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Density Dependence of the Compressive Behaviors of Closed-Cell Al Foams Manufactured Through Powder Metallurgy Route

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The compressive deformation behaviors of closed-cell Al foams manufactured through powder metallurgy route with various relative densities have been studied. The high-density specimens displayed smoother stress-strain curves and more stable compressive behaviors. The stress-strain curves for low-density specimens displayed a regular fluctuation and more than one stress drop were observed. This can be attributed to the different deformation mode due to density variation. The effect of relative density on the stress drop ratio was studied. The results show that the stress drop ratio decreases with relative density. The compressive deformation mode changes as the relative density is <0.15.

Keywords aluminum foams, powder metallurgy, relative density and mechanical properties

1. Introduction

Metallic foams have received increasing attention in recent years. Significant progress has been made in the studies on production, characterization, and performance test of metallic foams (Ref 1-8). The results of such studies raised awareness of the potential application prospects. For example, they are promising candidates for functional and structural applications (Ref 1, 2), sound absorption, and energy absorption (Ref 9-12). Aluminum (Al) foam is one of the common metallic foams. Many researchers have investigated the mechanical properties of various Al foams, e.g., Alulight (Ref 4), Alporas (Ref 3, 13), and Alcan (Ref 3). All the results show that the Young's modulus and yield stress are related to the relative density. In addition, Gibson and Ashby model (Ref 14) also shows the relation between them by:

$$\frac{E^*}{E_s} \approx \left(\phi\frac{\rho^*}{\rho_s}\right)^2 + (1-\phi)\frac{\rho^*}{\rho_s} \quad \text{(Eq 1)}$$

$$\frac{\sigma^*}{\sigma_s} \approx 0.3\left(\phi\frac{\rho^*}{\rho_s}\right)^{3/2} + (1-\phi)\frac{\rho^*}{\rho_s}, \quad \text{(Eq 2)}$$

where ϕ is a measure of the distribution of the solid between the cell walls and edges. E^*, σ^*, and ρ^* are the Young's modulus, yield stress, and density of metallic foam, respectively. E_s, σ_{ys}, and ρ_s are the Young's modulus, yield stress, and density of matrix material, respectively. Although various studies on compressive behaviors of metallic foams have been conducted, little work has been done on the stability of compressive deformation for Al foams manufactured through a powder metallurgy route. It has been shown that the significant stability on compression implies the smooth stress-strain curve and long stress plateau. For metallic foams, the compressive stability is obviously of great importance to the energy absorption since the intensity and stability of plateau stress determine the energy absorption level and controllability.

In this study, the evident fluctuation was found in stress-strain curves for specimens with low-relative densities (<0.11), but such fluctuation for high-relative densities specimens was not observed. This indicates that the relative density has a notable effect not only on plateau stress, but also on the stability of compressive stress-strain curves. It is, therefore, necessary to investigate the effect of relative density on the compressive stability of closed-cell Al foams.

2. Experimental Procedure

The closed-cell Al foams with various densities have been manufactured through powder metallurgy route. This preparation process consists of mixing three powders, usually the aluminum powder with a purity of more than 99.0% and D_{50} of 117 μm, the foaming agent, typically TiH_2 (0.6 wt.%), with purity of 99.6% and D_{50} of 33 μm and the additive Mg powder(1.0 wt.%) with purity of more than 98.0% and D_{50} of 129 μm, and then pressing the mixture under a pressure of 400 MPa to obtain more than 99% of theoretical density. Subsequently, the precursor material was foamed in a preheated resistance furnace at 800 °C. The samples with various densities can be obtained by controlling the foaming time. After a certain period, the foamed samples were cooled down by water quenching. Al foams produced by this technique exhibit a closed porosity. The relative density is defined as ρ^*/ρ_s, where ρ_s is the density of the matrix. Quasi-static

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compression tests were conducted in CMT5105 material testing system with a rate of 2 mm/min, i.e., with a strain rate of 1.1×10^{-3} in the specimens.

The architecture and the cell morphology of a sample are shown in Fig. 1. According to Gibson and Ashby (Ref 14), the smaller the cell size and the thicker cell wall, the larger the relative density will be. From Fig. 1(a), it can be seen that cells in the center of the sample exhibit both a greater size and a thinner wall. The architecture in the center of the sample is more consistent with the "foam." Compressive specimen with a diameter of 30 mm and a length of 30 mm therefore was cut in the center position of a sample. Figure 1(b) and (c) displays Plateau borders of two compressive specimens with relative densities of 0.15 and 0.07. It is clear that the cell wall thickens with the increasing relative density.

3. Results and Discussion

Two representative compressive stress-strain curves for Al foams are shown in Fig. 2. The relative densities of two specimens are 0.22 and 0.13, respectively. It is obvious that the high-relative density specimen exhibits a higher yield stress. The low-relative density specimen, however, exhibits a longer stress plateau. Figure 2(b) and (c) is the detail with enlarged scale of Fig. 2(a).

Comparing with two figures, one can see that the stress-strain curve for specimen with the relative density of 0.22 (see Fig. 2b) is smooth and there is no distinct demarcation between elastic region and plateau region, the flow stress steadily increases with the strain. In addition, the strain softening, followed by strain hardening, begins at a strain of approximately 0.006 (I region in Fig. 2b). II region represents the strain-hardening region as the strain exceeds 0.037. In this region, plateau stress slowly rises with the strain. The distinct deformation bands are not found throughout the compression test for the specimen, indicating a homogeneous deformation for high-relative density specimen.

Figure 2(c) displays three similar regions in the stress-strain curve for the specimen with the relative density of 0.13 at the strain range of 0-0.5. In I region, the linear elastic region is followed by a sudden decrease of stress after the first peak stress. A randomly formed localized deformation band with a width of approximately single cell is observed during the test (see Fig. 3), and yielding begin with the weak links, which are the weakest parts in cell walls as shown in Fig. 1(c). Figure 3 shows the surface of deformed specimen with the relative density of 0.13, where the specimen is compressed at a strain of 0.37. Deformation band is indicated by surrounding dashed lines. There distinct deformation bands surrounded by white dashed lines could be found in the certain strain. Another impending formation of deformation band (surrounded by red dashed lines) is also marked in further compression.

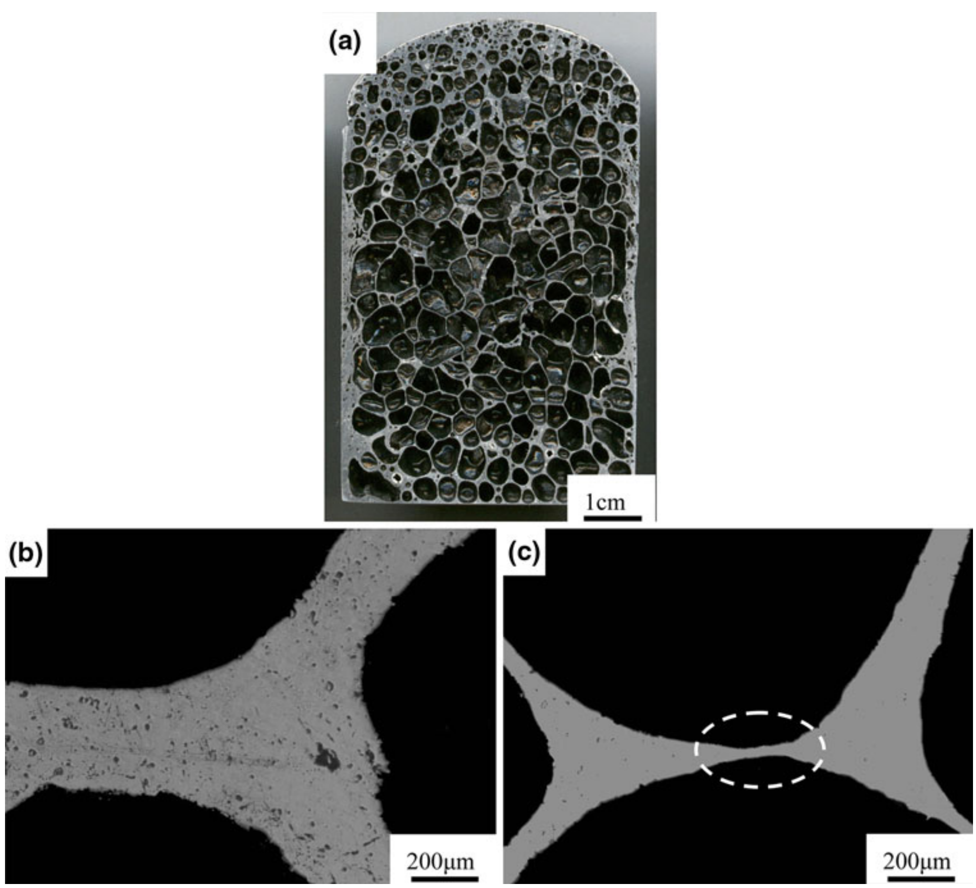

Fig. 1 The architecture and the cell morphology of Al foams. (**a**) Al foam sample manufactured through a powder metallurgy route; (**b**) and (**c**) Plateau border in cell wall, the weak link was marked with oval-shaped *dotted line*. Relative densities of (**b**) and (**c**) are 0.15 and 0.07, respectively

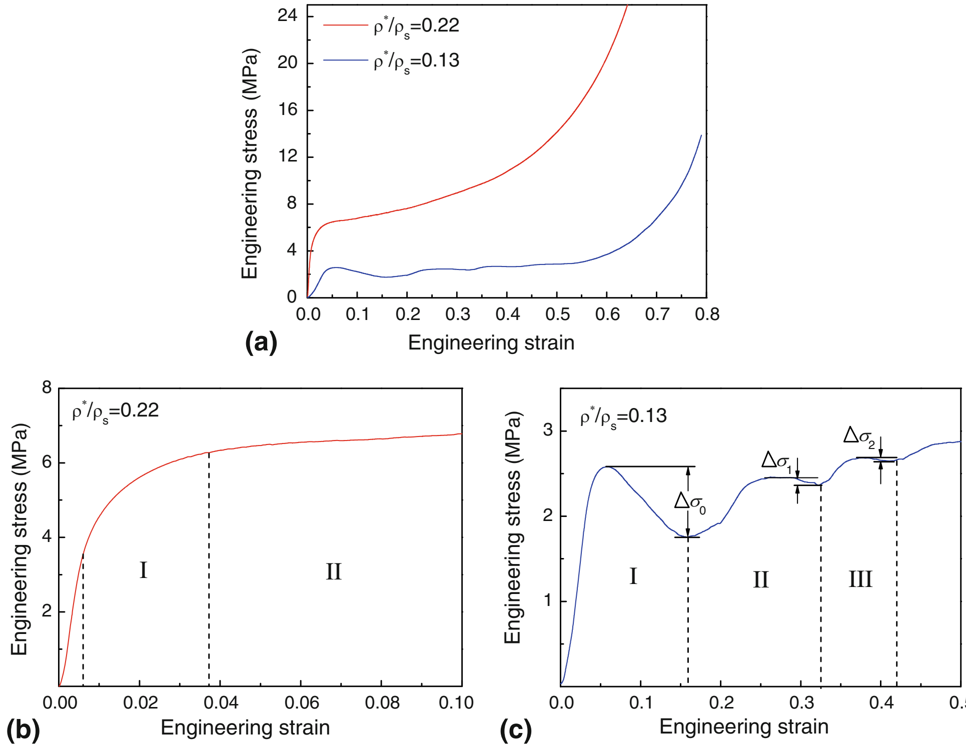

Fig. 2 Compressive stress-strain curves for Al foams specimens with relative density of 0.22 and 0.13 (a) up to densification strain (b) for specimen with the relative density of 0.22 (c) for specimen with the relative density of 0.13, the stress drop $\Delta\sigma_0 = 0.82$, $\Delta\sigma_1 = 0.09$, and $\Delta\sigma_2 = 0.03$

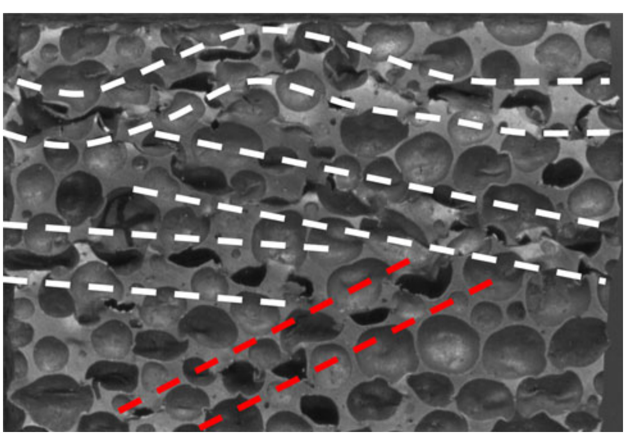

Fig. 3 Surface of compressed specimen ($\varepsilon = 0.37$) with the relative density of 0.13. Deformation bands are indicated by surrounding *dashed lines*

The process spreads the collapse across the entire loaded section. The stress recovered slightly as the layer of cell is nearly compacted and the valley stress occurred in the stress-strain curve, the difference between peak stress and low valley stress being $\Delta\sigma$. With the increase of the strain, the collapse occurred in new layers and the process above constantly repeated, as evidenced by the $\Delta\sigma_1$ and $\Delta\sigma_2$ in II region and III region. However, $\Delta\sigma_0 > \Delta\sigma_1 > \Delta\sigma_2$ can be clearly seen in Fig. 2(c), indicating that released stress decreased gradually as a layer of cell collapsed, primarily because a certain amount of plastic deformation in new layers have accumulated during previous deformation stages.

In light of the above results, it is suggested that relative density have significant effect on the compressive deformation mechanism of closed-cell Al foams manufactured through a powder metallurgy route. Compared with the high-density specimen, low-density specimen exhibits different deformation mode. It can be attributed to the weak-links and thin cell walls in low-density specimen.

In order to determine the density dependence of compressive deformation modes of Al foams with various relative densities, the compressive tests for specimens with relative density from 0.056 to 0.24 were conducted. The results are shown in Fig. 4(a), where the stress-strain curve achieved increasingly smooth with the increase of relative density of Al foams. The ratio between the first stress drop $\Delta\sigma_0$ and plateau stress σ^* is plotted versus the relative density in Fig. 4(b), where two regions are divided.

For the specimens with a relative density of <0.11, the ratio of $\Delta\sigma_0/\sigma^*$ reaches more than 30% (even up to 53%) in I region, indicating that the compressive stress is highly unstable. The ratio of $\Delta\sigma_0/\sigma^*$ exhibits a rapid decline as relative density rises from 0.11 to 0.14, which shows that the stress is sensitive to change of relative density in this stage. In II region, the values of $\Delta\sigma_0/\sigma^*$ are <0.05 as the relative density exceeds approximately 0.15, indicating a slightly stress drop in the stress-strain curve. Thus, the relative density $\rho^*/\rho_s = 0.15$ can be taken as the critical relative density. It can be concluded that the stress-strain curve will get smoother with the increase of relative density, indicating an increasing stability for high-density Al foams. However, the compressive behaviors of Al foams prepared by powder metallurgy route with higher relative density (up to 0.3) are not discussed due to the experimental limits.

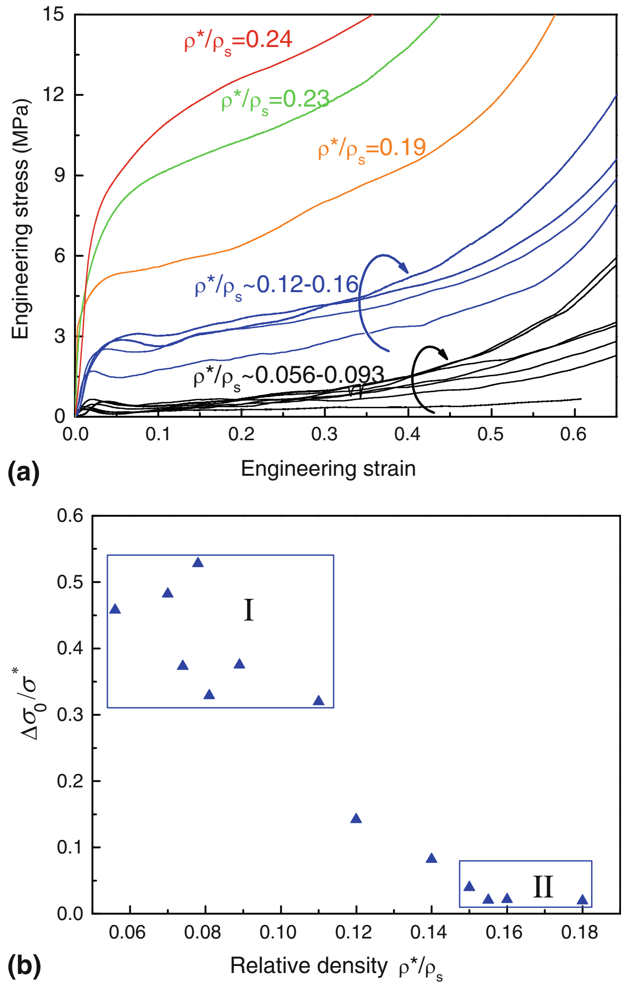

Fig. 4 Compressive stress-strain curves for Al foams (a) for specimens with relative density from 0.056 to 0.24. (b) The ratio of $\Delta\sigma_0/\sigma^*$ plotted against the relative density ρ^*/ρ_s. I region—the low-density region with high $\Delta\sigma_0/\sigma^*$; II region—the high-density region with the $\Delta\sigma_0/\sigma^*$ almost zero

4. Conclusions

The relative density has significant effect on the compressive deformation behaviors of closed-cell Al foams manufactured through powder metallurgy route. The compressive deformation modes for Al foams with various relative densities are different. The higher relative density is, the smoother the stress-strain curve, and the more stable compressive process will be. The fluctuation of stress-strain curve for low-density foam is consequent on the weak links and thin cell walls. The results also show that the ratio of $\Delta\sigma_0/\sigma^*$ decreases with increasing relative density. Moreover, the critical relative density $\rho^*/\rho_s = 0.15$ is determined.

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