

## Thermomechanical study of cycling, relaxation, and creep sequences in polymers

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### Abstract

Specially designed experiments were performed to study the thermomechanical aspects of cycling, relaxation, and creep in polymers. Sheet samples of the material were subjected to a special program of the tensile deformation in a testing machine. An infrared camera was used in order to measure the temperature changes of the sample surface during the deformation. The mechanical and the thermal characteristics were obtained both in elastic and plastic ranges of straining, as well as after the process.

### 1. Introduction

The characterization of the mechanical behaviour of polymer fabric materials requires investigation of its visco-elasto-plastic properties, which can be determined as a result of loading in a monotonous tensile test or cycling test, with relaxation and creep sequences. All kinds of mechanical loading always modify the temperature fields of tested materials [1,2].

The interaction between stress (strain) and temperature fields ("thermomechanical coupling") during elastic strain can be described by Kelvin's law according to which the change of temperature is a linear function of the first invariant of the stress tensor:  $\Delta T = -k\Delta\sigma_{ii}$ . Thus, in the elastic range of deformation the temperature decreases during tension, increases during compression and does not change during shear or torsion [3]. The plastic deformation of a solid is always accompanied by an increase in temperature. It is caused by conversion of a significant part of the plastic energy into heat. There are some experimental works concerning thermomechanical coupling in metals. In these materials it is easy to find the transition between elastic and plastic deformation. However, in semi-crystalline polymers, as polyamide, this transition does not exist. Moreover, the relatively low melting temperature of these materials causes more significant thermomechanical coupling interactions. Thus, it is necessary to study thermomechanical coupling effects in polymer materials experimentally, especially relaxation and creep.

### 2. Experimental details

The experiments were performed on sheet samples of solid polyamide PA66. They were cut out from the polyamide plate, preserving the same direction of sample orientation. The cross-section of the specimens was  $16 \times 8.5 \text{ mm}^2$ , their length 155 mm. The rate of deformation was  $2.5 \times 10^{-2} \text{ s}^{-1}$  for the creep testing and  $10^{-2} \text{ s}^{-1}$  for the relaxation. The gauge length of the extensometer was 25 mm + 50%. The load, the elongation, and the field of infrared radiation (emitted by the sample surface) were continuously registered during the straining. The distribution of infrared radiation was measured using a thermography camera coupled with a computer system of data acquisition and conversion. This allowed us to obtain the thermography pictures (thermograms) and later a temperature evolution of the samples subjected to the cycling. The accuracy of the temperature measurement is 0.02 K. More details about the temperature measurements were presented previously [4,5].

### 3. Methodology

Various kinds of experiments were performed to investigate the visco-elastoplastic material properties.

### 3.1 Creep

The program of testing of the creep effects after some material history was:

1. Loading to above 3% of deformation, unloading to below 2% of deformation,
2. Loading to above 6% of deformation, unloading to below 5% of deformation,
3. Loading to above 9% of deformation, unloading to below 8% of deformation,
4. Loading to above 12% of deformation, unloading to below 1% of deformation keeping the stress constant, with instantaneous registration of stress and temperature.

The mechanical characteristics and the temperature distribution registered during the test allowed to derive the stress-strain relations and the temperature evolution of the sample subjected to deformation. Examples of stress and temperature characteristics presented as a function of time are shown in Figure 1. The average temperature of the sample surface reflects immediately the balance between the processes causing the heat production, namely the plastic deformation which is always related to the increase in temperature, and the processes causing the temperature alteration due to the volume changes which are particularly significant in the elastic range of straining.

The first cycle of the curve (Figure 1) describes purely elastic deformation, while the next 3 cycles are composed of both elastic and plastic parts. The initial cycles are accompanied by very similar cycles of the temperature curves showing significant temperature drops by up to  $-1.3$  K, followed by temperature rises, measured from the point when the stress increment changes its sign. The last cycle of the temperature is dominated by plastic deformation and also by the process of thermoelastic unloading, related to a significant increase in temperature.

In the subsequent cycles the thermoelastic effects are not so significant, because the part of the crystallographic structure in the polymer sample is changing in the process. Temperature increments become higher and higher because of the heat development due to the visco-elastoplastic deformation and the small heat exchange with the surrounding.

The process of creep (Fig. 1) at the level of 60 MPa (in the elastic domain), and starting after 20 sec., is characterized by a parabolic increase in temperature. Such characteristics have been also registered after stopping the cycling process (Figure 2).

The characteristics show that in polymers the processes of maintaining the level of stress, even in the elastic range of stress (Fig. 1), or remaining after some material history (Fig. 2), are related to a smooth temperature rise. It means that the processes of microstructure evolution that occurs at this stage of deformation are still related to heat dissipation.

The mechanical and the thermal characteristics shown in Fig. 2 were measured both in elastic and plastic ranges of reversible strain cycles, as well as after the process. Generally, the temperature smoothly decreases in the elastic range of deformation and significantly increases in the plastic domain [3,4]. Thermoelastic effects are seen during loading and unloading in every cycle. These effects change slightly in each of the next cycles in accordance with decreasing stress. Conversely, the temperature change influences the mechanical behavior. The average temperature of the sample increases as a result of heat production due to visco-plastic processes [5].

### 3.2 Relaxation

Two programs of testing of the relaxation effects after some material history were performed:

Rel.1; straining to  $\varepsilon = 3.2$  %, stop at this level, 3 min waiting at the instantaneous registration of stress and temperature, unloading at the same rate of straining  $\dot{\varepsilon} = 10^{-2} \text{ s}^{-1}$ .

Rel.2; straining to  $\varepsilon = 8 \%$ , stop at this level, 3 min waiting at the instantaneous registration of stress and temperature, unloading at the same rate of straining  $\dot{\varepsilon} = 10^{-2} \text{ s}^{-1}$ .

The stress- strain curve for Rel. 1 and Rel. 2 are shown in Fig. 3. During the relaxation, namely 3 min waiting, the stress decreases by about 26 MPa (almost 38% of the loading) for both tests. The obtained stress and temperature characteristics presented as a function of time are shown in Figs. 4, 5.

The stress and the temperature as a function of strain during relaxation tests of Rel.1 and Rel. 2 are shown in Figs 6, 7. The stress and the temperature traces seem to be similar, although the stress in Rel. 2 is more extended. The value of the temperature shown in Figs. 5,7,9 is a little higher and its shape is slightly different since it is more intensified concerning plastic deformation.

The temperature variations presented as a function of stress are shown in Figs 8, 9.

The characteristics differ both in shape and in values. The thermoelastic effect during loading is similar, but with a much higher increase in the temperature accompanying the relaxation and a lower increase in the temperature related to thermoelastic unloading for the second test, (Rel. 2, see above) has been registered. All the stress and temperature characteristics indicate that the relaxation 2 is involved with plastic deformation while relaxation 1 takes place in the range of elasticity and high-elasticity.

#### 4. Concluding remarks

Elastic, visco-plastic, and plastic deformation of polyamide are accompanied by significant temperature variations.

In the elastic and high-elastic regions of polyamide deformation, the thermo-elastic effect is registered, i.e. significant drop in temperature up to  $-1.2 \text{ K}$  due to elasticity and high-elasticity during loading and the temperature increase up to  $1 \text{ K}$  during unloading.

The temperature variations obtained in a remote way with a high accuracy and related to the mechanical characteristics are very useful for investigation of the relaxation processes.

During the 3 min relaxation the stress decreases by about 40 % and the temperature increases by about  $1 \text{ K}$ .

The smooth parabolic temperature characteristics are slightly different for the two performed relaxation tests; the discrepancies between them indicate the heat balance evolution, related to the polymer microstructure.

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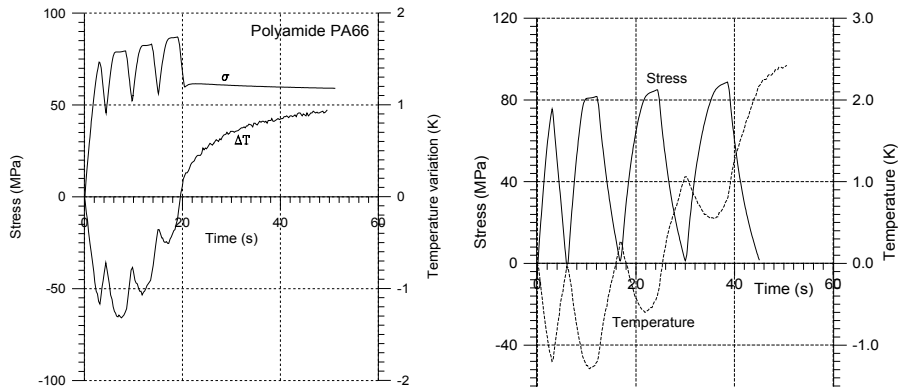


Fig. 1, 2. Changes of stress and temperature vs. time during cycling of polymer

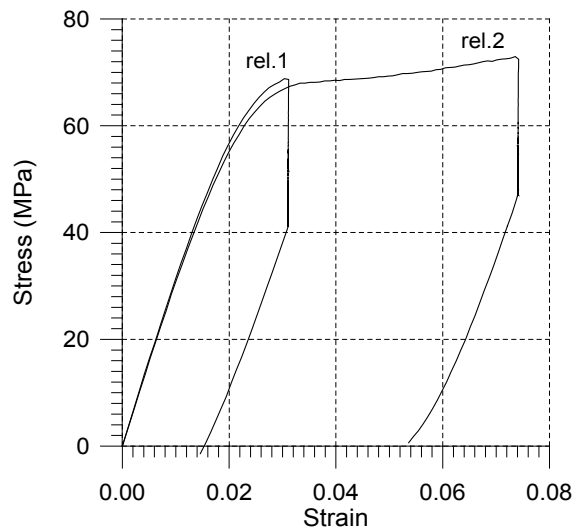


Fig. 3. Superposition of two stress – true strain characteristics of PA66 Polyamide subjected to relaxation tests; rel.1 – up to  $\epsilon = 3.2\%$ , rel.2 – up to  $\epsilon = 8\%$ .

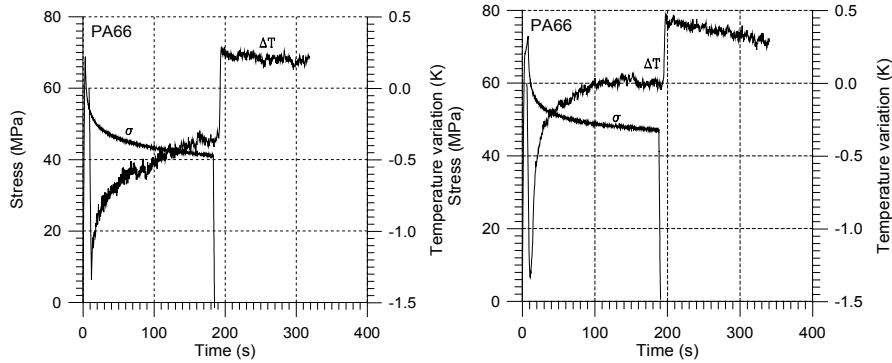


Fig. 4, 5. Stress and temperature vs. time during relaxation tests

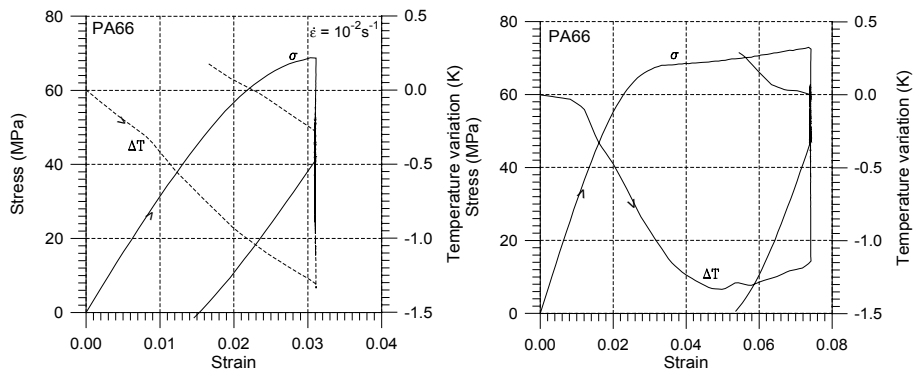


Fig. 6, 7. Stress and temperature vs. strain during relaxation tests

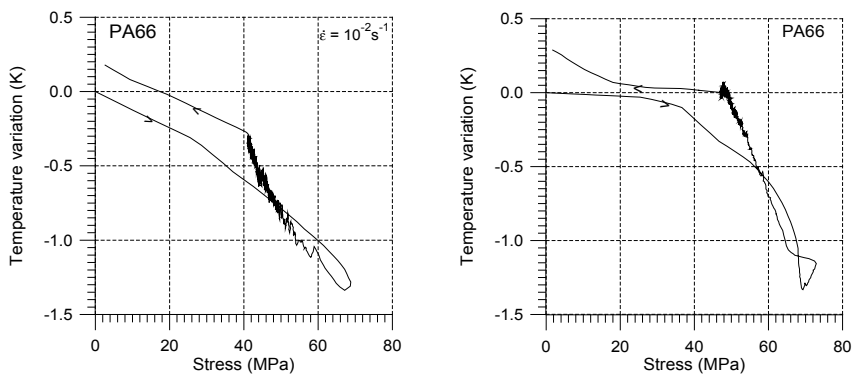


Fig. 8, 9. Temperature vs. stress during the relaxation test