Influence of polymer samples preparation procedure on their mechanical properties

M. Żenkiewicz [a,*], J. Richert [b]

[a] Department of Materials Engineering, Kazimierz Wielki University,
ul. Chodkiewicza 30, 85-064 Bydgoszcz, Poland
[b] Institute of Polymeric Materials Engineering and Dyes,
ul. M. Skłodowskiej-Curie 55, 87-100 Toruń, Poland
* Corresponding author: E-mail address: marzenk@ukw.edu.pl

Properties

ABSTRACT

Purpose: The aim of this paper is to study the effect of the preparation procedure for the samples of five engineering polymers on the values of offset yield stress at 0.2% strain (σ_{02}), tensile stress at yield (σ_y), and tensile stress at break (σ_B) as well as tensile strain at yield (ε_y) and tensile strain at break (ε_B).

Design/methodology/approach: A single-screw extruder was used to obtain films from which one group of measuring samples was cut out. Another group of these samples was obtained by injection moulding, using a laboratory injection moulding press with a 200-MPa nominal injection pressure. Determination of the material strength under static tension was performed using a tensile testing machine.

Findings: The values of the three characteristics stresses (σ_{02}, σ_y, and σ_B) for the injected samples of all the studied polymers are greater than those for the extruded ones, the largest differences on average being in case of σ_y. Tensile strains (ε_y and ε_B) for the extruded samples are always greater than those for the injected ones.

Research limitations/implications: The observed differences in mechanical properties result from different structures of the sample materials, caused by different respective production technologies. Detailed discussion on these differences and determination of quantitative relationships between them and the mechanical properties require further investigation.

Practical implications: It is necessary to obey precision and caution while analysing and comparing the data acquired at various laboratories. In order to draw correct conclusions from such analyses, the respective samples have to be prepared and examined in a similar way.

Originality/value: The values of characteristics stresses (σ_{02}, σ_y, and σ_B) determined for all five polymers are much greater then those for the corresponding extruded ones.

Keywords: Mechanical properties; Engineering polymers; Tensile stress-strain; Extruded or injected samples

1. Introduction

Mechanical properties of polymeric materials, determined under static tension, belong to a group of basic quantities that define the extent of possible applications of these materials. Among these quantities, offset yield stress at 0.2% strain (σ_{02}), tensile stress at yield (σ_y), and tensile strain at yield (ε_y) are of a great importance. Other quantities, like tensile stress at break (σ_B), tensile strength (σ_M), tensile strain at break (ε_B), and tensile strain at tensile strength (ε_M), are less significant because they deal with the range of irreversible plastic strains that are not expected to appear during regular use of polymeric materials. Modulus of

elasticity in tension (E), also known as Young's modulus, complements the characteristics of these materials. According to a respective standard [1], this quantity is being determined from a difference between the stresses corresponding to the 0.05 and 0.25% tensile strains of a sample, i.e., in the range of slight elastic strains. It has to be emphasised that, depending on the properties of an examined polymeric material, some of the above-mentioned quantities may become identical (e.g., σ_y and σ_M, or σ_B and σ_M) or even be absent (e.g., σ_y and ε_y of crosslinked polyurethane) if they cannot be determined under static tension [1,2].

The mechanical properties of a polymeric material, determined under static tension, are controlled by chemical bond strengths and interaction forces between polymer macromolecules, also known as cohesion forces. They depend on the kind as well as structure of the examined material. To some extent, these forces increase as the degree of polymerization and average molecular weight grow. The strength of polymers, calculated theoretically from the chemical bond strengths and intermolecular interactions, is many times greater than that determined experimentally. The difference is caused mainly by the structure heterogeneity of the investigated material. Points of the structural discontinuity are the places of stress concentration in which micro-cracks of the material start to develop, leading to a final breakage of the material. According to recent remarkable advances in computer science, there are worked out many new methods of analysis and modelling of mechanical properties of materials [3-9].

The operative standards [1,10,11] specify an investigation procedure, sample sizes, and a method for calculating the results of measurements. According to one of these standards [1], nine different tension rates are recommended. Based on the other one [6], which concerns investigation of films and plates, six such rates are indicated. Furthermore, there are suggested different sizes of samples under investigation, e.g., six [5] and four [6] types of the samples are defined. As a consequence, various ways of performing the measurements can be chosen, which makes the results difficult to be compared.

The tension rate significantly affects the results obtained under static tension. This rate influences the process of sample deformation and, thus, the pattern of cracking [12,13]. The higher the tension rate, the larger the amount of heat dissipated in the material. At the same time, the deformation process transforms from the isothermal to adiabatic one, which affects the measured quantities [14]. For example, σ_y of polypropylene as determined at the tension rate of 1000 mm/min is by ca. 43% bigger than that at 1 mm/min and this quantity measured at 200 mm/min is by more than 9% bigger than that at 50 mm/min [15]. Similar variations in the tensile stress at yield occur for polyamide 6.6 (PA 6.6), the effect of the tension rate on σ_y being larger for the non-filled PA 6.6 than for PA 6.6 filled with glass fibre. The value of σ_y for PA 6.6 decreases when the sample temperature increases from 20 to 80 ºC [16].

The composition and structure of polymer composites also considerably influence the quantities determined under static tension. As for single-component polymeric materials, these quantities depend on the way the measurements are being performed. Mass fractions of individual components of the composites and kinds of the applied compatibilizers are important as well [16-18].

The preparation procedure for the samples to be examined under static tension is also of a great importance to the results of investigation. This is caused by the fact that the production technology affects the material structure, including such important factors as crystallinity, crystal sizes, orientation of polymer macromolecules, structural homogeneity, and the number of structural defects. Therefore, the quantities such as temperature, pressure, and rate of injection or extrusion, pressure and temperature of press moulding, and rate (or time) of cooling the samples significantly influence the investigation results obtained under static tension [19,20].

The present work is aimed at evaluation of the effect of the preparation procedure for the samples of low-density polyethylene (LDPE), high-density polyethylene (HDPE), polypropylene (PP), polystyrene (PS), and poly(ethylene terephthalate) (PET) on the values of σ_{02}, σ_y, and σ_B as well as ε_y and ε_B, measured under static tension. Realisation of this objective would enable a better understanding of a relationship between these factors and strength of the studied polymeric materials.

2. Experimental

2.1. Materials

The studied samples were made of the following polymers:
- Low-density polyethylene (LDPE) Malen-E FABS 23-D0022 (Basell Orlen Polyolefins, Płock, Poland), manufactured by the high-pressure polymerisation, with density (ρ) equal 0.919-0.923 g/cm^3 (23° C) and melt flow rate (MFR) equal 1.6-2.5 g/10 min (2.16 kg, 190 ± 0.5° C).
- High-density polyethylene (HDPE) Hostalen ACP 5831 D (Basell Orlen Polyolefins, Płock, Poland), manufactured by the low-pressure polymerisation over Ziegler-Natta catalysts, with $\rho = 0.959$ g/cm^3 (23° C) and MFR = 1.2 g/10 min (5.00 kg, 190 ± 0.5° C).
- Isotactic polypropylene (PP) Malen P F 401 (Basell Orlen Polyolefins, Płock, Poland), manufactured by the suspension polymerisation, with $\rho = 0.905\text{-}0.910$ g/cm^3 (23° C) and MFR = 2.4-3.2 g/10 min (2.16 kg, 230 ± 0.5° C).
- Polystyrene (PS) Owispol 945 E (Dwory SA, Oświęcim, Poland), manufactured by the continuous bulk polymerisation, with $\rho = 1.03$ g/cm^3 (23° C) and MFR = 4-5 g/10 min (5.00 kg, 200 ± 0.5° C).
- Amorphous poly(ethylene terephthalate) (PET) Elpet-A (Boryszew SA, Elana Branch, Toruń, Poland), manufactured by the polycondensation of terephthalic acid and ethylene glycol, with $\rho = 1.4$ g/cm^3 (23° C) and intrinsic viscosity (η) equal 0.615 ± 0.010 dL/g.

2.2. Instruments

A single-screw extruder of the W25-30D type (IPTSz „Metalchem", Toruń, Poland), equipped with a segmented screw, was used to obtain films from which one group of measuring samples was cut out. Another group of these samples was

obtained by injection moulding, using a laboratory injection moulding press of the Battenfeld Plus 35/75 UNILOG B2 type (Battenfeld GmbH, Germany) with a 22-mm screw, 38-cm^3 injection volume, and 200-MPa nominal injection pressure.

Determination of the material strength under static tension was performed using an Instron 3367 (Instron, USA) tensile testing machine.

2.3. Sample preparation and measurements

Both the extruded and the injected samples were dumbbell-shaped while prepared in accordance with appropriate standards ([6] and [5], respectively). The velocity for testing each sample was 50 mm/min. Fifty samples of each polymer were made and an arithmetic mean of fifty individual measurements was assumed as a final result of the determination of a given quantity. When comparing the mean values of the quantities, determined for the injected and extruded samples, the test of significance for the respective two means was performed, assuming the significance level $\alpha = 0.05$ and applying the Snedecor's F-test and Student's t-test. In all the examined cases, the hypothesis about equality of two means was rejected in favour of an alternative hypothesis that the arithmetic mean of a measured quantity for the injected sample is greater than that for the extruded one. Thus, all the compared quantities significantly differ from one another statistically.

3. Results and discussion

The results of the measurements shown in Fig. 1 indicate that the values of the offset yield stress at 0.2% strain for the injected samples of all the studied polymers are greater than those for the extruded ones.

The differences are 14, 23, 21, 43, and 6% for LDPE, HDPE, PP, PS, and PET, respectively. The same applies to the tensile stress at yield (Fig. 2), the differences for LDPE, HDPE, and PET being much larger than in case of σ_{02} while for PP and PS, being similar. The differences in σ_y are 49, 68, 21, 40, and 13% for LDPE, HDPE, PP, PS, and PET, respectively.

Although the tensile stress at break is of a less practical meaning than σ_{02} and σ_y are, it is often discussed in the literature. As the results shown in Fig. 3 point out, the values of σ_B for the injected samples of polyolefines (i.e., LDPE, HDPE, and PP) are slightly greater than those for the extruded ones while in case of PS and PET, the differences are much larger. In particular, the differences in σ_B are 9, 4, 10, 39, and 139% for LDPE, HDPE, PP, PS, and PET, respectively.

The values of the tensile strain at yield (Fig. 4) for the injected samples of all the polymers, except LDPE, are much smaller than those for the extruded ones. The individual differences in ε_y are 6, 45, 44, 24, and 12% for LDPE, HDPE, PP, PS, and PET, respectively.

The differences in the tensile strain at break are still larger. In particular, the values of ε_B for the injected samples are over 8, 87, 53, 2, and 20 times smaller than those for the extruded samples of LDPE, HDPE, PP, PS, and PET, respectively.
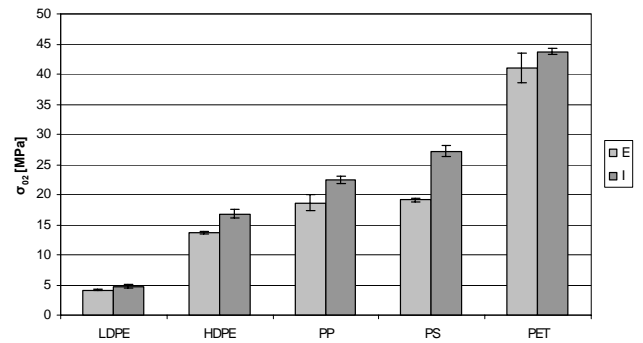

Fig. 1. Offset yield stress at strain 0.2% for extruded (E) and injected (I) samples of the investigated polymers
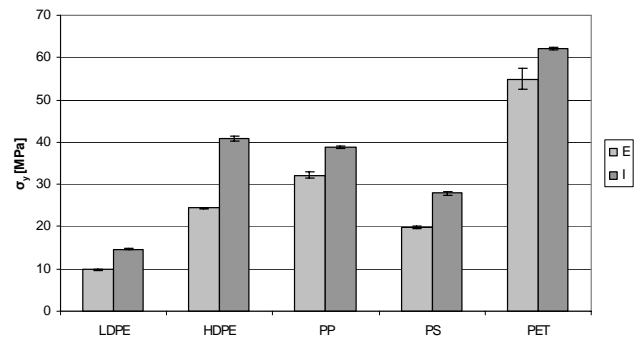

Fig. 2. Tensile stress at yield for extruded (E) and injected (I) samples of the investigated polymers
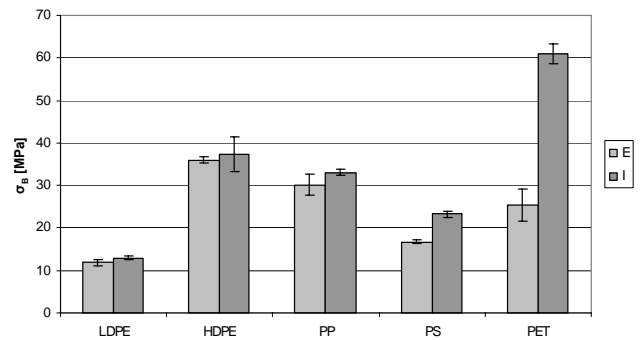

Fig. 3. Tensile stress at break for extruded (E) and injected (I) samples of the investigated polymers

Based on the presented results, three regularities can be formulated. Firstly, the values of the three discussed stresses (σ_{02}, σ_y, and σ_B) for the injected samples of all the studied polymers are greater, and mostly much greater, than those for the extruded ones, the largest differences on average being in case of σ_y. Secondly, the values of the tensile strains (ε_y and ε_B) for the extruded samples are always greater than those for the injected ones. Thirdly, the values of ε_B for the extruded samples are many (from over 2 to over 87) times greater than those for the injected ones.
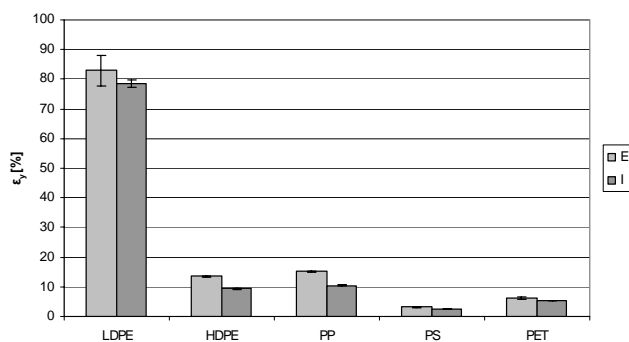
Fig. 4. Tensile strain at yield for extruded (E) and injected (I) samples of the investigated polymers

The observed differences in mechanical properties of the studied samples result from different structures of the sample materials, caused by different respective production technologies. Variations in the material structure may consist in different arrangements of macromolecules, crystallinities, and properties of crystallites. Detailed discussion on these differences and determination of quantitative relationships between them and the mechanical properties are rather difficult tasks and require further investigation.

4. Summary

The results obtained under static tension for engineering polymeric materials are commonly considered as belonging to a group of basic quantities characterising such materials. The operating standards allow the investigators to choose measurement conditions from many available ones. The most important conditions are the tension rate and sample sizes. The sample preparation procedure (injection, extrusion or press moulding) is also a significant factor. In the latter case, the choice is not always possible because a sample to be examined may be made of an industrial material produced by a pre-determined technology.

The demonstrated results unequivocally confirm the need to obey precision and caution while analysing and comparing the data acquired at various laboratories. The same applies to the data published in the scientific and technical literature as well as supplied by manufacturers of polymeric materials. In order to draw correct conclusions from such analyses, the respective samples have to be prepared and examined in a similar way.

References

[1] PE-EN ISO 527-1 (1998), Plastics - Determination of tensile properties - Part 1: General principles.

[2] B. Łączyński, Plastics. Types and Properties, WNT, Warsaw, 1982 (in Polish).

[3] H.G. Elias, An Introduction to Polymer Science, VHC, Weinheim, 1997.

[4] L.A. Dobrzański, Engineering Materials and Materials Design, Fundamentals of Materials Science and Physical Metallurgy, WNT, Warsaw, 2006 (in Polish).

[5] M.S.J. Hashmi, M.D. Islam, A.G. Olabi, Experimental and finite element simulation of formability and failures in multiplayer tubular components, Journal of Achievements in Materials and Manufacturing Engineering 24/1 (2007) 212-218.

[6] Y.T. Im, H.W. Lee, H.C. Lee, M. Awais, Y.G. Jin, K.H. Jung, Research activities of computer-aided materials processing laboratory, Journal of Achievements in Materials and Manufacturing Engineering 24/1 (2007) 219-229.

[7] 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.

[8] B. Smoljan, S. Smokvina Hanza, N. Tomašić, D. Iljkić, Computer simulation of microstructure transformation in heat treatment, Journal of Achievements in Materials and Manufacturing Engineering 24/1 (2007) 275-282.

[9] M.J. Tan, K.M. Liew, H. Tan, Analysis of cavitation and its effects on superplastic deformation, Journal of Achievements in Materials and Manufacturing Engineering 25/2 (2007) 7-10.

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

[11] PN-EN ISO 527-3 (1998) Plastics-Determination of tensile properties-Part 3: Test conditions for films and sheets.

[12] R. Gensler, C.J.G. Plummer, C. Grein, H.H. Kausch, Influence of the loading rate on the fracture resistance of isotactic polypropylene and impact modified isotactic polypropylene, Polymer 41 (2000) 3809-3819.

[13] R. Brown, Handbook of Polymer Testing. Short-Term Mechanical Tests, Rapra Technology Ltd, Shawbury, 2002.

[14] A. Dasari, R.D.K. Misra, On the strain rate sensitivity of high density polyethylene and polypropylene, Materials Science Engineering A 358 (2003) 356-371.

[15] S. Sahin, P. Yayla, Effects of testing parameters on the mechanical properties of polypropylene random copolymer, Polymer Testing 24 (2005) 613-619.

[16] B. Mouhmid, A. Imad, N. Benseddiq, S. Benmedakhène, A. Maazouz, A study of the mechanical behaviour of a glass fibre reinforced polyamide 6,6: Experimental investigation, Polymer Testing 25 (2006) 544-552.

[17] R. Strapasson, S.C. Amico, M.F.R. Pereira, T.H.D. Sydenstricker, Tensile and impact behavior of polypropylene/low density polyethylene blends, Polymer Testing 24 (2005) 468-473.

[18] A. Halimatudahliana, H. Ismail, M. Nasir, The effects of various compatibilizers on mechanical properties of polystyrene/polypropylene blend, Polymer Testing 21 (2002) 163-170.

[19] G. Guerrica-Echevarría, J.I. Eguiazábal, J. Nazábal, Influence of the preparation method on the mechanical properties of a thermotropic liquid crystalline copolyester, Polymer Testing 20 (2001) 403-408.

[20] A.H.I. Mourad, N. Bekheet, A. El-Butch, L. Abdel-Latif, D. Nafee, D.C. Barton, The effects of process parameters on the mechanical properties of die drawn polypropylene, Polymer Testing 24 (2005) 169-180.