Uniaxial and biaxial failure behaviors of aluminum alloy foams

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ABSTRACT

Combined shear–tensile test have been performed on a closed-cell aluminum alloy foams with three relative densities over a wide range of loading rates in order to probe their failure behaviors under biaxial loading conditions. Quasi-static uniaxial compressive and tensile tests have also been conducted to investigate uniaxial failure behaviors of the aluminum alloy foams. The materials exhibit uniaxial failure stress asymmetry due to different failure mechanism in the uniaxial tensile and compression. Comparison is made between three phenomenological failure criteria and the measured failure stresses under different loading conditions to verify these criteria. The experimental failure surfaces of the aluminum alloy foams provide support for the three phenomenological failure criteria when suitable Poisson’s ratio is employed. The shape of the experimental failure surface in principal stress plane was not significantly influenced by variation in the relative density. The slight expansion of the failure surfaces with loading rate happened to be isotropic for this investigated closed-cell aluminum alloy foams in combined shear–tensile tests.

1. Introduction

Composi...
tests are notoriously difficult to conduct. Hence, this paper presents a combined shear–tensile test for a closed-cell aluminum alloy foams, with two objectives in mind. The first objective is to determine the experimental failure surfaces of the closed-cell aluminum alloy foams under shear–tensile stress states, and to further verify three phenomenological failure criteria. On the other hand, metallic foams can be subjected to different loading rates in engineering applications. The loading rate should be taken into consideration in modeling mechanical behaviors of foams. However, the existing literatures relate to the loading rate effect of foams have been focused on the uniaxial mechanical behaviors, such as failure strength, the plateau stress, the densification behavior and the energy absorption capacity [24–36]. The loading rate effect on the failure surface of foams has not been reported. Therefore, the second objective of this paper is to investigate the influence of loading rate on the failure surface of foams. Moreover, the different failure mechanism of the foams in uniaxial tensile and compressive conditions will be discussed in detail.

2. Materials and testing procedure

The material considered for this investigation was a closed-cell aluminum alloy foams produced by the China Shipbuilding Industry Corporation (CSIC). The chemical composition of the cell wall material is AL–0.45 wt.%Mg–0.52 wt.%Ca–0.21 wt.%Ni. The nominal relative density (defined as the density of the foam divided by the density of the cell wall material) of the closed-cell aluminum alloy foams are about 10%, 15%, and 20%. It should be pointed out that the relative densities of the closed-cell aluminum alloy foams have variations of ±0.8% from the mean value. The main reason for the variations is the cell diameter change. The cell diameters of the aluminum alloy foams have a range of value from 1 mm to 4.5 mm. The average diameters of the cells are 3.1 mm, 2.4 mm, 1.5 mm for 10%, 15% and 20% respectively. In this investigation, the foam specimens were fabricated with high precision to minimize the local cell wall damage. Electrical Discharge Machining method (EMD) was adopted to cut the foam specimens. The foam specimens were cut from rectangular blocks with dimension of 1500 × 500 × 100 mm supplied by the manufacturers. It is well known that mechanical properties of cellular solids are strongly sensitive to the ratio of the specimen size to the cell size at length scales where the two are of the same order of magnitude [37–40]. Thus, the average cell numbers in different directions of the foam specimens with three relative densities are listed in Table 1, respectively.

2.1. Uniaxial tests

Uniaxial compression tests performed on cylindrical specimens with three relative densities using a universal material testing machine with a load cell of 10 kN. The specimens had the following nominal diameter and height: 25 mm \(L\) × 50 mm \(H\). The cylindrical foam specimens were compressed between two steel circular compression platens, as shown in Fig. 1. The uniaxial compression tests were conducted by controlling a constant displacement rate of 1 mm/min. The displacement and load signals from the universal testing machine were reported by a computer during the entire process of loading. Uniaxial tensile tests were performed using dogbone specimens with a waisted section. The dogbone specimens are 30 mm \(H\) × 16 mm \(W\) in waisted cross section and 90 mm long \(L\) (shown in Fig. 2). The dogbone specimens were placed inside the wedge grips in the whole loading process, as shown in Fig. 3. The uniaxial tensile tests were carried out at a constant displacement rate of 1 mm/min using a universal material testing machine with a load cell of 10 kN. The uniaxial compression and tensile tests were repeated three times, respectively. It should be noted that three cylindrical specimens and three dogbone specimens were cut in three orthogonal directions of rectangular blocks. The aim of this cutting method is to investigate the anisotropic behaviors of the aluminum alloy foams, which should be taken into consideration in modeling their mechanical behaviors [19].

2.2. Combined tensile–shear tests

The goal of the experiments is to determine failure stresses of the aluminum alloy foams under combined shear–tensile stress states which is the most realistic loading mode. For this purpose, the Arcan test rig, which was originally designed to study the biaxial responses of unidirectional fiber-reinforced composites [20], was employed to investigate shear–tensile failure behaviors of
the closed-cell aluminum alloy foams, as illustrated in Fig. 4. The rig consists of two pairs of plane semi-circular loading plates. The array of pin holes in the loading plates allows the loading plates to be attached to the clamped configuration at different orientations. This allows a range of values of the loading angle $\theta$ between the loading axis and the direction parallel to the central section of the butterfly-shape specimen. The butterfly-shape specimens were extracted from the rectangular blocks of foams using EDM technique and subsequently bonded to the steel intermediate grips using the Epoxy glue. Finally, the butterfly-shape specimens with the steel intermediate grips were set in a bonding fixtures which applied a constant pressure on the specimens until they were ready for testing, as shown in Fig. 5. The butterfly-shape
specimens are 25 mm (L) × 10 mm (W) in central cross-section. Let x and y denote coordinates perpendicular and parallel to the central section of the butterfly-shape specimens respectively. The normal stress and the shear stress at the central section are given by [19]:

\[ \sigma_{xy} = \frac{\cos \alpha}{(\beta_x - 1) \sin \alpha + 1} V \frac{S}{S} \]

\[ \sigma_{xx} = \frac{\beta_y \sin \alpha}{(1 - \beta_x) \cos^2 \alpha + \beta_x} V \frac{S}{S} \]

\[ \sigma_{yy} = \gamma \sigma_{xx} \]

Here, V represents the vertical force applied by the universal material testing machine, S denotes the cross-section area at the central section, and \( \gamma \) is the elastic Poisson's ratio of the foam specimen. The value of the elastic Poisson's ratio is 0.3. While \( \beta_x \) is the specimen's stiffness ratio. For an isotropic specimen with elastic Poisson's ratio of \( \gamma \), the stiffness ratio is

\[ \beta_x = \frac{2}{1 - \gamma} \]

Combined tensile–shear tests were carried out using an Instron 5544 testing machine with a load cell of 2 kN (shown in Fig. 4) and the force–displacement curves were recorded. The proportional loading rates from 0.5 mm/min to 500 mm/min were performed on three relative densities.

3. Results

3.1. Uniaxial test results

All macroscopic stresses and strains in uniaxial tests were based on the engineering stress and strain definition. The stress versus strain curves for uniaxial compression tests on the cylindrical specimens with three relative densities are shown in Fig. 6. The curves are all consisted of a linear elastic region, a failure stress (peak point), a “plateau” region where the stress increases slowly as the cells deform plastically, and a densification region where the stress increases rapidly. It should be pointed out that the present work focuses on the failure behaviors of the foams. Thus, only the axial stress–strain curves before the occurrence of densification are taken into consideration here. As shown in the Fig. 6, the failure stress and the plateau stress of the foams all markedly increase as the relative density increases. The stress versus strain responses for the uniaxial tensile tests on the dogbone specimens with three different relative densities are shown in Fig. 7. The stress was determined as the ratio of the load divided by the waisted cross-sectional area and the strain was determined as the ratio of the displacement divided by the original length of the waisted section. As shown in Fig. 7, Each curve of the foams shows approximately linear elastic behavior at small strains, and the tensile stress reaches the peak value when the approximately linear elastic behavior ends, followed by rapidly drop. The stress–strain curve before the peak point indicates linear–elastic elongation behavior. The peak point of the curve is the tensile failure stress of the foams. The failure stress of the foams increases as the relative density increases, and this result is well consistent to the uniaxial compressive result. But the strain at the peak point (failure stress) remarkably decreases with increasing relative density. As shown in Figs. 6 and 7, the aluminum alloy foams for three relative densities all exhibit isotropy.

3.2. Combined compression–shear results

Examples of the vertical force versus displacement curves for relative densities 10% during combined shear–tensile test are illustrated in Fig. 8. In the elastic regime, the vertical stress versus displacement curve is initially linear, but becomes non-linear at the following short stages due to the loss of stiffness caused by the elastic buckling of cell walls. This behavior continues until the peak stress is achieved, and the peak stress represents the onset of diffuse necking of cell walls at the central section, eventually leading to ductile fracture. The ductile crack propagates along the central...
are the density and failure strength of the foam; \(q\) are the density, and failure strength of the metal matrix. \(r, q\) are constants related to the cell geometry. Ratcheting is the dominant mechanism of cell-wall deformation at low relative densities. The mechanisms by which the cells deform and fail [1]. Under uniaxial compression, the stress–strain curve is initially linear, but becomes non-linear at the following short stages due to elastic collapse of the cell walls in compression. The aluminum alloy foams are approximately linear-elastic in uniaxial tensile right up to fracture point, the small strain elastic mechanism of the aluminum alloy foams in tension is the same as that in compression due to cell wall bending and stretching. But, the failure behavior in tension is quite different from that in compression. In compression the aluminum alloy foams crush progressively; in tension they fail corresponding to the propagation of a single crack. So tensile failure can be regarded as ductile fracture due to the contribution of cell walls bending and stretching. The measured failure stresses of the closed-cell aluminum alloy foams in uniaxial tests are summarized in Table 2. It is should be point out that the main reason for experimental error is that the relative density of the foams have the maximum variations of approximately ±0.8% from the mean value. The failure stresses in uniaxial compression and tensile all become larger when the relative density increases, as shown in Table 2. There results indicate that the relative density of the aluminum alloy foams is the main effective factor to the failure stress, and it is controlled by the cell wall thickness and the cell size. In present investigation, the main reason for the variation of the relative density is the cell size change. As shown in Table 2, the tensile failure stresses of the aluminum alloy foams are all obviously higher than the corresponding compressive failure stresses for three relative densities. The results for uniaxial mechanical behaviors of the ductile foams were quite consistent with those reported by Sugimura et al. [41]. Based on the experimental results, they proposed that Alporas aluminum foam (the ductile foam) was stiffer and stronger in tension than in compression. The ratio values of the average compressive failure stress \(\sigma_c\) to the average tensile failure stresses \(\sigma_t\) all remain in the range of 0.7 ± 0.03, as shown in Table 2. The aluminum alloy foams for three relative densities all exhibit obvious uniaxial failure stress asymmetry. The main reason for the failure stress asymmetry is the difference in failure mechanisms of the aluminum alloy foams: local ductile fracture in tension and plastic collapse in compression. Gibson et al. [1] proposed that the failure stress of metallic foams strongly depend upon the relative density, and gave a theoretical model to describe the failure stress of the closed-cell foams. The normalized failure stresses of the closed-cell aluminum alloy foams are compared with this theoretical model, as shown in Fig. 10. It should be note that the compressive failure stresses

\[
\frac{\sigma_c}{\sigma_t} = C_2 \left( \frac{\rho_s}{\rho_t} \right)^{3/2} + C_3 (1 - \phi) \left( \frac{\rho_s}{\rho_t} \right)
\]

where \(\rho_s\) and \(\sigma_t\) are the density and failure strength of the foam; \(\rho_t\) and \(\sigma_t\) are the density, and failure strength of the metal matrix, \(C_1\) and \(C_2\) are constants related to the cell geometry, \(\phi\) is the volume fraction of solid contained in the cell edges. Finite element simulations of a unit tetrahexahedral closed cell with flat faces give [41]:

\[
\frac{\sigma_c}{\sigma_t} = 0.33 \left( \frac{\rho_s}{\rho_t} \right)^2 + 0.44 \left( \frac{\rho_s}{\rho_t} \right)
\]

![Fig. 9. Measured failure forces for the 10% foam specimens under different loading rates.](image)

### Table 2

<table>
<thead>
<tr>
<th>Relative density of foams (%)</th>
<th>10</th>
<th>15</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressive yield stress (MPa)</td>
<td>1.6; 1.6; 1.6</td>
<td>3.0; 3.0; 3.2</td>
<td>4.7; 4.5; 4.6</td>
</tr>
<tr>
<td>Average yield stress, (\sigma_c) (MPa)</td>
<td>1.6</td>
<td>3.1</td>
<td>4.6</td>
</tr>
<tr>
<td>Tensile yield stress (MPa)</td>
<td>2.2; 2.3; 2.1</td>
<td>4.6; 4.4; 4.1</td>
<td>6.6; 6.3; 6.1</td>
</tr>
<tr>
<td>Average yield stress, (\sigma_t) (MPa)</td>
<td>2.2</td>
<td>4.4</td>
<td>6.3</td>
</tr>
<tr>
<td>(\beta = \frac{\sigma_t}{\sigma_c})</td>
<td>0.68</td>
<td>0.7</td>
<td>0.73</td>
</tr>
<tr>
<td>(\frac{\sigma_c}{\sigma_t}) (MPa)</td>
<td>1.9(1.19(\sigma_c))</td>
<td>3.75(1.21(\sigma_c))</td>
<td>5.45(1.20(\sigma_c))</td>
</tr>
</tbody>
</table>

4. Discussion

#### 4.1. Uniaxial compressive and tensile behaviors

Metallic foams are finding applications as core materials in composite sandwich structures for weight saving applications and also as cushioning materials in automobiles and packaging. There applications require to develop an understanding for uniaxial tensile and compressive behaviors of metallic foams. An extensive review of available literature is conducted to understand the uniaxial compressive and tensile behaviors of metallic foams. The present discussion is focused on comparisons of the uniaxial tensile and compressive behaviors of the aluminum alloy foams. The mechanical behaviors of the foams can be modeled by considering the mechanisms by which the cells deform and fail [1]. Under uniaxial compression, the stress–strain curve is initially linear, but becomes non-linear at the following short stages due to elastic buckling of the cellular microstructure caused by the progressive crushing of cells. It is well known that the linear-elastic mechanism of the closed-cell foams is strongly influenced by cell wall bending and stretching. Under uniaxial loading conditions, bending is the dominant mechanism of cell-wall deformation at low relative densities [1]. When the local stresses in the cell walls exceed the failure threshold, the elastic regime ends and the plastic collapse starts due to plastic buckling of the cell walls. This point is characterized by a peak stress that is followed by a short softening regime preceding the crushing regime. It is clear that the failure behavior of the aluminum alloy foams are dominated by the plastic collapse of the cell walls in compression. The aluminum alloy foams are approximately linear-elastic in uniaxial tensile right up to fracture point, the small strain elastic mechanism of the aluminum alloy foams in tension is the same as that in compression due to cell wall bending and stretching. But, the failure behavior in tension is quite different from that in compression. In compression the aluminum alloy foams crush progressively; in tension they fail corresponding to the propagation of a single crack. So tensile failure can be regarded as ductile fracture due to the contribution of cell walls bending and stretching. The measured failure stresses of the closed-cell aluminum alloy foams in uniaxial tests are summarized in Table 2. It is should be point out that the main reason for experimental error is that the relative density of the foams have the maximum variations of approximately ±0.8% from the mean value. The failure stresses in uniaxial compression and tensile all become larger when the relative density increases, as shown in Table 2. There results indicate that the relative density of the aluminum alloy foams is the main effective factor to the failure stress, and it is controlled by the cell wall thickness and the cell size. In present investigation, the main reason for the variation of the relative density is the cell size change. As shown in Table 2, the tensile failure stresses of the aluminum alloy foams are all obviously higher than the corresponding compressive failure stresses for three relative densities. The results for uniaxial mechanical behaviors of the ductile foams were quite consistent with those reported by Sugimura et al. [41]. Based on the experimental results, they proposed that Alporas aluminum foam (the ductile foam) was stiffer and stronger in tension than in compression. The ratio values of the average compressive failure stress \(\sigma_c\) to the average tensile failure stresses \(\sigma_t\) all remain in the range of 0.7 ± 0.03, as shown in Table 2. The aluminum alloy foams for three relative densities all exhibit obvious uniaxial failure stress asymmetry. The main reason for the failure stress asymmetry is the difference in failure mechanisms of the aluminum alloy foams: local ductile fracture in tension and plastic collapse in compression. Gibson et al. [1] proposed that the failure stress of metallic foams strongly depend upon the relative density, and gave a theoretical model to describe the failure stress of the closed-cell foams.
where \( \rho_f, \rho_s, \sigma_s, \) and \( \sigma_m \) are the density of the foam, the density of the matrix material, the von Mises equivalent stress and the mean stress, \( \sigma_p \) is the uniaxial plastic collapse strength. It was taken as the average of the compressive failure stress \( \sigma_c \) and the tensile failure stress \( \sigma_t \), i.e. \( \sigma_p = \frac{\sigma_c + \sigma_t}{2} \).

As von Mises criterion for engineering alloys (metals) and Drucker–Prager criterion for soils, similarly Miller [13] proposed a failure criterion for foams and other types of materials exhibiting uniaxial failure stress asymmetry and plastic compressibility. It is given by

\[
f = \sigma_c - \gamma \rho + \frac{\rho'}{d_0 \sigma_c} \rho^2 - d_0 \sigma_c \leq 0
\]

where \( \sigma_c \) is the uniaxial compressive strength, \( p \) is the hydrostatic stress in compression and the constants \( \gamma, \xi \) and \( d_0 \) depend on the ratio of the uniaxial compressive to tensile strengths and the plastic Poisson's ratio \( \gamma_p \). Therefore, the plastic Poisson's ratio of the foams is required in order to determine this theoretical failure surfaces. Particular attention has been paid to measurement of the plastic Poisson's ratio for the foams, but in spite of this, no rational result was obtained. The effect of the plastic Poisson's ratio on the theoretical failure surfaces is detailedly discussed in Section 4.2.2. The value of the plastic Poisson's ratio employed here is assumed to be 0.17 for the closed-cell aluminum alloy foams.

Based on the powder compaction model, Deshpande and Fleck [14] proposed a phenomenological constitutive model for metal foams, which is named self-similar model, given by:

\[
f = \frac{1}{1 + (\alpha/3)^2} \left[ \sigma_e^2 + \sigma_m^2 \right] - \sigma_0^2 \leq 0
\]

where \( \sigma_e \) is the von Mises' effective stress, \( \sigma_m \) is the mean stress, \( \sigma_0 \) is the uniaxial failure stress and \( \alpha \) and \( \nu \) are a parameter that defines the aspect ratio of the elliptical failure surface. \( \alpha \) is also related to the plastic Poisson's ratio by

\[
\alpha = 3 \left[ \frac{0.5 - \gamma_p}{1 + \gamma_p} \right]^{1/2}
\]

The three types of lines plotted in Fig. 11a–c represent the theoretical failure surfaces suggested by Gibson et al. [12], Miller [13] and Deshpande and Fleck [14] respectively in principal stress plane. It is clear that three phenomenological failure criteria give an approximate description of the measured failure stresses of the aluminum alloy foams when proper plastic Poisson's ratio is employed. But the experimental failure surfaces for three relative densities are more in agreement with Miller criterion than other two phenomenological failure criteria. The main reason for this result is the uniaxial failure stress asymmetry of materials is involved in Miller failure criterion. The closed-cell aluminum alloy foams used in this investigation apparently exhibit unequal uniaxial tensile and compressive strengths due to different failure mechanism in the uniaxial tensile and compression. The experimental failure perimeters of three relative densities overall convex in shape, and are approximately consistent with quadratic curve in normalized principal stress plane, as shown in Fig. 12. Within variations in data, failure stress points for three relative densities in Fig. 12 delineate essentially the same curve. This result implies that the shape of the failure surface does not depend on the relative density for the closed-cell aluminum alloy foams over the explored range (10–20%) if failure stress components are normalized as the uniaxial compressive failure stress \( \sigma_e \) of the corresponding foam, respectively.

4.2.2. Effect of plastic Poisson’s ratio

Great efforts have been made to experimental measure the value of the plastic Poisson’s ratio for the tested foams by many
researchers [14–16, 44–45]. However, scattered experimental data was acquired and the differences in the measured values could be up to 10 times. The plastic Poisson’s ratio of Alporas foam with relative density of 8% was 0.024 as obtained by Gioux et al. [16], but it was 0.33 by Motz and Pippan [45]. This data deviation is mainly caused by the localized deformation of the foams. During compressing process, the weakest layer of foam cells initially collapses. Local deformation will happen subsequently in this weakest layer until these cells are fully compacted and the next series of cells starts to collapse. These series of simultaneously collapsing cells are usually regarded as localization deformation bands. It should be noted that these bands are different from shear bands that occur in granular materials or metals as a result of a plastic flow instability. Localization deformation bands of metallic foams commonly form as the material properties are heterogeneous. The irregularities of the cellular foam microstructure are significant and have neglected effect on its mechanical properties, such as the elastic modulus, the failure strength and the plastic Poisson’s ratio. On the other hand, the foam cells have different cell geometries, different matrix material properties and other kinds of imperfections. Thus, the weakest cells will fail within a first localization band followed by the next weakest layer. The cells fail in groups of subsequent localization bands according to the local strength of a given layer of cells [46]. Based on the aforementioned analysis, the value of plastic Poisson’s ratio is highly sensitive to specimen size and the layer measured, and it is difficult to precisely measure the value of plastic Poisson’s ratio. However, it is essential to investigate the influence of the plastic Poisson’s ratio on the shape of the theoretical failure surfaces, and to determine suitable values of plastic Poisson’s ratio to fit the experimental

Fig. 11. Failure surfaces of the aluminum alloy foams under different loading rate with relative density of (a) 10%, (b) 15%, and (c) 20%.

Fig. 12. Failure stresses of the aluminum alloy foams with three relative densities under different loading conditions.
failure surfaces of the foams. Here, we take an example of the foam with relative density 10%. The Deshpande–Fleck and Miller theoretical failure surfaces for the foams are plotted in principal stress plane when different values of plastic Poisson’s ratio are employed, as illustrated in Fig. 13. It is evident that both theoretical failure surfaces of Miller and Deshpande–Fleck strongly depend on the value of this plastic Poisson’s ratio. It should be pointed out that the plastic Poisson’s ratio can be regarded as the constitutive property of materials, and thus the value of the plastic Poisson’s ratio must be unique for an isotropic material. Within variations in data, failure stress points for the three relative densities in Fig. 12 delineate essentially the same curve. Based on above-mentioned reasons, the values of the plastic Poisson’s ratio for three relative densities are all assumed to be 0.17 in this investigation. But accurate measurement method for the plastic Poisson’s ratio should be further investigated.

4.2.3. Effect of loading rate

Many previous researches [24–36] have been performed to investigate the loading rate effect on the mechanical behaviors of the foams, such as the uniaxial failure stress, the plateau stress, the densification behavior and the energy absorption capacity. However, little literature has been concerned with the experimental failure surface of the foams under multiaxial loading conditions, especially combined tensile–shear conditions which is the most realistic loading mode. In this section, the shear–tensile failure behaviors of the aluminum alloy foams at different loading rates ranged from 0.5 mm/min to 500 mm/min are detailedly discussed. The failure stresses of the butterfly-shape specimens with relative density 10% at different loading rates are summarized in Fig. 9. The experimental results showed that the aluminum alloy foams were not sensitive to the loading rate over the range of 0.5 mm/min to 50 mm/min, but it is of interest to note that the failure stresses

Fig. 13a. Effect of plastic Poisson’s ratio on Deshpande–Fleck failure surface.

Fig. 13b. Effect of plastic Poisson’s ratio on Miller failure surface.
at loading rate of 500 mm/min are all slightly higher than the corresponding failure stresses under other loading rate, respectively. The increases of the failure stresses for different loading angles all remained in a narrow range of 4–13%. The similar phenomenon also emerges from the relative density of 15% and 20%. The experimental failure surfaces of the aluminum alloy foams at different loading rates are shown in Fig. 9. It is evident that three phenomenological failure criteria are capable of predicting the failure stresses of the aluminum alloy foams over a wide range of the loading rate. The main goal in this paper is to investigate the loading rate effect on the shape and size of the experimental failure surface, so the failure stresses for three relative densities at different loading rates were normalized by the corresponding average failure stress ($\sigma_f$) obtained from uniaxial compression tests at loading rate of 1 mm/s, as shown in Fig. 11. It is can be seen that the slight expansion of the experimental failure surface over the range of loading rates investigated is almost isotropic. Generally speaking, the mechanisms of rate sensitivity of cellular materials may be attributed to the effects of intrinsic length scale of the material, the rate sensitivity of base material, the compression and flow of gas in cells, micro-structural morphology including the form, shape, size of the individual cell and other effects such as inertia effect, which may cause the different deformation modes of the material at high strain rate cases. On the other hand, the mechanical properties of commercial foams usually have variations of ±5% from the mean value as highly heterogeneity of materials. Based on these considerations, we adopt the criterion of a 20% increase in failure stress to define the loading rate sensitivity. It is consistent with the fact that metallic foams are highly heterogeneous materials with scatter width of the order of 20% [47]. It can be seen that there is no obvious loading rate effect on the failure stress and the experimental failure surface for the closed-cell aluminum alloy foams over the range of loading rates investigated. It is essential for the foams to further investigate the loading rate effect on the failure surface under higher loading rate conditions, which is still on the way.

5. Conclusions

Three different types of tests, i.e. uniaxial compression, uniaxial tensile and combined shear–tensile, were performed on the closed-cell aluminum alloy foams with nominal relative densities of 10%, 15% and 20% to investigate their failure behaviors under different loading conditions. Under uniaxial loading conditions, Bending is the dominant mechanism of cell-wall deformation in the linear–elastic stage. The failure mechanism in uniaxial tension is quite different from that in uniaxial compression. The aluminum alloy foams crush progressively due to plastic buckling of the cell-wall in compression; in contrast, they local ductile fracture corresponding to the propagation of a single crack in tension. This difference in the mechanism results in that the tensile failure stresses of three relative densities are all significantly higher than the corresponding compression failure stresses, respectively. The materials apparently exhibit uniaxial failure strength asymmetry. The failure stresses of three relative densities under combined shear–tensile conditions were measured to determine the experimental failure surfaces. The shape of the failure surface is not sensitive to the relative density over the explored range (10–20%) if failure stress components are normalized as the uniaxial compressive failure stress ($\sigma_f$) of the corresponding foam, respectively. Three phenomenological failure criteria can give an approximate description of the experimental failure stresses of the aluminum alloy foams when proper plastic Poisson’s ratio is employed. The accurate measurement method for the plastic Poisson’s ratio should be further investigated. The failure stresses of three relative densities at loading rate of 500 mm/min are all slightly higher than the corresponding failure stresses at other loading rate under combined tests. The experimental failure surfaces for three relative densities all exhibit an almost isotropic expansion over the range of loading rates studied. It is essential for the foams to further investigate the loading rate effect on the failure surface under higher loading rate conditions, which is still on the way.

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