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The effect of cell-size dispersity on the mechanical properties of closed-cell aluminum foam

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ABSTRACT

The mechanical properties of open-celled and closed-celled metallic foam are strongly influenced by the cellular microstructure and material properties of the base material from which the foam is made. The present study investigated the microstructure and mechanical properties of ALPORAS closed-cell Al foam. In particular, the effect of cell-size dispersity on the Young's modulus of foam was investigated through crushing experiments and numerical simulations. Crushing experiments were first conducted on two mutually perpendicular directions. Numerical models of varying cell-size dispersity and complexity were subsequently developed, including the monodispersed model that is based on the Kelvin structure, the bidispersed model, and the polydispersed model that is based on the random Laguerre tessellation algorithm. The numerical models were discretized using shell elements, and the simulations were conducted using the ABAQUS finite element method software. Relative Young's moduli with various relative densities were predicted, and the numerical convergence on the model size was studied accordingly. Numerical results obtained from all three numerical models developed were found to overestimate the experimental results by a factor of approximately 3. The difference between the numerical and experimental results can be attributed to the difference in detailed microstructural characteristics. Furthermore, the difference among numerical results obtained from the three models was insignificant.

1. Introduction

Closed-cell foams are a class of cellular material with unique physical and mechanical properties. Their lightweight nature coupled with their high strength make them attractive candidates in applications that require such properties. Additionally, foams exhibit excellent energy-absorbing capabilities. When subjected to impact compressive loadings, they can dissipate the impact energy by collapsing their cellular microstructure; consequently, they are often used for protective purposes [1–3]. The microstructure of closed-cell foam consists of complex irregular polyhedra, and the materials are concentrated on the cell walls and the struts that are formed by intersecting cell walls.

To investigate the mechanical properties of closed-cell foam, numerous numerical models have been proposed. For instance, in their numerical study, Ma et al. [4] attempted to treat complex 3D cellular microstructures as 2D microstructures. They determined that numerical models that were based on 2D structures oversimplified the 3D cellular microstructures and thus failed to reproduce the mechanical properties of the foam studied. As for 3D numerical models, Gibson and Ashby [5] proposed a cube structure for foam simulations. Implementing it was straightforward, but the structure seemed too simple to be realistic when compared with real foam microstructures. Meguid et al. [6] constructed a multi-cell model to investigate the compressive mechanical behavior of closed-cell foam and successfully reproduced the deformation localization phenomenon that they had observed during their experiments. Kadkhodapour and Raeisi [7] developed numerical models that were based on pyramidal, ellipsoidal, and spherical geometry and studied the effect of cell irregularity and cell-wall thickness distribution on the mechanical properties of closed-cell foam. The Young's moduli that he obtained were greater than those of the experimental results, whereas the local stress peaks were close to those obtained during experiments.

Another widely known example is the tetrakaidecahedron structure proposed by Lord Kelvin [8], which has 14 slightly curved faces (6 hexagons and 8 squares) and an average of 5.1 edges per face. The Kelvin structure resembles the geometric characteristics of the cellular microstructure of many foams. Because the Kelvin structure is realistic and easily implemented, it has been adopted by many researchers as the numerical model for open- and closed-cell foams. For example, Gong et al. [9] and Jang et al. [10] performed comprehensive studies on the mechanical properties of respectively PU and Al open-cell foams by means of experimental as well as numerical efforts. They both

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concluded that the Kelvin structure was representative as compared to the foam characteristic cellular microstructure and was able to successfully reproduce experimental results. Gholami et al. [11] adopted the Kelvin structure to investigate the effect of partially opened windows on mechanical properties of PU foams. They reported that Young's modulus of the foam increases as the percentage of closed windows increases. On the other hand, the Poisson's ratio decreases for the same amount of variation in closed pore content. In the case of closed-cell foams, Song et al. [12] studied numerical models based on both the Kelvin structure and the Voronoi tessellation algorithm. They determined that the stress plateau of the Voronoi model was slightly higher than that of the Kelvin model. Later, Weaire and Phelan [13] proposed a structure consisting of two 12-faced polyhedra and six 14-faced polyhedra. Although this structure also exhibited the morphology of many foams, implementing it was complicated, and therefore it has not been adopted by many researchers.

The foregoing studies have mainly employed numerical models that were based on ideal (and thus unrealistic) structures or structures of monodispersed cell size, others, by contrast, have focused on the effect of cell-size dispersity on foam behavior. For instance, Czekanski et al. [14] developed a numerical model that was based on ellipsoids of two different sizes to investigate the compressive mechanical behavior of foam material. They determined that the effects of the cell size and shape were insignificant on the foam compressive mechanical response. Grenestedt [15] proposed a bidispersed structure consisting of an 18-faced polyhedron and three 12-faced polyhedra stacked in a face-centered cubic arrangement. The average number of faces per cell was 13.5 and the average number of edges per face was 4.9; both figures were similar to those of the microstructure of real foams. Lautensack [16] analyzed CT (computed tomography) images to acquire geometric parameters. He then employed the Laguerre tessellation algorithm to use these parameters to develop cell-size polydispersed random numerical models. These numerical models had the advantage of structural randomness, which enabled the models to embody the elaborateness of the cellular microstructure. The major disadvantage, on the other hand, was the complexity of model generating procedure. Redenbach et al. [17] adopted the Laguerre numerical models to investigate the degree of cell-size variation in the Young's modulus. They determined that the Young's modulus gradually decreased as the degree of cell-size variation increased if the relative densities remained the same.

The present study investigated the effect of microstructural characteristics on the mechanical properties of closed-cell foam through crushing experiments and numerical simulations. The effect of cell-size dispersity on the Young's modulus was of particular interest. Both regular and random numerical models were developed for this purpose on the basis of statistical measurements from an independent study [18].

2. Methods

2.1. Material

The closed-cell foam used in the present study was manufactured by Shinko Wire Co., Ltd. (Japan). The dimensions of the as-received foam block were $600 \times 600 \times 150\text{mm}^3$. To prevent distortion and damage to the cellular microstructure, the specimens were removed from the foam block using a wire electrical discharge machining technique. A typical specimen was a cube whose dimensions were $35 \times 35 \times 35\text{mm}^3$, as shown in Fig. 1. A specimen with the selected dimensions, i.e., $35 \times 35 \times 35\text{mm}^3$, comprised approximately 10 cells in each of the 3 principal directions and was found to yield “converged” mechanical response [18].

Fig. 1. Typical tested specimen.

2.2. Experiments

2.2.1. Crushing Experiment Procedure

Crushing experiments were conducted using an MTS 810 universal material testing system machine. In the experiments, the specimen to be tested was placed between two parallel rigid platens as shown in Fig. 2. The upper platen remained fixed, whereas the lower one moved upward under displacement control. So that the test could be performed in a quasistatic condition, the displacement rate $\dot{\delta}/H$ was set at $7.5 \times 10^{-4} s^{-1}$, where H is the initial height of the specimen and δ is the upward displacement of the lower platen. The reaction force of the upper platen and the displacement of the lower platen were outputted for the compressive mechanical response.

2.2.2. Typical Compressive Mechanical Response

Fig. 3 shows the compressive stress (σ_1 = force / undeformed area, where the subscript “1” indicates that the crushing was performed in the D_1 direction defined in Section 2.3)-displacement (δ/H, where H is the initial height of the specimen) response that is characteristic of many other cellular materials. The response consisted of a linear regime during which the cells deformed rather uniformly. The linear regime terminated into a local stress maximum σ_l (σ_l = 486 psi at $\delta/H = 0.048$). An unloading was performed immediately after the local stress maximum and the Young's modulus of this particular specimen was measured as the slope of the unloading section of the response [19], as

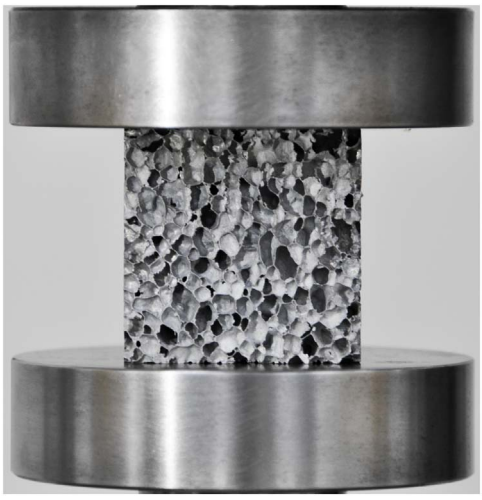

Fig. 2. Experimental setup.