

TWO-PHASE MODEL OF SHAPE MEMORY POLYMERS AT FINITE STRAINS: FORMULATION AND EXPERIMENTAL VERIFICATION

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1. Introduction

Shape memory polymers (SMP) can play different functions, such as sensing, actuating and crack-healing. They have good physical properties and favorable economical indicators. The shape memory effect is temperature driven. The elastic modulus and the yield stress are high at temperatures below the glass transition temperature T_g and low above T_g . If SMP is deformed at temperatures above T_g and cooled down to temperatures below T_g , the deformed shape is fixed and SMP can carry large load. If the shape-fixed SMP element is heated up to temperatures above T_g under no load, the original shape is recovered [1]. Physical explanation for such behavior is as follows. Thermoplastic polyurethanes are block copolymers composed of hard and soft segments distributed randomly within volume element. With the increased volume fraction of domains dominated by hard segments, these domains are better cross-linked and interconnected. Two types of domains are usually well separated although such separation is never complete. Hard domains are responsible for the inelastic properties of polyurethanes. Deformation of the material above the glass transition temperature, when soft domains dominate, is mainly entropic being caused by changes in the alignment of polymer chains. Numerous works can be found that concern the characterization and applications of various types of SMP. Much less work is dedicated to modelling of these materials. Departing from the proposal [2] a constitutive model of SMP, formulated at large strain format, is developed. SMP is described as a two-phase material composed of a soft rubbery phase and a hard glassy phase.

2. Model formulation

Within the model at a given temperature SMP is assumed to be composed of two phases: a soft rubbery phase and a hard glassy phase. The volume fraction of each phase is postulated as a logistic function of temperature using the relation proposed in [2]. Furthermore, during cooling yet another phase is assumed to be formed: a frozen rubbery phase. This phase behaves similarly to a native glassy phase. The constitutive relations are formulated separately for each phase and the resulting behavior of the material depends on the actual material composition. The relations are written in the large strain framework. For the rubbery phase the hyperelastic Arruda-Boyce model is used, which accurately describes the behavior of isotropic homogeneous elastomers. The glassy phase is assumed to be hyperelastic-viscoplastic with the Zener-type behavior. Effective behavior of the shape memory polyurethane is the resultant response of individual phases. When we do not have to do with cooling, a simple Voigt-type averaging scheme is used, i.e. each phase is assumed to share the same deformation gradient being equal to the macroscopic one. The overall Cauchy stress tensor in the material is a volume average of stresses in the

individual phases. The first assumption is modified when a frozen rubbery phase is formed during cooling. More advanced averaging schemes can be used in the future [3]. Further details of model formulation can be found in [2, 4].

3. Comparison with experimental results

Identification of model parameters has been performed using the experimental tensile loading-unloading tests with different strain rates conducted in IPPT at thermal chamber at temperatures $T_g - 20^\circ\text{C}$ and $T_g + 20^\circ\text{C}$, with the help of the similar tests performed at the intermediate temperatures. Glass transition temperature $T_g = 25^\circ\text{C}$ is identified for the considered SMP. The parameters have been optimized with a focus on valid predictions for low strain rates and a room temperature. In Fig. 1 selected comparisons of experimental results with the model predictions are shown.

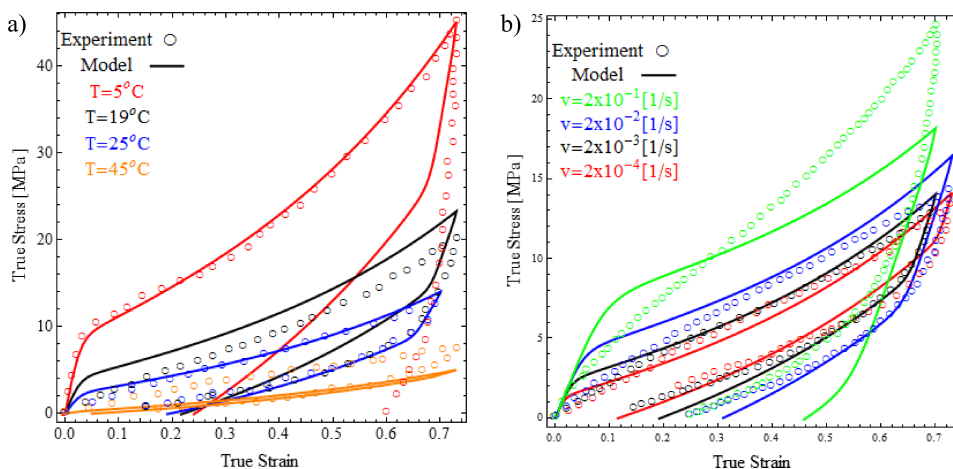


Fig. 1. Comparison of experimental results and modelling predictions for SMP tension: a) with strain rate $2 \times 10^{-3} \text{ s}^{-1}$ at different temperatures, b) with different strain rates at temperature 25°C .

It is seen that the model satisfactorily predicts the dependence of material response on temperature (Fig. 1a), although some discrepancies are visible as concerns the unloading part of the curve for the lowest temperature and the width of hysteresis loop for the highest strain rate. The second discrepancy is due to the model assumption that the rubbery phase is purely hyperelastic. As seen in Fig. 1b, influence of the strain rate at constant temperature 25°C is also well accounted for by the model for the strain rate up to 2×10^{-2} . The stress level is underestimated for the highest strain rate.

Acknowledgments

The research has been carried out with the support of the Polish National Center of Science under Grant No. 2011/01/M/ST8/07754.

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