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THERMOMECHANICAL ANALYSIS OF SHAPE MEMORY POLYURETHANE PU-SMP

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ABSTRACT

Experimental results of effects of thermomechanical couplings occurring in polyurethane shape memory polymer (PU-SMP) during tension at different strain rates are presented. Stress-strain curves were recorded by MTS 858 testing machine. The temperature changes were estimated by using a fast and sensitive infrared camera (Phoenix FLIR IR System). The stress and temperature vs. strain characteristics obtained during the tension enable to investigate the SMP deformation process and distinguish 3 different stages: the first, accompanied by a drop in temperature called thermoelastic effect, related to a limit of the material reversible deformation, the second plastic stage, associated with change of the material structure and significant increase in temperature, and the third - related to the mechanisms of damage - a breaking of the polymer chains, leading to the specimen rupture.

Keywords: shape memory polymer, thermomechanical coupling, tension, infrared camera.

INTRODUCTION

Shape memory polymers (SMPs) are new attractive materials, since like some metal alloys exhibit the shape memory properties. The mechanism of exhibiting this effect in polymers is definitely different than observed in shape memory alloys, because the crystallographic phase transition does not occur in polymers. Whereas, the functional characteristics of SMPs, e.g. the rigidity, elastic modulus, coefficient of thermal expansion, change drastically above and below their glass transition temperature T_g. This is caused by differences of molecular motion vs. temperature [Hayashi S., 1993, Tobushi H. *et al., 2013*]. In family of SMPs can be distinguished the polyurethane shape memory polymers (PU-SMPs). They are currently of great practical interest because of their good mechanical and shape memory properties and also low weight, good shape fixity and recovery, easy production techniques, the transition temperature which can be set around the room and human body temperature as well as low cost in comparison to Ti- based shape memory alloys [Huang *et al*, 2012, Pieczyska *et al*. 2010]. These properties allow to use PU-SMP in different fields, e.g. in medical, protection of food, textile, space and aviation industries.

Thermomechanical couplings, i.e. the “strong” or “weak” interactions between the mechanical and temperature fields, play a significant role in nature, technology and our daily life, causing heating or cooling objects under loading and straining. The effects of thermomechanical couplings have been the subject of theoretical and experimental research, carried out by L.Kelvin [Thomson, 1853], [Chrysochoos, 2012] and others. Since the melting point and

coefficient of thermal conduction are relatively low in polymers, the effects of thermomechanical couplings substantially influence their behaviour under different loadings.

RESULTS AND CONCLUSIONS

Strong thermomechanical couplings are observed in shape memory polymers subjected to loading, which is shown in Fig. 1.

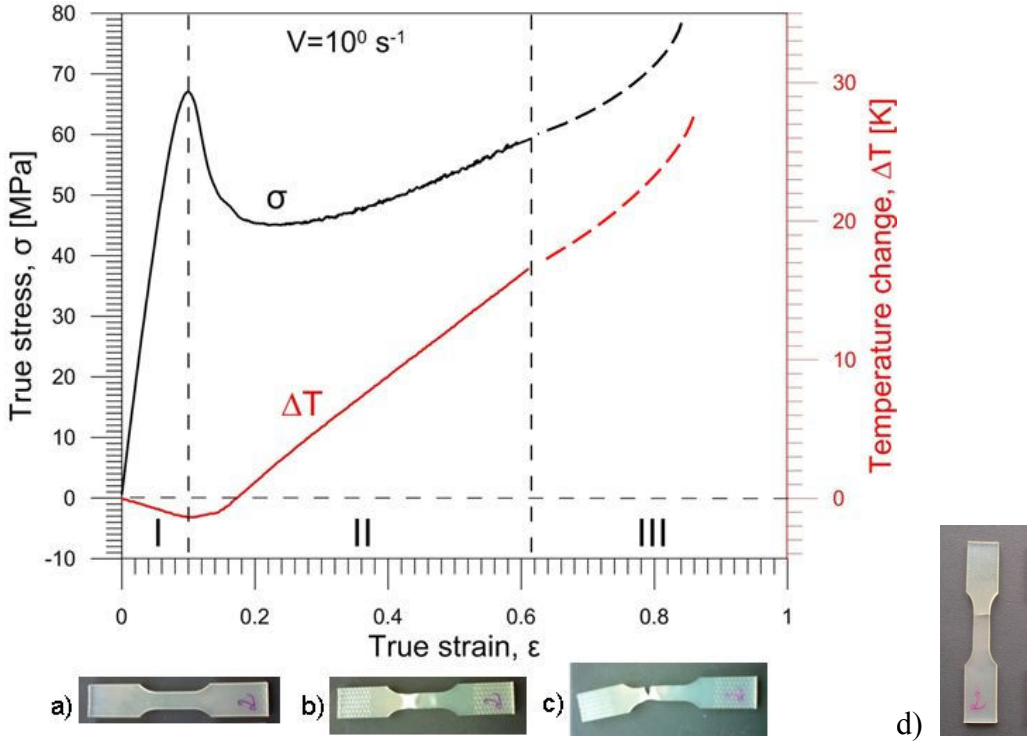

Fig. 1 - Stress σ and temperature change ΔT vs. strain ε showing 3 various stages of PU-SMP tension: a) elastic, b) plastic, c) after loading, d) after loading and subsequent heating at temperature T_g + 20°C

The stress and temperature vs. strain characteristics obtained during the PU-SMP tension enable to distinguish initial, reversible elastic stage of deformation, related to the small drop in temperature from the plastic one, accompanied by significant temperature increase. Empirical identification of the boundary between the elastic and the plastic stage of deformation is really complex. Especially it is difficult to identify it in materials without pronounced yield point, like most of polymers. In this case, the methods utilizing a thermal emission and based on a qualitative change of the temperature behaviour of the specimen under mechanical loading are usually very efficient. During tension, in the initial, elastic stage the temperature changes due to thermoelastic couplings are negative, while during the subsequent, plastic deformation the temperature changes are always positive. The change of temperature ΔT of the specimen, subjected to adiabatic uniaxial elastic deformation can be described by Kelvin equation as follows [Thomson, 1853]:

$$\Delta T_{el} = -\frac{\alpha T \Delta \sigma_s}{c_p \rho}, \tag{1}$$

where α – the coefficient of linear thermal expansion, T – the sample absolute initial temperature, $\Delta\sigma_s$ – the isentropic change of stress, c_σ – the specific heat at constant pressure, ρ – the material density. So, the value of maximal drops in the material temperature can be used for evaluating of a limit of the reversible material deformation [Oliferuk *et al*., 2012].

The stress and temperature vs. strain characteristics obtained during the tension enable to distinguish 3 different deformation stages, related to the SMP structure (Fig. 1). The first (I) is the elastic stage of the reversible deformations, described by theory of elasticity. The strain is low and the SMP specimen does not change significantly (Fig 1a). The second (II) is the plastic stage, associated with change of the material structure, namely the polymer chains straightening. Moreover, the strong localization effects can be observed (Fig. 1b). Like in metals, this deformation stage is characterized by a dissipative character. A significant increase of the sample temperature, depending on the strain rate, accompanies the deformation process. The polymers are very sensitive to the strain rate and their deformation is accompanied by significant temperature changes. The higher the strain rate, the more dynamic run of the deformation mechanisms and the larger temperature changes are observed.

Stage III is related to the mechanisms of damage (Fig. 1c). In this stage a breaking of the polymer chains occurs, leading to the specimen rupture. A huge increase of the specimen temperature is observed, especially in the rupture area. However, this stage, denoted by a dotted curve, is only an approximation of the stress and temperature changes. What is interesting, after the subsequent heating at T_g + 20°C the shape recovery is observed (Fig. 1d).

This study shows experimental effects of thermomechanical couplings occurring during tension loading of polyurethane shape memory polymer. Values of limits of the reversible SMP deformation basing on the maximal drops in the sample temperature were evaluated with a high accuracy. It was found that the PU-SMP manifests good mechanical and shape memory properties, manifested by both mechanical and thermal results.

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REFERENCES

[1]-Hayashi S., “Properties and Applications of Polyurethane-series Shape Memory Polymer”. Int. Progress in Urethanes, vol. 6, pp. 90 – 115, 1993.

[2]-Tobushi H., Matsui R., Takeda K., Pieczyska E.A., “Mechanical Properties of Shape Memory Materials. Nova Science Publishers, New York, 2013.

[3]-Huang W.M., Young B. and Fu Y.Q., “Polyurethane Shape Memory Polymers”. Taylor & Francis Group, 2012.

[4]-Pieczyska E.A., Nowacki W.K., Tobushi H. and Hayashi S., “Thermomechanical properties of shape memory polymer subjected to tension in various conditions”. QIRT Journal, vol. 6, pp.189 – 205, 2010.

[5]-Thomson W. (Lord Kelvin), "On the thermoelastic and thermomagnetic properties of matter". Transactions of the Royal Society of Edinburgh, vol. 20 (161), pp. 57-77, 1853.

[6]-Oliferuk W., Maj M., Litwinko R., Urbański L., "Thermomechanical coupling in the elastic regime and elasto-plastic transition during tension of austenitic steel, titanium and aluminium alloy at strain rates from 10^{-4} to$10^{-1}s^{-1}$". European Journal of Mechanics A-Solids, vol. 35, pp. 111-118, 2012.

[7]-Chrysochoos A., "Infrared thermography applied to the analysis of material behaviour: a brief overview". QIRT Journal, vol. 9 (2), pp.193-208, 2012.