Polymer 83 (2016) 190–198

Contents lists available at ScienceDirect

Polymer

journal homepage: www.elsevier.com/locate/polymer

Nonlinear stress-strain behavior of elastomer foams investigated by various types of deformation

Hiroki Iba, Yukihiro Nishikawa, Kenji Urayama*

Department of Macromolecular Science and Engineering, Kyoto Institute of Technology, Sakyo-ku, Kyoto 606-8585, Japan

ARTICLE INFO

Article history:
Received 17 November 2015
Received in revised form
12 December 2015
Accepted 12 December 2015
Available online 15 December 2015

Keywords:
Foam
Biaxial deformation
Cellular rubber
Cellular elastomer

ABSTRACT

Nonlinear stress-strain behavior of the elastomer foams of high porosity is investigated in several types of biaxial tension, and uniaxial tension and compression. The values of Poisson's ratio for the open- and closed-cell foams are estimated to be about 0.24 almost independently of the imposed tensile strain, indicating that the foams undergo finite volume increase under tension. Unequal biaxial tensile experiments reveal no explicit cross-effect of strains between different axes in the elastomer foams: The deduced strain energy density function (W) has no appreciable contribution from the term of I_2 which is the second invariant of deformation gradient tensor representing the explicit cross-effect of strains, while *in general* W for conventional non-cellular elastomers involves finite contributions from I_2-term. No explicit cross-effect of strains result in a unique feature in biaxial tensile behavior that the effect of the strain in one direction on the stress in the other direction is considerably small. These features in tensile behavior are commonly observed for the open- and closed-cell foams. In contrast, the cell type has a pronounced effect on the compression behavior accompanying the buckling and collapsing processes of the cells, as observed in earlier studies. The stress-strain relations in compression accompanying the cell buckling are markedly different from the expectation of W obtained from the data of biaxial and uniaxial tension where the cell bucking is not possible.

1. Introduction

Elastomer foams (cellular elastomers) have been extensively employed in applications utilizing their excellent vibration damping and thermal insulation properties [1–5]. The highly porous elastomer foams are also superior in terms of the costs and weights of the materials. The unique mechanical properties of the elastomer foams originate from their cellular structures with low densities of constituent polymer solids. For instance, the air phase in the open-cell foams provides viscoelastic effects due to the stress-driven airflow: The air increases the stiffness of the foams at short time scale which is shorter than the characteristic time regarding the stress-driven airflow, while it does not contribute stiffness at long time scale where the air can escape freely through the cells [1,6,7]. Furthermore, the stress-strain relations in compression are remarkably non-linear, resembling that for the bucking of a thin beam [1–5,8,9]. The bucking and collapsing of the individual cells enable the elastomers to be compressed by very small load, and the compression accompanying the cell buckling induces no significant lateral expansion. In contrast, the compression of conventional non-cellular elastomers requires finite load and causes considerable degrees of lateral expansion due to the volume conservation. The unique features in the compression behavior of the elastomer foams explain the reasons for their extensive use as shock absorbers.

Mechanical properties of polymer foams have been investigated especially on the relations with geometric microstructural characteristics [1,9]. The earlier studies revealed that the relative density, ρ^*/ρ_s where ρ^* and ρ_s are the densities of the foam and constituent solid, respectively, is a crucial structural parameter to control various mechanical properties such as initial Young's modulus, yield stress, and Poisson's ratio. Much effort has also been made in constructing the constitutive models to describe the nonlinear stress-strain relations for elastomer foams [10–15]. Nonlinear micromechanics models [16–18] have also been developed to incorporate the effects of the polymer solids and the shape, size and their distribution of the constituent cells. Experimentally, most of the earlier studies focused on the markedly non-linear stress-strain behavior in compression involving the bucking process of the cell

* Corresponding author.
E-mail address: urayama@kit.ac.jp (K. Urayama).

http://dx.doi.org/10.1016/j.polymer.2015.12.021
0032-3861/

struts. They showed that the cell type (e.g., open- or closed-cells) significantly influences the compression behavior [1,2]. In contrast, the tensile behavior of elastomer foams has not been studied experimentally to nearly the same extent, although it is qualitatively known that the tensile behavior, where the cell bucking is not possible, is considerably different from the compression behavior [1,19].

An important and intriguing characteristic of the mechanical properties of elastomer foams is that they are markedly compressible and undergo finite change in volume before and after deformation. The reported values of Poisson's ratio (μ) in the linear elasticity regime, which is a measure of compressibility, are about 0.3 for several polymer foams [1,7,11,13,20,21]. This is a property unparalleled in elastomeric materials, because in general, non-cellular elastomers are substantially incompressible and exhibit almost no volume change under deformation ($\mu \approx 1/2$). Degree of compressibility is expected to have a pronounced effect on the stresses in multi-axial deformation, because it influences the dimensional change in the stress-free directions. For instance, in the case of planar extension where the specimens are uniaxially stretched while keeping the dimension in one direction unchanged, the linear elasticity theory for infinitesimal deformation postulates that the ratio of the stresses in the stretching and constrained directions is equivalent to μ [22]. However, it still remains incompletely characterized how finite compressibility affects the multiaxial stresses at large strain where the linear theory is not applicable. Little experimental research has been performed to characterize the stress-strain relations in multiaxial tension for elastomer foams, presumably because of the technical difficulties, although the buckling behavior in multiaxial compression has been investigated for brittle polymer foams [1].

In present work, the stress-strain relations under several types of biaxial extension including uniaxial extension are investigated for the highly porous elastomers with open- and closed cells using a custom-built biaxial tensile tester. Biaxial stretching which varies independently the strains in the two directions covers a wide range of physically accessible homogenous deformation [23,24]. Such biaxial stress-strain data provide a definite basis to characterize the nonlinear elasticity, and they enable us to deduce an accurate form of the strain energy density functions (W) of the elastomeric materials [25–30]. The reliable W functions for elastomer foams have not yet been obtained due to the lack of the multiaxial data. Furthermore, the effect of the cell type on the multiaxial tensile properties has been left uncharacterized. The present work evaluates the W functions for the elastomer foams using the biaxial data and the measured values of Poisson's ratio, and elucidates the effects of the cell type as well as finite compressibility on the nonlinear tensile behavior. The compression behavior for the same specimens is also investigated together with the X-ray CT observation for the buckling process of the cells. The differences in nonlinear stress-strain behavior between tension and compression are discussed for the elastomer foams with open- and closed-cells. The results in present work will contribute to deep and comprehensive understanding of nonlinear elasticity of the cellular (compressible) elastomers, and they provide an important basis for the design and fabrication of the elastomer foams with excellent mechanical properties.

2. Experimental

The two types of cellular elastomer specimens, each of which was made of the open cells of polyurethane (PU) and the closed cells of carbon black-filled natural rubber (NR), respectively, were kindly supplied from INOAC Corporation. The content of carbon black is 60 phr. Each specimen is designated as PU-75-O and NR-100-C, respectively. The values of density (ρ^*) and relative density for each specimen are listed in Table 1. The relative density is defined by ρ^*/ρ_s where ρ_s is the density of the solid component in the foams (ρ_s = 1.2 and 1.1 g/cm^3 for PU-75-O and NR-100-C, respectively).

Biaxial tensile measurements were conducted with a custom-built biaxial tester using the specimens with a dimension of 65 × 65 × 3 mm. This biaxial tester enables us to provide the strains in the two (x- and y-) directions independently, and to measure the tensile force in each direction. The details of the biaxial tester were described elsewhere [28]. Before the collection of the stress-strain data under several types of deformation, the virgin specimens were equally stretched in the two directions up to the maximum elongation (λ_{max}) of interest (λ_{max} = 2.6 and 1.7 for PU-75-O and NR-100-C, respectively), and subsequently the applied strains were completely released. This pretreatment procedure was done to eliminate undesirable initial relaxation components such as surface effect. After this pretreatment, the specimens behaved in purely elastic manner, i.e., they exhibited no residual strain after the release of imposed large deformation. The elongation beyond λ_{max} resulted in rupture, which was confirmed in the preliminary experiments.

The two types of biaxial extension, i.e., equibiaxial and planar extension, were mainly employed. In equibiaxial extension (EB), the specimens are equally stretched in the two directions ($\lambda_x = \lambda_y$). In planar extension (PE), the specimens are uniaxially stretched whereas the dimension in one direction was kept unchanged (λ_y = 1). For PU-75-O, a two-step unequal biaxial extension (designated as T-UB) was also employed. In T-UB, the specimen was firstly stretched by planar extension up to λ_x = 1.5, and subsequently stretched in the x- and y-directions with the same crosshead speed: In the second stretching of $\lambda_x > 1.5$, the specimens are biaxially stretched with maintaining a relation of $\lambda_x = \lambda_y + 0.5$. Each biaxial extension is schematically shown in Fig. 1. Uniaxial tensile and compression measurements were conducted with a AC-500N-CN (T.S.E, Japan) using the specimens with a dimension of 65 × 6 × 3 mm and 15 × 15 × 15 mm, respectively. In compression tests, the top and bottom surfaces of the specimens were coated with a highly viscous silicone oil, which was non-solvent for the specimens, in order to eliminate undesirable friction between the specimens and metal plates. The crosshead speed for tensile or compression tests was 0.1 or 0.002 mm/s, respectively, each of which was sufficiently slow to exclude the time effect on force. The resulting stress-strain data correspond to the quasi-equilibrium one without viscoelastic effect.

Poisson's ratio of each specimen was evaluated from the thickness variations under several types of imposed biaxial deformation. The thicknesses before and after deformation in the steady states were measured by a laser displacement sensor LT-9500 and LT-9010M (Keyence).

The morphology of the foam specimens was observed by digital optical microscope (Hilox KH8700). Three-dimensional (3d) internal structure of each specimen was observed by X-ray CT, FLEX-M345 (Beamsense Co. Ltd., Japan). The details of the observation technique are given elsewhere [31]. For computer tomography, the cubic specimens with 3 × 3 × 3 mm were rotated with 0.25 degree intervals over 180 degree, i.e., 720 projections. The series of the

Table 1
Characteristics of elastomer foam specimens.

	Polymer solid	Cell type	ρ^*(g/cm^3)	ρ^*/ρ_s
PU-75-O	Polyesteruretane	Open cell	0.075	0.063
NR-100-C	CB-filled natural rubber	Closed cell	0.100	0.090