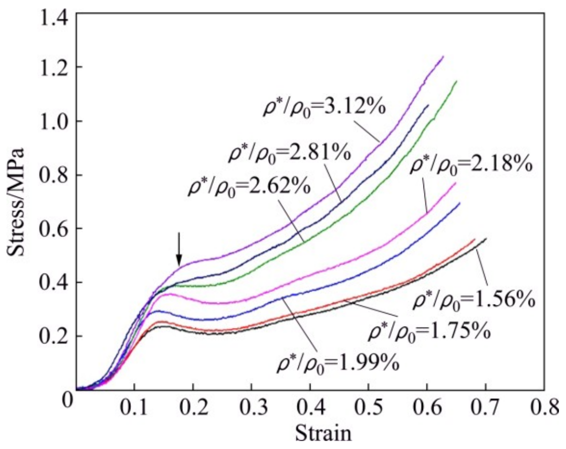

Fig. 3 Compressive stress−strain curves of nickel foams with different relative densities

After the linear elastic deformation state, the curve displays a peak stress value followed by a short plateau. The peaks on the curves tend to disappear with the increase of relative density. With the arrow indicted in Fig. 3, the peaks on the curves of nickel foams with relative densities of 2.62%, 2.81% and 3.12% disappear obviously. Such peaks mean the end of the elastic deformation state. Then, the next state is the collapse plateau state. In this state, the cell walls and ligaments buckle and the foam structure collapse layer by layer [14]. As seen in Fig. 3, the stress at the plateau increases with the increase of the relative density. However, the change trend of the densification strain with the increase of relative density is opposite. Usually, the densification strain is taken as the strain at which the corresponding stress is equal to 2 times the yield strength. When the strain reaches the densification strain, the compressive behavior of the foams comes close to the end. After the densification strain, the nickel foam is compressed densely. Different from the stress at the plateau, the densification strain of nickel foams does not increase with the increase of relative density. The densification strains of nickel foams with relative densities of 1.56%, 1.75%, 1.99%, 2.18%, 2.62%, 2.81% and 3.12% are 0.594, 0.598, 0.563, 0.590, 0.488, 0.485 and 0.501, respectively. The nickel foams with higher relative density seemingly have smaller densification strain. The reason is that all the cells are compacted so that the nickel foams with larger relative density reach the densification state faster than the nickel foams with lower relative density. The nickel foam with higher relative density has a shorter plateau state.

The third state is the densification state. Smooth curves with obvious slope can be observed in Fig. 3. The slopes of the curves become steeper with the increase of relative density. In this region, the cell walls and ligaments contact to each other gradually. This is because the nickel foams with higher relative density have lower porosity. This means that the nickel foams with higher relative density enter into the densification state faster under the condition of the same strain. In other words, the densification degree of nickel foams with higher relative density is higher than that of nickel foams with lower relative density under the condition of the same strain.

3.2 Compressive yield strength of nickel foams

Unlike the normal compressive behavior of entitative metal, the compressive stress does not increase with the increase of strain after the linear elastic deformation strain. This phenomenon indicates that the nickel foams yield. The yield strength is one of the most important parameters to evaluate the compressive property of nickel foams. According to Ref. [10], the yield strength is defined as the peak stress between the linear elastic deformation region and the collapse plateau region on the curves. If there is no peak on the curve, the yield strength is defined as the stress at the point of the intersection of the linear elastic deformation region's tangent line and the collapse plateau region's tangent line.

Figure 4 shows that the yield strength of nickel foam increases obviously with the increase of the relative density of the foam. This is due to the deposition quantity of the nickel on the polyurethane foam. The more the nickel deposit on the surface of the polyurethane foam is, the higher the relative density of the nickel foams is obtained because of the increase of the thickness of the nickel. The nickel foams with thicker metal layer have higher yield strength.

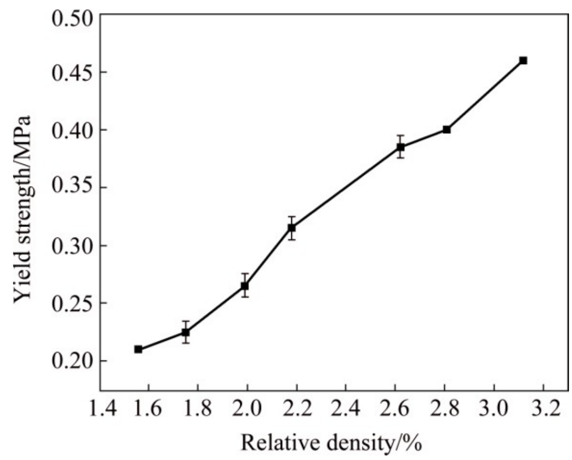

Fig. 4 Variations of yield strength with relative density

The relationship between the yield strength and pre-stretching degree is shown in Fig. 5. With the pre-stretching degree increasing from 1% to 8%, the values of yield strength of nickel foam with different relative densities of 2.62%, 2.18%, 1.99%, 1.75% and 1.56% decrease by 32.42%, 38.15%, 47.41%, 49.86% and 38.98%, respectively. This is because the pre-deformation changes the orientation of ligaments in the foams. In the progress of pre-stretching, the orientation of the majority of ligaments in the origin polyurethane foams converges with the stretch direction gradually, which is perpendicular to the direction of compression. The change of the orientation of ligaments results in the decline of the compressive properties in the direction of compression. So, the yield strength decreases with the increase of the pre-stretching degree. The change can also be seen from the compressive stress−strain curve. Figure 6 shows the compressive stress−strain curves of nickel foams with relative density of 1.75% at different pre-stretching degrees.

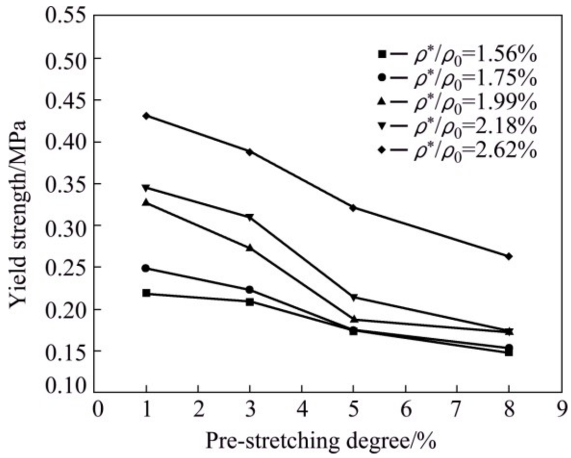

Fig. 5 Relationship between yield strength and pre-stretching degree of nickel foams with different relative densities

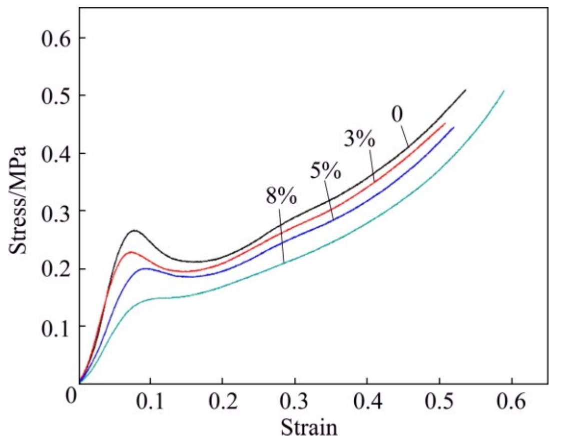

Fig. 6 Compressive stress−strain curves of nickel foams with relative density of 1.75% at different pre-stretching degrees

3.3 Energy absorption characteristics

Energy absorption characteristics are important parameters for nickel foams to explain or illustrate the ability to resist the deformation. The more the energy of the nickel foam absorbed in the deformation process is, the more deformation it can resist. Usually, two parameters, the energy absorption density and the energy absorption efficiency, are used to describe the energy absorption characteristic of the nickel foams.

3.3.1 Energy absorption density

The energy absorption density can be considered as the area under the stress−strain curves with a certain strain. It can be expressed as [9]

$$W=\int_0^{\varepsilon}\sigma \mathrm{d}\varepsilon \tag{2}$$

where W is the energy absorption density and σ is the compressive stress when strain is ε.

As the deformation strain ranges from 10% to 70%, the energy absorption density of nickel foams with different relative densities was calculated respectively, and the results are shown in Fig. 7.

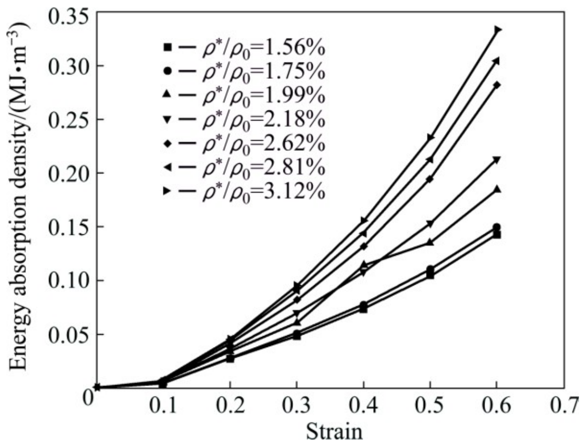

Fig. 7 Energy absorption density of nickel foams with different relative densities

According to Fig. 7, the value of energy absorption density of nickel foams increases with increase of strain. In addition, it increases with the increase of the relative density at any certain strain.

The energy absorption density of metallic foams depends on the yielding, bending, fracture of the ligaments and the interaction among different ligaments during the process when they are compressed [2]. The foams with higher relative density have higher yield strength and ultimate fracture strength. At the same time, because of the higher volume fraction of matrix metal in the foams, the foam with higher relative density can also provide more friction sources during the collapse course. Therefore, the nickel foams with higher relative density can absorb more energy than those with lower relative density during the compression progress. These factors are the main reasons for the higher energy absorption density of higher relative density foams.

The energy absorption density at the densification strain is also calculated and shown in Fig. 8. It can be concluded that with the increase of relative density, the value of energy absorption density increases. The relationship between the energy absorption density and the pre-stretching degree at the densification strain is shown in Fig. 9. The value of energy absorption density decreases with the increase of pre-stretching degree. The reason for the decline of the value of energy absorption density is that the pre-stretching leads to the anisotropy of the orientation of ligaments in the nickel foam. The orientation of ligaments converges with the stretch direction during the pre-stretching progress, resulting in the decline of energy absorption density. Another noticeable phenomenon is that with the increase of pre-stretching degree, the values of energy absorption density of nickel foams with low relative density are gradually close to the same. Figure 9 obviously shows that the values of energy absorption density of nickel foams with relative densities of 1.56%, 1.75%, 1.99%, 2.18% gather to 0.077 MJ/m^3 gradually when the pre-stretching degree is 8% because the influence of the

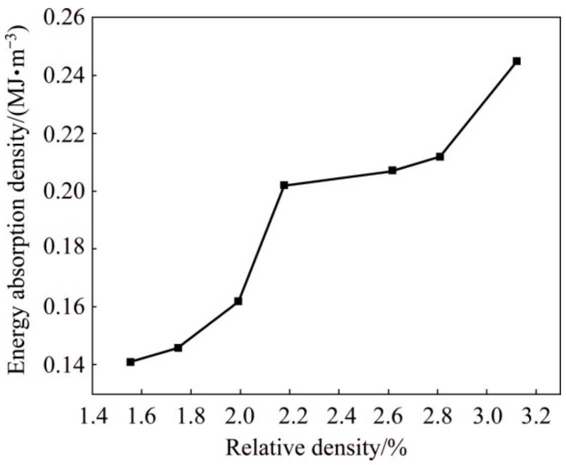

Fig. 8 Relationship between energy absorption density and relative density at densification strain

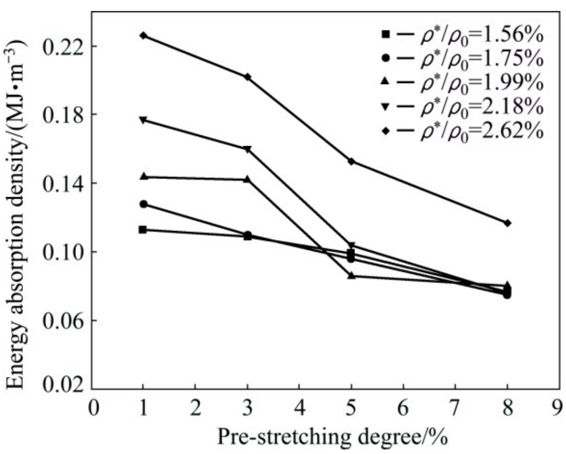

Fig. 9 Relationship between energy absorption density and pre-stretching degree at densification strain for nickel foams with different relative densities

anisotropy of ligaments' orientation reduces with the increase of pre-stretching degree. The phenomenon can be explained as follows. The pre-stretching progress leads to the anisotropy of the ligaments' orientation. With the increase of the pre-stretching degree, the influence on the anisotropy becomes smaller. The ligaments with orientation perpendicular to the compress direction contribute slightly to the compressive properties of the nickel foams. In spite of the relative density, the energy absorption density comes close to the same when the pre-stretching degree is large enough.

3.3.2 Energy absorption efficiency

Energy absorption efficiency is another important parameter to characterize the energy absorption characteristics of the nickel foam. This parameter is the ratio of the actual value of the energy of which the nickel foam absorbed at a certain strain to the ideal value of the energy it absorbed. Energy absorption efficiency is often used to evaluate the energy absorption characteristics of different foams. It can be calculated using the following equation [16]:

$$\eta=\frac{1}{\sigma_m \varepsilon_m}\int_0^{\varepsilon_m}\sigma \mathrm{d}\varepsilon \tag{3}$$

where σ_m is the stress at a certain strain ε_m, η is the energy absorption efficiency when strain is ε_m.

Energy absorption efficiency at a series of certain strains is calculated, respectively. Figure 10 shows the change of energy absorption efficiency during the compressive progress of nickel foams with different relative densities. It can be concluded from Fig. 10 that the energy absorption efficiency increases at first, and then decreases obviously as the strain increases. It is clearly that there is a peak value of η in the curve. In spite of the difference of relative density, the peak value of η mostly appears at strains of 0.2−0.3. Associating this phenomenon with the stress−strain curve of nickel foams' compressive progress, it is obviously that it is

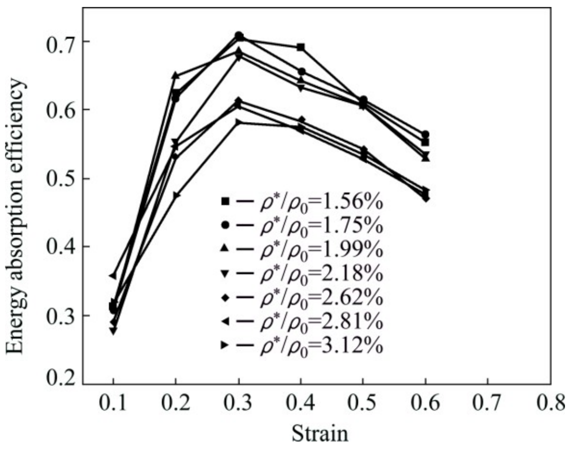

Fig. 10 Energy absorption efficiency of nickel foams with different relative densities

nearly the end of the collapse plateau region when the strains are 0.2−0.3. That is to say, the peak value of energy absorption efficiency happens at the end of the collapse plateau region.

Figure 11 shows the relationship between the energy absorption efficiency and the pre-stretching degree. It is clearly seen that with the increase of pre-stretching degree, the energy absorption efficiency decreases at any certain strain. It can also be concluded from Fig. 11 that there are peak values of energy absorption efficiency in the curves. The peaks appear at strains of 0.2−0.3. Associating this phenomenon with the stress−strain curves of compressive progress of nickel foams with different pre-stretching degrees, the same rule like the former one can be found. The peaks of the energy absorption efficiency appear almost at the end of the collapse plateau region.

Because the densification strain is taken as the strain at which the stress is equal to 2 times the yield strength at the end of the compressive progress, the energy absorption efficiency at the densification strain (η_d) is discussed specially in this paper. Figure 12 shows that η_d values of nickel foams with different relative densities are nearly the same. It can be summarized that η_d exhibits the independence of relative density.

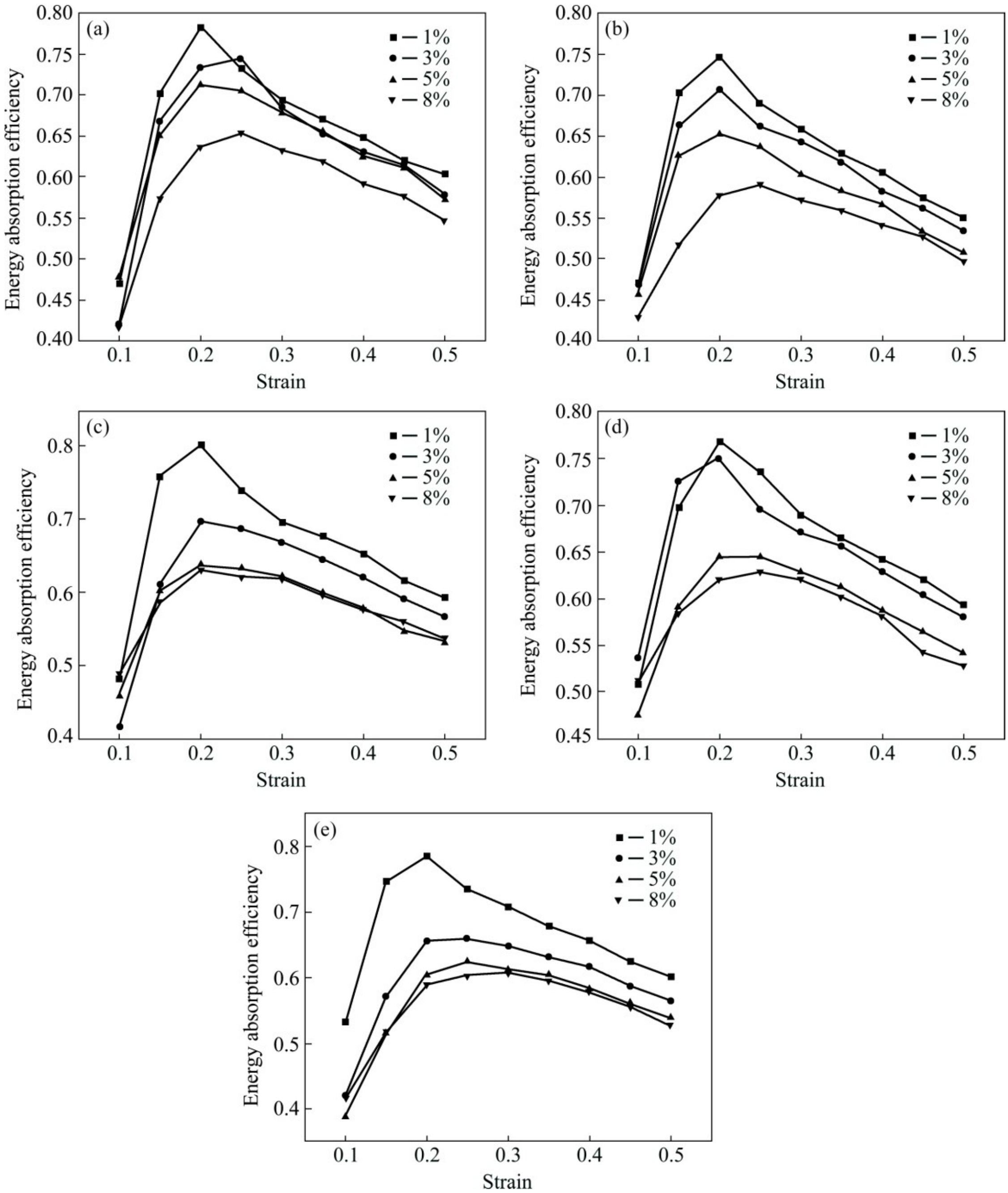

Fig. 11 Energy absorption efficiency of nickel foams with different relative densities at different pre-stretching degrees: (a) ρ^*/ρ_0=1.56%; (b) ρ^*/ρ_0=1.75%; (c) ρ^*/ρ_0=1.99%; (d) ρ^*/ρ_0=2.18%; (e) ρ^*/ρ_0=2.62%

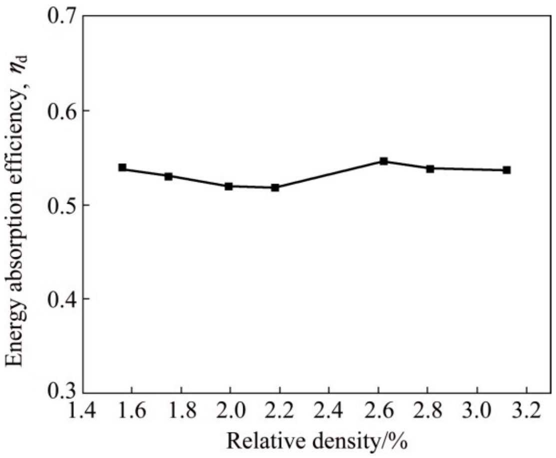

Fig. 12 Relationship between energy absorption efficiency at densification strain (η_d) and relative density

The relationship between the energy absorption efficiency η_d and pre-stretching degree is shown in Fig. 13. The values of η_d are all about 0.55. It can be concluded that the energy absorption efficiency η_d also exhibits the independence of pre-stretching degree. In spite of different relative densities, the energy absorption efficiency at the densification strain almost remains the same at different pre-stretching degrees. So, with the increase of pre-stretching degree, the energy absorption density decreases, while the energy absorption efficiency at the densification strain remains the same. In a word, the energy absorption efficiency at the densification strain is independent of the relative density and the pre-stretching degree.

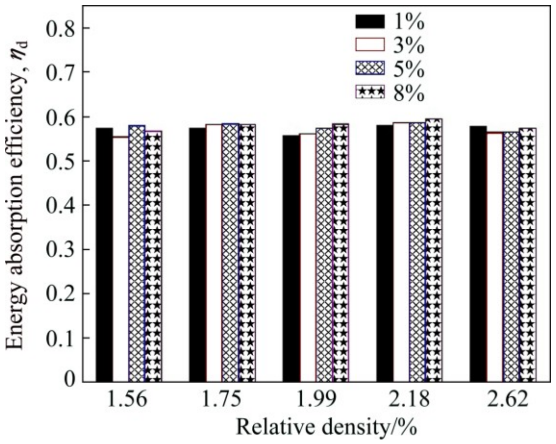

Fig. 13 Relationship between energy absorption efficiency η_d and pre-stretching degree of nickel foams with different relative densities

3.4 Elastic modulus

Elastic modulus is also an important parameter to evaluate the compressive properties. Elastic modulus of the nickel foams is calculated from the slope of the unloading load−deflection curve taken at approximately the yield strength of the nickel foams [17].

The relationship between the elastic modulus and the relative density is shown in Fig. 14. It can be concluded that the elastic modulus increases with the increase of relative density. The value of elastic modulus of nickel foam with relative density of 1.56% is 36.04 MPa, while that of the nickel foam with relative density of 3.12% is 57.50 MPa.

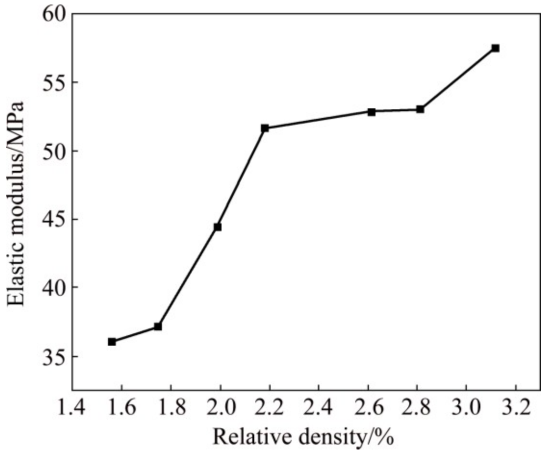

Fig. 14 Variations of elastic modulus with relative density

Figure 15 shows the relationship between the elastic modulus and the pre-stretching degree. It is obvious that the elastic modulus decreases with the increase of pre-stretching degree. With the pre-stretching degree increasing from 1% to 8%, elastic modulus values of the nickel foam with relative densities of 1.56%, 1.75%, 1.99%, 2.18% and 2.62% decrease by 48.88%, 47.76%, 55.36%, 54.42% and 44.06%, respectively. The reason for the decrease of elastic modulus with the increase of pre-stretching degree is that the pre-stretching leads to the anisotropy of the orientation of ligaments in the nickel foam. The anisotropy results in the decline of the compressive properties in the direction of compression.

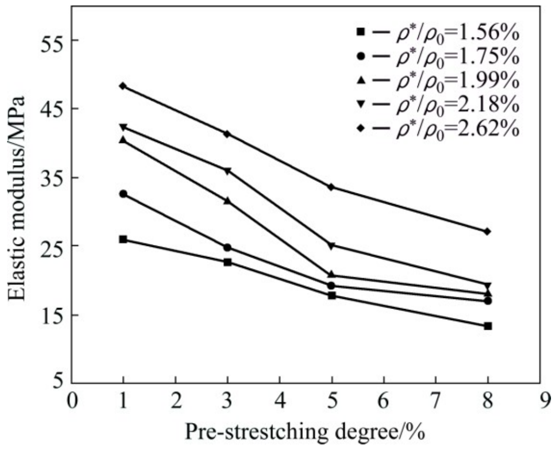

Fig. 15 Relationship between elastic modulus and pre-stretching degree for nickel foams with different relative densities

4 Conclusions

1) Most of nickel foams' compressive parameters increase with the increase of relative density. For example, the yield strength, energy absorption density and elastic modulus increase with the increase of relative density. Although the energy absorption efficiency at any certain strain abides the same rule, the energy absorption efficiency at the densification strain exhibits the independence of relative density. The energy absorption efficiency reaches its peak when the strain is at the end of the collapse plateau region.

2) The pre-stretching of the nickel foam is harmful to the compressive properties. The yield strength, energy absorption density and elastic modulus decrease with the increase of pre-stretching degree. While the energy absorption efficiency at a certain strain decreases with the increase of pre-stretching degree, and it exhibits the independence of pre-stretching degree at the densification strain. The energy absorption efficiency reaches its peak when the strain is at the end of the collapse plateau region.

References

[1] KONSTANTINIDIS I C, PARADISIADIS G, TSIPAS D N. Analytical models for the mechanical behavior of closed and open-cell Al foams [J]. Theoretical and Applied Fracture Mechanics, 2009, 51(1): 48−56.

[2] YU Si-rong, LIU Jia-an, WEI Ming, LUO Yan-ru, ZHU XIAN-yong, LIU Yao-hui. Compressive property and energy absorption characteristic of open-cell ZA22 foams [J]. Materials and Design, 2009, 30(1): 87−90.

[3] BANHART J. Manufacture, characterisation and application of cellular metals and metal foams [J]. Progress in Materials Science, 2001, 46(6): 559−632.

[4] XU Z G, FU J W, LUO T J, YANG Y S. Effects of cell size on quasi-static compressive properties of Mg alloy foams [J]. Materials and Design, 2012, 34: 40−44.

[5] MALEKJAFARIAN M, SADRNEZHAAD S K. Closed-cell Al alloy composite foams: Production and characterization [J]. Materials and Design, 2012, 42: 8−12.

[6] WANG Zhi-hua, MA Hong-wei, ZHAO Long-mao, YANG Gui-tong. Studies on the dynamic compressive properties of open-cell aluminum alloy foams [J]. Scripta Materialia, 2006, 54(1): 83−87.

[7] PANG Q, WU G H, XIU Z Y, JIANG L T, SUN D L. Microstructure, oxidation resistance and high-temperature strength of a new class of 3D open-cell nickel-based foams [J]. Material Characterization, 2012, 70(4): 125−136.

[8] XIAO Li-jun, SONG Wei-dong, TANG Hui-ping, ZHU Zhi-wu, WANG Jian-zhong, WANG Hui. High temperature compression properties of open-cell Ni−20Cr foams produced by impregnation [J]. Materials and Design, 2015, 85: 47−53.

[9] METZGER W, WESTFALL R, HERMANN A, LYMAN P. Nickel foam substrate for nickel metal hydride electrodes and lightweight honeycomb structures [J]. International Journal of Hydrogen Energy, 1998, 23(11): 1025−1029.

[10] GIBSON L J, ASHBY M F. Cellular solids: Structure and properties [M]. 2nd ed. Cambridge: The University of Cambridge, 1997.

[11] HUANG X L, WU G H, ZHANG Q, DOU Z Y, CHEN S. Compressive properties of open-cell Fe−Ni foams [J]. Materials Science and Engineering A, 2008, 497(1−2): 231−234.

[12] DEVIVIER C, TAGLIAFERRI V, TROVALUSI F, UCCIARDELLO N. Mechanical characterization of open cell aluminium foams reinforced by nickel electro-deposition [J]. Materials and Design, 2015, 86: 272−278.

[13] PANG Qiu, WU Gao-hui, SUN Dong-li, XIU Zi-yang, ZHANG Qiang, HU Zhi-li. Compressive property and energy absorption characteristic of 3D open-cell Ni−Cr−Fe alloy foams under quasi-static conditions [J]. Transactions of Nonferrous Metals Society of China, 2012, 22(S2): s566−s572.

[14] LUO Yan-ru, YU Si-rong, LIU Jian-an, ZHU Xian-yong, LUO Yan-he. Compressive property and energy absorption characteristic of open-cell $SiC_p/AlSi_9Mg$ composite foams [J]. Journal of Alloys and Compounds, 2010, 499(2): 227−230.

[15] LI Yong-gang, WEI Ying-hui, HOU Li-feng, GUO Chun-li, YANG Sheng-qiang. Fabrication and compressive behavior of an aluminium foam composite [J]. Journal of Alloys and Compounds, 2015, 649: 76−81.

[16] MILTZ J, GRUENBAUM G. Evaluation of cushioning properties of plastic foams from compressive measurements [J]. Polymer Engineering and Science, 1981, 21(15): 1010−1014.

[17] ANDREWS E, SANDERS W, GIBSON L J. Compressive and tensile behavior of aluminum foams [J]. Materials Science and Engineering A, 1999, 270(2): 113−124.

开孔泡沫镍的压缩和吸能性能

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摘 要：研究在室温条件下不同相对密度、不同预拉伸程度的泡沫镍的准静态压缩性能。准确地测定包括屈服强度、弹性模量、能量吸收密度和能量吸收效率等压缩性能。结果表明，屈服强度、弹性模量和能量吸收密度的压缩性能随着泡沫镍的相对密度的增加而增加。压缩性能对泡沫镍基体的拉伸程度较为敏感，屈服强度、弹性模量和能量吸收密度随着预拉伸程度的增加而降低。然而，能量吸收效率对相对密度和预拉伸程度并不敏感。能量吸收效率在坍塌平台区末期达到最大值。

关键词：泡沫镍；压缩性能；相对密度；预拉伸程度

(Edited by Wei-ping CHEN)