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On compressive deformation behavior of hollow-strut cellular materials

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ABSTRACT

We investigated the compressive deformation behavior of hollow-strut cellular materials. The present cellular structure consists of pentagon and/or hexagonal shaped cellular network, where the individual strut cross-section is hollow triangular prism. The porosity of entire cellular material network is 96.5%. Uni-axial compressive test was applied, and both macroscopic (network-level) and microscopic (strut-level) deformation behaviors were investigated. The macroscopic nominal stress–strain curve showed a linear relationship during elastic deformation, and then a stress plateau region was observed, followed by the gradual increase in plastic flow stress. Next, by using X-ray micro-CT technique, the strut geometry was quantitatively identified, and based on which finite element method (FEM) was carried out to elucidate the relationship between the strut geometry and the microscopic/macroscopic elastoplastic deformation. A three dimensional spatial structure unit model was established to mimic the present open-cell structure, where the employed strut material properties were obtained from micro-indentation experiments. The FEM computational result agrees reasonably with experimental one of the macroscopic Young's modulus and yield stress. It also suggests that the stress concentration occurs in the minimum cross-section of strut, and then plastic deformation starts at this local point. Such a local yield phenomenon becomes a trigger of buckling for strut, leading to macroscopic plastic deformation characteristics. Furthermore, strain rate effect of the present cellular material was investigated numerically. The obtained result showed reasonable deformation behavior, but this may be improved in the future.

1. Introduction

Low-density porous/cellular materials and foams have been widely used for a variety of applications, such as light structural components and impact energy absorption. The macroscopic deformation for such materials is strongly dependent on the cellular structure (i.e. porosity, pore shape and strut geometry etc.) [1–3]. Their deformation mechanisms have been well investigated, in particular the relationship between the porous structure and macroscopic deformation. The pioneering work (by Gibson and Ashby) systematically established the simple analytical model for prediction of stiffness and strength with respect to a relative density of the foam [3]. Many previous studies have shown that the macroscopic stiffness and strength are governed by cell wall (strut) bending [3,4]. For these cellular materials, the cell wall and strut cross-section were typically homogeneous solid.

With increasing industrial demand, new ultra-light materials processing great specific stiffness and strength have been developed. To further decrease the weight while improving the mechanical properties, new geometry of strut was explored [5]. In particular, hollow strut (sometimes called hollow lattice structure) has been recently investigated [5–8]. It was suggested that the hollow-strut foams/lattice structures are expected to have superior mechanical properties, compared to the solid-strut foam of the same relative density [5,9–12]. In particular the hollow cross-section enhances bending stiffness of the strut at the same relative density, resulting in enhancement of the macroscopic mechanical properties. In order to produce the hollow-strut foam, polyurethane foam was firstly used as the template [12], and then electroplating was conducted to make the hollow-strut structure, forming a cellular network.

Despite few previous studies on the hollow-strut cellular material, the relationship between the microscopic (strut-level) and macroscopic (cellular network-level) deformation mechanisms remains unclear. The enhancement of the Young's modulus of the hollow-strut foam was found not to be large [3], whereas the enhancement in steady-state creep performance [13] was reported to be significant and may exceed an order of magnitude. More recently, the yield stress, buckling strength, damage tolerance of the hollow-strut foam were investigated analytically by Fan et al. [9]. However, to our best knowledge, experimental investigations for such materials were insufficient, compared to solid-strut cellular material. Moreover, a systematic framework

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relating the microscopic structural and macroscopic property is crucial and still lacking.

This study investigates the elastoplastic deformation behavior of hollow-strut cellular material, from both experimental and numerical aspects. An electroplating Ni–Cr cellular material with hollow-strut was employed, and uni-axial compressive test was carried out to understand the microscopic and macroscopic deformation behavior. The microstructure was observed by using X-ray CT (computed tomography) imaging and SEM (scanning electron microscope). In parallel, numerical simulation with finite-element method (FEM) was carried out to simulate the deformation behavior of the cellular material. The coordination between simulation and experiment, as well as that between microscopic and macroscopic material behaviors, elucidated the deformation mechanism of the hollow strut cellular material network.

2. Materials

The specimen used in this study was a hollow-strut cellular material, which is commercially available (as CELMET® made by Sumitomo Electric Industries, Ltd.). Scanning electron microscope (SEM, Quanta250) were used to observe the microstructure as shown in Fig. 1. It was found that the specimen consists of cellular network of Ni–Cr strut with three dimensional pentagon and hexagonal shape, which organizes the periodic cellular structure. The pore structure was nearly uniform. For a typical unit-cell, the pore diameter was about 0.9 mm. The macroscopic porosity was measured to be 96.5%.

For the manufacturing process of the present cellular material, polyurethane foam was first used as the template, and then Ni–Cr electroplating was conducted to make the cellular network. Subsequently, heat treatment was carried out to burn the template of polyurethane foam, and then the hollow-strut of Ni–Cr remained. The enlarged images in Fig. 1(c) show the cellular structure of Ni–Cr strut, whose unit-cell was approximately pentagon or hexagonal shape with three dimensional open-cell structure. Each junction of the cell connected with the other strut. However, the strut was not straight, indicating that the cross section of the strut as not uniform. X-ray CT technique (Micro-CT system, SkyScan 1172, Bruker Corp.) was thus used to carefully observe the geometry of one strut. The scanning parameters were set as X-ray source voltage of 59 kV, image pixel size of 4.08 µm and rotation step of 0.2°.

Fig. 2(a) shows the cross section of one-unit cell, whose strut was hollow triangular shape. In addition, it was found that the cross-section

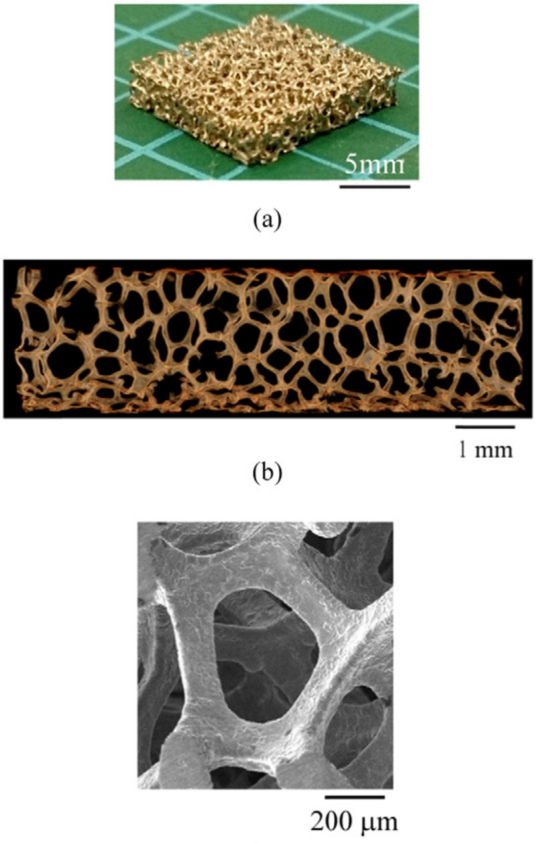

Fig. 1. Configuration and microstructure of the hollow-strut cellular material; (a) macroscopic view (the configuration of tested specimen is 10 mm × 10 mm × 2.5 mm), (b) cross section, and (c) magnified view of one-unit cell.

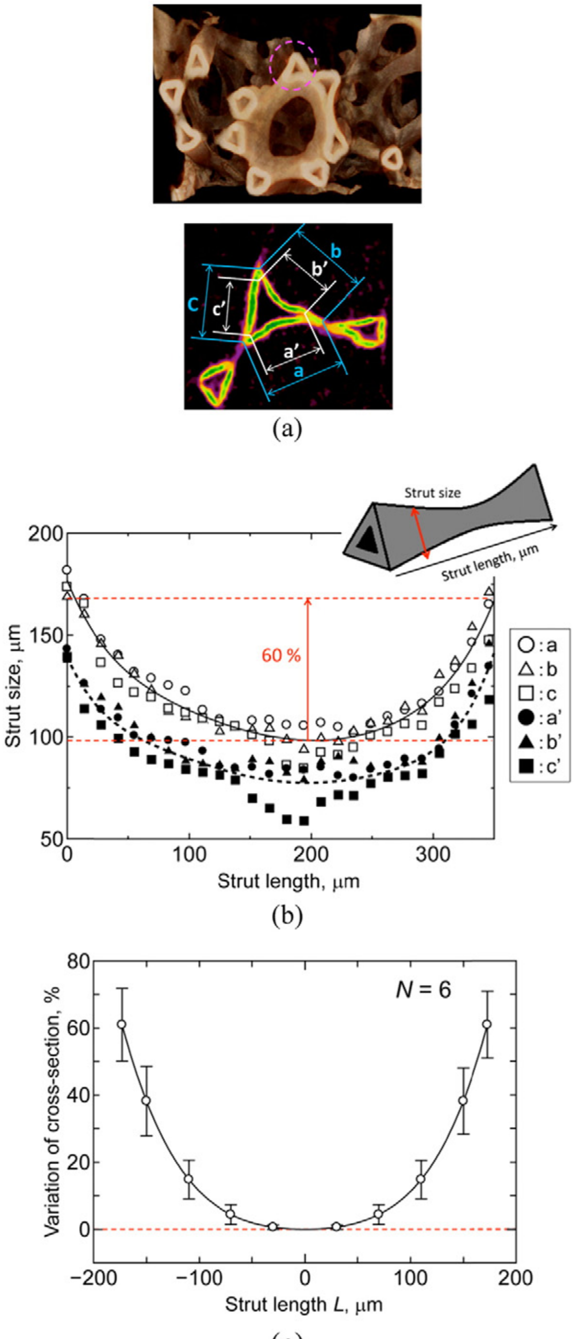

Fig. 2. Cross section of one-unit cell and strut observed by X-ray micro-CT technique (a), changes in cross-section size of one strut (b), and averaged variation of strut cross-section (c).