Kaunas University of Technology
Institute of Physical Electronics of
Kaunas University of Technology

Daiva Zeleniakienė

MODELLING OF SOFT POROUS POLYMER MATERIALS DEFORMATION BEHAVIOUR

Summary of Doctoral Dissertation

Technological Sciences, Materials Engineering (08 T)

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Scientific Supervisor

Assoc. Prof. Dr. **Tadas KLEVECKAS** (Kaunas University of Technology, Technological Sciences, Materials Engineering - 08 T).

Scientific Consultant

Prof. Dr. Habil. **Jonas LIUKAITIS** (Kaunas University of Technology, Technological Sciences, Materials Engineering - 08 T).

Council of Materials Engineering trend:

Dr. Viktoras GRIGALIŪNAS (Institute of Physical Electronics of Kaunas University of Technology, Technological Sciences, Materials Engineering - 08 T),
Dr. Habil. Audronis KVIKLYS (Lithuanian Energy Institute, Technological Sciences, Materials Engineering - 08 T),
Assoc. Prof. Dr. Eugenija STRAZDIENĖ (Kaunas University of Technology, Technological Sciences, Materials Engineering - 08 T),
Prof. Dr. Habil. Sigitas TAMULEVIČIUS (Institute of Physical Electronics of Kaunas University of Technology, Technological Sciences, Materials Engineering - 08 T) – *chairman*,
Prof. Dr. Vaclovas TRIČYS (Šiauliai University, Technological Sciences, Materials Engineering - 08 T).

Official Opponents:

Dr. Rimantas LEVINSKAS (Lithuanian Energy Institute, Technological Sciences, Materials Engineering - 08 T),
Prof. Dr. Habil. Antanas ŽILIUKAS (Kaunas University of Technology, Technological Sciences, Mechanical Engineering 09 T).

Public defence of the Dissertation will take place at the open meeting of the Council of Materials Engineering trend at 11 a.m. on December 17, 2004 in Dissertation Defence Hall at the Central Building of Kaunas University of Technology.
Address: K. Donelaičio g. 73 - 403, 44029 Kaunas, Lithuania.
Tel.: (370) 37 300042, fax: (370) 37 324144; e-mail: mok.grupe@adm.ktu.lt
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KTU Fizikinės elektronikos institutas

Daiva Zeleniakienė

MINKŠTŲJŲ PORINGŲJŲ POLIMERINIŲ MEDŽIAGŲ DEFORMACINĖS ELGSENOS MODELIAVIMAS

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Mokslinis vadovas

Doc. dr. **Tadas KLEVECKAS** (Kauno technologijos universitetas, technologijos mokslai, medžiagų inžinerija - 08 T).

Mokslinis konsultantas

Prof. habil. dr. **Jonas LIUKAITIS** (Kauno technologijos universitetas, technologijos mokslai, medžiagų inžinerija - 08 T).

Medžiagų inžinerijos mokslo krypties taryba:

Dr. Viktoras GRIGALIŪNAS (KTU Fizikinės elektronikos institutas, technologijos mokslai, medžiagų inžinerija - 08 T),
Habil. dr. Audronis KVIKLYS (Lietuvos energetikos institutas, technologijos mokslai, medžiagų inžinerija - 08 T),
Doc. dr. Eugenija STRAZDIENĖ (Kauno technologijos universitetas, technologijos mokslai, medžiagų inžinerija - 08 T),
Prof. habil. dr. Sigitas TAMULEVIČIUS (KTU Fizikinės elektronikos institutas, technologijos mokslai, medžiagų inžinerija - 08 T) – *pirmininkas*,
Prof. dr. Vaclovas TRIČYS (Šiaulių universitetas, technologijos mokslai, medžiagų inžinerija - 08 T).

Oficialieji oponentai:

Dr. Rimantas LEVINSKAS (Lietuvos energetikos institutas, technologijos mokslai, medžiagų inžinerija - 08 T),
Prof. habil. dr. Antanas ŽILIUKAS (Kauno technologijos universitetas, technologijos mokslai, mechanikos inžinerija - 09 T).

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Adresas: K. Donelaičio g. 73 - 403, 44029 Kaunas, Lietuva.
Tel.: (370) 37 300042; faksas: (370) 37 324144; el. paštas: mok.grupe@adm.ktu.lt
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INTRODUCTION

Relevance of the Doctoral Dissertation. The use of porous polymer materials is increased because they are forward and met the request of consumer. Consequently, these materials are designed very intensively. The technologies of these materials manufacturing are designed and improved, also. For the purposeful design of porous materials with desirable properties, it is very important to know the influence of various factors on porous material properties. The scientific knowledge about this is not enough, so the investigation of various factors on soft porous polymer materials properties is relevant.

Investigative problem. Porous materials are mostly investigated in the macrolevel. However, in this way it is unclear which factor influence on the behaviour of material. Macromechanical behaviour of soft porous polymer material in a large part is determined by microstructural peculiarity of this. The problem is the lack of scientific knowledge about the influence of pores distribution mode, microdefects, and geometric parameters of microstructure on soft porous materials stress and strain. The investigation of material microstructure would clarify material behaviour.

The Aim of the Doctoral Dissertation is to investigate the influence of geometrical parameters of microstructure, pores distribution mode, microdefects on soft porous polymer materials deformation behaviour and determine the laws of dependences of above-mentioned factors on the material stress and strain.

Objectives of the Doctoral Dissertation:

- To investigate the influence of porosity, pores distribution mode, periodicity orientation with respect to the loading direction, geometrical parameters of microstructure on stress and strain of the porous polymer material loaded by tension.
- To evaluate the influence of microdefects on the porous polymer material strength and deformability, such as being of the open pores or ice fillers in the material microstructure.
- To investigate the behaviour of layered system with soft porous polymer material layer and evaluate this system in the viewpoint of strength.
- To investigate the stress distribution of plane (2D) and bulk (3D) models and evaluate the influence of pores distribution mode differences in these models on the stress values.

Scientific novelty and practical value of the doctoral dissertation. The influence of microstructure geometrical parameters, pores distribution mode, microdefects on soft porous polymer materials deformation behaviour was investigated. It was determined:

- the relationships of stress concentration factor with respect to porosity value and pores distribution mode of soft porous polymer material loaded by constant strain;

- the influence of microstructure periodicity orientation with respect to the direction of constant deformation loading on the distribution of porous polymer material stress concentration factor.
- the relationships of stress and strain with respect to porosity value and pores distribution mode of porous polymer material loaded by constant force;
- the influence of porosity value and pores distribution mode on stress and strain of porous polymer material with open pores;
- the influence of ice fillers in the microstructure on the porous polymer material strength and deformability;
- the influence of microstructural geometric parameters on stress concentration factor of high porosity value polymer material;
- the influence of porosity mode on the stress and bending force of layered system with soft porous polymer material layer;
- the influence of pores distribution mode differences in 2D and 3D porous polymer material models on the stress values.

Scientific research could be applied to:

- the creation and improvement of new porous polymer materials;
- the creation and improvement of new porous polymer materials manufacturing technologies;
- the solving of questions of the material deformation and strength;
- the analysis of breakage and fracture reasons.

Defensive propositions:

- By variation of the pores distribution mode, it is possible to secure the lower stress concentration factor of porous polymer material than this of nonporous ones.
- The stress of porous polymer material is decreasing as the stiffness changes of matrix adjacent zones are decreasing.
- The open pores increase the stress of soft porous polymer material loaded by constant force.
- The ice fillers in soft porous polymer material microstructure decrease the strength and deformability of material.

Approbation of the research results. The results of the research were presented in 14 scientific publications. 3 of them correspond to the list of Lithuanian Department of Science and Education. The main theses of the research were presented at 2 international and 10 Lithuanian conferences.

Structure of the doctoral dissertation. The dissertation consists of: introduction, three chapters, conclusions, list of scientific publications, list of references (140 entries) and appendixes. Total volume is 99 pages, containing 79 figures and 8 tables.

CONTENT OF THE DISSERTATION WORK

1. LITERATURE REVIEW

This chapter contains an overview of relevant publications related to the theme of dissertation. New investigations of mechanical behaviour of metals, ceramics and polymers are discussed here. The influence of porosity value on moduli (Young's, shear, bulk moduli, Poisson's ratio) of porous material are analysed. The research of porous materials stress-strain curves, the prediction of porous material life, the influence of various loads, environment, defects on mechanical behaviour of porous materials are discussed, also. The review of the application of the forward homogenization method, which is used for prediction the macromechanical behaviour of heterogeneous systems from micromechanical this, is given.

2. METHODICS

The image analysis method (IAM) was used to investigate the microstructure of soft porous polymer materials presented in Table 2.1. The structure of these materials was analysed using microscope MBS-9 and standard computer programs. The form, density, distribution mode of pores, level of heterogeneity was determined. In account of this and of porous polymer material microstructure modes presented in literature the models of microstructure were created.

In order to predict properties or properly to interpret relationship between the tensile behaviour and microstructure of porous material the models of

Table 2.1. Investigated materials and their mechanical characteristics

Material	Method of investigation	Young's modulus E, MPa	Poison's ratio μ
High resilience polyurethane foam HR3737A	IAM	-	-
Polyurethane foam VB2540	IAM	-	-
Porous isoprene rubber	IAM	-	-
Porous polyvinylchloride	IAM	-	-
Porous polyurethane	IAM	-	-
High resilience polyurethane foam HR3030A	IAM, QTT	1.46	-
Urethane rubber SKU-10-4b	FEM, PEM	3.98	0.46
Butadiene-nitrile rubber SKN-40	FEM, QTT	2.67	0.48
Chromic leather	FEM	24.5	0.49
Carton „Texon“	FEM	224.5	0.30

porous polymer material microstructure were investigated using quasistatic tension test (QTT), finite element method (FEM), and method of photoelasticity (PEM). Models were described by representative volume element (RVE). The distribution of homogeneous and heterogeneous pores was periodic in the RVE (Fig. 2.1). Periodicity orientation was evaluated by angle θ, which shows the deflection of column axe from the tension direction. The models matrix have mechanical characteristic of isotropic optical sensitive urethane rubber SKU-10-4b. This rubber was chosen because it can be investigated by PEM and it was necessary to compare results of FEM and PEM.

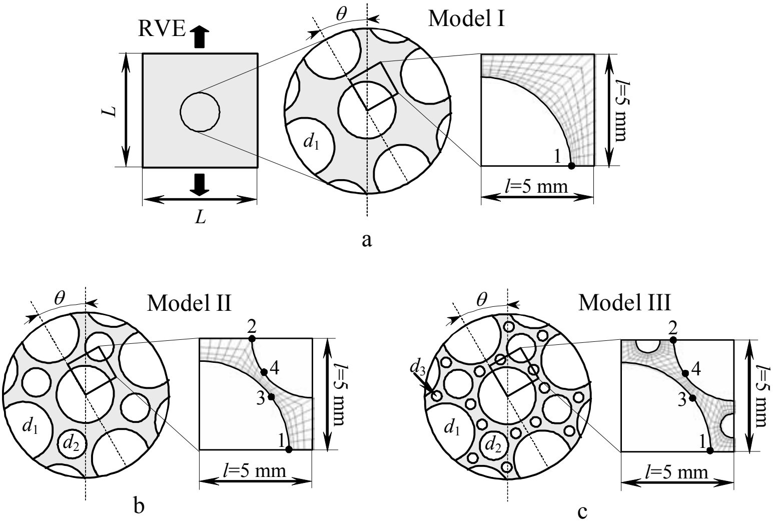


Fig. 2.1.Models of porous materials microstructures : a, b, c – pores distribution mode of models I, II, III; L, l – edges of the RVE and unit element, d_1, d_2, d_3 – diameters of heterogeneous pores, θ - angle of periodicity orientation, 1, 2, 3, 4 – the location of control points for stress state evaluation

On purpose to determine the difference between results obtained by solving plane (2D) and bulk (3D) problem, it was created 2D models and 3D identical to these models (Fig. 2.2). These models matrix have mechanical characteristic of isotropic butadiene-nitrile rubber SKN-40.

In order to determine the influence of microdefects such as open pores or broken microstrips on porous polymer material stress and strains it was created models with broken microstrips. Models were design on the basis of I, II, III models. The openings were made in thinnest zones of microstrips, where the maximal stress concentration factor of undamaged model was found. The models matrix have mechanical characteristic of rubber SKU-10-4b.

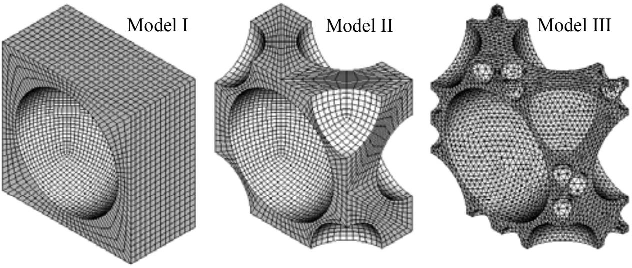


Fig. 2.2 3D numerical models with finite elements

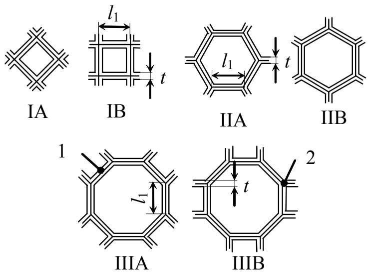
The models I and II with broken microstrip and without this were made from butadiene-nitrile rubber SKN-40 for the estimation stress-strain relation and fracture mode of porous polymer material with open pores. The quasistatic tension test was performed for these models using tension-testing machine FP10/1 with strain rate of 100 mm/min.

Sometimes during exploitation of porous materials, the water can enter into the pores inside. If temperature becomes negative, the water passes into an ice and in a such way, the ice fillers form in the microstructure of material. In order to estimate the influence of ice fillers on porous material stress and strain it was created five numerical models with different ice fillers distribution mode. The models matrix have mechanical characteristic of rubber SKU-10-4b.

The investigation of numerical models underestimated the influence of adhesion between matrix and ice filler and the influence of negative temperature on properties of matrix material. Therefore, it was made concrete models with ice fillers intended for investigation by quasistatic tension test. Dogbone shaped specimens were machined using press PKP-10 from the sheet of high resilience polyurethane foam HR3030A. The specimens had the same orientation in the sheet. They were impregnate with the water. After this, specimens were frozen 24 h in the freezing camera at -5°C temperature. The tensile tests were run on tensile testing machine FP10/1 with strain rate 100 mm/min. The maximal time since the getting out of specimens from the freezing camera to the end of testing was up to 2 minutes. It was determined that the first marks of ice melting occur after 9-10 minutes. Whereas the ice fillers in the inner layers would be melted afterwards it was decided that the influence of positive temperature on the result of experiment is insignificant. Two specimens groups were made for the comparison purposes. In one of them, the specimens without ice fillers were holded under conditioned environment, in the other specimens without ice fillers were frozen in the freezing camera at -5°C temperature.

Described models simulate the microstructures of porous materials with pores akin to sphere form. But from the literature review and from the analysis of structure of porous polymers materials it is known that the thin strips and small interpores zones in the nodes of them can be dominated in the structure of porous material. Such microstructure is typical for high porosity foamed materials with open pores. The cells of models created for the investigation of this microstructure are presented in Fig. 2.3.

In order to investigate the influence of geometric parameters on the stress concentration factor it were designed three models groups on the basis of model IA (Fig. 2.4).



Cells	Porosity γ_p
IA, IB	0.74
IIA, IIB	0.78
IIIA, IIIB	0.86

Fig. 2.3 Cells of high porosity foamed materials; 1 – microstrip, 2 – node of microstrip, l_1 – length of microstrip, t – thickness of microstrip

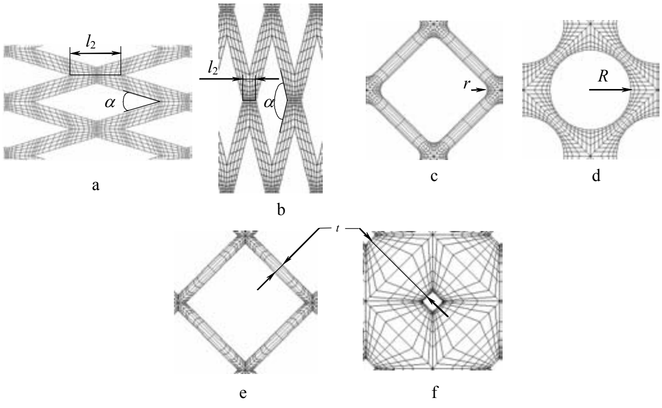
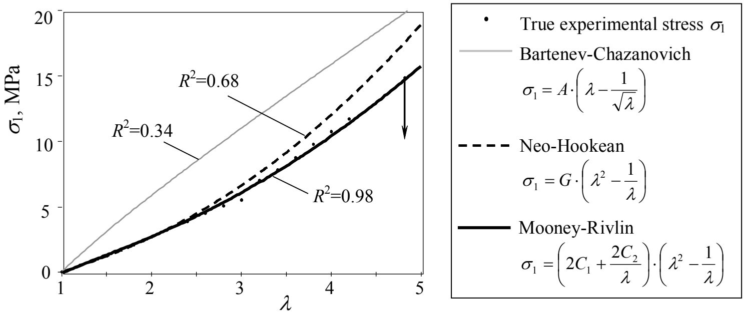


Fig. 2.4 Numerical models: variable angle α between microstrips and variable length of microstrips node l_2 (a, b); variable rounding radius r of angle α (c, d); variable thickness of microstrip t (e, f)

Porous materials are often used in layered systems. In order to design the model of such system, the layered systems with soft porous polymer layer were analysed. The diameter and the density of pores were investigated and the distribution of them in the length and thickness was determined. According to this, the layered system with porous polymer layer and with surface pattern was designed. During analysis of layered systems, it was noted that sometimes the porosity mode with a large amount of small pores and single large pores is characteristic. The model with such porosity mode of elastomeric layer was created.

Microstructural models were loaded by either homogeneous or heterogeneous unidirectional tension. The load was either constant strain or constant force. The magnitude of load was chosen suchlike porous polymer materials exploitation ones. Besides it was required the deformation would be in the zone of Hook's low limits. According to literature exploitable porous polymer materials are taken the deformation equal to ε=0.1÷0.5. Hook's low is valid until ε=0.5 for investigated urethane SKU-10-4b and butadiene-nitrile SKN-40 rubbers. According to this in the case of constant strain loading the relative strain of RVE was equal to 0.2 because some reserve was required as several zones of porous polymer material microstructure can be deformed markedly more, i. e. the local strains can be higher than this of RVE. In the case of constant force, the magnitude of force was chosen in the same principle. The case of linearity was chosen because of several reasons. First of all this load was enough for the determination the influence of porosity and pores distribution mode on the tendency of stress concentration.

The deformation behaviour of soft porous polymer material was investigated as the relation between stress and strain is non-linear. The relation between true stress and elongation ratio of matrix material - butadiene-nitrile SKN-40 rubber – was determined from experimental results. The equations of neo-Hookean, Bartenev-Chazanovich, and Mooney-Rivlin were used. Mooney-Rivlin equation corresponded to experimental points better than others did, so this equation was chosen for the description of matrix behaviour.



2.5 pav. The relation between true stress σ_1 and elongation ratio λ of butadiene-nitrile SKN-40 rubber; R^2 – determination factor, G – shear modulus, G=0.88 MPa, A, C_1, C_2 – material constants, A=4.55 MPa, C_1=0.259 MPa, C_2=0.265 MPa

Layered models were bent at the corner of 30°. The bending line was either circle or parabola shaped. In the first case, systems were bent with a segment of circle. In the second case, the system was loaded by bending moments at the ends of tested specimens.

The stress and node displacements of microstructural models were determined using finite element codes ALGOR and ANSYS. ALGOR was used for 2D linear analysis; ANSYS was used for 3D linear and 2D non-linear analysis. The principal stress σ_1 and concentration factor K_σ were determined. In the case of constant force load the total strain of RVE, strain of microstrip and strain of matrix in the contour zone of pore were determined, also.

3. INVESTIGATION RESULTS AND DISCUSSION

The Investigation of Stress and Strain of 2D and 3D Models

FEM was used for investigation of 2D and 3D models I, II and III. After they were loaded by constant strain $\varepsilon = 0.2$, the stress of von Mises was determined. The stress of 2D models was compared to this of 3D models. It was determined that in both 2D and 3D cases the highest value of stress is in model I, lower value is in model II and the lowest value is in model III. It means that the investigation of 2D models shows the tendency of characteristic behaviour of 3D models. But the difference between stress of plane and bulk models is not equal. In the case of model I the difference of stress of 2D and 3D models is equal to 9 %. In the case of models II and III this is equal to 35 % and to 34 %, respectively. Therefore, in this case the difference is significant. However if it is necessary to determine the influence of microstructure parameters on stress increasing or decreasing it could be done by interchanging this parameters and investigating 2D model.

The Influence of Porosity and Pores Distribution Mode on Stress Concentration of Polymer Material, in the Case of Constant Strain Load

2D models I, II and III were loaded by constant strain ε=0.2. The influence of material porosity γ_p on stress concentration factor changes for model I is presented in Fig. 3.1. Seems that for low material porosity the stress shows high stress concentration values. As the material porosity increases up to 0.5, the significant decrease of concentration factor values is obtained. This decrease is decided by the decreasing of deformation force due to increasing of pore diameters and decreasing of volume fraction of the matrix. The relationship of deformation force F with porosity γ_p is

$$\frac{F}{F_\mathrm{N}} = 1 - 2\sqrt{\frac{\gamma_\mathrm{p}}{\pi}} = 1 - 1.28\sqrt{\gamma_\mathrm{p}}\,. \tag{3.1}$$

So, from (3.1) it is clear seen that the increase of material porosity leads to the decrease of relative deformation force. The theoretical results obtained according to (3.1) and those by method of FEM are presented in Fig. 3.2. As the porosity is higher than γ_p=0.5, independently on the decrease of deformation force, stress monotonously increases. For this porosity mode significant changes of material geometry appear. Between pores in equator zones, only thin material strips are formed, but interpores zones are relatively large. Due to abrupt stiffness changes of the matrix adjacent zones, the stress markedly increases.

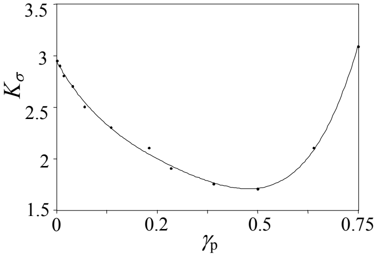


Fig. 3.1 The relationship of stress concentration factor K_σ with respect to porosity γ_p for model I

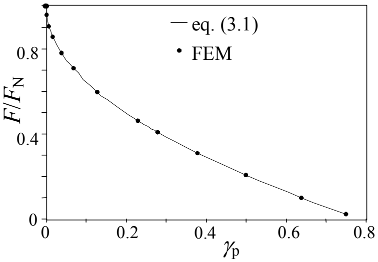


Fig. 3.2 The changes of relative force F/F_N in dependence of porosity γ_p for model I

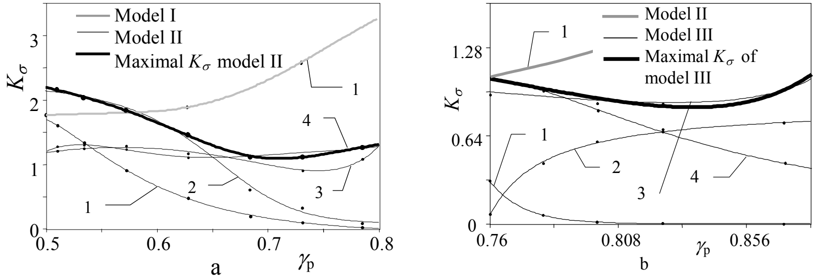


Fig. 3.3 The changes of stress concentration factor K_σ in dependence on material porosity γ_p for models I and II (a) and for models II and III (b) (curves numbered according to Fig. 2.1)

Maximal concentration factors K_σ of models II and III decrease as porosity increase and for high material porosity it insignificant increase (Fig.3.3). The decrease of K_σ is leaded of the decrease of deformation force as in the model I case. The increase of it is related with appearance of higher stiffness changes of the matrix adjacent zones. The concentration factor of model III is the lowest, because these changes are lowest.

The Influence of Periodicity Orientation on Porous Polymer Material Stress Concentration in the Case of Constant Strain

Models I, II and III were investigated by FEM. The angle θ of periodicity orientation of these models varied from 0° to 45°. After they were loaded by constant strain $\varepsilon = 0.2$ the stress concentration factor K_σ was determined.

In the model I the stress concentration factor is the highest when θ=0° (Fig. 3.4, a). In this case, the longitudinal axis of microstrip superposes with the direction of tensile. As the θ increases the stress factor decreases and it is the lowest when $\theta = 45°$. In Fig. 3.4, b seems, that stress maximum is decreased as angle of periodically orientation increase from 0° to 45°.

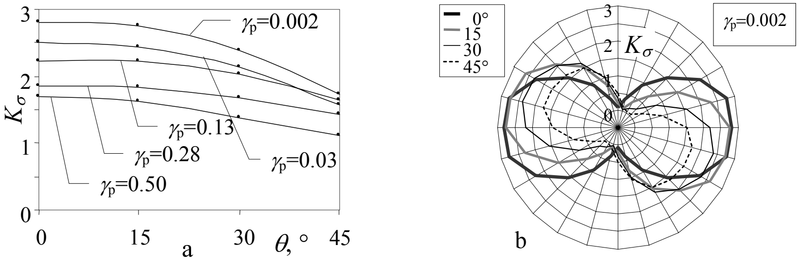


Fig. 3.4 The relationship of maximal stress concentration factors K_σ with respect to angle θ of periodicity orientation and porosity γ_p for model I (a) and stress concentration factor K_σ near pore d_1 (b)

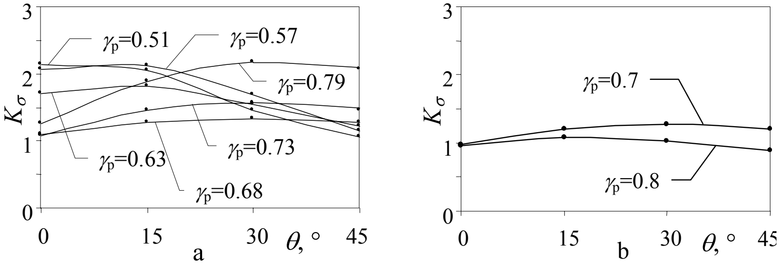


Fig. 3.5 The relationship of maximal stress concentration factors K_σ with respect to angle θ of periodicity orientation and porosity γ_p for model II (a) and for model III

The mode of curves of model II is leaded by porosity value (Fig. 3.5, a). Decreasing dependences are characteristic for low porosity value models. These models exhibit very small pores d_2 therefore they are similar to model I. Increasing dependences are characteristic for high porosity value models. The thin strips with 45° orientation as $\theta = 0°$ are characteristic to these models. As the angle θ increasing thin strips are oriented in the direction of tension and the stress concentration factor increases.

The influence of periodically orientation on stress concentration of model III is insignificant because the stiffness changes of the matrix adjacent zones are low in this model.

The Influence of Porosity and Pores Distribution Mode on Stress and Strain of Polymer Material, in the Case of Constant Force Load

The deformation behaviour of models I, II and III was determined in the case of constant force load. The influence of material porosity γ_p on the stress changes for Model I is presented in Fig. 3.6, a. The plot indicates that increase of model porosity results in the increase of stress values. It seems that increase of porosity up to 0.5 stress values increase insignificantly. The increase of porosity from 0.5 up to 0.75 results in the drastic increase of stress. As a reason of this, it could be some changes in material geometry, i.e., between pores in equator zones only thin material strips are formed. The strain of thin strips is higher than this of other zones (Fig. 3.6, b). Due to this, the increasing of total strain of RVE is more significant when porosity increases up to 0.5.

The data indicate that stress of model II increases with the increasing of porosity like in the case of Model I (Fig. 3.7, a). Up to porosity, 0.7 principal stress values in model II are only insignificantly higher than those for Model I; at the highest porosity values, they are lower than those ones for Model I. Model II shows higher deformability than Model I (Fig. 3.7, b).

In all investigated porosity range stress in Model III are higher than those in Model II, but the differences between them are not significant (Fig. 3.8, a). Otherwise, the deformability of Model III is markedly higher than that for Model II (Fig. 3.8, b).

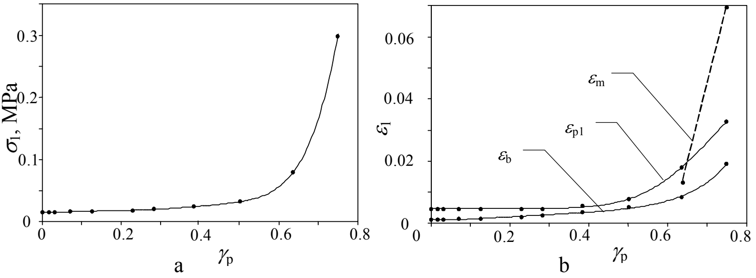


Fig 3.6 The influence of porosity γ_p on principal stress σ_1 (a) and on principal strain ε_1 (b) changes for model I; ε_{p1} – strain of matrix in the contour zone of pore d_1, ε_b – total strain of RVE, ε_m – strain of microstrip

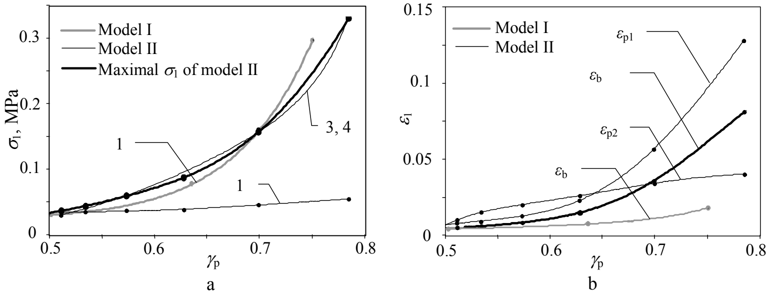


Fig. 3.7 The influence of porosity γ_p on principal stress σ_1 (curves numbered as in Fig. 2.1) (a) and on principal strain ε_1 (b) changes for models I and II; ε_{p1}, ε_{p2} – strains of matrix in the contour zone of pores d_1 and d_2, ε_b – total strain of RVE

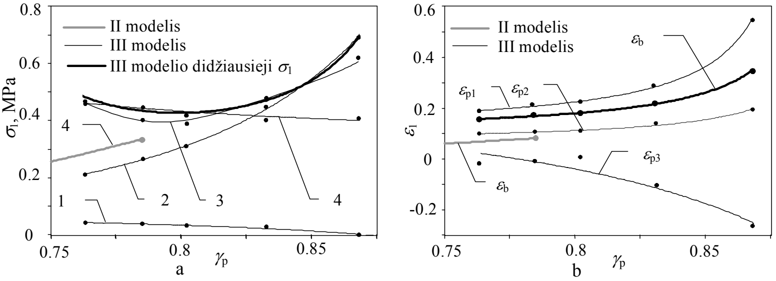


Fig. 3.8 The influence of porosity γ_p on principal stress σ_1 (curves numbered as in Fig. 2.1) (a) and on principal strain ε_1 (b) changes for models II and III; ε_{p1}, ε_{p2}, ε_{p3}– strains of matrix in the contour zone of pores d_1, d_2 and d_3, ε_b – total strain of RVE

The Influence of Porosity and Pores Distribution Mode on Stress and Strain of Porous Polymer Material with Open Pores

During the process of manufacturing or exploitation of porous materials, the microdefects, e.g. open pores or breaks of the microstrips, can originate. In order to determine the influence of microdefects the numerical models with broken microstrips were investigated. Models were loaded by constant force.

In the case of model I the stress of defected model is higher than this of model without defects (Fig. 3.9, a). At low porosity values, the total strain of RVE is only insignificant higher than total strain of RVE without defects (Fig. 3.9, b). When porosity increases, the influence of open pores on material deformability increases. Analogous results were obtained in the cases of models I and II.

QTT was executed to determine the dependence of strain on stress and fracture character. The material models I and II with broken strips were investigated. For the comparison purposes models I and II without defects were investigated, also. Typical tension curves are presented in Fig. 3.10. Seems, that the defect decrease Young’s modulus and strength of porous material.

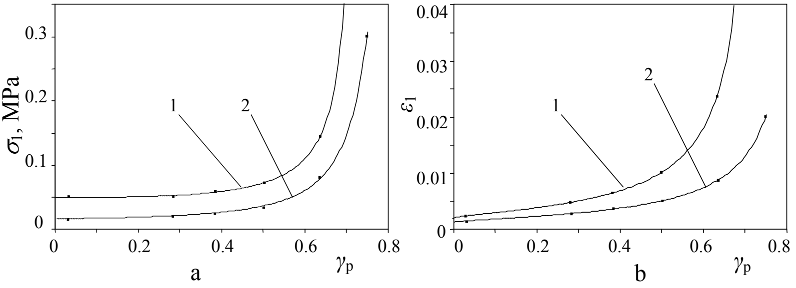


Fig 3.9 The influence of porosity γ_p on principal stress σ_1 (a) and on total strain of RVE ε_1 (b) changes for model I; 1 – with defects, 2 – without defects

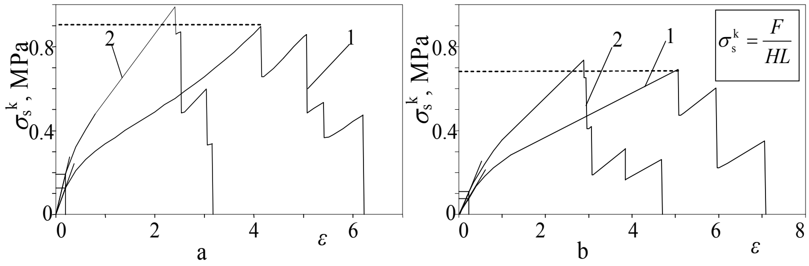


Fig. 3.10 Typical tension curves of models I (a) and II (b); 1 – with defects, 2 – without defects

The Investigation of Stress and Strain of Porous Polymer Materials with Ice Fillers in Microstructure

The investigation of stress and strain of porous polymer materials with ice fillers in their microstructure cleared the phenomenon which is often met but it is no scientific knowledge about it, before. That investigation establishes the model of mechanical behaviour of porous material with ice fillers. It allowed to evaluate the influence of few factors on this behaviour. It is known that solid fillers strengthen the soft materials in the case of high adhesion. The strengthening of material due to decreasing of temperature is observed, also. Nevertheless, the experimental results show the drastic decrease of the strength of porous material with ice fillers. The first reason of such behaviour could be the emission of heat over the elastic deformation. Due to this the adhesion between filler and matrix decreases. Therefore, the macromechanical strength of the system decreases, also. The second reason of decreasing of material strength could be the increased stress in microstructure of unstrained material. When the water passes into the ice, it expands and pores deform. This expanding could be the reason of appearing of microdefects. The third reason could be the angular form of pores. It is known, the more filler form differs from sphere, the higher stress is in the limit of phases. The third reason could be the disadvantageous ice fillers distribution mode. The investigation of influence of ice fillers distribution mode shows that at the same ice distribution modes strength decreases even if adhesion is ideal.

The Influence of Microstructure Geometric Parameters on Stress Concentration of High Porosity Value Polymer Material

The models of high porosity value and low stiffness changes of the matrix adjacent zones were investigated. It was determined that either the form and the orientation of cell influence on stress concentration factor. The influence of rounding radius of angle between microstrips on stress factor was evaluated. This relationship is presented in Fig. 3.11, a. The influence of thickness and length of microstrip relation on stress concentration was determined (Fig. 3.11, b). It was found that the higher this relation is, the higher stress concentration factor is. The influence of angle between microstrips on stress concentration was determined, also. If those models are not very close to porous materials microstructure, but the influence of microstructure geometric parameters on stress concentration is determined.

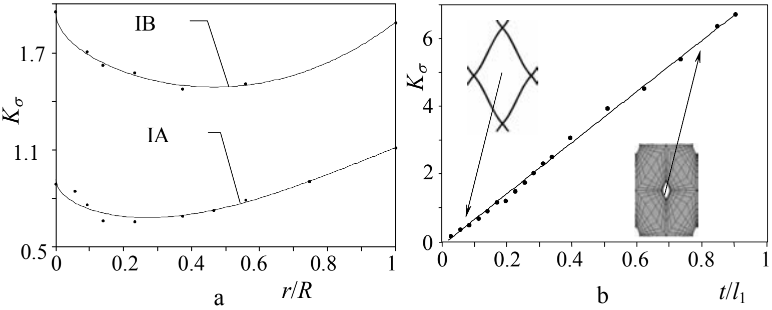


Fig. 3.11 The relationship of stress concentration factor K_σ with respect to relations r/R (a) and t/l_1 (b)

Non-linear Mechanical Behaviour of Soft Porous Polymer Materials

FEM was used for investigation of non-linear behaviour of models I, II and III. The dependences of elongation ratio λ on principal stress σ_1 were evaluated (Fig 3.12). Seems that the highest stress is in model I and the lowest stress is in

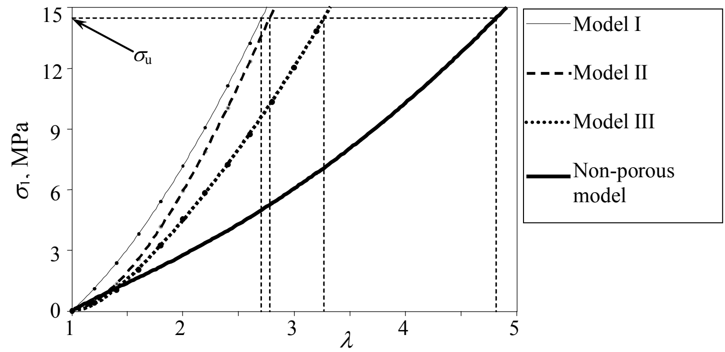


Fig. 3.12 The relation between principal stress σ_1 and elongation ratio λ of models I, II and III

the model III as elongation ratio is the same. The same result was obtained as the relationship of strains with stress was linear. In the case of low elongation ratio values, the stresses of models II and III are similar to stress of non-porous material. In the case of high elongation ratio, the stresses of models II and III are several times higher than those of model without pores.

The Investigation of the Behaviour of Layered Bent System with Soft Porous Polymer Material Layer

The bending force and principal stress at the bottom of the system pattern channel were determined. The obtained results were compared with those of analogical nonporous system. It was observed that the bending force of porous system is 20 % less than this of nonporous system. That is because the decrease of system stiffness occurs. Therefore, the stress of porous system at the channel is 12 % less than this of nonporous system.

However, sometimes, due to incorrect technological process or to other reasons, the porosity mode of soft polymer material layer could be such that stress in it increases, but not decreases. Usually for this porosity mode is characteristic a lot of small pores and some large pores. The influence of such large pores on the stress of system was determined. It was found that the large pore on the symmetry axis of the channel may increase stress up to the several times. The large pore in protuberant part of the system can decrease stress due to decrease of stiffness change between protuberant part and channel.

CONCLUSIONS

1. The stress concentration of soft porous polymer material loaded by constant strain ($\varepsilon = 0.2$) depends upon porosity value and pores distribution mode. It was determined that the appearance of small and rare pores results on high

stress concentration factor ($K_\sigma \approx 3$). In the case of low strains and high porosity ($\gamma_p \geq 0.5$), the stress concentration factor has a low value, if the stiffness changes of the matrix adjacent zones are not abrupt.

2. If at low strain values ($\varepsilon < 1$) the principal stresses of soft porous polymer material are similar to those of non-porous material with the same mechanical properties as the matrix, at high strain ($\varepsilon > 1$) the principal stresses of porous material are 1.5 - 3 times higher than those of non-porous one.
3. The periodicity orientation influences the stress concentration distribution of porous polymer material load by constant strain ($\varepsilon = 0.2$). The value of stress concentration factor depends upon the orientation of matrix microstrips with respect to loading direction and on the stiffness changes of the matrix adjacent zones. If the longitudinal axis of thin microstrips is in line with the direction of tensile, the stress concentration factor is the highest. If the angle between microstrips and the direction of tensile is equal to 45°, the stress concentration factor is the lowest.
4. The increase of porosity raises the stress of polymer material loaded by constant force in the limits of linearity. As porosity value is up to 0.5, the stress value is low. Therefore, the deformability of such material is low, also. Relatively low stress and high strain is in the case when porosity value is higher than 0.5 and the pores distribution mode is such as the stiffness changes between microstrips and interpore zones are nor abrupt.
5. As the stresses of plane (2D) and bulk (3D) RVE were evaluated ($\varepsilon = 0.2$), it was obtained that the difference of 2D and 3D models stresses depends upon the singularity of pores distribution modes in those models. If the porosity mode and pores distribution mode of 2D and 3D models is the same the highest difference of those models stresses is about 9 %. In the case of high porosity and heterogeneity of pores the pores distribution mode in 2D and 3D models is different even if the porosity mode is the same. Due to this, the values of stress can differ up to 35 % and more.
6. The being of opening pores in the polymer material microstructure increases the stress and strain, decrease material strength and stiffness. The higher porosity, the higher influence of open pores on deformation material behaviour. In the case of large pores and small material dimensions, the fracture occurs at higher values of stress than the matrix material limit of strength and than the stress of porous material without the open pores. Therefore the force for the destruction of the material with open pores is the less than this of the material without open pores.
7. The computation investigation shown, that the ice fillers in microstructure decrease the deformability of the porous polymer material. In the case of strong adhesion bond between ice filler and matrix, the stress increases or

decreases it depends on the ice fillers distribution mode. If the ice fillers distributed in such way, that the stiffness changes in microstructure are low and the high strain could occur, the stress of matrix is increased, in another way the stress is decreased. The experimental investigation shown, that the ice fillers decrease the strength and deformability of soft porous polymer material.

8. Both the form and the orientation of the cell influence on stress concentration factor of polymer material with a high porosity value and low stiffness changes in microstructure. The higher thickness relation with length of microstrip is the higher stress concentration factor is. Low stress concentration factor is when angle between microstrips is from 20° to 140° and the rounding radius of this angle from $0.25R$ to $0.4R$ (R – maximal rounding radius).
9. The stress of bent layered system with soft porous material layer and with surface pattern is lower than this of the analogous system with nonporous layer. The large pore on the symmetry axis of the channel may increase stress up to the several times. The large pore in protuberant part of the system can decrease stress due to the decreasing of stiffness change between protuberant part and channel.

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INFORMATION ABOUT THE AUTHOR

1992 – 1997: bachelor's degree studies at Kaunas University of Technology, Faculty of Design and Technologies; Bachelor of Science in Industrial Engineering.
1997 – 1999: master's degree studies at Kaunas University of Technology, Faculty of Design and Technologies; Master of Science in Industrial Engineering.
1999 – 2004: PhD studies in materials engineering at Kaunas University of Technology, Faculty of Design and Technologies.
2003 – 2004: junior research at Kaunas University of Technology, Faculty of Mechanical Engineering.

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REZIUMĖ

Darbo aktualumas. Vis plačiau poringosios polimerinės medžiagos, tarp jų ir minkštosios, naudojamos įvairiose srityse, siekiant jomis pakeisti brangias monolitines, o taip pat panaudoti jas kaip šiuolaikiškas, vartotojo poreikius tenkinančias medžiagas. Šiuo metu tokios medžiagos labai intensyviai kuriamos. Tuo pačiu kuriamos ir tobulinamos poringųjų medžiagų gamybos technologijos. Norint kryptingai kurti reikiamų savybių poringąsias medžiagas yra labai svarbu iš anksto žinoti nuo kokių veiksnių priklauso šių medžiagų savybės. Tokių mokslinių žinių trūksta, todėl įvairių veiksnių įtakos poringųjų medžiagų savybėms tyrimas labai aktualus.
Tiriamoji problema. Poringosios medžiagos dažniausiai tiriamos makrolygyje. Tačiau šiuo atveju taip ir lieka neaišku - kokie veiksniai nulemia medžiagos elgseną. Minkštųjų poringųjų medžiagų makromechaninė elgsena didele dalimi yra nulemta šių medžiagų mikrostruktūros ypatumais. Problema yra ta, kad trūksta mokslinių žinių apie mikrostruktūrinių veiksnių, tokių kaip porų išsidėstymo pobūdžio, mikrodefektų, mikrostruktūros geometrinių parametrų įtaką minkštųjų poringųjų polimerinių medžiagų įtempiams ir deformacijoms. Medžiagos mikromechaninės elgsenos tyrimas leistų paaiškinti priežastis, nulemiančias medžiagos makrosavybes.
Darbo tikslas. Ištirti minkštųjų poringųjų polimerinių medžiagų mikrostruktūros geometrinių parametrų, porų išsidėstymo pobūdžio, mikrodefektų įtaką šių medžiagų deformacinei elgsenai ir nustatyti įtempių bei deformacijų priklausomybių nuo šių veiksnių dėsningumus.

Uždaviniai:

- Nustatyti poringumo dydžio, porų išsidėstymo pobūdžio, periodiškumo orientacijos apkrovos pridėjimo krypties atžvilgiu, mikrostruktūros geometrinių parametrų įtaką tempiamos poringosios polimerinės medžiagos įtempių ir deformacijų dydžiui.
- Įvertinti galimų mikrostruktūrinių defektų, tokių kaip susisiekiančių porų arba šaltyje susiformavusių ledo užpildų, įtaką minkštosios polimerinės medžiagos stiprumui ir deformuojamumui.
- Ištirti lenkiamų trisluoksnių sistemų su minkštosios poringosios polimerinės medžiagos sluoksniu elgseną ir įvertinti ją stiprumo atžvilgiu.
- Nustatyti poringųjų polimerinių medžiagų plokščiųjų ir tūrinių modelių porų išsidėstymo skirtumų įtaką įtempių dydžiui ir pasiskirstymui.

Darbo mokslinis naujumas ir praktinis vertingumas:

Tiriant mikrostruktūros geometrinių parametrų, porų išsidėstymo pobūdžio ir mikrodefektų įtaką minkštųjų poringųjų polimerinių medžiagų įtempių ir deformacijų dydžiui, nustatyta:

- įtempių koncentracijos koeficiento ekstreminės priklausomybės su minimumais nuo poringumo dydžio ir porų išsidėstymo pobūdžio pastovios deformacijos atveju;
- medžiagos įtempių koncentracijos koeficiento dydžio ir pasiskirstymo dėsningumai nuo periodiškumo orientacijos pastovios deformacijos apkrovos krypties atžvilgiu;
- įtempių ir santykinių deformacijų priklausomybės nuo poringumo dydžio ir porų išsidėstymo pobūdžio pastovios tempimo jėgos atveju;
- poringųjų medžiagų su susisiekiančiomis poromis įtempių ir deformacijų priklausomybės nuo poringumo dydžio ir porų išsidėstymo pobūdžio;
- ledo užpildų neigiama įtaka minkštųjų poringųjų polimerinių medžiagų stiprumui ir deformuojamumui;
- didelio poringumo medžiagų įtempių koncentracijos koeficiento priklausomybės nuo mikrostruktūros geometrinių parametrų: struktūrinio elemento formos, orientacijos, mikrostrypelių ilgio ir pločio santykio, kampo tarp mikrostrypelių dydžio, jo apvalinimo spindulio;
- lenkiamų sistemų su minkštosios poringosios medžiagos sluoksniu įtempių ir sulenkimo jėgos priklausomybės nuo poringumo pobūdžio;
- plokščiųjų ir tūrinių modelių porų išsidėstymo skirtumų įtaka įtempių dydžiui ir pasiskirstymui.

Atlikti moksliniai tyrimai gali būti pritaikyti:

- kuriant naujas poringąsias medžiagas ir jas tobulinant;
- kuriant naujų poringųjų medžiagų gamybos technologijas ir jas tobulinant;
- sprendžiant poringųjų medžiagų deformavimosi ir stiprumo klausimus;
- analizuojant poringųjų medžiagų suirimo ir lūžimo priežastis.

Ginamieji disertacijos teiginiai:

- Keičiant poringosios polimerinės medžiagos porų išsidėstymo pobūdį, galima pasiekti, kad įtempių koncentracijos koeficientas, esant pastovios deformacijos apkrovai, būtų mažesnis už neporingosios tų pačių mechaninių savybių kaip ir matrica medžiagos.
- Mažėjant poringosios polimerinės medžiagos matricos gretimų zonų standumo skirtumams, medžiagos įtempiai mažėja.
- Susisiekiančių porų mikrostruktūroje buvimas didina tempiamos pastovia jėga minkštosios poringosios polimerinės medžiagos įtempių ir deformacijų dydį.
- Ledo užpildai minkštosios poringosios polimerinės medžiagos mikrostruktūroje mažina medžiagos stiprumą ir deformuojamumą.

Darbo apimtis. Disertacijos apimtis 99 puslapiai. Disertacija sudaryta iš įvado, 3 skyrių, išvadų, 140 pozicijų literatūros sąrašo, publikuotų mokslinių darbų sąrašo, priedų, 79 paveikslų ir 8 lentelių.

IŠVADOS

1. Minkštųjų poringųjų polimerinių medžiagų įtempių koncentracija mažos pastovios deformacijos $\varepsilon = 0,2$ atveju (tiesiškumo ribose) priklauso nuo poringumo dydžio ir porų išsidėstymo pobūdžio. Nustatyta, kad labai mažo poringumo atveju, kai mikrostruktūrai būdingos retos mažos poros, įtempių koncentracijos koeficientas yra artimas 3. Jei poringumas $\gamma_p \geq 0,5$, o porų išsidėstymo pobūdis yra toks, kad matricos gretimų zonų standumų skirtumai nedideli, įtempių koncentracijos koeficientas yra minimalus ir artimas 1, t. y. poringosios medžiagos įtempiai yra artimi neporingosios tų pačių mechaninių savybių, kaip ir matrica, medžiagos įtempiams.
2. Jei minkštųjų poringųjų polimerinių medžiagų didžiausieji svarbiausieji įtempiai, esant sąlyginai mažoms deformacijoms ($\varepsilon < 1$), yra artimi neporingosios tų pačių mechaninių savybių, kaip ir matrica, medžiagos įtempiams, tai, esant didelėms deformacijoms ($\varepsilon > 1$), šie įtempiai gali būti didesni 1,5 – 3 kartus.
3. Nustatyta, kad pastovios deformacijos atveju ($\varepsilon = 0,2$) periodinės struktūros poringosios polimerinės medžiagos įtempių koncentracijos koeficiento dydis priklauso nuo mikrostrypelių orientacijos tempimo krypties atžvilgiu ir nuo matricos gretimų zonų standumo skirtumų. Jei plonų mikrostrypelių išilginė ašis sutampa su tempimo kryptimi, medžiagos įtempių koncentracijos koeficientas didžiausias, jei su tempimo kryptimi sudaro 45° kampą – mažiausias.
4. Pastovios tempimo jėgos atveju (tiesiškumo ribose), didėjant poringumui, įtempiai poringoje polimerinėje medžiagoje didėja netolygiai. Įtempiai didėja neženkliai, kai poringumas neviršija 0,5, tačiau tokios medžiagos de-

formacinis pajėgumas yra mažas. Santykinai maži įtempiai ir didelės deformacijos yra tada, kai poringumas yra didesnis už 0,5, o porų išsidėstymo pobūdis yra toks, kad medžiagoje nesusidaro tarp porų stambūs vientisos medžiagos elementai ir labai ploni tarpporiniai mikrostrypeliai.

5. Ištyrus poringųjų polimerinių medžiagų plokščiųjų ir tūrinių modelių įtempius ($\varepsilon = 0{,}2$), nustatyta, kad skirtumas tarp šių modelių įtempių priklauso nuo porų išsidėstymo ypatumų. Jei to paties poringumo pobūdžio plokščiųjų ir tūrinių modelių porų išsidėstymas yra toks pats, didžiausias skirtumas tarp modelių įtempių siekia 9 %. Didelio poringumo atveju, plokščiųjų ir tūrinių modelių heterogeninių porų išsidėstymas yra skirtingas ir dėl to šių modelių įtempiai gali skirtis 35 % ir daugiau.
6. Susisiekiančios poros didina tempiamų poringųjų medžiagų įtempius, mažina jų stiprumą, standumą ir didina jų deformuojamumą. Kuo medžiagos poringumas didesnis, tuo susisiekiančių porų įtaka medžiagos deformacinei elgsenai didesnė. Santykinai didelių porų ir mažų medžiagos matmenų atveju irimas prasideda esant didesnėms įtempių vertėms ne tik už matricos medžiagos stiprumo ribą, bet ir už tokios pačios, bet nedefektuotos medžiagos. Tačiau tokios defektuotos medžiagos suardymui reikia mažesnės jėgos, nei tokios pačios nedefektuotos.
7. Skaičiuotiniai rezultatai parodė, kad minkštosios poringosios polimerinės medžiagos užpildymas ledu mažina jos deformuojamumą. Sistemos įtempių sumažėjimą ar padidėjimą geros adhezijos atveju lemia ledo užpildų išsidėstymo pobūdis. Jei ledo užpildai išsidėstę taip, kad mikrostruktūroje susidaro dideli standumo skirtumai ir sąlygos didelėms deformacijoms, matricos įtempiai padidėja, o kitu atveju – sumažėja. Remiantis eksperimentiniais minkštųjų poringųjų polimerinių medžiagų su ledo užpildais tyrimais, ledo intarpai mažina sistemos stiprumą ir deformuojamumą.
8. Didelio poringumo polimerinių medžiagų, kurioms būdingi maži matricos gretimų zonų standumų skirtumai, įtempių koncentracijos koeficiento dydžiui didelės įtakos turi struktūrinių elementų forma ir orientacija. Nustatyta, kad kuo mikrostrypelio pločio ir ilgio santykis didesnis, tuo didesnis mikrostruktūros įtempių koncentracijos koeficientas. Mažas įtempių koncentracijos koeficientas yra tada, kai kampas tarp mikrostrypelių nuo 20° iki 140°, o šio kampo apvalinimo spindulys yra nuo $0{,}25R$ iki $0{,}4R$ (R – didžiausiasis apvalinimo spindulys).
9. Lenkiamos trisluoksnės medžiagų sistemos su poringu paviršiaus raštą turinčiu minkštosios polimerinės medžiagos sluoksniu įtempiai yra mažesni už tokios pačios, tik su neporingu sluoksniu sistemos, nes pirmosios sistemos standumas yra mažesnis. Jei poringoje medžiagoje griovelio ašyje arti griovelio dugno yra stambi pora, įtempiai griovelio dugne yra dideli. Stambios poros iškyšulio ašyje neskatina sistemos irimo.

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Išleido leidykla „Technologija”, K. Donelaičio g. 73, 44029, Kaunas
Spausdino leidyklos „Technologija” spaustuvė, Studentų g. 54, 51424, Kaunas