

Thermomechanical properties of shape memory polymer subjected to tension and simple shear process

E.A. Pieczyska*, W.K. Nowacki*, H. Tobushi** and S. Hayashi***

*Institute of Fundamental Technological Research, PAS, Warsaw, Poland

**Department of Mechanical Engineering, AIT, Toyota-city, Japan

*** DiAPLEX Co., Tokyo, Japan, Ltd

Thermomechanical and functional properties of shape memory polymer (SMP) have been presented. Taking advantages from high quality testing machine and infrared camera, mechanical characteristics and temperature changes of the shape memory polyurethane specimens subjected to tension and simple shear processes were recorded, worked out, completed and discussed.

The material is said to demonstrate a shape memory properties since it can be deformed, fixed into a temporary shape, and recover its original shape, during exposure to an external stimulus. The shape memory property of polymer is related to the change of its elastic modulus under various conditions, however the most common activator is heat. Elastic modulus differs at temperatures above and below the glass transition temperature T_g , and therefore the rigidity of SMP elements vary depending on temperature. Shape memory polymer processed into permanent shape is deformed and fixed with this shape. After heating above its glass transition temperature, the parent shape is recovered, as it was schematically shown in Fig.1. These characteristics can be applied to intelligent elements in various fields. In order to use them to design intelligent systems properly, it is important to understand their thermomechanical properties. The main reason why the SMP is drawing attention is their low weight, high in shape recoverability and fixity, easy production techniques, the phase transition temperature around the room and body temperature and low cost, in comparison to shape memory alloys. Since the characteristics are being used for design of temperature sensors and actuators working in various regimes, the above described properties are investigated in various conditions.

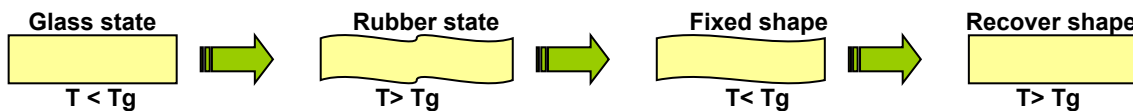


Fig.1. Scheme of shape memory phenomena in shape memory polymers activated by heat.

The research methodology applied in this research for investigation into thermomechanical properties of SMP is as follows. A specimen is fixed in the testing machine, allowing for obtaining the required kind of the test carried out with the proper strain rate. On the other hand, an infrared camera (ThermaCAMtm PM 695) is used in order to find the temperature distributions of the material subjected to deformation, i.e. thermograms, stored in a digital form with a max frequency of 50Hz. That allows for reproduction and calculation of the specimen temperature variation in contact-less way, straightforward, as a function of time or other parameters of the deformation process. The average temperature was calculated over the area located in the central part of the specimen, the same for particular kind of the test. The accuracy was up to 0.02K. The all tests were performed at room temperature and at the air humidity of 60%.

Effects of thermomechanical coupling in solids that are of frequent occurrence in nature have had a long history in both theoretical and experimental works. The problem has been started to be develop by Kelvin [1]. The coupling effects accompanying the initial elastic deformation are related to the pressure or volume change of the body subjected to loading:

$$\pm \Delta p \rightarrow \pm \Delta T \quad \text{or} \quad \pm \Delta V \rightarrow \pm \Delta T;$$

where: p is the pressure, V is the volume and T is the absolute temperature of the body.

The temperature change of a specimen subjected to adiabatic uniaxial elastic deformation (ΔT_{el}), related to the pure volumetric deformation and called the thermoelastic (piezocalorimetric) effect was derived by Kelvin [1] from the first law of thermodynamics, and defined as follows:

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

where: α - the coefficient of thermal expansion, T - the absolute temperature, $\Delta \sigma_s$ - the isentropic stress change, c_p - the specific heat per unit volume at constant pressure, ρ - the material density.

The temperature changes can be positive, negative or equal zero, according to the kind of deformation (compression, elongation, shear, torsion), and while for the metals do not exceed 0.2 K with initial reversible deformation ranges, for polymers are significantly higher [2-4].

The temperature effects accompanying the plastic deformation are always positive and can be significant. The temperature level depends on the material applied, the applied strain rate and the test conditions [2, 3].

In the presented paper, the effects of thermomechanical coupling of shape memory polymer have been presented. To this end, a specimen of polyurethane series produced by Mitsubishi have been subjected to tension tests and simple shear tests, in quasistatic range of deformation: 10^{-2}s^{-1} , 10^{-1}s^{-1} , 10^0s^{-1} .

During the tension tests an extensometer was used in order to register the specimen strain with high accuracy. From the beginning of the SMP deformation, almost a linear dependence between the stress and the strain is observed, Fig. 2a. At the strain of 25% a band of localized deformation appears, inclined by about 50 degree to the tension direction. Initially, the localization was noticed only by infrared camera due to the higher temperature, next it was more significant and noticeable also by naked eye due to some bands and white color (polymer crazing phenomena), and finally interesting development of significant necking was observed. The temperature at the area of localization increases, while the average specimen temperature does not change (Fig. 2b).

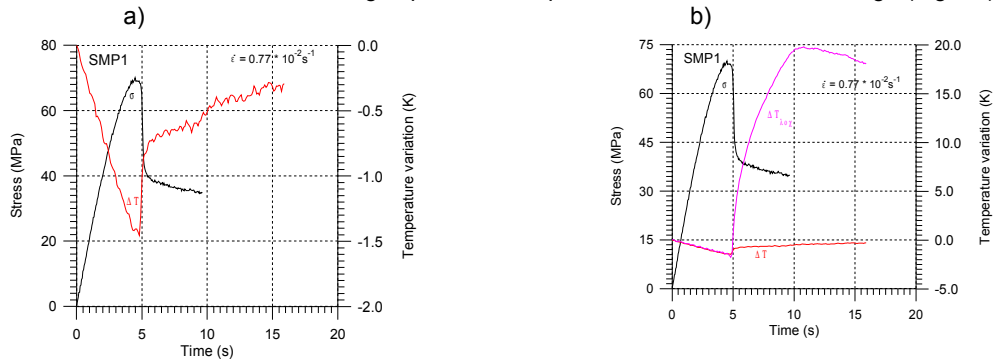


Fig. 2. a) Stress and average temperature ΔT vs. time, b) stress and average ΔT and the point of localization temperature ΔT_{loc} vs. time for SMP tension test at room temperature with the strain rate $0.77 \times 10^{-2} \text{s}^{-1}$.

The mechanical and temperature results obtained for the shape memory polyurethane subjected to simple shear deformation with various strain rates are also interesting. The higher the strain rate, the higher value of the stress level was achieved, like for other kinds of polymers [3, 4], while for metals no difference in this range of the strain rates are noticed. After significant range of the elastic deformation, quite long range of almost uniform shear deformation has been recorded. At higher stresses, a localisation on the SMP specimens during the shear process has been also observed, noticeable first of all on the infrared pictures and evaluated temperature data. The localised deformation was also observed on the specimen surface after the process, while during the subsequent heating at temperature above the polymer glass transition temperature the localised patterns vanished.

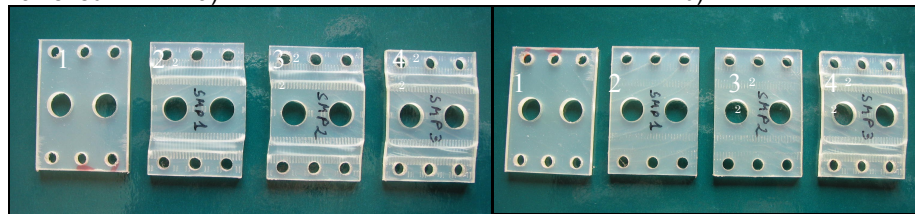


Fig. 3. Shape memory polyurethane specimens for shear test; a), b) (1)– before test, (4) after shear test, a) (2),(3),(4) – after test; b) (2),(3) after the shear test and subsequent heating at temperature above T_g

Concluding remarks

The shape memory polyurethane is characterized by high elastic and good mechanical properties which was confirmed by both the tension and the shear tests.

The stress-strain curves for the SMP are very sensitive for the strain rate, in quasi-static range of the strain rates applied, for both the tension and shear tests.

The strain localization during tension test performed with low strain rates has been observed, while for higher strain rates the process is much more homogeneous. On the other hand, during the shear test the localization was observed for higher strain rates. Infrared technique is very useful in monitoring of the localised strain nucleation and further developing, since it was not detected by traditional technique.

During the heating above the polymer glass transition temperature the localisation vanishes which confirms the material shape memory properties.

Acknowledgments: This research has been partly carried out with the financial support of the Polish Ministry of Science and Higher Education under Grant No. N N501 0106 33.

References:

1. W. Thomson, (Lord Kelvin), Quart. J. Pure and Appl. Math. 1, 57, 1857; Math. and Phys. Papers, v.1, 291,1882
2. E.A. Pieczyńska, S.P. Gadaj, Thermoelastic Effect during Tensile Cyclic Deformation, Engin. Trans., 45, 2 (1997), 295-
3. E.A. Pieczyńska, S.P. Gadaj, W.K. Nowacki; Thermoelastic and thermoplastic effects investigated in steel, polyamide and shape memory alloys; Proc. of SPIE, Thermosense XXIV, USA, 4710 (2002), 479-497
4. E.A. Pieczyńska, S.P. Gadaj, W.K. Nowacki; Temperature changes in polyamide subjected to tensile deformation;

