Archives of Materials Science and Engineering

Volume 36
Issue 2
April 2009
Pages 89-95

International Scientific Journal
published monthly by the
World Academy of Materials
and Manufacturing Engineering

Creep damage mechanisms in gas pipes made of high density polyethylene

A. Pusz, K. Michalik*
Division of Metal and Polymer Materials Processing,
Institute of Engineering Materials and Biomaterials,
Silesian University of Technology, ul. Konarskiego 18a, 44-100 Gliwice, Poland
* Corresponding author: E-mail address: katarzyna.michalik@polsl.pl

Received 15.01.2009; published in revised form 01.04.2009

ABSTRACT

Purpose: The purpose of this article is to present results of creep damage mechanisms in gas pipes made of high density polyethylene [HDPE]. High density polyethylene has been widely used in the piping industry as raw material. Even though there are large numbers of experimental and analytical investigations on HDPE, few of them have examined the effects of manufacturing techniques on the small and finite deformation behaviors of HDPE. Since HDPE is semi-crystalline polymeric material the rate of crystallinity, molecular morphologies and molecular structure extensively influence its mechanical behaviors.

Design/methodology/approach: Tensile creep experiments on HDPE with a duration of examinations from four till nine days were performed at temperature of 20°C.

Findings: In this study, findings are indicating differences of the property in individual layers walls of the pipe.

Research limitations/implications: Applying this method is limited to thermoplastic materials.

Practical implications: Presented method can be applied for other thermoplastic materials in the future.

Originality/value: The expressed method can be applied in the future for developing the research on the process with creeping of polymers.

Keywords: Engineering polymers; Creep-resistance; Mechanical properties; Pipe; HDPE High Density Polyethylene

Reference to this paper should be given in the following way:

A. Pusz, K. Michalik, Creep damage mechanisms in gas pipes made of high density polyethylene, Archives of Materials Science and Engineering 36/2 (2009) 89-95.

PROPERTIES

1. Introduction

In view of the fact that many products are designed with plastics, a thorough knowledge of the mechanical behaviour of this class of material is essential. The application of accurate models to describe this behaviour will allow designers to make products lighter and cheaper. The growing use of polymeric materials in engineering applications demands new methodologies in order to assess the material capability to withstand loads.

Most processes for forming thermoplastic products, particularly injection moulding and extrusion, involve a melt flow followed by cooling. Invariably the cooling through the whole product, and this is particularly significant for plastic materials since their properties are very sensitive to thermal history. As a result, there are at least three important factors that need to be considered carefully in assessing plastic products, namely, anisotropies or preferred orientations, inhomogeneities or variations in properties form one area to another and residual stresses that become frozen into the material during solidification. Mechanical behavior of polymers has recently received considerable interest due to the increased use of polymers in many applications such as pressure tubing, nuclear engineering components, central heating systems, cable insulation, pipe line, drainpipes, gear and bearing [1,2]. Material behavior of polymers can change from brittle to vicoplastic depending upon loading conditions and temperature. Their behavior can be explained in terms of their microstructures. Polymers can have either amorphous or semi-crystalline structure. The degree of crystallinity and the size and distribution of the crystallites in a semi-crystalline polymer have a large effect on the mechanical properties of these materials [3-5]. If the polymer has amorphous structure, inelastic behavior depends on the molecular chain flexibility, entanglement and on differences in the structure of the molecular chains. The mechanical behavior of polymeric materials depends on both time and temperature; quite a lot of experimental techniques may be used to measure and quantify this behavior. The most important objective of understanding the deformation behavior at varying strain rates is to support the designer with reliable data applicable to practical applications. The study of deformation behavior at different strain rates is important in engineering design because the mechanical properties and deformation mechanism are strongly dependent on the applied strain rate [6-17].

The first plastic pipes were installed in the mid-1930s, with their usage increasing rapidly in the 1950s. Plastics have steadily replaced clay, copper, asbestos-cement, aluminum, iron and concrete pipes in various applications. Polyethylene (PE) is mostly used pipe material for water and gas distribution - often under pressure. The production of polyethylene piping involves the cooling of an extruded melt, normally by spraying cold water onto the outer wall as the pipe passes through a series of spray tanks. Combined with the low thermal conductivity of polymers, this procedure inevitably produces substantially different cooling rates as a function of position in the pipe wall. This leads to significant variations on the microstructure, affecting such parameters as crystallinity, spherulite size, lamella thickness etc. These parameters, in turn, control a wide range of other dependent material properties, including density, strength, stiffness, and creep behaviour, which vary through the pipe wall thickness. Furthermore, as the outside is rapidly cooled it solidifies and this solid outer layer then prevents contraction of the inner layers of the pipe as they solidify. When solidification is complete, this process inevitably leads to the presence of residual stresses, in which the outer layers of the pipe are in compression and these forces are counteracted by the inner layers, which are in tension. Comments give some idea of the wide ranging and complex phenomena that occur during the extrusion and cooling plastic pipe [18-21].

Although the overall pressure is bellow the yield stress of the material, mechanical failure always occurs before the final chemical degradation takes place. HDPE pipes used for gas transport are under pressure for the duration of their useful service. Often fluctuations in pressure render the load to be dynamic. Therefore, it is important to establish the maximum load that such a pipe can withstand without deformation and damage over its expected lifetime – many decades. There are several experimental researches that characterized mechanical behavior of HDPE [22-25]. These experimental studies are investigated singly or combined aspect of deformation such, as loading-unloading, relaxation, creep, multiple creep, multiple relaxation. Beijer and Spoormarker [26] conducted tensile loading and creep test at different stress and strain rate levels on injection molding HDPE specimens. These works are represented long-term creep and short-term creep data from HDPE at a wide range of stresses. Hillmansen et al. [27] performed tensile loading test on a pipe grade polyethylene samples with different molecular mess at a variety of temperatures and reported that the yield stress decreases with an increase in molecular mass. Boneer et al. [28] carried out tensile creep test at different stress levels on three grade compression molded HDPE samples. the mechanical behavior of an extruded plastic pipe is not only governed by its material characteristics and pipe dimensions, but also by processing which imparts orientation and hence determines material morphology. Since processing can significantly influence the final performance, material testing should be made on samples having the same processing history of extruded pipes [22-24].

Creep is not only an important occurrence in its own right within the structure of viscoelasticity but is also of immense connotation in the design of plastics product, as it reflects the load-bearing capacity of end-products. Structural invent engineers are faced with challenge of creep rupture and other time – dependent failures of polymer structures in engineering. An assessment of durability should be made at the design stage in order to prevent premature failures and to avoid intolerably large deformation [29].

In this work, creep behaviour of HDPE extruded specimens were investigated. The assessment of the impact of the thickness of the wall of the pipe to the speed of creeping was a purpose of the work.

2. Experimental setup

Tubular wires produced by the company of of ELPLAST + Sp. z o.o. Jastrzębie Zdrój were used to examinations of creeping.

The type of material and diameters of pipes were placed in Table 1.

Table 1.
Material for examinations

Type of material	Pipe external diameter ϕ [mm]	Layer	Thickness of layer [mm]
HDPE – High Density Polyethylene	90	without the division	5
	110	internal	5
		outside	5
	160	internal	5
		centre	5
		outside	5

Pipes were divided in stretches of the l = 20 length cm, and then in the process of carrying on, to layers about the thicknesses equal of 5 mm. In Figure 1 a fragment of the pipe of the division into classes was described.

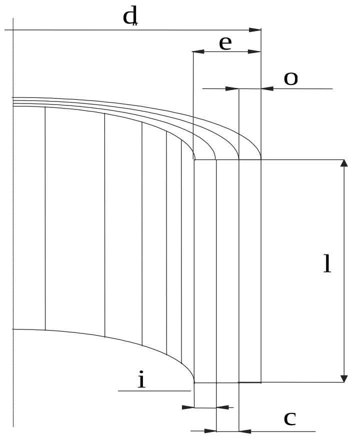

Fig. 1. Fragment of the pipe of the division into layers [4]: i - internal layer, c. - centre layer, o - outside layer,l - length, d_n - external diameter, e_n - thickness of the partition wall

Samples were prepared for examinations of creeping according to the norm PN-EN ISO 6259 - 1 (Figure 2) [30]. A blanking tool was used with keen edges, without breakdown a shape and dimensions of the sample were received the way a norm stipulates PN-EN ISO 527 - 2 (Figure 3) [30-32].

Three series were carried out for six samples - altogether eighteen samples dumbbell.

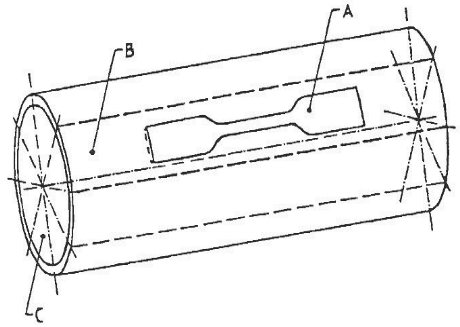

Fig. 2. Preparation of samples for examinations according to PN-EN ISO 6259 – 1; A - sample for examinations, B- strip, C- segments [30]

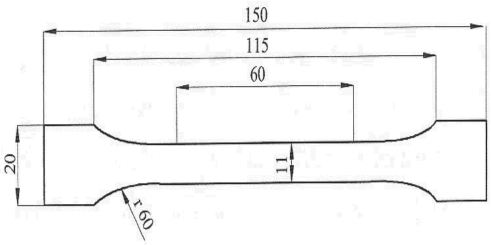

Fig. 3. Dimensions of the sample for examinations [30-32]

The research on the process of creeping was conducted according to the norms PN-EN ISO 899-1:2005 and PN-EN ISO 9967:2007 [33, 34].

A device described schematically in the Figure 4 was used to examinations of creeping. Fastened samples (6) in handles (4) are being subjected to permanent stretching power extorted by the weight (7). For measurements of the deformation a used clock (5) which was adapted to measurements of internal sizes. The whole is immersed in the bathtub (3) with the water bath. The bathtub is equipped with electric heaters (2) with the thermostat and insulate with rock wool in the destination of protecting against loss the warmth. The whole of the device is stiffened frame from channel bars (1).

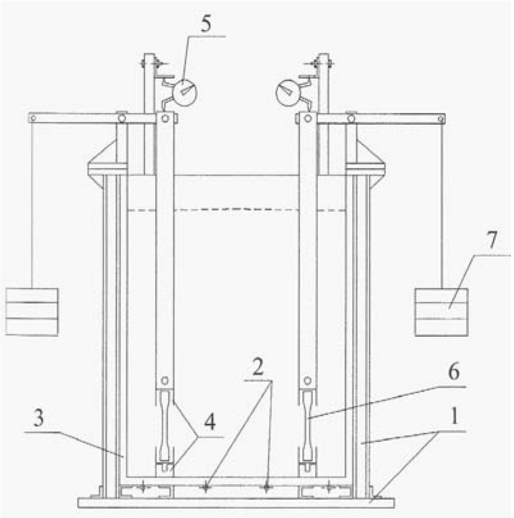

Fig. 4. Scheme of the device for examining creep (side section): 1 - outside frame, 2 - electric heaters, 3 - bathtub with the water bath, 4 - handles, 5 - clock, 6 - sample, 7 - burden

Research program:

- examinations were conducted in two cycles for nine samples (on account of the capacity of the measuring bathtub),
- duration of examinations from four till nine days,
- straining next samples was being commenced every 10 minutes,
- extending every sample was being measured after the passage: 10.100, 200.400, 800,..., of 700 000 seconds. for every sample was made 14 measurements,
- samples were plunged in the bathtub with water about temperature 20 °C,
- samples were encumbered initially with 1 kg,
- the tension was permanent 10 MPa.

3. Results

For life-time prediction of the components made out of polymeric materials, the creep responses of the polymers are quite important especially at high temperatures.

Figure 5 is introducing results of crawling received for samples cut from the pipe about the diameter ϕ 90. However Figure 7 is showing results received for samples cut from the pipe about ϕ 110 diameter. Received results for samples cut from the pipe about diameter ϕ 160 were presented on Figure 9.

Every of curves get on graphs they were approximating with linear equation (y = ax + b) and for every a directional rate was received "a" and coefficient of correlation R^2. A Table 2 is showing these results.

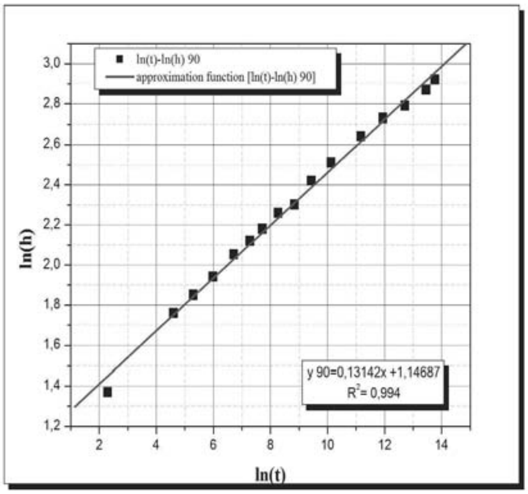

Fig. 5. The graph of the relation ln(t)-ln(h); pipe ϕ 90 approximation with first degree function

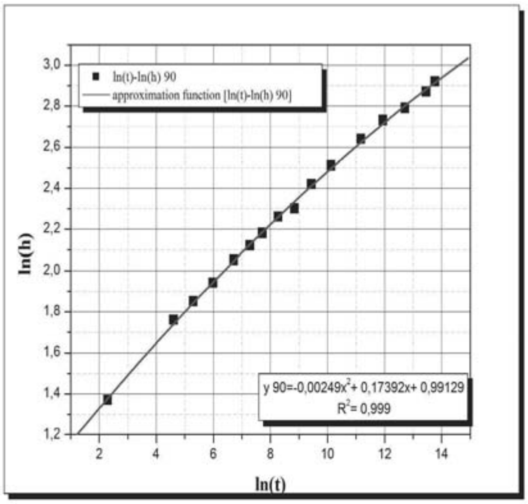

Fig. 6. The graph of the relation ln(t)-ln(h); pipe ϕ 90 approximation with second degree function

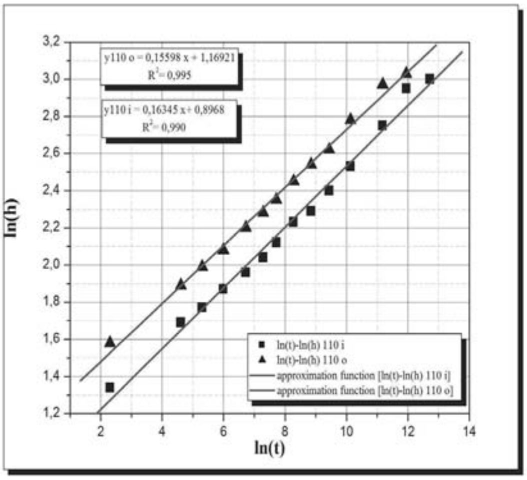

Fig. 7. The graph of the relation ln(t)-ln(h); pipe ϕ 110: i - internal layer, o - outside layer approximation with first degree function

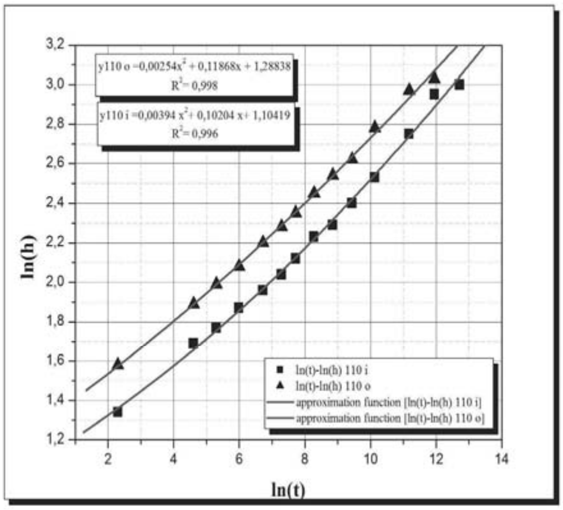

Fig. 8. The graph of the relation ln(t)-ln(h); pipe ϕ 110: i - internal layer, o - outside layer approximation with second degree function

Directional rate "a" is passing the information about the speed of the deformation on. The maximum value of the rate is attesting to the fact that the sample more quickly is crawling. Graphs were also carried out approximating is eating with second degree equation ($y = ax^2 + bx + c$) in order to receive the higher R^2 coefficient of correlation. For every curve values of rates were received „a" and „b" and R^2 coefficient of correlation. Table 3 is showing results.

Graphs approximate with the first degree equation (Figure 5, Figure 7, Figure 9.) and the second degree equation they presented below (Figure 6, Figure 8, Figure 9). The received R^2 coefficient of correlation has the higher accuracy in comparing to the R^2 rate in case of the approximation with first degree function.

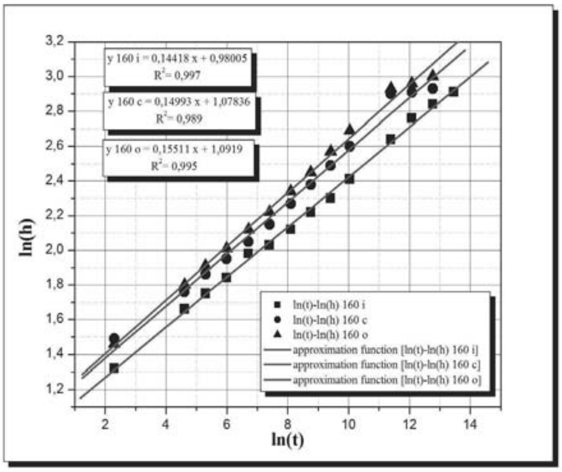

Fig. 9. The graph of the relation ln(t)-ln(h); pipe ϕ 160: i - internal layer, c – centre layer, o - outside layer approximation with first degree function

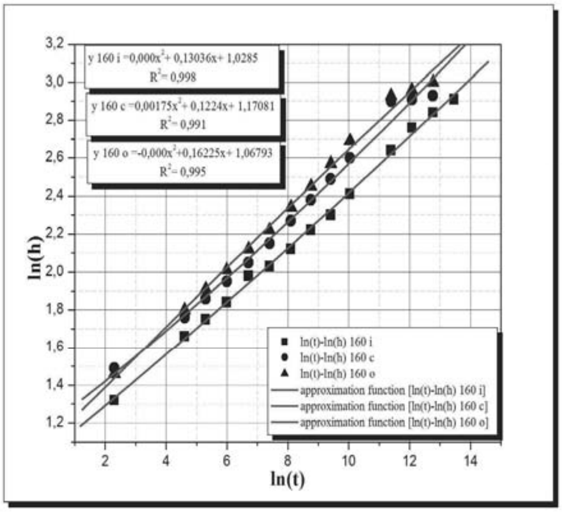

Fig. 10. The graph of the relation ln(t)-ln(h); pipe ϕ 160: i - internal layer, c – centre layer, o - outside layer approximation with second degree function

Table 2.
Equations curves of the approximation

Pipe external diameter ϕ [mm]	Linear equation	a	R^2
90	y = 0.1314x + 1.1468	0.1314	0.994
110 o	y = 0.1559x + 1.1692	0.1559	0.995
110 i	y = 0.1634x + 0.8968	0.1634	0.990
160 o	y = 0.1551x + 1.0919	0.1551	0.995
160 c	y = 0.1499x + 1.0783	0.1499	0.989
160 i	y = 0.1441x + 0.9800	0.1441	0.997

Table 3.
Equations curves of the approximation second degree

Pipe external diameter ϕ [mm]	Linear equation	a	b	R^2
90	$y = -0.0024x^2 + 0.1739x + 0.9912$	-0.0024	0.1739	0.999
110 o	$y = -0.0025x^2 + 0.1186x + 1.2883$	-0.0025	0.1186	0.998
110 i	$y = 0.0039x^2 + 0.1020x + 1.1041$	0.0039	0.1020	0.996
160 o	$y = -0.000x^2 + 0.16225x + 1.06793$	0	0.1622	0.995
160 c	$y = 0.00175x^2 + 0.1224x + 1.1708$	0.0017	0.1224	0.991
160 i	$y = 0.000x^2 + 0.1303x + 1.0285$	0	0.1303	0.998

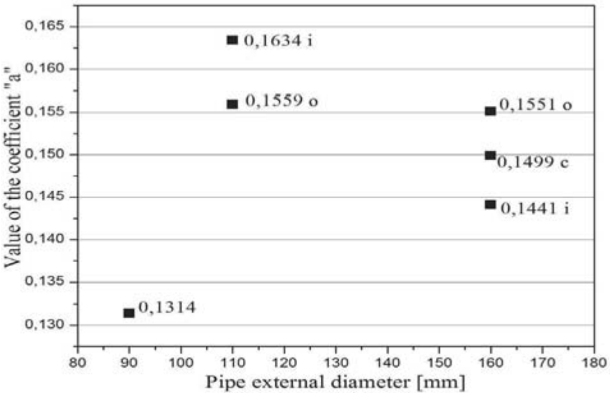

Fig. 11. The graph of the relation pipe external diameter to value of the coefficient “a” – approximation with linear equation

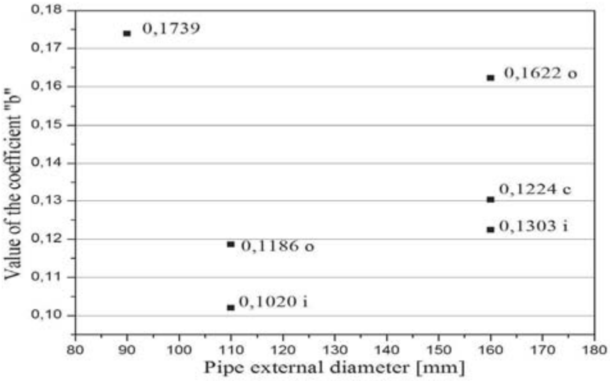

Fig. 12. The graph of the relation pipe external diameter to value of the coefficient “b” - approximation with second degree equation

Rate "a" received as a result of the approximation with second degree equation is attesting to character of the deformation. However rate „b" is attesting to the speed of the progression of deforming for them is smaller with it the sample more slowly is crawling.

In Figure 11 received values of directional rates "a" were described, approximate with linear equation. However in Figure 12 received values of rates "b" were described, approximate with second degree equation.

On the basis of received graphs it is possible to state that samples depending on pipe diameter and layer from whom they come have different speeds of creeping.

4. Conclusions

The results of this work are summarized as follows:

- Samples have different speeds of creeping depending on the thickness of the wall of the pipe and of layer from whom they come.
- Approximation of received graphs with second degree equation let for receiving the high R^2 coefficient of correlation.
- Analyzing the value of the R^2 coefficient of correlation it is possible to state, that stability of losing its shape of centre layer is repeatedly bigger than the stability of losing its shape of layers internal and outside.

Acknowledgements

The authors thank ELPLAST Sp z o.o. for pipes.

References

[1] L.A. Dobrzański, Engineering materials and material design. Principles of materials science and physical metallurgy, WNT, Warsaw, 2006 (in Polish).

[2] H.B.H. Hamouda, M. Simoes-betbeder, F. Grillon, P. Blouet, N. Billon, R. Piques, Creep damage mechanisms in polyethylene gas pipes, Polymer 42 (2001) 5425-5437.

[3] D. Monas, M. Monas, M. Starek, M. Danek, Improvement of plastic properties, Archives of Materials Science and Engineering 32/2 (2008) 69-76.

[4] A. Pusz, K. Michalik, Examining the hardness of high density polyethylene with method of the cone, Archives of Materials Science and Engineering 28/8 (2007) 467-470.

[5] K. Michalik, A. Pusz, Optimization of the lacquering process, Archives of Materials Science and Engineering 32/2 (2008) 113-116.

[6] A. Gnatowski, P. Palutkiewicz, E. Bociąga, Numerical analysis of stress state during single point bending in DMTA examinations, Journal of Achievements in Materials and Manufacturing Engineering 28/1 (2008) 47-50.

[7] M. Parsons, E.V. Stepanov, A. Hiltner, E. Baer, Correlation of fatigue and creep slow crack growth in a medium density polyethylene pipe material, Journal of Materials Science 35 (2000) 2659-2674.

[8] V. Favier, T. Giroud, E. Strijko, J.M. Hiver, C. G'Sell, S. Hellinckx, A. Goldberg, Slow crack propagation in polyethylene under fatigue at controlled stress intensity, Polymer 43 (2002) 1375-1382.

[9] J. Cazenave, R. Seguela, B. Sixou, Y. Germain, Short - term mechanical and structural approaches for evaluation of polyethylene stress crack resistance, Polymer 47 (2006) 3904-3914.

[10] G. Pinter, M. Haager, W. Balika, R.W. Lang, Fatigue crack growth in PE-HD pipe materials, Plastics and Rubber Composites Processing Applications 34 (2005) 25-33.

[11] M. Żenkiewicz, J. Richert, Influence of polymer samples preparation procedure on their mechanical properties, Journal of Achievements in Materials and Manufacturing Engineering 26/2 (2008) 155-158.

[12] D. Barry, O. Delatycki, The effect of molecular structure and polymer morphology on the fracture resistance of high density polyethylene, Polymer 33 (1992) 1264-1265.

[13] S. Castagnet, J.C. Grandidier, Structural effect in the creep behavior of thermoplastic pressure pipes at high temperature - role of geometrical defects, Archive of Applied Mechanics 76 (2006) 567-578.

[14] R. Schouwenaars, V.H. Jacob, E. Ramos, A. Oritz, Slow crack growth and failure induced manufacturing defects in HDPE - tubes, Engineering Failure Analysis 14 (2007) 1124-1134.

[15] J. Tusek, Analysis of a joint of steel and high-density polyethylene, Journal of Achievements in Materials and Manufacturing Engineering 19/2 (2006) 7-15.

[16] M. Szymiczek, G. Wróbel, Influence of temperature on the viscoelastic properties of drawn PE pipes, Journal of Achievements in Materials and Manufacturing Engineering 19 (2007) 287-290.

[17] O. Balkan, H. Demirer, H. Yildirim, Morphological and mechanical properties of hot gas welded PE, PP and PVC sheets, Journal of Achievements in Materials and Manufacturing Engineering 31/1 (2008) 60-70.

[18] C.J.G. Plummer, A. Goldberg, A. Ghanem, Micromechanisms of slow crack growth n polyethylene under constant tensile loading, Polymer 42 (2001) 9551-9564.

[19] P.A. O`Connell, M.J. Bonner, R.A. Duckett, I.M. Ward, The relationship between slow crack propagation and tensile creep bahaviour in polyethylene, Polymer 36 (1995) 2355-2362.

[20] J. Koszkul, J. Nabiałek, Selected methods of modelling of polymer during the injection moulding process, Journal of Achievements in Materials and Manufacturing Engineering 24/1 (2007) 253-259.

[21] D. Kwiatkowski, J. Nabiałek, P. Postawa, Influence of injection moulding parameters on resistance for cracking on example of PP, Journal of Achievements in Materials and Manufacturing Engineering 17 (2006) 97-100.

[22] E. Krempl, F. Khan, Rate (time) dependent deformation behaviour an overview of some properties of metals and soild polymers, International Journal of Plasticity 19 (2003) 1069-1095.

[23] O.U. Colak, N. Dusunceli, Modeling viscoelastic and viscoplastic behavior of high density polyethylene (HDPE), Journal of Engineering Materials and Technology 128 (2006) 572-578.

[24] X. Lu, Z. Zhou, N. Brown, The anisotropy of slow crack growth in polyethylene pipes, Polymer Engineering and Science 34 (1994) 109-115.

[25] G. Wróbel, M. Szymiczek, Evaluation of effects of geometric parameters of reducing die on after-deformation return of polyethylene pipes, Proceedings of the 12th Scientific International Conference „Achievements in Mechanical and Materials Engineering" AMME'2003, Gliwice – Zakopane, 2003, 1049-1052 (in Polish).

[26] J.G.J. Beijer, J.L. Spoormaker, Modeling of creep behavior in injection - moulded HDPE, Polymer 41 (2000) 5443-5449.

[27] S. Hillmanses, S. Hobeika, R.N. Haward, S. Aleevers, The effect of strain rate, temperature and molecular mass on the tensile deformation of polyethylene, Polymer Engineering Science 40 (2000) 481-489.

[28] M. Bonner, R.A. Duckett, I.M. Ward, The creep beahaviour of isotropic polyethylene, Journal of Materials Science 34 (1999) 1885-1897.

[29] A. Shah, E.V. Stepanov, M. Klein, A. Hiltner, E. Baer, Study of polyethylene pipe resins by fatigue test that simulates crack propagation in real pipe, Journal of Materials Science 33 (1998) 3313-3319.

[30] PN-EN ISO 6259-1:2003 Thermoplastics pipes - Determination of tensile properties - Part 1: General test Method.

[31] PN-EN ISO 527-1:1998 Plastics - Determination of tensile properties – Part 1: General principles.

[32] PN-EN ISO 527-2:1998 Plastics - Determination of tensile properties - Part 2: Test conditions for moulding and extrusion plastics.

[33] PN-EN ISO 899-1:2005 Plastics - Determination of creep behaviour - Part 1: Tensile creep

[34] PN-EN ISO 9967:2007 Thermoplastics pipes - Determination of creep ratio.