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Thermal effects under elastic and plastic deformation of polyethylene

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ABSTRACT

Thermal effects occurring under tensile deformation were analyzed for polyethylene samples with different level of crystallinity and dimensions. Temperature changes were measured by IR camera at all stages of deformation (from elastic region until fracture) at various strain rates. At the initial stage of drawing energy is consumed and temperature of the polymer slightly decreases (endothermic effect). Onset of necking gives rise to intensive heat generation and substantial increase in temperature in the element where neck originates. When front of neck moves away, analyzed element begins to cool down. At the region of strain hardening a new increase in temperature is observed. Maximal degree of heating during necking was found to depend on the level of crystallinity of the polymer, tensile rate and the speed of the front of neck.

Calculations were conducted to estimate the maximum adiabatic temperature provided no energy is dissipated outside the heat source. Adiabatic temperature was compared with values of temperature registered in the experiment for specimens with different dimensions. It was found that starting from strain rate 500%/min deformation process of rather "large" samples proceeds nearly adiabatically.

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1. Introduction

Investigation of processes of elastic and plastic deformation in pure and filled polymers is an important goal of modern materials science because of the wide application of such objects in technology and household use. Many publications describe mechanical behavior of various classes of polymers [1–9]. It is well known, that deformation of any solids (including polymers) is accompanied by either exo- or endothermic phenomena. Thermal effects, observed during loading, depend on characteristics of the sample under study as well as conditions of mechanical tests. If deformation process is adiabatic, a part of mechanical work performed on the sample during deformation is converted into heat, and a second part is transformed into internal energy of the specimen. Generally, conditions of experiments are non-adiabatic and a part of energy is dissipated outside the heat source by: conduction into cooler parts of polymer, convection from surface to air and radiation from surface.

Thermal phenomena under deformation of elastomers and some solid polymers were carefully investigated by Godovsky and co-workers. The main results of this research group are summarized in the monograph [10].

For measuring thermal effects in deformed samples, they developed an experimental technique, based on registration of heat fluxes from the working area of the specimen in a deformation calorimeter. This method enables to obtain values of the basic thermodynamic parameters (work W, heat of deformation Q_{def} and change in the internal energy ΔU) as a function of strain ε. A similar technique was used in the recent work [11], which focuses on thermal effects during uniaxial compression of polyethylene samples with varying degrees of crystallinity C_{cryst} in the deformation range $\varepsilon = 0–50\%$. Extrapolation of the experimental plots to the values $C_{cryst} = 0\%$ and $C_{cryst} = 100\%$ made it possible to find contributions of amorphous and crystalline phases to the overall thermodynamics of deformation. The dependence Q_{def} was found to increase linearly with C_{cryst}, when $C_{cryst} \to 0$, values of Q_{def} are also close to zero, i.e. experimentally measured heat is almost entirely evolved from the crystalline phase of PE. According to the authors, heat release during plastic deformation is due to movement of dislocations along crystallographic planes of a polymer crystal.

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Significant limitation of the above method is that it provides integral values of heat of deformation Q_{def} and it is impossible to determine in which particular portion on the working area of the sample the heat was evolved. It is not important for elastomers since their working area is deformed uniformly, but it is crucial for crystalline and glassy polymers exhibiting necking. In these polymers during loading tests different parts of the sample have different local strains and structure (from initial isotropic to highly oriented), so the temperature field is distributed along the working part of the sample very non-uniformly.

Electromagnetic radiation emitted from surface of objects cooler than 500 °C is completely within infrared range. It means that an infrared camera can be used to monitor distribution of temperature in polymers under deformation [12–15]. This technique allows to obtain local temperatures, in small portions of the specimen. Thermovision camera was applied to study temperature effects under tensile experiments of polymers [16–20,23,24] and during development of fatigue cracks and fracture of materials [12,25–27].

Yamauchi [16] used this technique to trace changes in temperature at different stages of tensile deformation of polypropylene (PP), polyethylene (PE), poly(ethylene terephthalate) (PETF) and poly(vinyl chloride) (PVC). PET and PVC deformed uniformly under tension, PE and PP exhibited necking. A small decrease of temperature (0.1–0.25 °C) was found on the beginning of test in all polymers. It was followed by gradual raise of temperature during a plastic deformation period in PET and PVC and by rapid increase in the neck initiation zone in PP and PE. During the neck propagation the highest temperature was noticed near one of the neck propagation zones. Similar behavior was reported by Baravian et al. for stretched HDPE [17].

Drawing of high density polyethylene, polyamide 66, and poly(ethylene terephthalate) was examined by Haward [18]. He discovered that during deformation with fast rates the increase in temperature causes softening effect which exceeds the opposing influence of strain hardening, so the nominal stress is predicted to fall continuously with increased strain.

PP and HDPE prepared by different methods were used in the studies [19,20]. Preparation procedure was found to have a strong effect on mechanical and thermal phenomena. In case of PP, the increase in temperature was 27 °C for extruded sheets, 14 °C for slowly cooled samples and 11 °C when the polypropylene was quenched [19]. During tensile deformation of polymers Pawlak et al. [21,22] also measured changes in volume to obtain information about the process of cavitation. Influence of cavities on deformation and thermal processes was examined. The largest temperature changes were found in samples with the greatest number of voids, while in non-cavitating materials temperature rise was insignificant.

Thermal effects under high-rate stretching were studied in polyethylene, polypropylene, and polyamide (PA) specimens by Hasebe et al. [23]. Drawing rates were 200 and 2000%/min, maximal temperature rise registered in the experiment was 60 °C for PE, 90 °C for PP and PA. The heat generation was interpreted in terms of melting of crystallites and re-crystallization induced by large deformation.

There are much fewer publications about thermal phenomena in filled polymers. Recently Alghamdi et al. [24] studied the correlation between nanoparticle type and internal heat generation during the tensile deformation of UHMWPE/HDPE blended polymers containing various nanofillers: carbon nanotubes, carbon black and inorganic nanoclay. The temperature of nanocomposites was investigated by thermovision, simultaneously with tensile tests. The results showed that measured temperature increase depends on nanoparticle type, content, dispersion and interaction with polymer. At low fractions of nanofiller (i.e. 0.5–1 wt %), carbon nanotubes resulted in higher temperatures than seen with carbon black.

According to the above experimental observations, changes of temperature during tensile deformation depend on the stage of deformation. When the deformation is elastic, in the beginning of test, the energy is consumed for stretching and orientation of macromolecular chains and the temperature of sample decreases. When plastic deformation processes are activated, the heat is generated. Observed rise of temperature depends on the scale of plastic deformation, i.e. it may be expected to depend on level of crystallinity.

This was one of the motivations of our thermovision studies presented here. To confirm this assumption, we explored temperature changes at all stages of deformation in polyethylene samples with different crystallinity. Thermal effects were examined in conjunction with deformation parameters and structural changes induced by loading.

In most mechanical tests deformation process is not adiabatic, and a part of deformation heat Q_{def} generated in the sample is dissipated irreversibly into the environment. Therefore, the change in temperature of the material is determined not only by deformation parameters – stress and elongation, but also by the speed of the heat exchange with the air and with the colder areas of the sample located near the zone of heat release. The rate of heat exchange is primarily dependent on the dimensions of the working area of the polymer and rate of drawing.

In the above-cited publications experiments were performed on samples of the same size and the influence of these factors was not considered. Therefore, the first phase of this work focused on the effect of sample size and strain rate on the magnitude of the heat loss to the environment. This study is necessary to establish conditions when experimentally measured temperature is to a greater extent determined by structural processes occurring in the sample during deformation, and when the processes of dissipation of thermal energy are predominant.

2. Experimental

In this work, PE samples with different crystallinity levels (Table 1) manufactured by the polymer plant “Volzhskiy” (Russia) were used as objects of study. To obtain platelets, pellets of PE were pressed in an aluminum ring at temperature 160 °C and pressure 0.5 MPa during 5 min between two fluoroplastic sheets, then quenched in the water at 20 °C during 30 s.

Density of thus prepared samples was measured by hydrostatic weighing, level of crystallinity was determined by wide angle X-ray diffraction (Table 1). X-ray analysis was done using DRON-3 diffractometer (USSR). The measurement conditions were: copper radiation CuK_α monochromatized with graphite monocrystal, wavelength $\lambda = 0.154$ nm, ambient temperature.

Another series of samples were composites with PE-1 matrix. The filler was organically modified Na^+-montmorillonite – Cloisite 20A (C20 A), supplied by the company Southern Clay Products. Clay particles were introduced into the matrix polymer by means of melt blending under shear stresses. Procedure of filler preparation

Table 1
Characteristics of studied polymers.

Code	Brand of PE	Density ρ, g/cm^3	Viscosity average molar mass, M_v	Level of crystallinity C_{cryst}, %
PE-1	107-02K	0.906	190 000	30
PE-2	PY-342	0.935	400 000	50
PE-3	277	0.950	175 000	65

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