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TENSILE BEHAVIOUR OF POLYETHYLENE UNDER DIFFERENT LOADING RATES IN THE PRESENCE OF IMPERFECTIONS

ZATEZANJE POLIETILENA PRI RAZLIČITIM BRZINAMA OPTEREĆENJA U PRISUSTVU GREŠAKA

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Keywords
- tensile tests
- polyethylene pipes
- imperfections

Abstract

This paper highlights the changes of polyethylene behaviour during various loading rates. The experimental programme was carried out on samples taken from PE80 polyethylene gas pipes with simulated imperfections with bilateral V-notch, U-notch and central hole. The hybrid technique tensile test – infrared test was used for examining the fracture behaviour of PE80 thermoplastic material samples under different loading rates. Correlation between the loading rate and tensile strength of polyethylene has been established. It has been shown that tensile strength varies with loading rate according to a logarithmic law. Also, it was shown that viscoelastic-plastic character of the polymer material influences directly the specific response of material to loading rates.

Ključne reči
- ispitivanje zatezanjem
- polietilenske cevi
- greške u materijalima

Izvod

Ovaj rad ukazuje na promene u ponašanju polietilena pri različitim brzinama opterećenja. Eksperimenti su sprovedeni na uzorcima polietileskih PE80 cevi za transport gasa sa simuliranim greškama u vidu dvostranog V-zareza, U-zareza i centralne rupe. Hibridna tehnika ispitivanja zatezanjem korišćena je za ispitivanje ponašanja loma uzoraka termoplastičnog PE80 materijala pri različitim brzinama opterećenja. Utvrđen je odnos između brzine opterećenja i zatezne čvrstoće polietilena. Pokazano je da zatezna čvrstoća varira u odnosu na stepen opterećenja prema logaritamskom zakonu. Viskoelastično-plastičan karakter polimernih materijala direktno utiče na specifičan odgovor materijala na različite stepene opterećenja.

INTRODUCTION

Currently, the use of plastics in pipeline construction has grown since these materials have main advantages in relation to metals: higher resistance to corrosive agents and low weight. These new materials show special thermo-mechanical properties and are produced and used in practice because of their important applications. Deformation of these materials in different thermo-mechanical conditions, /1/, involves consideration of several mechanisms and phenomena: mechanical, thermal and strain rate effect. Failure behaviour of polymeric materials has become a major concern in recent years, with the start of their introduction into critical structures such as gas pipelines. Failure at the atomic level involves breaking of chemical bonds. A specific feature of polymers is that they have two types of chemical bonds: primary covalent bonds between carbon atoms and secondary, Van der Waals bonds, between the segments of molecular chains. The final failure normally requires cessation of both types of bonds, but in many cases the secondary bonds play an important role in the mechanism of deformation that leads to failure. For this reason these materials exhibit a complex mechanical visco-elastic-plastic behaviour, /2-5/.

High density polyethylene (HDPE) is a thermoplastic polymer which can be used up to 110°C. For water networks (up to 70°C) HDPE pipes are used in various standardized dimensions, according to ISO 4065 thermoplastic pipes - Universal wall thickness table and ISO/TC 138 - Plastics pipes, fittings and valves for the transport of fluids.

Tests carried out by conventional destructive methods provide information on the structure and mechanical characteristics of the virgin material, or estimate them after a certain operation interval in different loading conditions and environments, /6-8/. In order to obtain a product with certain characteristics, in many cases the material choice is influenced by its long term properties, /9-11/. As a result of this trend, in order to study the new materials and for their full characterization, there have been developed new techniques based on the concepts and theories of fracture mechanics, /12/. Thus, for the evaluation of the deformation and fracture behaviour of polymers, hybrid test techniques, /13/, can be used (such as: acoustic emission, thermography, laser extensometry).

Any material containing a geometric discontinuity will increase the stress in its vicinity. This local effect of stress raiser is caused by redistribution of the force lines transmission through the material when a discontinuity appears. Stress raisers may be holes, notches, grooves, edges.

Research of polymers and composites fracture behaviour is still developing, in comparison with the research of metal failure. The factors that govern the toughness and ductility of polymers include the strain rate, temperature and molecular structure. Fracture more often occurs as a result of abruptly severe strain localization in a thinning mode, especially for highly ductile polymers. While metals yield by dislocation motion along the slip planes, polymers can exhibit two failure mechanisms: yielding and crazing.

Polyethylene is a viscoelastic-plastic material, thus its time-dependent properties are determined best from the time course of indenter displacement under constant load, but for characterization of instantaneous elastic and plastic response, fast loadings are necessary, /14/.

In this paper mechanical tensile tests are performed under different loading rates. This method allows us to evaluate the fracture behaviour of the material, without or in the presence of stress concentrators and localization of failure initiation.

MATERIALS AND METHODS

The experimental programme used samples extracted from PE80 SRD 11 GAS ϕ 160×15.5 mm polyethylene pipes. Strip samples of width b = 20.0 mm and thickness a = 15.5 mm are cut from sample pipes of length L = 200 mm. Experimental sets consisted of the following test conditions and samples:
- loading rate: v = 1; 5; 10; 25; 50; 75; 100; 125; 150 mm/min.;
- test temperature: $T = 23 \pm 2$ºC
- test environment: air
- no. of sets: 9 with 5 samples (1 set for each loading rate).

The sample set is used for assessment of imperfection type and dimension influence on the failure dynamics and fracture character. Simulated imperfections are obtained by milling or drilling (Fig. 1), as follows:
- bilateral V-notched samples with notch depth h = 1.0; 1.5; 2.0; 2.5; 3.0 mm;
- bilateral U-notched samples with notch depth h = 1.0; 1.5; 2.0; 2.5; 3.0 mm;
- sample with central hole of diameter d = 2.0; 3.0; 4.0; 5.0; 6.0 mm.

The testing conditions are:
- loading rate: v = 50 mm/min.;
- test temperature: $T = 23 \pm 2$ºC
- test environment: air
- number of sets: 15 sets of 5 samples (1 set for type/ dimension of simulated imperfection).

Notes: In case of V-notched specimens, the notches are obtained using a milling tool of 2 mm width and 0.25 mm radius at the notch tip. In case of U-notched specimens, a cylindrical milling tool of 2 mm width is used. Central hole specimens are drilled in mid width.

There are many imperfection simulation techniques. For this experimental research the mechanical processing technique has been applied. It should be stated that in order to avoid the difficulties that may arise in processing of these simulated imperfections, optimization of the splintering process is necessary to minimize the sample heating. In the case of accentuated material warming, the splintering becomes cumbersome; the superheated material adheres to the splintering tool resulting in alteration of shape and dimensional accuracy of the simulated imperfections.

In the case of milling cutters, used for making the simulated imperfections, the recommended cutting speed, v is:

$$v = \frac{v_1}{Nn} = 0.010 \pm 0.002 \quad \left(\frac{\text{mm}}{\text{rpm} \times \text{tooth}}\right), \qquad (1)$$

where: v_1 – feed rate (mm/min); N – teeth number of the splintering tool (teeth); n – splintering tool speed (rpm).

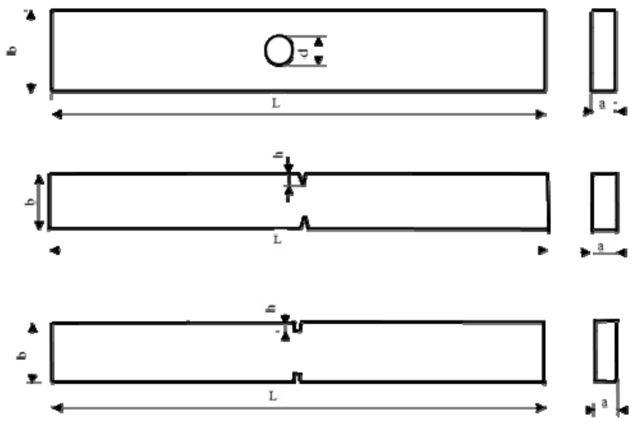


Figure 1. Shape and dimensions of samples for experiments.

The experimental setup is consisted of: universal testing equipment ZD 10/90 type; air conditioned room; infrared camera FLIR System A40; and a personal computer with appropriate software for data acquisition and processing:
- field of view/minimal focal distance: 24° × 18°/0.3 m
- instantaneous field of view (IFOV): 1.3 mrad
- thermal sensitivity at 50/60Hz: 0.08°C to 30°C
- focus: automatic
- type of infrared detector: ‘Focal Plane Array’ (FPA)
- atmospheric window: 7.5–13 µm
- temp. ranges: –40 to +55 °C; 0 to +120 °C; 0 to +1500 °C
- automatic emissivity correction: variable form 0.1 to 1.0
- port (IEEE-1394): 16 bit images.

EXPERIMENTAL RESULTS

Experimental results from tensile testing performed on sample sets designed to evaluate the influence of the loading rate on the tensile strength are presented in Fig. 2.

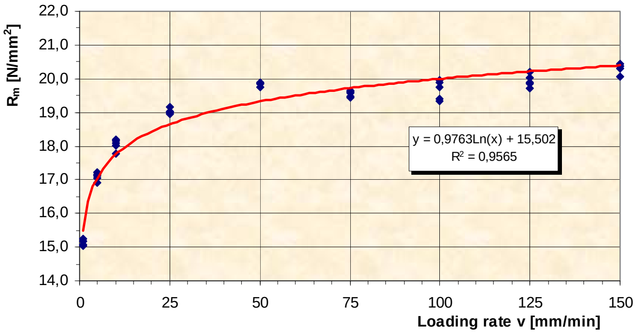
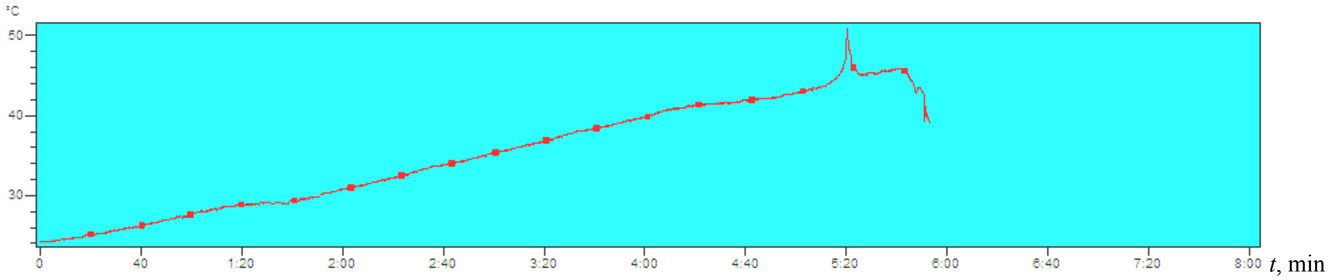
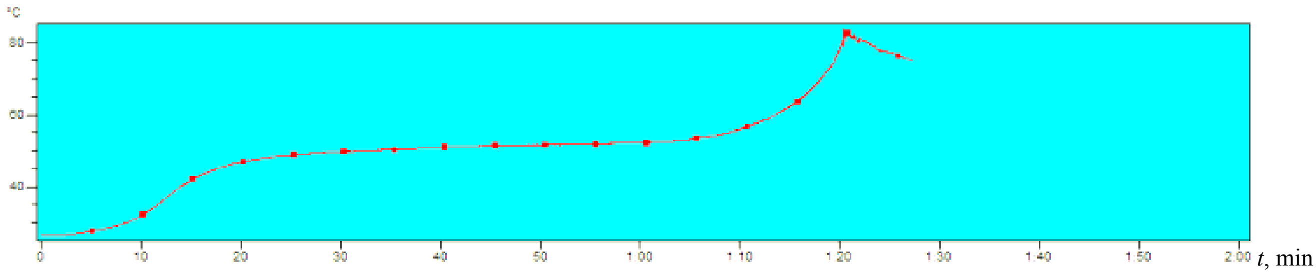


Figure 2. Tensile strength of PE 80 vs. loading rate.

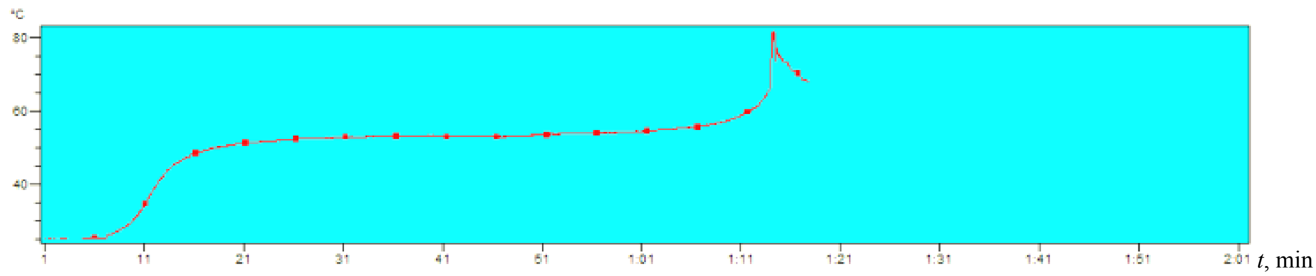
Evolution of sample temperature during tensile testing performed on strip samples extracted from the base material of the pipe is presented in Fig. 3, for three different loading rates (5; 75; and 125 mm/min). One can notice extremely slow change of temperature with low loading rate (Fig. 3a), with significantly lower maximum temperature compared to other two loading rates (Figs. 3-b and c). One should also notice that in the case of strip samples, there is no effect of imperfections, i.e. the results shown in Fig. 3 indicate only the effect of the loading rate.



a) loading rate: v = 5 mm/min



b) loading rate: v = 75 mm/min



c) loading rate: v = 125 mm/min

Figure 3. Evolution of the base material sample's temperature during the tensile tests.

DISCUSSION

Referring to Figure 2, it is noticeable that the testing rate significantly influences the tensile strength in the range of 1-50 mm/min, and to less extent at testing rates exceeding 50 mm/min. Thus, a decrease of approximately 25% of tensile strength is determined at a testing rate of 1 mm/min, compared to that determined at testing rate of 50 mm/min. Also, it can be seen that in the range of 50-150 mm/min, the tensile strength obtained does not vary by more than ± 5% from the reference value for standard test conditions (50 mm/min).

The explanation for this phenomenon lies in the fact that these materials have viscoelastic-plastic behaviour and a significant yield capacity given by the phenomenon of creep at ambient temperature, as a result of the molecular structure. Between neighbouring molecules or between different segments of the same chain of folded molecules, secondary Van der Waals forces occur. These forces oppose the forces which tend to deform the molecule. Accordingly, the elasticity modulus of a thermoplastic polymer is significantly lower than the elasticity modulus (Young modulus) for metals and ceramics, since Van-der-Waals bonds are much weaker than the main covalent bonds.

At temperatures well below the glass transition temperature, the elasticity modulus is relatively high and molecular motion is constrained. Around the glass transition temperature, the elasticity modulus decreases rapidly, and the polymer has reinforced elastic behaviour. At high temperatures, the elasticity modulus is low and the polymer reaches a highly elastic state. If the temperature is high enough, the polymer loses all apparent strength ability and behaves like a viscous fluid.

Thus, at low loading rates, the test duration is relatively high and the material has sufficient time to yield by creep, and also the relaxation of internal stress occurs since the loading increase rate is low, such that the polymer molecules have enough time to move. The macromolecule chains slip one to another without breaking covalent bonds of molecules, except for only the dipole-dipole bonds (Van-der-Waals) between them.

At higher loading rate, the failure mechanism is similar but the material does not have enough time to relax, as explained in /15/. This is indicated by the maximum temperature during the test, Fig. 3. This temperature is much lower at the testing rate 5 mm/min (51 °C), compared to the testing rate 75 mm/min (83°C) and the testing rate 125 mm/min (82°C).

A similar fracture enhancing effect is also driven by the stress concentrators, as shown in /15/, where besides the local stress state caused by the type and severity of the imperfections, the thermal effect is also added. This thermal effect is created by the impossibility for effective removal of heat from their vicinity. These synergic effects should be further investigated for a comprehensive explanation of the relationship between polymer microstructure and its mechanical properties.

CONCLUSION

The correlation between the loading rate and tensile strength of polyethylene has been established. Due to the viscoelastic-plastic character of the polymeric material, it responds specifically to different loading rates. In the case of homogeneous polyethylene of type PE 80, the loading rate has an important influence on the achieved characteristics. In this case it is shown that the tensile strength varies with loading rate according to a logarithmic law. For loading rates over 50 mm/min, the tensile strength R_m is not significantly modified with respect to loading rate. Thus, unlike for metallic materials, where the static tensile test loading rate should be as low as possible, in case of viscoelastic-plastic materials - the loading rate of the tensile test should be much higher.

Overall fracture behaviour of a material is determined by three factors affecting the failure mechanism: loading rate, local stress, and temperature. Whereas thermoplastic materials have a low thermal conductivity, the loading rate has a multiplier effect, since it directly influences the material temperature. Thus, in case of high loading rate the heat released during deformation has no time to disperse within the material, causing local temperature increase, which leads to an accelerated fracture process by local altering of the plasticity and strength characteristics of the material.

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