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Analysis of stress state in DMTA and photoelasticity examinations

A. Gnatowski*, P. Palutkiewicz, K. Lubczyńska
Department of Polymer Processing and Production Management, Czestochowa University of Technology, Al. Armii Krajowej 19c, 42-200 Częstochowa, Poland
* Corresponding author: E-mail address: gnatowski@kpts.pcz.czest.pl

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ABSTRACT

Purpose: Determination of stresses at the change of Young modulus values in temperature function for polystyrene samples, by DMTA and photoelasticity method, was the aim of work. The numerical simulations of stress, strain and displacement in PS samples was presented. The numerical simulations of injection moulding process (using Moldflow Plastic Insight 5.0 software), include effects after injection process were conducted.

Design/methodology/approach: Investigations were carried out for samples subjected to the one-axial bending. The computer simulations of changes of the stress and strain distribution within the range of elastic strains phase were done. The change in the value of the dynamic Young modulus and the mechanical loss tangent in function of temperature and oscillation frequency by the DMTA method was determined. To verify numerical simulation the photoelasticity research was done.

Findings: Examinations made possible the determination of dynamic mechanical properties of polystyrene and changes in the stress distribution during the dynamic loading of the sample in function of temperature. Higher values of the Young modulus were observed within the range of elasticity. The stress increased with the increase in Young modulus, at the strain generated from push rot oscillation

Research limitations/implications: The injection moulded part have large internal stresses, with higher value than stresses made from oscillation pushrot. The accuracy of used approximate method for computer simulations was not sufficient to indicate the Bielajew point.

Practical implications: Investigated polymer is characterized by viscoelastic properties, so all indicators of the physical and chemical properties depend on not only the time but and also the temperature.

Originality/value: To characterize properties of investigated polymer and to estimate the polymer usage in particular conditions, dependences of the storage module and the mechanical losses tangent was determined in function of temperature at the one-axial bending. The impact of internal stresses in the sample was investigate.

Keywords: Computer Assistance in the Engineering Tasks and Scientific Research; Numerical techniques; Computational Material Science

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METHODOLOGY OF RESEARCH, ANALYSIS AND MODELLING

1. Introduction

Traditional, mechanical characteristics received as a result of the investigations under static, tensile, torsion and compression load are insufficient to predict the behaviour of polymeric materials under the extreme usage conditions as well as during the long time. Therefore, the problem is the choice of research methods which enable to predict change of viscoelastic properties as a function of time on the basis of empirical data [1-6]. Due to the fact that polymers are characterised by viscoelastic properties, all the factors of their physical and mechanical properties depend strongly only on the time, but also on the temperature. Therefore, methods of investigations performed on such materials must take this dependencies into account.

Constructional polymers have good mechanical properties and the resistance on many physical, chemical and biological factors. Properties of constructional polymers allow their wide use in the production of structural components of different machines and devices. The range of their using can be broadening by chemical or physical modification of polymers. Also during the polymer processing the auxiliary additives are used, which make easier to run the process of polymer processing and in some way permit to control it. All these additives cause changes in polymer properties and the investigations of the range of these changes are necessary to obtain good results of parts production [7-12]. Examinations of the mechanical properties of polystyrene determined by DMTA method was the aim of this work. Stress distribution in function of temperature increase during parts dynamic loading was determined. Dynamic mechanical thermal analysis (DMTA) is one of methods which allow to estimate the transformations occurring in polymer during its loading in the broad range of temperature and frequency of load changes (load time). From this analysis one can receive a pattern of changes for dynamic Young modulus and the loss tangent. The knowledge of these changes course enables to establish the relationship between molecular parameters and mechanical properties of polymeric materials [13-27].

The polystyrene was used in examinations. The dynamical mechanical properties of moulded parts by DMTA method were determined. Also the results of numerical simulation using the finite elements method in ADINA System were carried out. The numerical simulation permit to calculate the stress, displacement and strain distribution in parts from polystyrene. Also the numerical simulations of injection moulding process (using Moldflow Plastic Insight 5.0 software), include effects after injection process, especially cooling and warpage were done.

The photoelasticity experimental method were used in this work. The name photoelasticity reflects the nature of this experimental method: photo implies the use of light rays and optical techniques, while elasticity depicts the study of stresses and deformations in elastic bodies. Through the photoelastic-coating technique, its domain has extended to inelastic bodies too. This is an experimental method to determine stress distribution in a glossary polymers. The method is mostly used in cases where mathematical methods become quite cumbersome. Unlike the analytical methods of stress determination, photoelasticity gives a fairly accurate picture of stress distribution even around abrupt discontinuities in a material. The method serves as an important tool for determining the critical stress points in a material and is often used for determining stress concentration factors in irregular geometries.

2. Materials and investigation methodology

For purpose of investigation, domestic thermoplastic material has been used, namely polystyrene with commercial name of Owispol 525 manufactured by Dwory S. A. Oświęcim, characterized by melt flow rate (MFR) amounting 10 g / 10 min (determined at the temperature of 200 °C and with load of 5 kg).

Samples for investigations have been prepared by injection moulding. The investigated sample was obtained through cutting out of a paddle-shaped moulded pieces used for tensile strength tests. The samples were obtained from double-cavity mould. Injection moulding parameters have been as follows:

- melt temperature 230 °C, mould temperature 45 °C, injection velocity 60mm/s,
- holding pressure dependant on injection pressure and equal to 60% of injection pressure value,
- holding time 15 s,
- cooling time 25 s,
- mould clamping force 650 kN.

The examinations by DMTA method were run using the testing device type DMA242 Netzsch. The device allowed to test samples by three-point bending (Fig. 1).

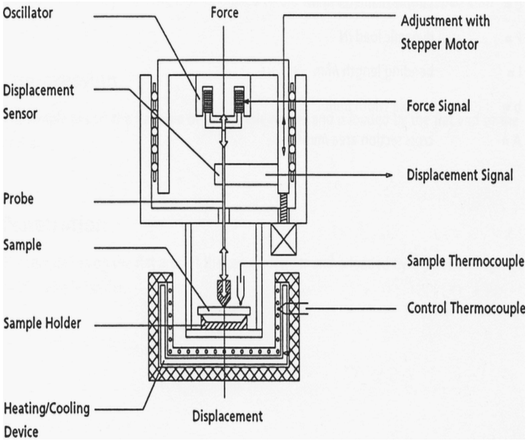

Fig. 1. The scheme of the device for the three-point bending of sample

On the sample placed in the holder, the sinusoidal variable load with the frequency 10Hz and constant amplitude, at simultaneous heating from the temperature 25 °C to 80 °C, was applied through the push rot. The results were presented in the form of graph showing the course of changes of storage modulus E' and loss tangent $\tan\delta$ in the function of temperature (Figs. 1, 2). Examinations were done in accordance with obligatory standards.

Photoelasticity is an experimental technique for stress and strain analysis that is particularly useful for members having complicated geometry, complicated loading conditions, or both. For such cases, analytical methods (that is, strictly mathematical methods) may be cumbersome or impossible, and analysis by an experimental approach maybe more appropriate. While the virtues of experimental solution of static, elastic, two-dimensional problems are now largely overshadowed by analytical methods, problems involving three-dimensional geometry, multiple-component assemblies, dynamic loading and inelastic material behaviour are usually more amenable to experimental analysis.

Modern experimental methods of the physical modelling of the stress - strain state, including the optical-polarization method of investigating stresses (photoelasticity method), are used in design practice for engineering designs and structures. The successful development of this method is determined largely by the presence of modern polymer materials with the required set of optical-mechanical properties. The problem of directed synthesis of optically sensitive polymer materials, and, consequently, also the prediction of the properties of polymers from their chemical structure, primarily the coefficient of optical sensitivity from the stresses and Young module, therefore assumes major significance.

Since in addition to general requirements set forth for model, optically sensitive polymers, separate trends in the optical-polarization method call for additional material requirements, the need arises to predict certain other polymer properties. Among other things, the photoelasticity method requires a material exhibiting a clearly expressed viscoelastic behaviour, together with high optical sensitivity.

Photoelastic analysis is widely used for problems in which stress or strain information is required for extended regions of the structure. It provides quantitative evidence of highly stressed areas and peak stresses at surface and interior points of the structure - and often equally important, it discerns areas of low stress level where structural material is utilized inefficiently.

3. Results of investigation and discussion

The results of DMTA investigations of polystyrene were presented in the form of graph showing the course of storage modulus E' and mechanical loss tangent tan δ in function of temperature (Figs. 2, 3).

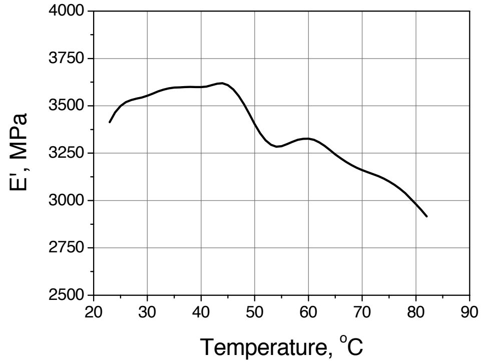

Fig. 2. Courses of changes of storage modulus vs. temperature for polystyrene

In the range of higher strain frequencies or within the area of temperature lower than the glass temperature, the polymer is in glassy state, it is hard and fragile. In the glassy range the thermal energy is not sufficient to overcome the potential barrier for dislocation and rotational movements of the particle segments.

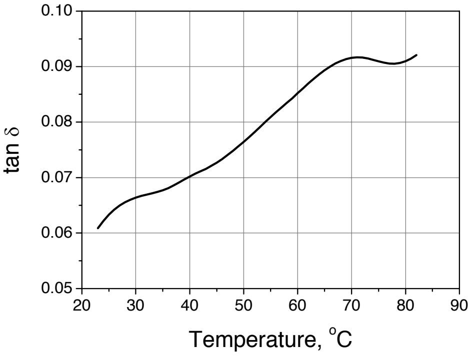

Fig. 3. Courses of changes of mechanical loss tangent vs. temperature for polystyrene

The system remains in a state of thermodynamic imbalance. With the temperature increase or with the deformation time extension the quite rapid decrease in modulus occurs and the mechanical loss tangent curve goes to its maximum. The polymer is in the area of glassy transition, where mechanical loss tangent reaches its maximum at the given deformation frequency 10 Hz. In mechanical interpretation the value of loss tangent may be treated as a stress relaxation indicator. The maximal value of this coefficient appears when $\omega\tau_r = 1$ (ω - angular frequency, τ_r – relaxation time). In the area of glassy transition the initiation of the Brownian movements inside the molecular chain occurs.

The thermal energy becomes comparable with the barrier of the potential energy for the chain rotation. Near the temperature of the glassy transition the polymer viscoelastic properties change very quickly both with time, as well as with the changing temperature. Relaxation modulus decreases significantly, the creep compliance increases, the coefficient of thermal expansion and internal friction change in a very big range. The glass temperature depends on the chemical and molecular structures.

After the glassy transition, the changes in the modulus are comparatively independent on time and temperature and the composite properties are highly elastic. During further temperature or time increase, modulus is temperature and time dependent again and the component of the viscous flow appears.

In the last area the modulus is very low, material is characterized by very low strain recovery and remains in a flow state. The highest values of the storage modulus were obtained within the range of elastic strains at the temperature 32 °C - 43 °C. The maximum of the storage modulus was obtained at the temperature 44 °C and its value was 3619 MPa. The maximum value of the mechanical loss tangent was obtained at the temperature 71 °C. The investigation was finished within the range of high-plasticity phase, at decreasing values of the storage modulus and mechanical loss tangent.

For the purpose of presentation the reduced stress, strain and displacement distribution, the numerical analysis using the finite elements method, in ADINA System 8.3 program, was carried out. The mathematical model was created, in which into the test sample (the beam of rectangular cross-section situated on two supports) the moving push rot penetrates in cycles with the frequency 10 Hz and the constant value of displacement (0.24 mm). Dimensions and the locations of restrains (arcs R2) and the push rot (R1.5) in the mathematical model are shown in Fig. 4.

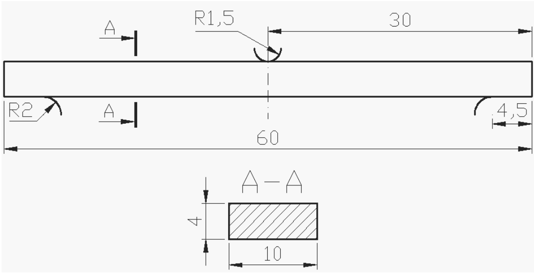

Fig. 4. The schema of the sample load

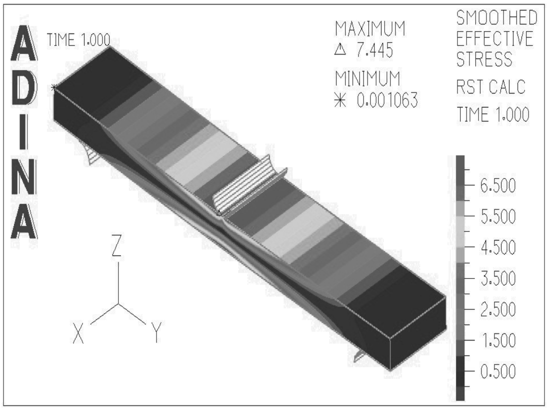

Fig. 5. The reduced stress distribution in sample for the temperature T = 25ºC

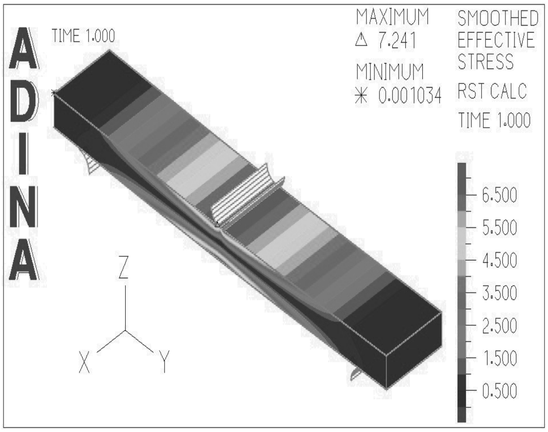

Fig. 6. The reduced stress distribution in sample for the temperature T = 50ºC

In simulation the stress, strain and displacement were examined in the range of the elastic strains phase for three temperatures: 25ºC , 50ºC, 70ºC and extreme Young modulus values: 3499 MPa, 3403 MPa and 3160 MPa and at the constant value of the Poisson's ratio υ = 0.4. The exemplary results of numerical calculations: reduced stress, strain and displacement for the parts made of polystyrene used in DMTA tests, at maximum push rot penetration (0.24 mm), obtained using ADINA System are presented in Figs. 5-9.

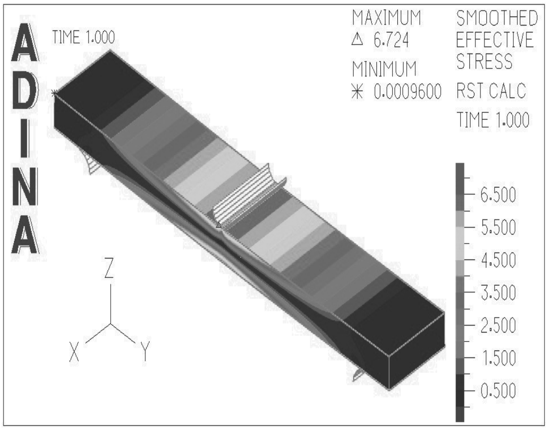

Fig. 7. The reduced stress distribution in sample for the temperature T = 70ºC

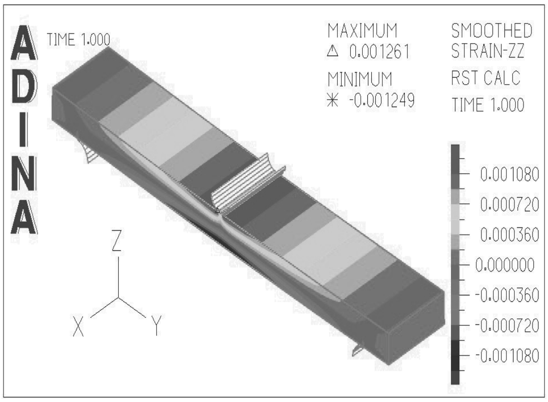

Fig. 8. The Z-axis strain distribution in sample, for the temperatures T = 25, 50, 70ºC

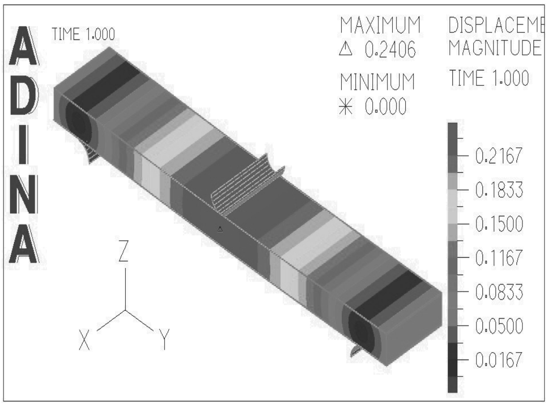

Fig. 9. The displacement magnitude distribution in sample for the temperatures T = 25, 50, 70ºC

The results of simulation enabled representation of reduced stress distribution, the Z-axis strain distribution and the displacement magnitude distribution in the tested samples. Reduced stress (Figs. 5, 6 and 7) took different values, depending on the temperature at which the pushrod worked and decreased with the rise in temperature. At the temperature of 25 ºC a maximal value of reduced stress amounted to 7.4 MPa, then at 50 ºC 7.2 MPa, and at 70 ºC 6.7 MPa. This was caused by plastic softening.

Fig. 10 presents the results of own investigations obtained by means of polariscope with linear light polarization. No essential stress that resulted from oscillation movement of the pushrod was observed and residual stress from the performed process was recorded.

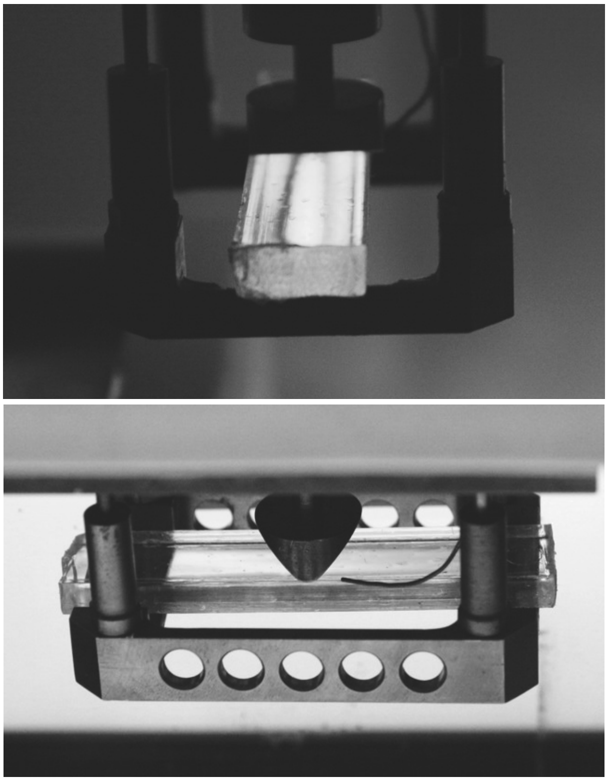

Fig. 10. Residual stress in the sample during DMTA tests. The photographs obtained by means of linear light polarization polariscope

Z-axis strain distribution and displacement magnitude showed the same value throughout the whole range of temperature since pushrod oscillated only at the amplitude of 0.12 mm (peak-to-peak value 0.24 mm).

Photograph of residual stress distribution in the moulded piece from which samples for tests were cut is presented in Fig. 11.

In order to verify the results of elastooptical tests and to investigate the impact of processing method on the results, computer simulations by means of Moldflow Plastic Insight 5.0 software were conducted. The focus was mainly on the phase of plastic solidification and on temperature distribution in tested sample at the stage of mould cooling.

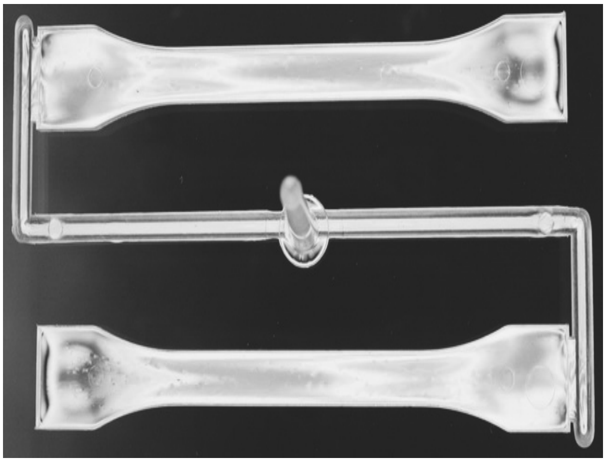

Fig. 11. Photograph of residual stress distribution in the moulded piece from which samples for tests were cut

Temperature distribution in the mould obtained by means of computer simulations allows to assume that residual stress revealed by means of elastooptical tests results from uneven solidification of the plastic and thus from different temperature of the moulded piece during cooling cycle (Figs. 12, 13). The consequence of this phenomenon are depressions being ca. 4% in the part of a moulded piece from which test samples (Fig. 14) were obtained and volume shrinkage being at the level of 4% in this location (Fig. 15). There are also deformations of 0.3 mm in central part (Fig. 16).

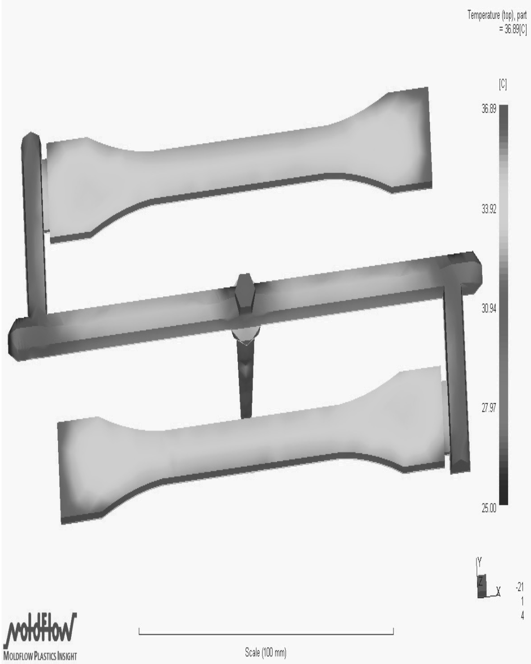

Fig. 12. The temperature distribution after cooling process in investigate sample. The middle part section of moulded part was used to DMTA research

Fig. 13. Frozen layer fraction at time 30 s after injecting process. The middle part section of moulded part was used to DMTA research

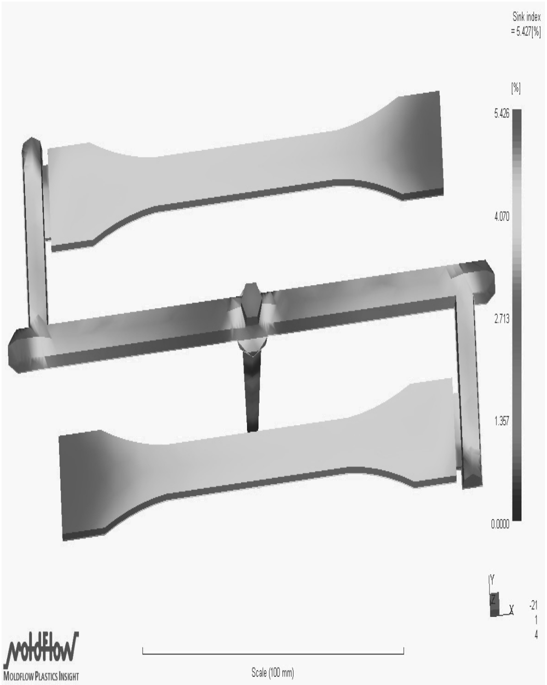

Fig. 14. The sink index in investigate sample. The middle part section of moulded part was used to DMTA research

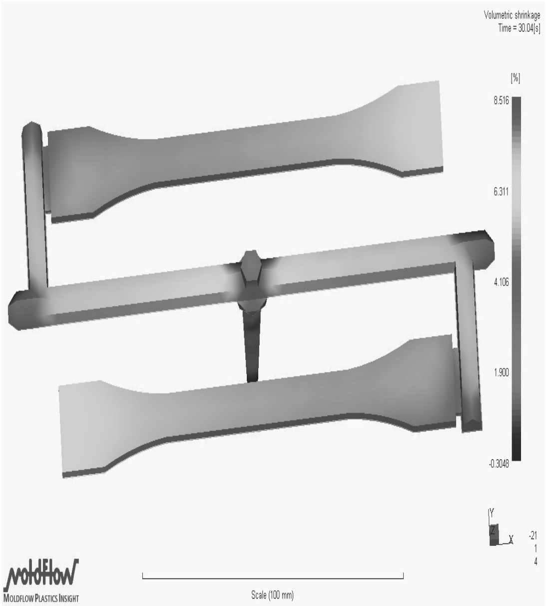

Fig. 15. The volumetric shrinkage in investigate sample. The middle part section of moulded part was used to DMTA research

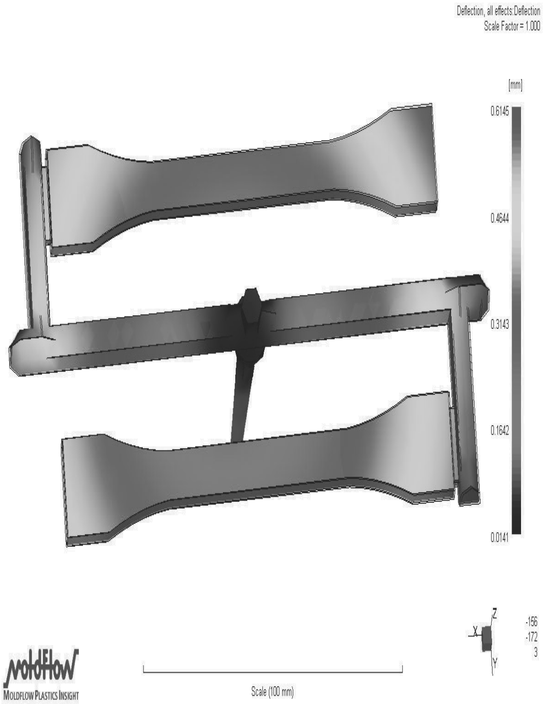

Fig. 16. The deflections values in investigate sample. The middle part section of moulded part was used to DMTA research

4. Conclusions

Examinations allowed determination of properties of polystyrene. In this work was presented:

- the changes of storage modulus and mechanical loss tangent using DMTA examinations,
- the elasticity stress and strain values using numerical analysis during three-point bending of test samples,
- the numerical simulations of flow of thermoplastic polymer using Moldflow Plastic Insight 5.0 software,
- the internal stresses using photoelasticity method in samples.

Analyzing results of calculations the following conclusions can be formulate:

- in the phase of elastic strains for three values of temperatures: 25ºC, 50ºC and 70ºC has not large changes in reduced stress values were obtained,
- strains and displacements in the whole range of the elastic phase are constants,
- using finite elements methodology it was not possible to indicate the Bielajew point, that is the area of the greatest effort of material, which is located under the sample surface in the contact area with the push rot; not sufficient accuracy of used approximate method is a reason of it.

The initial stress of injection moulded parts plays the important role. Comparisons between Moldflow simulations and the photoelasticity experimental data showed good correlation. It is difficult to comprehend the photoelasticity experimental data of magnitude of initial stress with the numerical analysis.

The results obtained from computer simulation allowed for verification of accuracy of elastooptical tests.

Mechanical characteristics received as a result of the tests carried out under the static load, in room temperature are not sufficient for prediction of material behavior in given usage conditions and longer times. To fully characterize proprieties of examined polymer and to estimate its behavior in conditions expected for this material using, temperature dependence of the module and mechanical loss tangent were determined. Examined polymeric material is characterized by viscoelastic proprieties, so all coefficients describing physicochemical properties depend significantly not only on time, but also temperature.

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