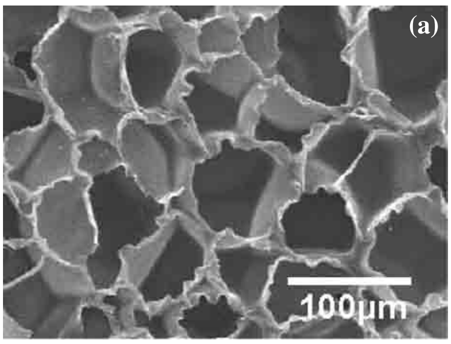
Imaging of polymer foam by three-dimensional computed tomography

In the design of footwear soles, one of the most important required functions is the shock-absorbing property for both injury prevention and athletic performance enhancement [1]. Polymer foam has been widely used for footwear soles because of not only its shock-absorbing property but also its flexibility and durability. The excellent shock-absorbing property of polymer foam is due to the microscopic cellular structure. Figure 1(a) shows an SEM image of polymer foam. Polymer foam has a closed cell structure comprising a polymer wall with thickness of 5–10 μm and cell of 50–500 μm in diameter. Figure 1(b) shows the typical stress-strain behaviors obtained from polymer foam and polymer (non-foam) under unidirectional compression. Polymer foam has high nonlinearity in its mechanical property compared with that of polymer (non-foam). The compressive stress-strain behavior of polymer foam can be classified into elastic, plateau, and densification regions. These mechanical behaviors are mainly a result of the cell (cell wall) deformation under compressive load. Since the shock-absorbing property predominantly depends on the amount of deformation energy accumulated in the plateau region, it is very important, for material design, to evaluate the deformation behavior of the cell in this region. In the evaluation of cell deformation behavior, surface observation has been performed by microscopy, but this is not appropriate because the surface is in the singular stress field. Exactly speaking, it is necessary to observe the inner structure to correctly evaluate cell deformation under compression. Three-dimensional X-ray computed tomography (CT) is a useful technique for non-destructively observing the inner structure of material. In the case of applying CT to polymer foam, both a large view field and high spatial resolution are needed. Since polymer foam consists of light elements such as carbon, hydrogen, and air, a high-flux light source is indispensable for polymer foam CT. In order to fulfill the above conditions, it is necessary to perform CT observation using synchrotron radiation. In this study, in order to improve the shock-absorbing property of polymer foam, the deformation behavior of the cell under various compressive stresses is evaluated by the CT technique.

In the experiment, cross-linked EVA (ethylene vinyl acetate) foam generally applied to footwear is used as the specimen. Its porosity is 0.79. EVA foam was fabricated by a one-shot press-molding process. The preformed compounds were composed of organic peroxide as a cross-linking agent, and azodicarbonamide as a chemical bowing agent. The molding conditions were as follows: temperature of 448 K, pressure of 10 MPa, and duration of 30 min. Under these conditions, the cross-linking agent and the bowing agent fully decomposed. The foaming reaction takes place during rapid decompression. The EVA foam specimen is cut to a cuboid shape, with 5 mm length, 5 mm width and 10 mm height. The CT experiment is performed at the Hyogo Prefectural beamline **BL08B2** by the absorption contrast method. In BL08B2, large-view-field and high-spatial-resolution CT measurements are possible. The X-ray energy is adjusted to 12.4 keV. Transmission X-rays are detected using the imager system comprising a P43-type powder phosphor screen, relay lens, and a 4008 × 2672-element cooled CCD camera. The effective pixel size of the detector is 4.28 μm, which is a satisfactory accuracy for observing cell deformation. The EVA foam specimen is inserted into an acryl tube on the rotation stage.



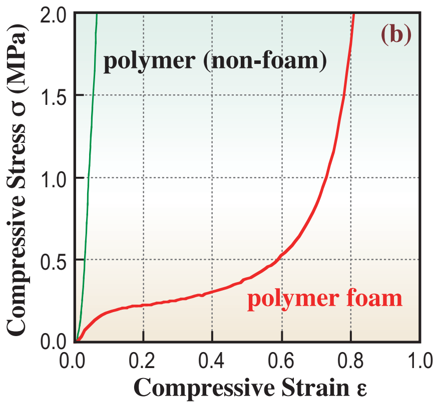


Fig. 1. Typical mechanical properties of polymer foam. **(a)** SEM image. **(b)** Typical stress-strain behavior of polymer foam and polymer (non-foam) under unidirectional compression.

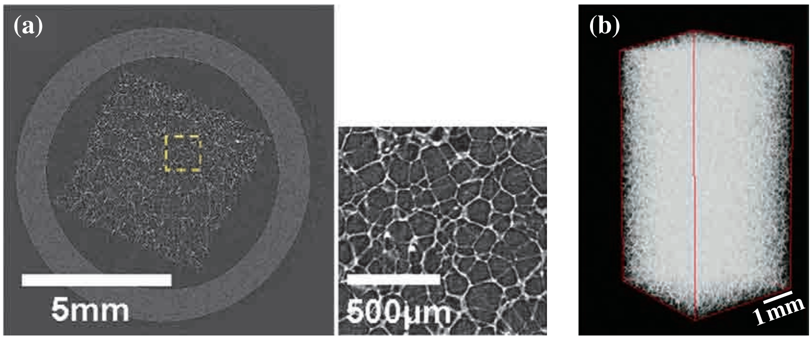


Fig. 2. CT image of polymer foam: **(a)** tomogram and **(b)** volume-rendering view.

The CT images are reconstructed by the back-projection method using 1000 transmission projections imaged through a 180° rotation of the specimen. It took 1.5 hour for the CT measurement.

Figure 2 shows a tomogram and three-dimensional rendering view of an undeformed EVA foam specimen. In Figure 2(a), the cell (dark domain) and cell wall (white linear structure) were clearly depicted, and closed cell structures were revealed. The diameter of the cell ranged from 100 to 300 μm, and the thickness of cell walls ranged from 10 to 20 μm. In Figure 2(b), the three-dimensional rendering view shows that cells were dispersed intricately in three-dimensions with size distributions. Figure 3 shows the stress-strain behavior of the specimen and CT images of the inner layer parallel to the compressive direction. Arrows in the stress-strain curve correspond to these images, and ε in the CT images denote compressive strain. When $\varepsilon = 0$, the uncompressed state, each cell shape is isotropic. When $\varepsilon = 0.1$, the buckling behaviors are induced by the compressive load in some cell walls. In particular, the buckling of thin cell walls is dominant. This strain corresponds to the end of the elastic region. With increasing strain (ε = 0.1–0.6), cell-wall buckling increases and many flat cells appear. Judging from the above results, it is considered that the plateau region is a result of cell wall buckling. Hence, the low-stress increase rate in the plateau region originates from the cell-wall buckling. The buckled cell walls interrupt stress transmission. When $\varepsilon = 0.8$, most cell walls fully buckle and densification occurs. Moreover, buckled cells come into contact with each other, whereby the stress increases rapidly. These results indicate that compressive buckling of a cell is one of the most important design parameters in improving the shock-absorbing property of polymer foam. For the clarification of the shock-absorbing mechanism of polymer foam in detail, it is effective to observe the dynamic deformation by high-speed CT, and to combining CT data with the finite-element method. In the future, CT observation can contribute designing the properties of polymer foam, such as not only the shock-absorbing property but also durability and flexibility.

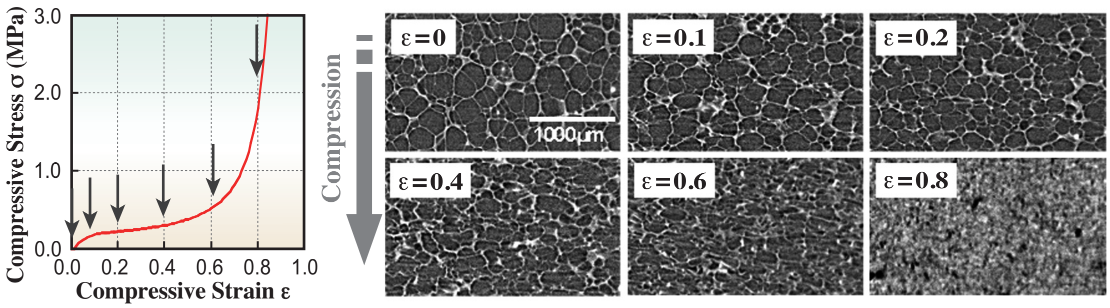


Fig. 3. Stress-strain curve of specimen and CT images of inner layer parallel to compressive direction. Arrows denote strain values corresponding to CT images.

Junichiro Tateishi* and Tsuyoshi Nishiwaki

Institute of Sport Science, ASICS Corporation

*E-mail: tateishi-ju@asics.co.jp

References

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