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Deformation mechanisms of spherical cell porous aluminum under quasi-static compression

Zhiqiang Fan [a,*], Bingbing Zhang [b], Yubo Gao [a], Xuefeng Guan [a], Peng Xu [a]

[a] *School of Science, North University of China, Taiyuan 030051, China*
[b] *School of Chemical and Environmental Engineering, North University of China, Taiyuan 030051, China*

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ABSTRACT

Quasi-static compression tests for a novel type of spherical cell porous aluminum prepared by the space-holder method were conducted. Formation and evolution mechanisms of deformation bands on the macro and micro scale were monitored and discussed by using a digital image correlation procedure. Effect of micro strain concentrations on the formation process and morphology of deformation bands at the macro level was analyzed in detail. In total three deformation modes of spherical cells and four failure modes of cell membranes including bending, shear, combined compression-shear, and eventually tearing were identified.

Aluminum foams are a group of structural materials which are highly valued due to their excellent performances in energy absorbing and damping with ultra-light in weight. It has been proposed that aluminum foams with homogeneous cell morphology and uniform cell size exhibit better isotropy and mechanical properties [1–2]. Therefore, as a novel kind of porous aluminum, spherical cell/pore porous aluminum materials have attracted great interest in the past decade. Cells in the materials are regular spherical and the size can be accurately controlled. Also the cells can be interconnected with each other by setting several openings in different orientations on cell walls. In consequence the spherical pore porous materials with high permeability contain abundant cell walls as compared to traditional open-cell Al foams, wherein cell walls degenerate to bar-beam system. This structure pattern contributes to energy absorption since the cell membranes could produce complex failure modes and appears to be more functional than close-cell aluminum foams in some special applications. Therefore preparation and mechanical properties of spherical cell/pore porous aluminum have been widely studied [3–5]. Nevertheless, the compressive behaviors of spherical cells are still unclear.

The compression behavior of aluminum foams could be generally classified into three stages, namely, a linear-like compression process at the first stage, a stress plateau with slight hardening at the second stage, and a densification process at the third stage. The stress plateau stage, which is associated with the cell collapse process incorporating with different evolutionary patterns of deformation bands, plays a dominant role in energy absorbing [6]. Besides, great efforts had been made to study the deformation mechanism of aluminum foams in the stress plateau stage [7–8]. It is widely accepted that the macro forming processes and evolutionary pattern of deformation bands significantly influence the yield strength and the plateau stress of foams. While such macroscopic phenomena are appreciated, the specific mechanisms operating at the cell/membrane level have yet to be adequately identified.

According to preliminary studies, typical deformation modes of cells and failure modes of membranes have been proposed and identified for closed-cell aluminum foams [9–10]. It is also demonstrated that behaviors and strain-induced damages of microstructures such as cells and membranes have a substantial effect on the mechanical properties and deformation mechanisms of materials [11–14]. However, the association of the deformation/failure modes and the energy absorption were mainly discussed in the results while the implications of micro-structural responses and the behaviors of deformation bands were not well characterized. Such investigations are still very limited, not even for spherical cell porous aluminum.

The purpose of this study is to investigate the compressive behavior and failure mechanism at macro and micro level for spherical cell porous aluminum. The associations of failure mechanisms at cell/membrane level and the forming process of deformation bands at the initial collapse stage are qualitatively explored by using a digital imaging correlation (DIC) approach.

Open-cell porous aluminum were manufactured by the space-holder method and provided by Qiangye Metal Foam Ltd. The cell size is 6 mm while the matrix is pure aluminum. There exist 4–6 openings

* Corresponding author.
E-mail address: fanzhq@nuc.edu.cn (Z. Fan).

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with size of 1–2 mm in different orientations on the wall of each spherical cell. The compression specimens were cut from the part of a block where the cellular structure is quite homogeneous. The cylindrical specimens had a uniform size, with diameter 40 mm and 40 mm in height as indicated in Fig. 1 (a). The density of specimens varied from 0.813 to 0.96 g/cm^3.

Axial quasi-static compression tests were conducted using a SUNS 6104 material testing system with a rate of 1.0 mm/min. Surface digital images of the deformation process were acquired by GOM 5M system. The system was equipped with two commercial video cameras with a CCD array of 2560 × 1920 pixels. Two optic light sources were used to provide oblique blue light illumination and shadow reduction. The testing system was precisely demarcated with a standard calibration panel of 40 × 50 mm^2. Accordingly, a fine pattern of random white-black speckles was sprayed on the surface of specimens, resulting in a well-defined contrast pattern as shown in Fig. 1 (b). Note that the irregular and roughness surface of samples somehow limited the quality of speckle pattern. Images were captured at 6 s intervals to facilitate the use of DIC method based on ARAMIS V8 to acquire deformation patterns on macro and micro scales.

Fig.1 shows a typical stress-strain curve and maps of axial nominal strain. It can be seen that the macro deformation bands dominated collapse behavior of cells in the stress plateau stage as mentioned before. It was also found that the bands have already formed at the initial plastic yielding stage, which could be divided into three sub-stages [9].

Stage I, nominally linear elasticity stage ($\varepsilon_A \le \varepsilon_E$), wherein the strains are approximately randomly and uniformly distributed as indicated in Fig. 1 (d). *Stage II*, at $\varepsilon_E \le \varepsilon_A \le \varepsilon_B$, characterized by non-linearity deformation, the tangent modulus E = 481 MPa rapidly decreases to a relatively stable value which corresponds to the hardening modulus in the stress plateau stage. The plastic collapse stress, which is in an exponential relationship with relative density [15], varies in 4.0–5.4Mpa for testing samples and is about 20% higher than that of spherical cell aluminum foams processed by powder metallurgy [3]. Meanwhile the overall strain contours tend to localize into multiple deformation bands as shown in Fig. 1 (e). *Stage III*, at $\varepsilon_A \ge \varepsilon_B$, the sample exhibits strain hardening behavior with a certain plasticity modulus, till the overall strain reaches the densification strain of about 0.52. In this stage, the spherical cells start to collapse as the bending moment exerted on the curved cell membranes exceeds the fully plastic moment. Collapse of cell occurs, forming macro localized deformation bands as indicated in Fig. 1 (f). With continued compression, the deformation band further causes collapse of its neighboring cells and finally leads to global failure of the specimen.

As the figure suggests, the deformation bands mainly take place at an angle of about 10–30°, validated by other tests and this range is also observed for closed-cell aluminum foams [9,10,16]. In general membrane wiggles as well as initial structural defects both disperse initial mechanical behavior of cells. When the foam is compressed, collapse first occurs at the weakest cells which are randomly distributed in the sample, thus forming multiple random deformation bands. Therefore, the mechanism of the deformation on the macro level could be summarized as the homogenous failure mode, characterized by a type of global distributed failure and acted on the entire specimen. This phenomenon is in accordance with that of closed-cell aluminum foam under quasi-static and low velocity impact loading [8].

It has been reported that energy absorption of aluminum foams are in relation to the cell shape and structural failure mode at the cell level [17]. Three deformation mechanisms proposed in Ref. [9] were also identified in the present study. Mechanism I, as shown in Fig. 2 (a1), cells go into large distortions along the compression axis, with limited shear deformation while without apparent rotation. Mechanism II involves large distortion and obvious rotation, which creates shearing stress as indicated in Fig. 2 (a2). Mechanism III, characterized by Fig. 2 (a3), includes distortion and in-plane shear failure, which exerts significant influence on axial shear deformation to cell walls. In total spherical cells show similar compressive behavior to typical closed-cell Al foams.

On the micro scale, failure patterns of membranes can be categorized into four modes [10]. Mode A involves bending of cell membranes and then inception of plastic hinges as shown in Fig. 2 (b1). Mode B and C occurs due to tension and shearing, as indicated in Fig. 2 (b2) and (b3) respectively. Tension is caused by tensile stress introduced by lateral deformation perpendicular to the loading direction, while shearing stress and deformation are parallel to the compression axis. However, limited ductile tearing on membranes is observed in the current study. Mode D is composed of lateral stretching and axial buckling, which result in a combination of crumple deformation and rupture along the compression direction at high strain level. This failure pattern was

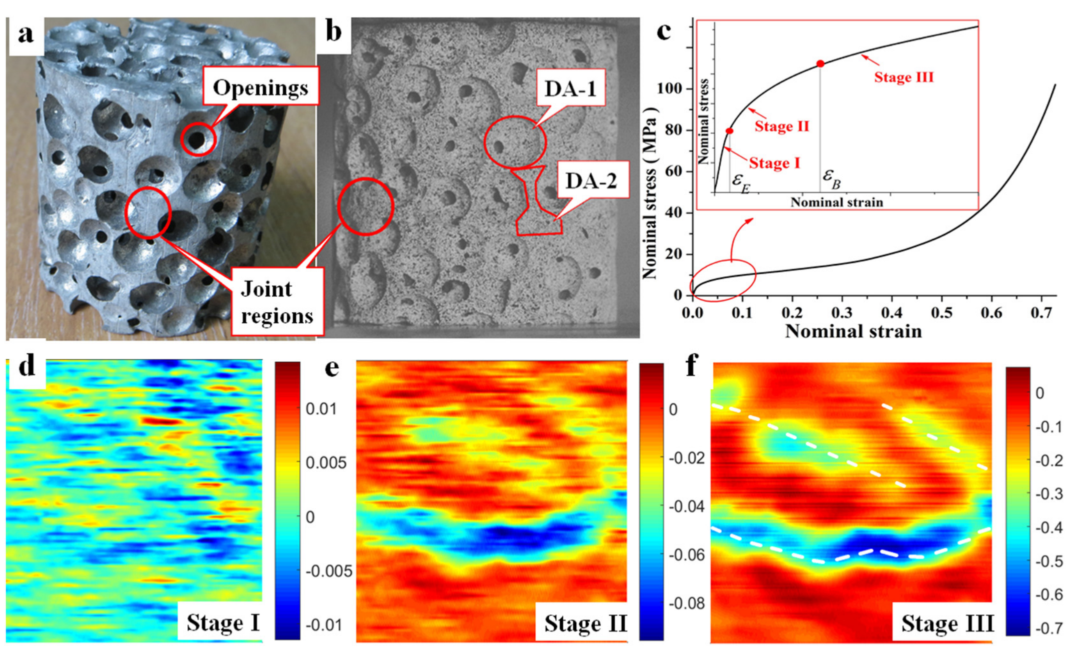

Fig. 1. Specimen and its compressive behavior. (a) Spherical pore porous aluminum sample. (b) Specimen with contrast random speckle pattern on the surface. (c) Typical stress-strain curve. (d–f) Axial strain maps in the three stages and deformation bands.