The effect of temperature, static load and electron beam irradiation on the deformation of linear polymers

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Abstract. A comprehensive experimental study on the effect of temperature, static load and electron beam irradiation on thermomechanical properties of polytetrafluoroethylene material was conducted. Four regions having different nature were detected on the curves of dependences of deformation (\(\varepsilon\)) from temperature (\(t\)). The obtained curves of \(\varepsilon\) from \(t\) prove the presence of phase transitions in this film. Irradiation significantly affects the dependence of \(\varepsilon(t)\) and \(\varepsilon(\sigma)\).

1. Introduction

Extensive use of polymeric materials and polymer-based composites in different fields of science and technology is due to particular combination of properties not possessed by a significant portion of traditional materials. One of the most important characteristics is the maintenance of high mechanical strength under external actions [1–8]. The use of polymers in industry contributes the identification of contradictions between price and properties, as the competition for the production of quality products is quite high. After mechanics of composite materials had found wide application and rapid development, its main goal was the modification of materials and improvement of their mechanical properties. The use of polymers in demanding industrial applications, when the mechanical load and temperature vary at the same time, determines the presence of the required thermomechanical properties in them [9, 11]. Among all PTFE materials have very good properties. It has a high melting point and densely packed linear chain gives it stiffness at increased temperatures [12, 13].

In this work, experimental studies on the effect of temperature, static load and electron beam irradiation on the deformation of non-irradiated and irradiated polytetrafluoroethylene were carried out.

2. Methodology

The appropriate experimental setup have been developed and manufactured for the experiments on the combined effect of temperature, pressure and irradiation. Its scheme is shown in Figure 1. The setup consists of the following blocks: rack, base, experimental chamber, holders, clamps, sample, thermo-electronic heater (TEH), temperature sensor, statistical load, measuring sensor for sample length. The heater is a U-shaped stainless steel tube with low heat capacity, inside of which the spiral wire with high resistivity is located. TEH is separated from the frame by insulator. Needle-electronic thermometer was applied to measure the temperature (\(t\)). The dependence of \(t\) from time (\(\tau\)) is shown in Figure 2. As follows from the figure when \(\tau > 5\) sec, this dependence is almost linear. To measure
the length of the sample a special body displacement sensor developed by ScienceCube was used. In addition, the experiments were recorded on video.

Industrial polytetrafluoroethylene with a thickness of 100 µm was selected as the test material. Film samples were cut using a special device. Length of the test material was 7 cm, the working part was 5 cm (2 cm of polymer sample were fixed in the clamps), and width was 0.5 cm. This film was subjected to uniaxial stretching at the constant statistic load.

![Figure 1. The experimental setup.](image)

| 1 – rack; 2 – base; 3 – experimental chamber; 4 – holders; 5 – clamps; 6 – sample; 7 – heater; 8 – temperature sensor; 9 – statistical load; 10 – measuring sensor for sample length |

Figure 1. The experimental setup.

![Figure 2. Dependence of temperature on time in the experimental chamber.](image)

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![Figure 3. Thermomechanical curves for polytetrafluoroethylene under different constant loads.](image)

Figure 3. Thermomechanical curves for polytetrafluoroethylene under different constant loads.

Previously the maximum load at which rupture of the tested polymer occurs had been determined using special cargo. For this experiment the stress was 21 MPa. Then the stress was calculated as a part of the limit stress. The next step was fixing the deformation at room temperature for a given load. During the experiment the load was not varied. After fixing, the sample was placed in the chamber and thermionic heater was turned on. Then all the necessary parameters were determined.
Irradiation of samples was carried out using ELU-6 linear electron accelerator with energy of 2 MeV in air. The dose was 5 kGy. Film samples were irradiated for three minutes at the distance of 40 cm from the output window of the accelerator. The height of the fixation of the samples during irradiation coincides with the center of the output window and was equal to 30 cm. Working temperature of the samples was equal to 23 °C and relative humidity was 55%.

3. Discussion
Experimental work on study of deformation dependence on temperature at the different stresses was conducted: \(\sigma_1 = 9; \sigma_2 = 11\) and \(\sigma_3 = 13\) MPa. Tests were conducted at the temperatures ranged from 23 to 120 °C. As a result of a series of experiments (Figure 3), it was found that PTFE behaves differently at different stages of heating. Application of too much stress results in destructive processes taking place in several stages: I. Straightening of free polymer chains (23 °C); II. Straightening of bonded chains (23–35 °C); III. Catastrophic destruction (35 – 45 °C); IV. Destruction of chains with strong bonds (45 – 120 °C) (Figure 3). When load is applied at room temperature it causes a sharp elongation of the samples. The reason for this behavior of material is the straightening of macromolecules, which constitute the twisted complexes. Further, in the interval of 23 – 35 °C there is a slight increase in related elongation, which is associated with the straightening of hard bonded chains. In the interval of 35 – 45 °C there is a catastrophic destruction of the weak chains, including those bonded with the presence of phase transitions. At \(t > 40\ °C\) \(\varepsilon(t)\) curve has a trend of a gradual recovery in saturation. This is due to the disruption of the hard, more durable chains. The maximum deformation at \(t = 85\ °C\) and \(\sigma = 13\) MPa reaches 500%.

![Figure 4](image1.png)
**Figure 4.** Dependence of deformation from stress for unirradiated (left and bottom axis) and irradiated (right and upper axis) polytetrafluoroethylene material.

1 – \(\sigma = 5; 2 – \sigma = 7\) MPa

![Figure 5](image2.png)
**Figure 5.** Dependence of deformation from temperature for polytetrafluoroethylene irradiated with a dose of 5 kGy under different constant loads.

Then the experimental dependence of \(\varepsilon\) from \(\sigma\) were determined both for non-irradiated (dots) and irradiated (crosses) polytetrafluoroethylene with a dose of 5 kGy. As it follows from the figure, with increasing stress the deformation slowly increases up to \(\sigma \sim 18\) MPa and then sharply grows exponentially. It also displays the curve calculated using cascade-probabilistic models [10] of \(\varepsilon(\sigma)\) dependence according to the formula: \(\varepsilon = \exp(\sigma/\sigma_0) - 1\), for this experiment \(\sigma_0 = 28\) MPa. A satisfactory agreement of experimental and calculated data is seen. And \(\sigma_0 = 20\) MPa. A similar dependence is shown for irradiated PTFE.
After irradiation by 5 kGy, samples of the material lose flexibility and begin to break at a lower deformation than before irradiation. While the decrease of elongation in 7 times is observed in comparison with unirradiated material (Figure 4), and the strength does not change significantly.

4. Conclusion

1. Experimental studies of the dependence of deformation $\varepsilon$ from the temperature at various stresses $\sigma_1 = 9$ MPa, $\sigma_2 = 11$ MPa, $\sigma_3 = 13$ MPa in the polytetrafluoroethylene were carried out. It was found that in the temperature range of 23 – 30 °C $\varepsilon$ varies slightly. Further, at $t = 30 – 55$ °C there is a significant elongation of the samples. At $t > 55$ °C elongation growth is slowing. The maximal deformation is ~500 % at $t = 85$ °C and $\sigma = 13$ MPa.

2. Irradiation of polytetrafluoroethylene samples leads to loss of plasticity, a significant decrease in deformation (in comparison with non-irradiated material) ~ 240 %, which is due to the destruction of all polymer chains. In this case, the strength is practically reduced to zero.

3. Experimental dependence of $\varepsilon$ from $\sigma$ for both unirradiated and irradiated materials is satisfactorily described by cascade-probabilistic model.

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