TEMPERATURE AND HEAT EFFECTS ON POLYETHYLENE BEHAVIOUR IN THE PRESENCE OF IMPERFECTIONS

by

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This paper highlights the changes of polyethylene behaviour during various loading rates as well as the influence of test temperature on the material characteristics. Passive infrared thermography method and a high speed infrared camera were used to observe the temperature changes of the sample surface during the tests. The experimental program was carried out on samples taken from PE80 polyethylene gas pipes with simulated imperfections with bilateral V-notch, U-notch, and central hole. Samples have been tensile tested and the results are correlated with the temperature distribution of the samples surface.

Key words: *tensile tests, polyethylene pipes, infrared thermography, imperfections*

Introduction

High density polyethylene (HDPE) is a product of particular importance, currently used to manufacture pipelines for gas and water supply. Polyethylene has a molecular structure in which monomers are linked together by attractive intermolecular forces, thus resulting polymers. Unlike metals, polymers do not contain a crystallographic plan and grain boundaries; they rather consist of long molecular chains. The factors that govern the toughness and ductility of polymers include the strain rate, temperature and molecular structure.

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 [1-4]. In order to achieve a product, in many cases the material choice is influenced by its long term properties [5-7]. 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 [8, 9].

In this paper passive infrared thermography is used to monitor mechanical tensile tests performed under different conditions (loading rate and temperature). 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.

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Materials and methods

The experimental program used samples extracted from PE 80 SRD 11 GAS ϕ160×15.5 mm polyethylene pipes. Strip samples with width b = 20.0 mm and thickness a = 15.5 mm were cut from sample pipes with length L = 200 mm. The experimental sets consisted of tree types of test samples:

(1) Sample set for evaluation of the influence of test temperature on the mechanical characteristics.

The testing conditions were:

- loading rate: v = 50 mm/min;
- test temperatures: T = 1 ºC; 5 ºC; 10 ºC; 15 ºC; 20 ºC; 23 ºC; 25 ºC; 30 ºC; 40 ºC; 50 ºC,
- test environment: water, and
- number of sets: 10 sets of 5 samples (1 set for each test temperature).

(2) Sample set for assessment of the influence of imperfection type and dimension on the failure dynamics and fracture character. The simulated imperfections were obtained by milling or drilling:

- 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, and
- sample with central hole with diameter d = 2.0; 3.0; 4.0; 5.0; 6.0 mm.

The testing conditions were:

- loading rate: v = 50 mm/min.;
- test temperature: T = 23 ± 2 ºC;
- test environment: air, and
- 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 were obtained using a milling tool of 2 mm width and a radius of 0.25 mm at the notch top. In case of U-notched specimens, a cylindrical milling tool of 2 mm width was used. In case of specimens with central hole, the holes were 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.

Tensile tests (TT) carried out in the experimental program were monitored by infrared thermography (IRT) by following the deformation and degradation process of the bilateral notched specimens up to fracture. The test method considered that during the mechanical loading process followed by plastic deformation, the majority of the materials heat up. Following this observation the thermography method was used, being based on the temperature distribution analysis of the specimen surface (analysis of the *cold* and *hot* points). The heat energy emission during the sample's loading time period is highlighted, through visualization and quantification by non-contact measuring of the temperature zone of interest (zone of stress raisers created by the presence of plane imperfections). This hybrid TT-IRT method was used for a better understanding of the fracture process in samples with simulated imperfections. Using this method the thermal images of the tested specimens are recorded on-line and analyzed. Thermal image distributions show continuous changes during the test, due to the heat released normally during the static tensile loading. The computerized infrared thermography is used to scan the thermal values of the areas with simulated imperfections and based on the values obtained the severity and progress phase are evaluated.

The experimental set-up (fig. 1) 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° x 18° / 0.3 m,
- instantaneous field of view (IFOV): 1.3 mrad,
- thermal sensitivity at 50/60 Hz: 0.08-30 °C,
- focus: automatic
- type of infrared detector: „Focal Plane Array" (FPA),
- atmospheric window: 7.5-13 μm,
- temperature ranges: –40-+55 °C; 0-120 °C; 0-1500 °C,
- automatic emissivity correction: variable form 0.1-1.0, and
- port (IEEE-1394): 16 bit images.

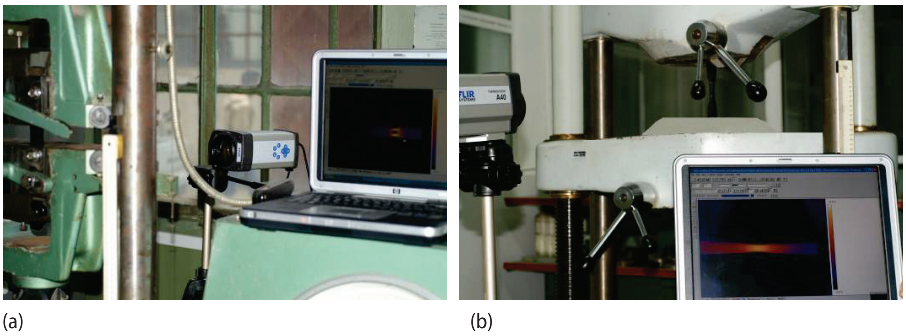

(a) (b)

Figure 1. Experimental set-up; (a) ZD10/90 Universal Testing Machine and IR camera FLIR System Type A40, (b) EDZ 40 Universal Testing Machine and IR camera FLIR System Type A40

Experimental results

The experimental results obtained by tensile testing, performed on sample sets designed to evaluate the influence of test temperature on the tensile strength, are presented in fig. 2.

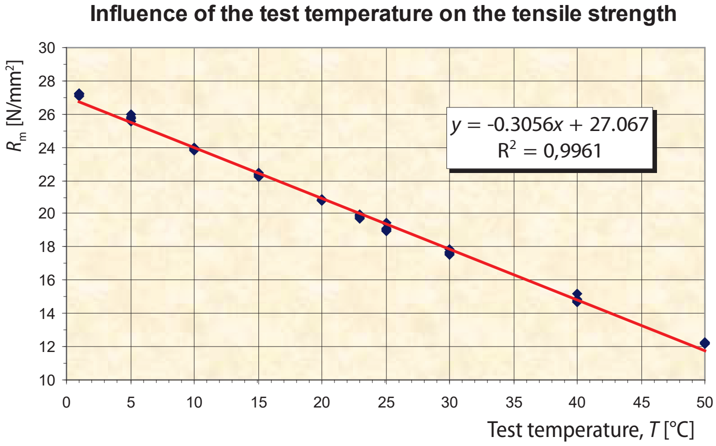
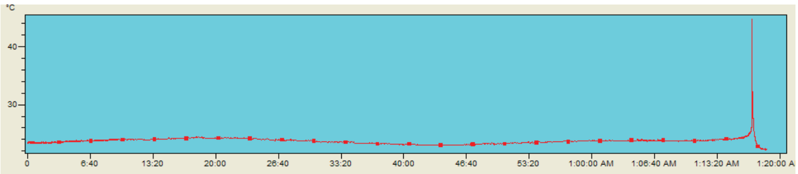
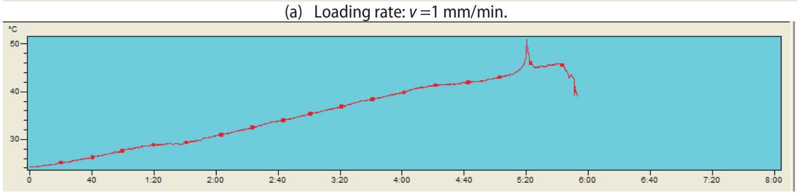


Figure 2. Variation of tensile strength for PE 80 with the test temperature

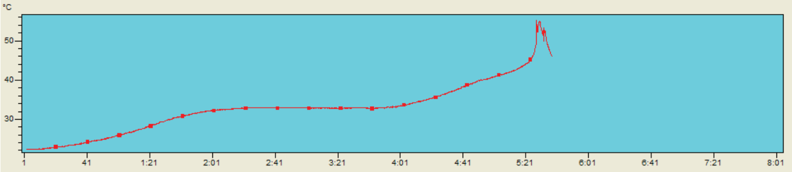
Evolution of the samples' temperature during the tensile testing, performed on strip samples extracted from the base material of the pipe, is presented in fig. 3. Figure 4 presents IR image of the tensile testing for loading rates 25, 75, and 150 mm/min.



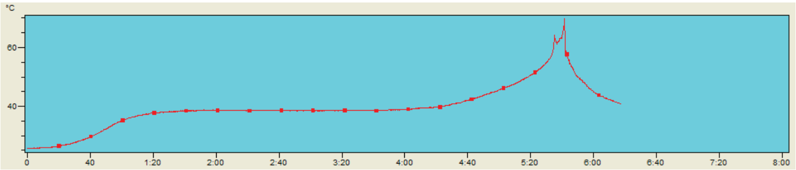
(a) Loading rate: *v* =1 mm/min.



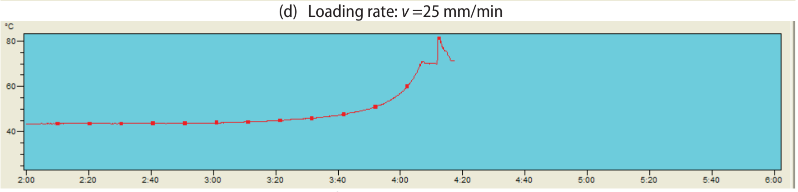
(b) Loading rate: *v* =5 mm/min.



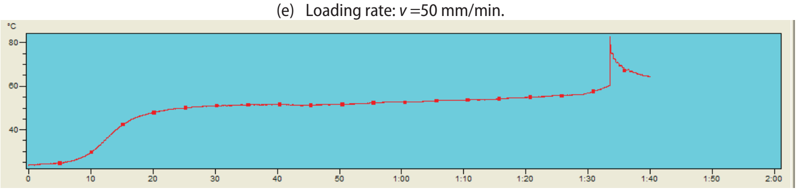
(c) Loading rate: *v* =10 mm/min.



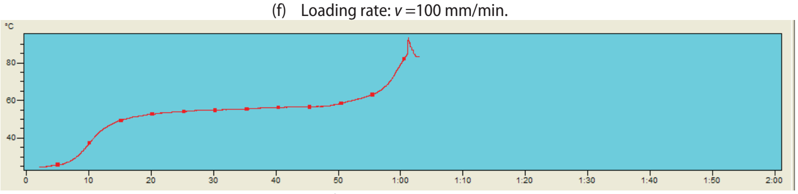
(d) Loading rate: *v* =25 mm/min



(e) Loading rate: *v* =50 mm/min.



(f) Loading rate: *v* =100 mm/min.

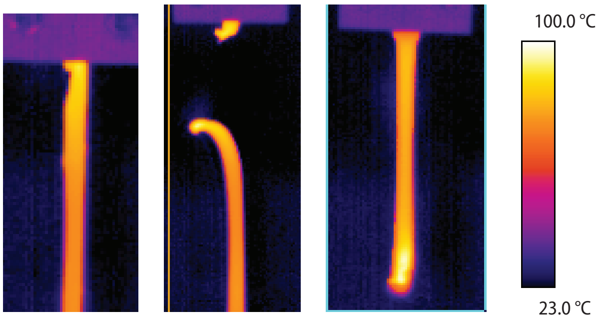


(g) Loading rate: *v* =150 mm/min

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

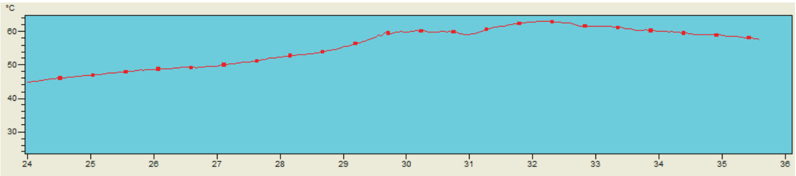
Evolution of the samples' temperature during the tensile testing, performed on the bilateral V-notched sample set, is presented in fig. 5.

Figure 6 presents IR image of the tensile testing for notch depths 1, 2, and 3 mm. Evolution of the samples' temperature during the tensile testing, performed on the bilateral U-notched sample set, is presented in fig. 7. Figure 8 presents IR image of the tensile testing for notch depths 1, 2 and 3 mm.

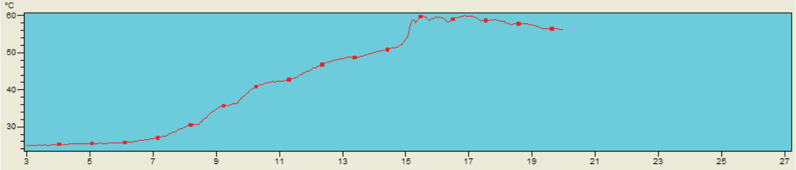


(a) (b) (c)

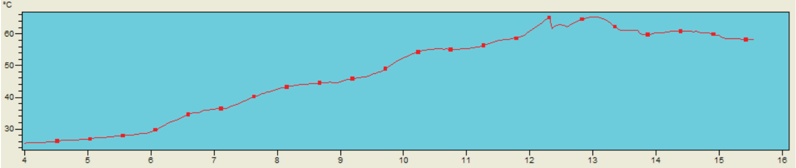
Figure 4. The IR image for different loading rates; (a) 25 mm/min, (b) 50 mm/min, (c) 150 mm/min (*for color image see journal web site*)



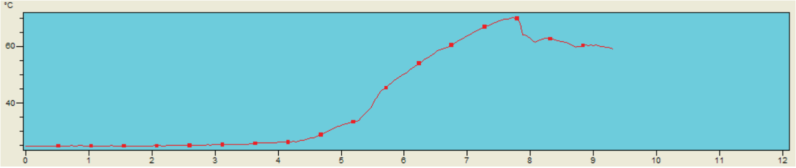
(a) notch depth *h* = 1.0



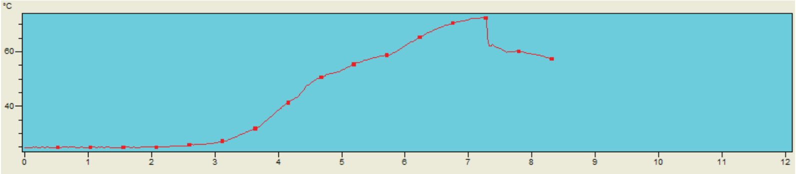
(b) notch depth *h* = 1.5



(c) notch depth *h* = 2.0

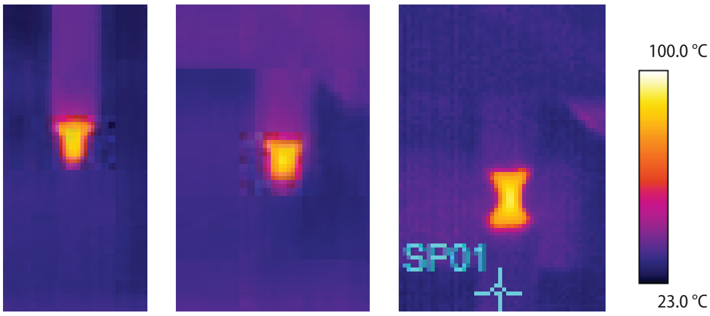


(d) notch depth *h* = 2.5



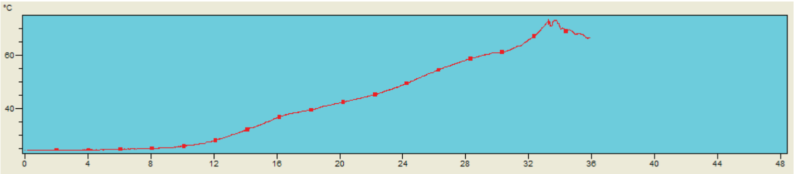
(e) notch depth *h* = 3.0

Figure 5. Evolution of the V-notched sample's temperature during the tensile tests

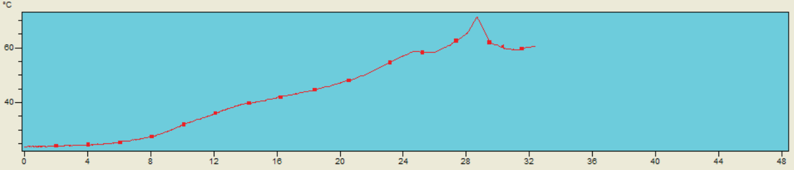


(a) (b) (c)

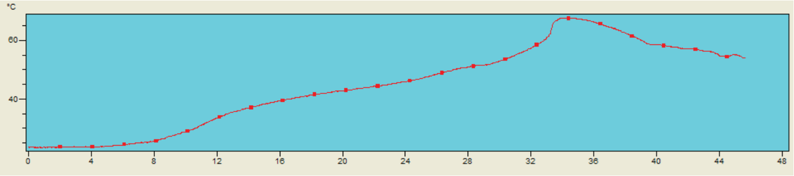
Figure 6. The IR image for different notch depths; (a) 1 mm, (b) 2 mm, (c) 3 mm (*for color image see journal web site*)



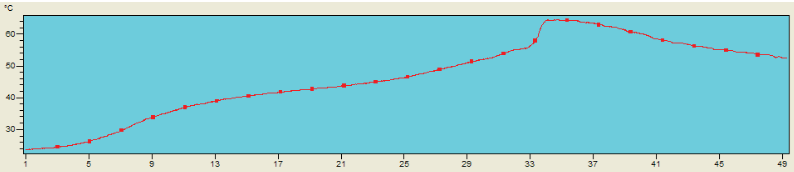
(a) notch depth $h = 1.0$



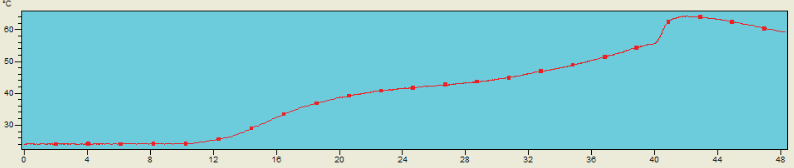
(b) notch depth $h = 1.5$



(c) notch depth $h = 2.0$



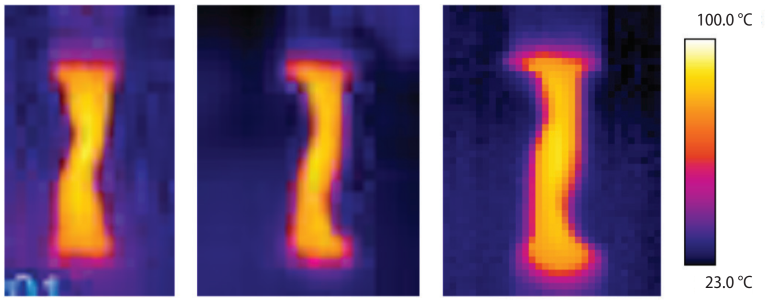
(d) notch depth $h = 2.5$



(e) notch depth $h = 3.0$

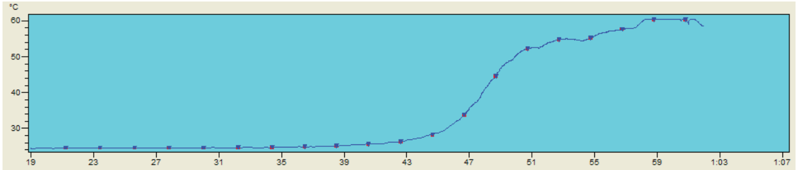
Figure 7. Evolution of the U-notched sample's temperature during the tensile tests

Evolution of the samples' temperature during the tensile testing, performed on the sample set with the central hole, is presented in fig. 9, whereas IR images are given in fig. 10.

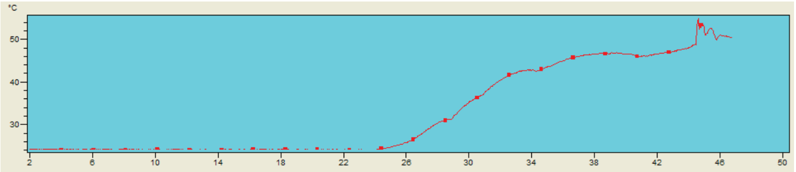


(a) (b) (c)

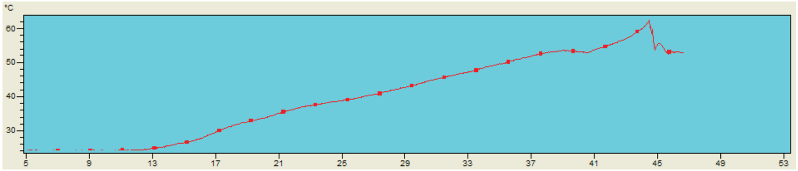
Figure 8. The IR image for different notch depths; (a) 1 mm, (b) 2 mm, (c) 3 mm (*for color image see journal web site*)



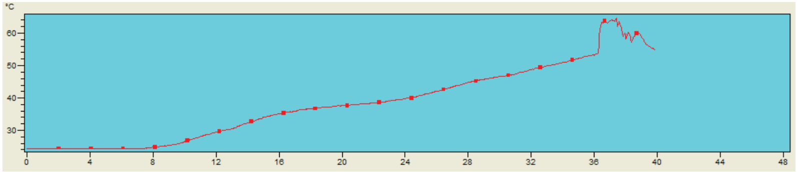
(a) hole diameter $d = 2.0$



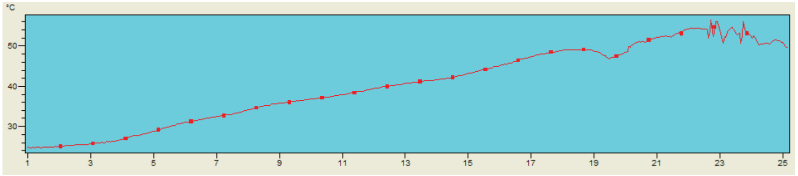
(b) hole diameter $d = 3.0$



(c) hole diameter $d = 4.0$



(d) hole diameter $d = 5.0$



(e) hole diameter $d = 6.0$

Figure 9. Evolution of the sample's temperature with the central hole, during the tensile tests

Discussion

As it can be seen in fig. 2, the test temperature plays a decisive role, since the tensile strength of PE80 thermoplastic material is linearly dependent with it, in the temperature range in which experimental tests were conducted (range included in the field of viscoelastic behaviour).

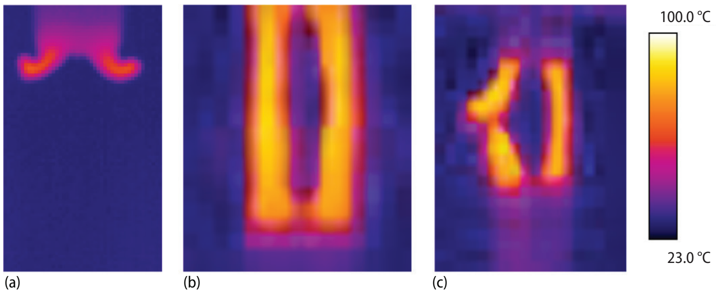


Figure 10. The IR image for different hole diameters; (a) 2 mm, (b) 4 mm, (c) 6 mm (*for color image see journal web site*)

The tensile strength determined at a temperature of 10 °C is about two times higher than the one determined at a temperature of 50 °C, while in the temperature range of 23 ± 2 ºC it varies by approximately ±5%, thus affecting the measurement uncertainty. This demonstrates both the need for specimen conditioning before the test and a rigorous control of the test temperature.

At higher loading rate the material does not have enough time to relax and so forced displacement of molecules appears that produces friction and a higher load is required for material deformation. Thus, by friction some of the energy is converted into heat which dissipates into the material. This aspect could be evidenced by the maximum temperature obtained during the test, as seen in fig. 11. This temperature is much lower at a testing rate of 1 mm/min. (44.8 °C) compared to the one measured at a testing rate of 50 mm/min. (81.7 °C) and the one measured at a testing rate of 150 mm/min. (93 °C). Complex behaviour in the range 50-150 mm/min might be attributed to different, competing mechanisms of internal heating.

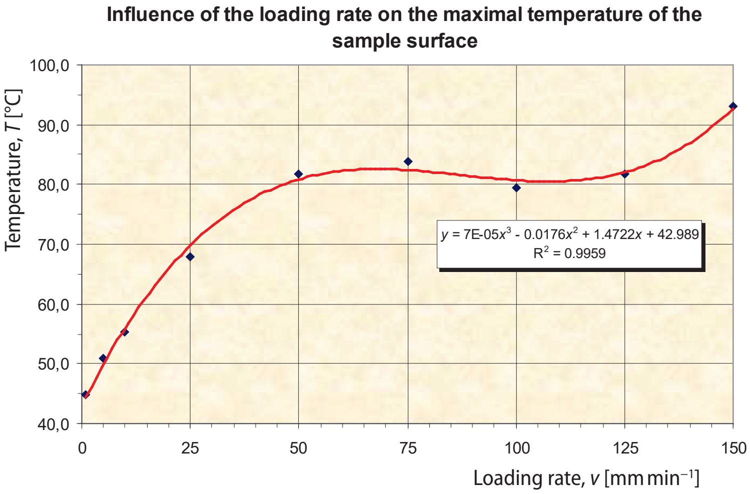


Figure 11. Evolution of the maximum temperature *vs.* loading rate recorded during the tensile test performed on samples extracted from the base material, without imperfections

To highlight how the imperfections effects on the tensile testing behaviour of polyethylene, by processing the data given within figs. 5, 7, and 9, fig. 12 presents the evolution of the maximum recorded temperature *vs.* the percentage of cross section occupied by the imperfections during the tensile test, performed on samples extracted from the base material with different type of simulated imperfections. Once again, complex behaviour might be attributed to competing mechanisms of internal heating.

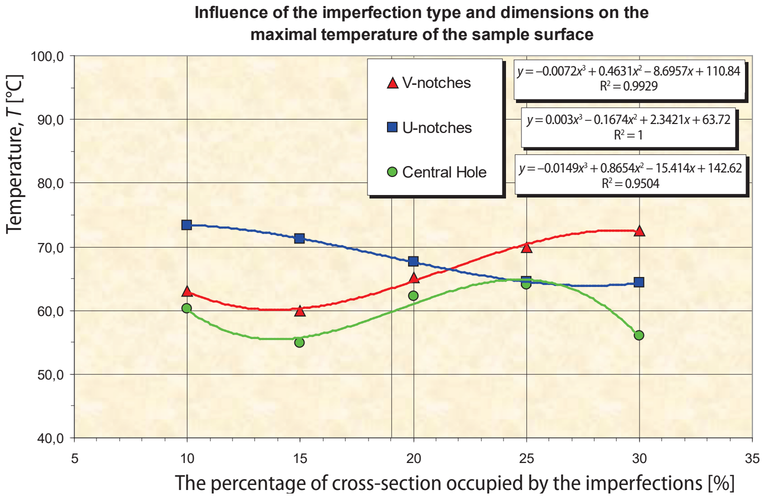


Figure 12. Evolution of the maximum temperature *vs.* the percentage of cross-section occupied by the imperfections during the tensile test performed on samples with different types of imperfections

Conclusions

It was found that recorded temperatures during the tensile tests are correlated with the local stress condition, induced by loading of the specimen with imperfections (geometrical discontinuities obtained by mechanical machining).

The maximum temperature recorded during the tensile test varies with the loading rate, the curve shape being altered by the imperfections depending on their type and the percentage of the specimen's cross-section occupied by them.

Further investigation is needed to understand mechanisms of complex temperature behaviour in presence of imperfections and with different loading rates.

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