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Property Modelling

On the large strain deformation behavior of silicone-based elastomers for biomedical applications

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ABSTRACT

The results of a comprehensive mechanical analysis of five silicone-based elastomers are presented. Large strain monotonic tests were performed under uniaxial, strip biaxial and equi-biaxial stress states. Based on the multiaxial experimental data, hyperelastic constitutive models were determined for each material. The small strain elastic modulus ranges from 49 kPa to 1.5 MPa, and the materials show different degrees of non-linearity of their stress-strain response. Data on the time and history dependence allow determining the deviation from the behavior predicted using a non-dissipative hyperelastic constitutive model. Next to representing a guideline for a comprehensive characterization of highly deformable materials, the present results provide data which can be used for the selection of an appropriate material, depending on the specific application. The corresponding models can be used to simulate the performance of each elastomer in applications involving large strains and multiaxial loading states.

1. Introduction

Wide range experimental results on the large strain deformation behavior of silicone elastomers are presented in this paper. Knowledge of the monotonic multiaxial mechanical response of these materials is relevant for numerous applications in (i) mechanobiological studies and (ii) biomedical devices. One of the main advantages of silicone substrates in mechanobiology is the fact that their stiffness can be selected to match values typically attributed to compliant biological tissues, see e.g. Refs. [1], [2]. Straightforward processability, transparency, non-toxicity and the possibility to tune the mechanical properties by changing the polymer to curing agent ratio, or curing conditions, represent further advantages which favored the application of silicone-based elastomers in dynamic bioreactors and experimental devices for mechanobiological studies (see e.g. Ref. [3]) where either polydimethylsiloxane (PDMS) or room temperature vulcanized (RTV) membranes are used [4], [5]. The strain field applied in these experiments is either directly measured [6] or calculated using finite element simulations [7]. In all cases, the model equations used to predict the mechanical response of the elastomers are of critical importance for the optimization of the set-up design and for the evaluation of the mechanical loading conditions experienced by cells. Silicone-based elastomers are also widely used in medical devices and components, e.g. for tubing, peristaltic pumps, catheters and cardiovascular devices such as heart pumps, ventricular assist devices, cannulas and vascular grafts [8]. In most of these applications, the elastomers are exposed to multiaxial stress states and large deformations. In such cases, the non-linear stress-strain response cannot be predicted based solely on uniaxial tension tests [9], [10]. For this reason, the present analysis includes experiments in uniaxial, strip biaxial and equi-biaxial stress states. In addition to reporting the experimental data, hyperelastic model equations are determined which can be used for the prediction of the elastomer response over a wide range of mechanical loading conditions.

Five commonly used silicone-based elastomers were selected for comprehensive mechanical characterization: two types of PDMS (Sylgard 184 and Sylgard 186, Dow Corning), and three RTV elastomers (SMI G/G 0.020", Specialty Manufacturing Inc.; RTV 4528 and RTV 4420, Blue Stars Silicones). They are shown to cover a range of mechanical characteristics representative of the materials used for mechanobiological studies and biomedical devices. The loading configurations and the range of deformations considered

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for the present work were originally motivated by a specific application of silicone-based elastomers, namely as blood propulsion membrane in a pulsatile Ventricular Assist Device (VAD). The "Zurich Heart" project [11] aims at developing a new concept of VAD with increased hemocompatibility, achieved through endothelialization of all the surfaces of the device in contact with blood. A key component of the system will be an elastomeric membrane optimized to host a functional endothelium [12].

2. Materials

The preparation of the elastomers analyzed in this study is summarized in Table 1. The properties of PDMS Sylgard 184, a two component system of base polymer and crosslinker, are tunable by the ratio of these components, the curing temperature and time. The 10:1 ratio is widely used for mechanobiology studies (e.g. Ref. [13]) and was adopted here. The preparation of PDMS Sylgard 186 in 10:1 ratio is analogous. It has similar deformation behavior as Sylgard 184 but was claimed to provide higher toughness. Silbione® RTV 4528 A&B is a Room-Temperature Vulcanized (RTV) two component silicone elastomer. Silbione® RTV 4420 A&B is a similar but stiffer elastomer. For both RTV elastomers, the two components are mixed in a 1:1 ratio. RTVs have been used in literature for skin-like application or external maxillofacial prosthetics [14], [15]. SMI G/G 0.020″, also belonging to the RTV family, is commercially available as 0.51 mm thick sheets, and does hence not require preparation in the laboratory. Consequently, its properties cannot be tuned. It is used for mechanobiology studies (see e.g. Ref. [16]).

2.1. Fabrication

Samples for the two component elastomers were prepared according to the following protocol, adopted from Refs. [17] and [18]. Part A (base polymer) and Part B (crosslinker) are mixed in the prescribed ratio (weight/weight) by hand for 2–3 min, in order to provide homogeneity. The mixture is degassed to remove air entrapped in the liquid, until all visible bubbles disappear (5–7 min). 2.5 g of the polymer are poured into petri dishes of 90 mm diameter, in order to obtain a membrane of 400 μm nominal thickness. The petri dishes are placed into a vacuum chamber for additional 45 min, in order to remove all air inclusions. Finally, the samples are cured in an oven for 4 h at 60 °C, except for RTV 4420 which is cured at room temperature (23 °C), according to the datasheet. PDMS Sylgard 186 was poured in a larger quantity (2.5–4 g) due to its high viscosity, and a spatula was used in order to flatten it and create a thin membrane. All test pieces for mechanical testing were cut out from the membrane using a scalpel or a punch. Sample dimensions are reported in Fig. 1. All samples were tested at least 14 days after preparation. This time point was selected based on the observed aging behavior of PDMS Sylgard 184, with major changes of mechanical properties occurring in the days following production [18], [19].

3. Experimental

3.1. Mechanical tests

Except for a few more comprehensive analyses [20] [21], previous studies focused mainly on the mechanical response of silicone elastomers to uniaxial tensile or compressive loading and on hardness/indentation tests, e.g. Refs. [22], [23]. In the present work, mechanical characterization is based on measurements performed in three different stress states: uniaxial (UA), strip biaxial (SB) and equi-biaxial (EB). Combination of the results from these different kinematic configurations allowed selecting an appropriate strain energy density function and identifying the specific material parameters. For each configuration, 3 samples of each material were tested. All tests were performed at room temperature. Table 2 shows all the tested samples and their dimensions (width, length and thickness).

3.1.1. Uniaxial and strip biaxial tests

Uniaxial and strip biaxial tests consist of an initial phase of cyclic loading (200 cycles at 30% nominal strain and 1 Hz), and a monotonic loading-unloading phase up to large strains (≥100%), with a strain rate of 0.3%/s. The loading phase is reversed when the nominal strain reaches 100% for all the tests in UA and SB configurations. The nominal strain is defined as the current total relative displacement of the clamping points divided by their initial distance. The set-up used for these tests consists of 2 horizontal hydraulic actuators (controlled in a way to keep the test piece in the center of the set-up), 100 N load cells (calibrated for up to 20 N, MTS System, Eden Prairie, USA), a CCD camera (Pike F-100B Allied Vision Technologies GmbH, Stadtroda, Germany) with 0.25x telecentric lens (NT55-349 Edmund Optics GmbH, Karlsruhe, Germany) used for local strain analysis (see Refs. [18] [24]). Force and grip position data are recorded at 500 Hz during the preconditioning and at 102 Hz during the monotonic loading-unloading phase. In both configurations, good grip of the sample is guaranteed by gluing a strip of sand paper on the surface of the custom-made metal clamps ($10 \times 10 \times 10$ mm^3 UA clamps and $60 \times 10 \times 10$ mm^3 SB clamps). Prior to sample positioning, the clamps are fixed in the machine at the correct distance from each other (40 mm for UA and 10 mm for SB). The position is then maintained with help of a metal bar that is fixed on the two clamps. The clamps are then removed from the machine, in order to provide easier handling. During the clamping, samples are first centered and then the clamps are closed using screws, that are evenly tightened in order to uniformly distribute the clamping pressure. The UA configuration leads to a uniaxial stress state while the in-plane stress component perpendicular to the main loading direction in the SB test is non-zero, due to the impeded lateral contraction. The set-up in strip biaxial configuration is shown in Fig. 2a.

3.1.2. Equi-biaxial tests

The equi-biaxial test configuration was obtained using a custom-made inflation set-up (see Ref. [25]). This set-up allows to apply air pressure to round specimens clamped at their circular

Table 1
Preparation of the elastomers analyzed in the study.

Elastomer	Ratio	Supplier	Preparation
PDMS Sylgard 184	10:1 (base:crosslinker)	Dow Corning	Mixing of base polymer and crosslinker, degassing, curing at 60 °C for 4 h.
PDMS Sylgard 186	10:1 (base:crosslinker)	Dow Corning	Mixing of base polymer and crosslinker, degassing, curing at 60 °C for 4 h.
Silbione® RTV 4528	1:1 (A:B)	BlueStar Silicones	Mixing of part A and part B, degassing, curing at 60 °C for 4 h.
Silbione® RTV 4420	1:1 (A:B)	BlueStar Silicones	Mixing of part A and part B, degassing, curing at room temperature.
SMI G/G 0.020″	None	Specialty Manufacturing Inc.	None