On fracture toughness of polyurethane foams

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Abstract. Polyurethane (PUR) foam materials are widely used as cores in sandwich composites, for packing and cushioning. They are made of interconnected networks of solid struts and cell walls incorporating voids with entrapped gas, Fig. 1. Of particular interest is the fracture toughness of such foams because foam failure weakens the structure's capacity for carrying loads.

Many efforts have been made in recent years to determine the fracture toughness of different types of foams in static and dynamic loading conditions. Micromechanical models and experimental investigations were used for estimating the fracture toughness. This paper presents the polyurethane foam fracture toughness results obtained for different foam densities. Single edge notch bend specimens were tested at room temperature and with different loading speeds. Our results are presented together with other experimental results and correlations related to micromechanical models are made.

Introduction

The main characteristics of PUR foams are lightweight, high porosity and good energy absorption capacity, [1]. Foam materials crush in compression, while in tension they fail by propagation of a single crack, [2]. Most of the rigid polymer foams have a linear – elastic behaviour in tension up to fracture, with a brittle type of failure. So, they can be treated using the fracture concepts of Linear Elastic Fracture Mechanics (LEFM).

Many attempts were carried on in order to predict the fracture toughness of foam materials using analytical – micromechanical models [1,3,4,5,6,7,8]. On the other hand, fracture toughness tests were performed to find the fracture toughness of cellular materials.

The first correlation between fracture toughness of PUR foams and density (< 200 kg/m^3) was proposed by McIntyre and Anderson [9] in a linear form. The same behaviour was observed by Danielsson [10] on PVC Divinycell foams and Viana and Carlsson on Diab H foams [11]. Brittle fracture without yielding produced in Mode I was observed in experiments. A correlation between the static fracture toughness and relative density ρ^*/ρ_s was proposed in [1]. Kabir et al. [12] used the procedure described by ASTM D5045 [13] for determining the fracture toughness of polyvinyl chloride (PVC) and polyurethane (PUR) foams. They investigated the effect of density, effect of specimen size, effect of loading rate and effect of cell orientation. Density has a significant effect on fracture toughness, which increases more than 7 times when the foam density increases 3.5 times. Burman [14] presented fracture toughness results for two commercial foams Rohacell WF51 (density 52 kg/m^3) and Divinycell H100 (density 100 kg/m^3). The mode I fracture toughness K_{Ic} was obtained on SENB specimens and has values 0.08 MPa $m^{0.5}$ for WF51, respectively 0.21 MPa $m^{0.5}$ for H100. He also determined the Mode II fracture toughness using End-Notch Flexure (ENF) specimen with values of 0.13 MPa $m^{0.5}$ for WF51, respectively 0.21 MPa $m^{0.5}$ for H100.

This paper presents the experimental results for the fracture toughness of PUR foams and comparison with the main micromechanical models from literature.

Micromechanical models for prediction of fracture toughness of cellular materials

Micromechanical analysis allows predicting the mechanical properties of cellular materials based on cell structures. Extensive studies of micromechanical models for cellular materials are presented by Gibson and Ashby [1], Marsavina [2], Mills [3]. Here only the main formulations relating to prediction of fracture mechanics for plastic foams will be presented. Micromechanical models relate the fracture toughness of the foam K_{Ic} to the tensile strength of the cell walls σ_{fs}, cell dimension l and the relative density $\rho*/\rho_s$.

Gibson and Ashby [1] assumed that the crack tip is located at half-edge length and considered an elastic mode I stress field at the crack tip. They start from the stress singularity at the tip of a crack of length 2a and normal to remote loading σ in an elastic continuum solid, at distance r (on a direction $\theta = 0$) from crack tip. They considered only the singular term in the Irwin's stress field solution, and the bending of struts. The proposed relation is:

$$\frac{K_{Ic}}{\sigma_{fs}\sqrt{\pi l}} = 0.65\left(\rho*/\rho_s\right)^{1.5}. \tag{1}$$

It should be mentioned that Gibson and Ashby did not predict the value 0.65, only the slope 1.5 of the power law relationship. They plotted experimental data and inferred that the coefficient for real foams might be 0.65.

Choi and Lakes [5] proposed a micromechanical model taking into account the blunting at the crack tip, and corresponding nonsingular stress field. A linear expression between non-dimensional fracture toughness and relative density was obtained in the form:

$$\frac{K^*_{Ic}}{\sigma_{fs}\sqrt{\pi l}} = 0.19\left(\frac{\rho*}{\rho_s}\right). \tag{2}$$

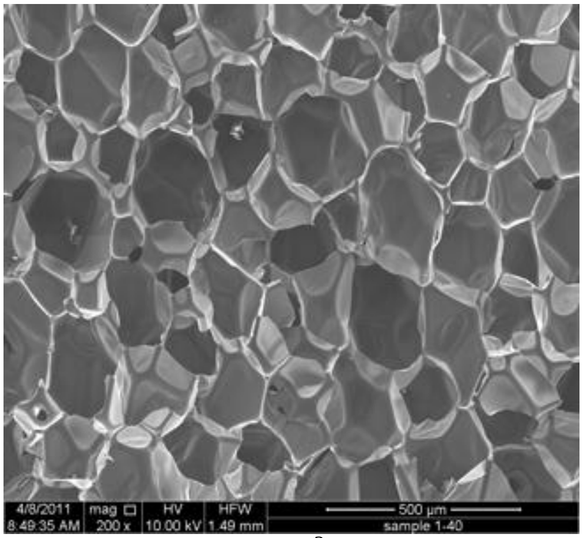
Similar correlation was proposed by Green [4] considering elastic deformation in shell theory of hollow sphere model for foam cells:

$$\frac{K^*_{Ic}}{\sigma_{fs}\sqrt{\pi l}} = 0.28\left(\frac{\rho*}{\rho_s}\right)^{1.3}. \tag{3}$$

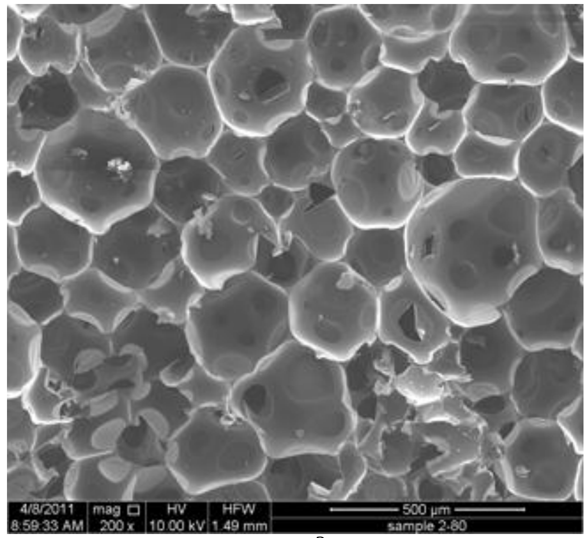
It should be noticed that all the micromechanical models should be verified using experimental results.

Experimental determination of fracture toughness for PUR foams

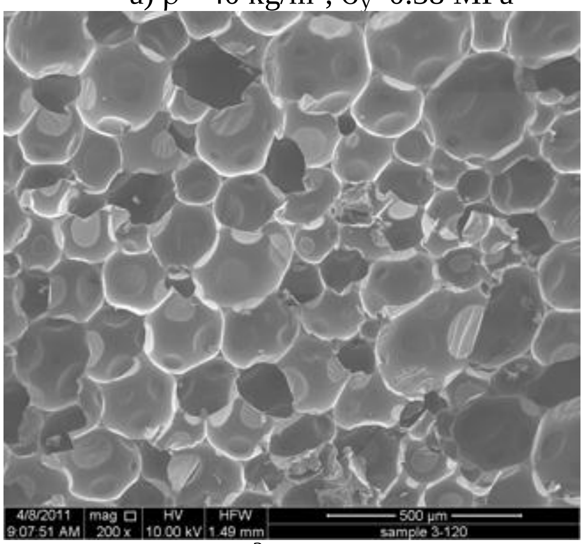
The experimental determination of fracture toughness was performed on PUR foams of different densities following the procedure proposed by ASTM D5045-99 [13]. The microstructure of the investigated foams (at 200X magnification) together with the yield stress values in compression are shown in Fig. 1.



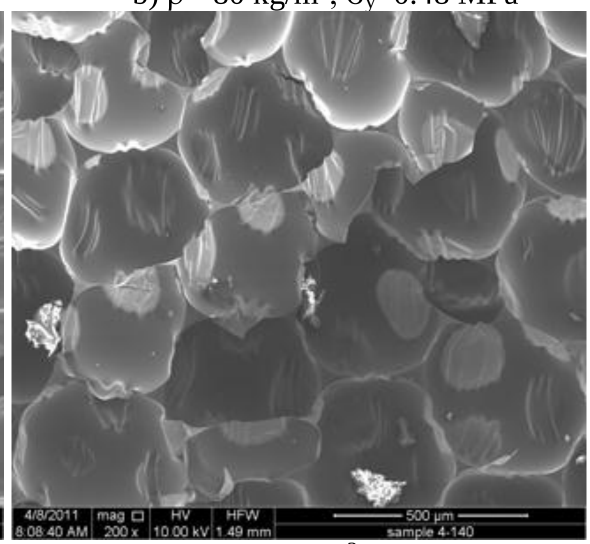
a) ρ^{*}=40 kg/m^3, σ_y=0.38 MPa



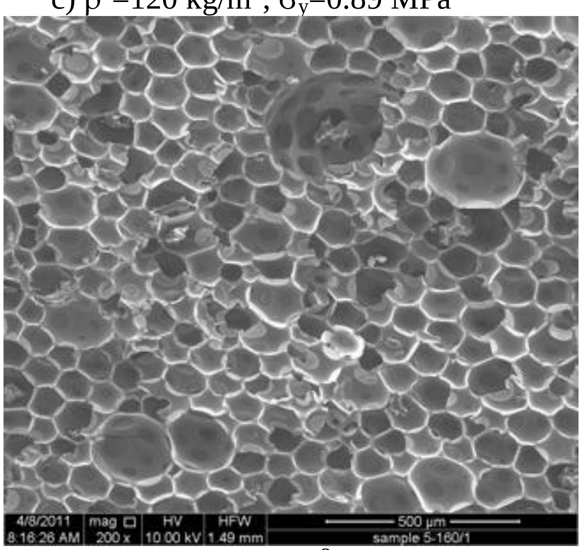
b) ρ^{*}=80 kg/m^3, σ_y=0.48 MPa



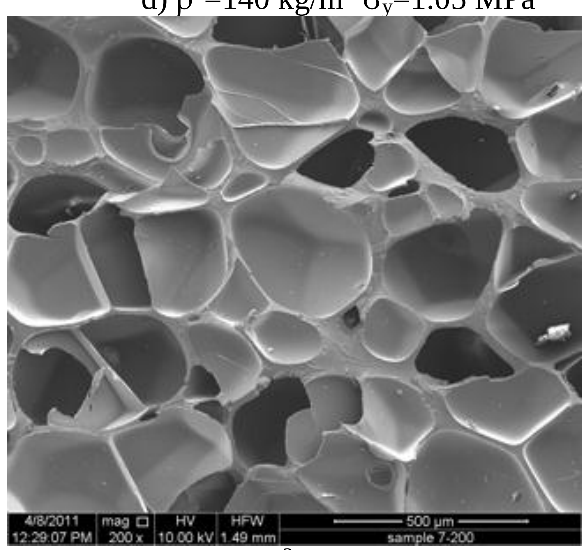
c) ρ^{*}=120 kg/m^3, σ_y=0.89 MPa



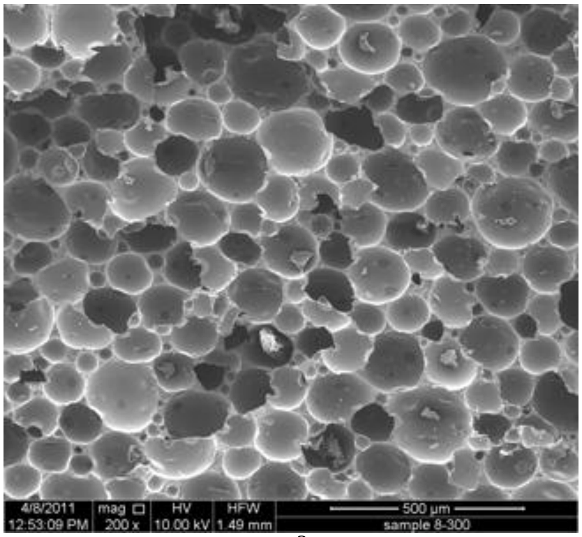
d) ρ^{*}=140 kg/m^3 σ_y=1.05 MPa



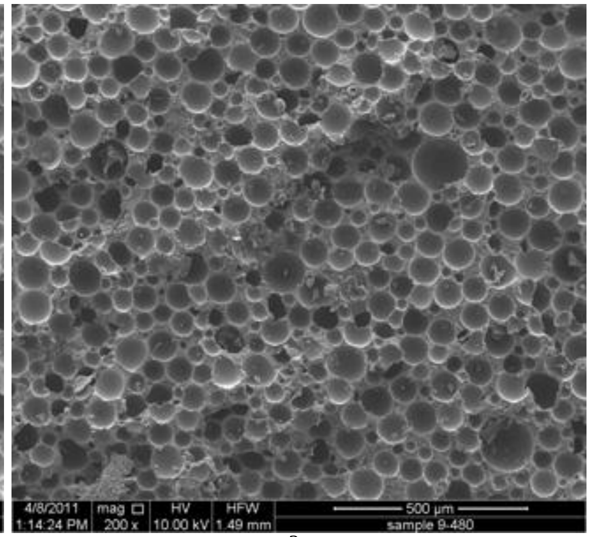
e) ρ^{*}=160 kg/m^3, σ_y=3 MPa



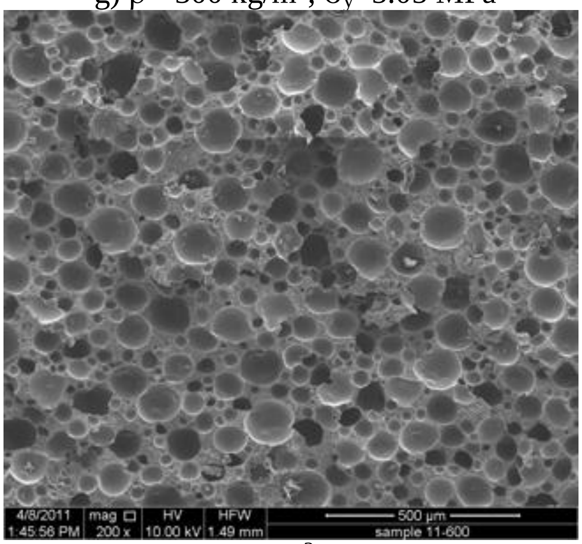
f) ρ^{*}=200 kg/m^3, σ_y=4.1 MPa



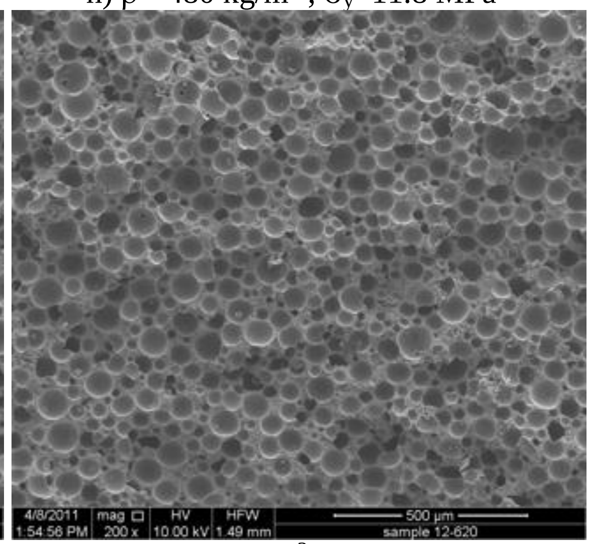
g) ρ^*=300 kg/m^3, σ_y=5.05 MPa



h) ρ^*=480 kg/m^3 , σ_y=11.8 MPa



i) ρ^*=600 kg/m^3, σ_y=22 MPa



j) ρ^*=620 kg/m^3 , σ_y=22 MPa

Fig. 1. Microstructure of investigated PUR foams

The fracture toughness determination was performed on Single Edge Notch Bend (SENB) specimens. The tests were done at room temperature with a loading rate of 2 mm/min, with exception of the tests investigating the effect of loading rate. The load versus loading-point displacement curve is recorded during tests carried on with a Zwick/Roell 5 kN testing machine. Typical load displacement curves are shown in Fig. 2. For all specimens a linear diagram was obtained with an abrupt drop of load to zero after reaching the maximum load. The K_Q was evaluated using the load value corresponding to compliance 5% greater than the initial linear part of the load-displacement diagram. Brittle fracture was observed for all tested specimens. The linear elastic behavior was confirmed during the tests when no cushioning occurs and no plastic deformations remain after the test, Fig. 3.

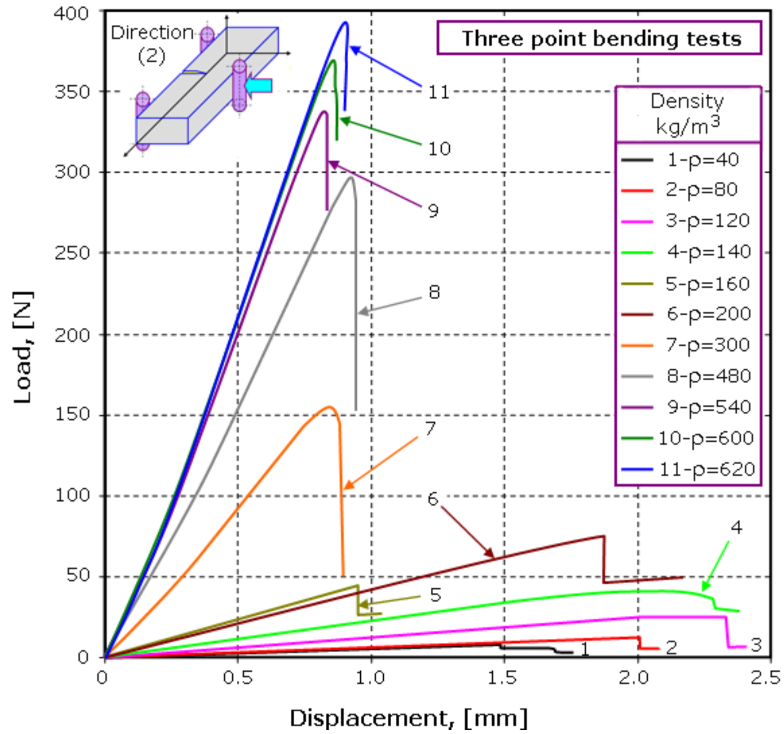


Fig. 2. Typical load – displacement curves obtained for SENB specimens.

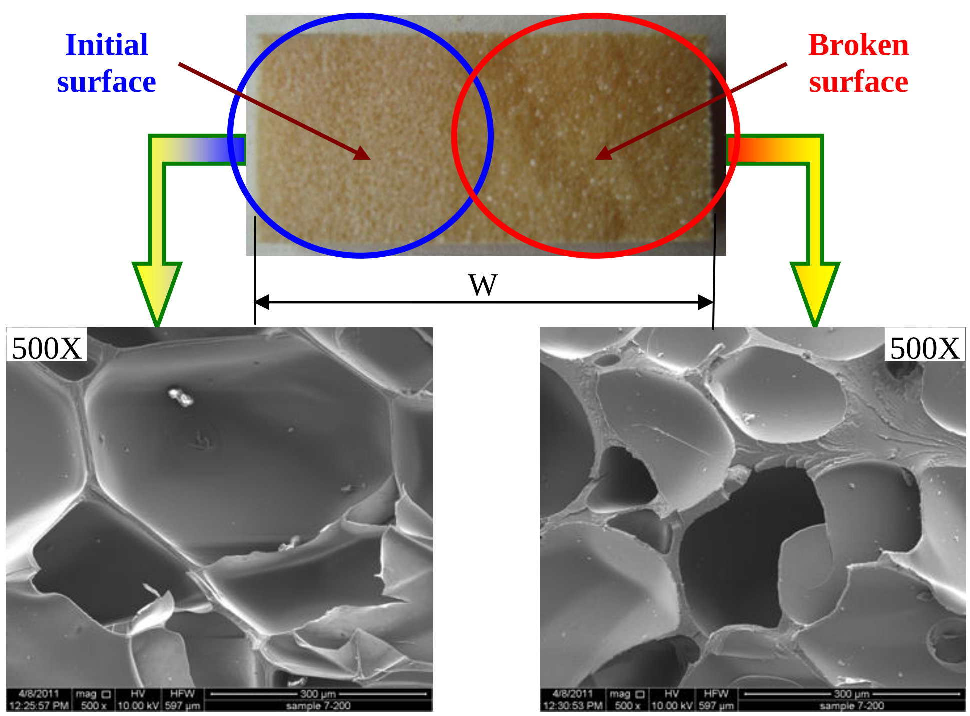


Fig. 3. Notch and fracture surfaces.

The plane strain condition was validated for all tests and the fracture toughness was considered: $K_{Ic} = K_Q$. The mean, minimum and maximum values of fracture toughness are shown in Fig. 4. The experimental results for fracture toughness are between 0.027 MPa $m^{0.5}$ for 40 kg/m^3 density to 1.46 MPa $m^{0.5}$ for 620 kg/m^3 density.

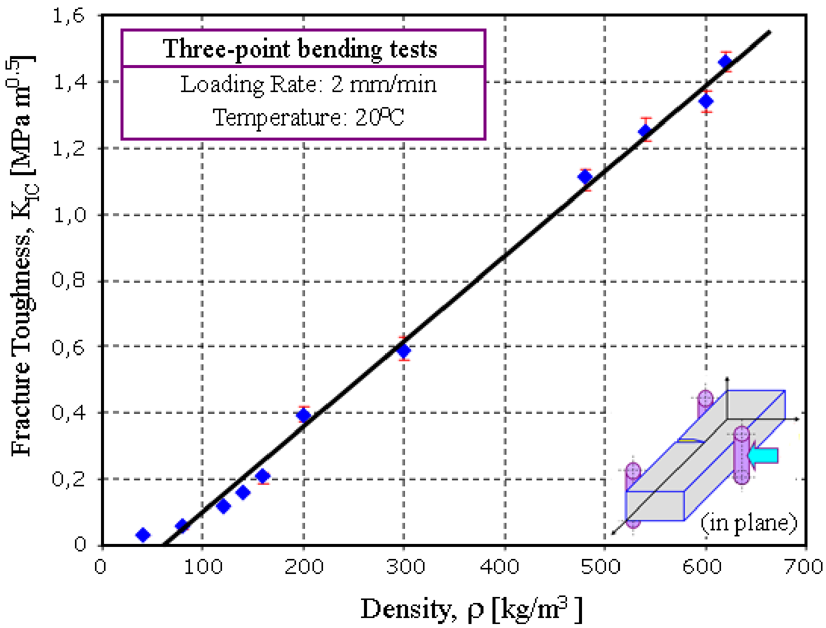
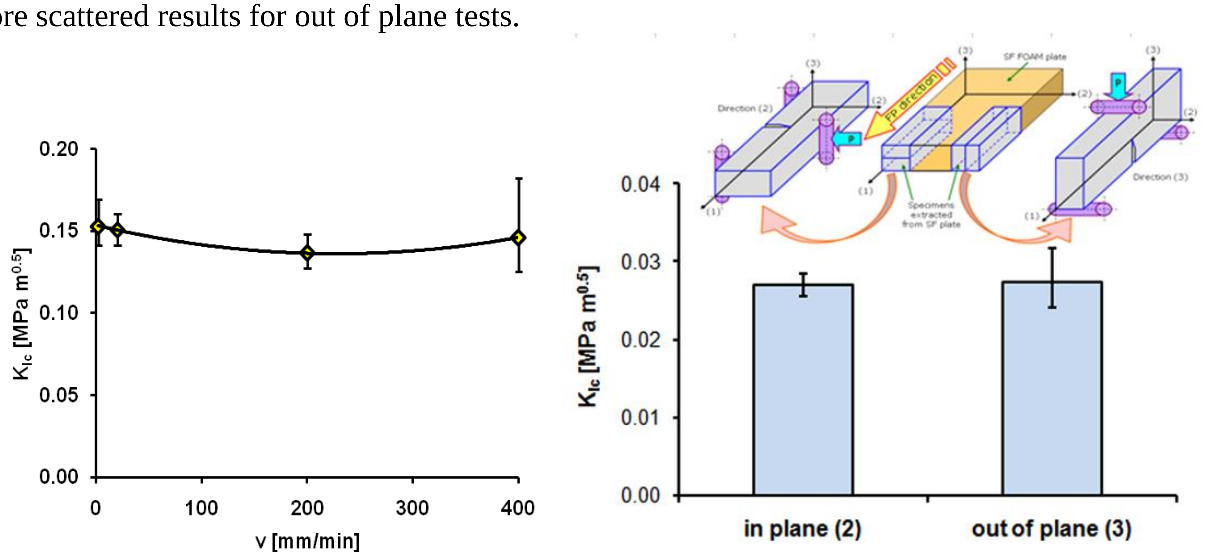


Fig. 4. Fracture toughness results versus density

The influence of loading rate on the fracture toughness of the PUR foam was investigated for the foam with 140 kg/m^3 density, Fig. 5.a. It could be observed a small decrease of fracture toughness around 200 mm/min loading speed. For the PUR foam of 40 kg/m^3 density a study of the orientation of specimens was performed, Fig. 5.b. Similar results were obtained for both orientations in-plane – direction (2) K_{Ic}= 0.0270 MPa m$^{0.5}$ and out-of plane – direction (3) K_{Ic}= 0.0274 MPa m$^{0.5}$, with more scattered results for out of plane tests.



a. Influence of loading rate (ρ^*=140 kg/m^3) b. Influence of crack orientation (ρ^*=40 kg/m^3)

Fig. 5. Factors influencing the fracture toughness of PUR foams

Comparison between micromechanical models and experimental results

A comparison between experimental results and micromechanical predictions of the normalised fracture toughness $K_{Ic}/[\sigma_{fs}\,(\pi\, l)^{0.5}]$ versus relative density is shown in Fig. 6. For low density foams a good agreement between experimental results and the micromechanical Choi and Lakes model ρ^*/ρ_s < 0.1 can be noticed. For higher relative densities (ρ^*/ρ_s > 0.1) the Ashby - Gibson model appears to fit better the experimental results. For the investigated PUR foams the Green micromechanical model looks to predict much lower results than the experimental ones. This could be explained by the use of the hollow sphere model, which could not be applied to these foams that have thick cell walls.

Conclusions

The main conclusions of this study are:

- The order of magnitude for fracture toughness of PUR foams is between 0.03 for density of 40 kg/m^3 to 1.46 MPa m$^{0.5}$ for density of 620 kg/m^3. Fracture toughness is strongly dependent on foam density, Fig. 4. Fracture toughness increase with increasing de density of foams.
- Other parameters influencing the fracture toughness are the loading rate and crack orientation, Fig. 5. For the investigated PUR foam the crack orientation appears to have no influence.
- The fracture of polyurethane foams in tensile is quasi brittlle, no plastic deformations remains after the test and no cushoning occurs during tests, Fig. 3.
- The obtained experimental results agree with Choi - Lakes micromechanical model for low density foams ($\rho^*/\rho_s < 0.1$) and with Ashby – Gibson model for higher relative densities ($\rho^*/\rho_s >$ 0.1), Fig. 6.

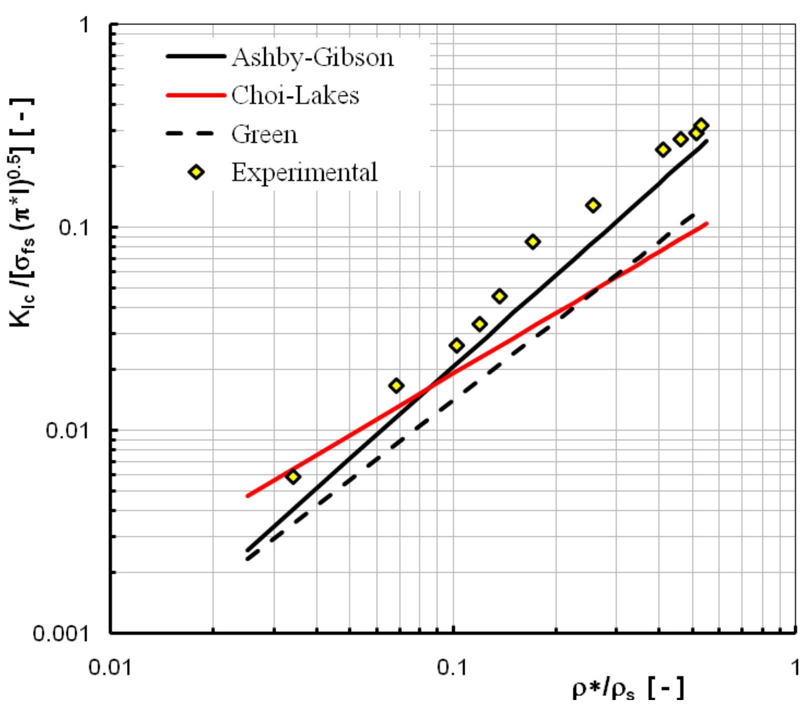


Fig. 6. Normalised fracture toughness versus relative density.

Acknowledgments

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