THE EFFECT OF LOADING RATE AND DIRECTION OF FORMATION ON FRACTURE TOUGHNESS OF RIGID POLYURETHANE FOAMS

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Abstract: This paper presents the effect of loading rate, (ELR), and direction of formation, (DF), of rigid polyurethane foams, (PUR 40 and PUR 140), on fracture toughness. Nominal densities of used foams in the experimental program were 140 kg/m^3, (for ELS) and 40 kg/m^3, (for DF), which is closed-cell rigid foams widely used for sandwich cores. Determination of fracture toughness for Mode I fracture of studied materials has made by three-point bending tests, (3PB), on specimens with notches, at room temperature (20 ± 2 ºC). All the specimens were cut from one and the same plate. The specimens were subjected to 3PB at a loading speed of 2 mm/min, except samples for determining the ELR where 2, 20, 200 and 400 mm/min loading speeds were used, and were taken into account the fact that the load must act exactly on the notch direction. All the specimens present brittle failure without plastic deformation.

Keywords: polyurethane foam, closed cells, fracture toughness, three point bend tests

1. INTRODUCTION

The main use of rigid polyurethane (PUR) foam is for sandwich panels because it presents a high stiffness, they are used as core, and that faces can use different types of materials (carbon fiber, aluminum), depending on panel destination. Also, these types of cellular material are used for packing and cushioning because of their structure shows great capacity to absorb impact energy [1, 2].

The main characteristics of foams are high porosity and workability, good energy absorption capacity, and a weight relatively low compared with other materials with the same mechanical characteristics [3].

Many efforts have been made in recent years to determine the fracture toughness of such foams under static and dynamic loading conditions, [4]. McIntyre and Anderson, [5], using single edge notch specimen, made of rigid closed-cell PU foams measured the K_{IC} for different densities. They found that the fracture toughness is independent of crack length and a linear correlation of K_{IC} with density for foams with densities less than 200 kg/m^3. At higher densities the correlation becomes non-linear. Linear relationship between K_{IC} and density (90 - 235 kg/m^3), was also obtained by Danielsson, [6] for PVC Divinicel HD using three point bend specimens. Burman, [7] presented fracture toughness results for two commercial foams Rohacell WF51 (density 52 kg/m^3) and Dyvinicell H100 (density 100 kg/m^3) using SENB specimens. Vianna and Carlsson, [8] presented results of fracture toughness for PVC foams of different densities, (36, 80, 100, 200 AND 400 kg/m^3). Kabir and Sasha, [9] using 3PB tests have determined fracture toughness for polyvinyl chloride (PVC) and polyurethane (PU)

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foams. Also, fracture toughness was investigated by Marsavina and Linul, [3], and Linul et al., [10] for three different densities of rigid polyurethane (PUR) foams, (40, 140 and 200 kg/m^3).

In order to establish that a valid K_{IC} has been determined, it is first necessary to calculate a conditional result, K_Q, which involves a construction on the test record, and to then determine whether this result is consistent with the size of the specimen.

Figure 1 presents the force-displacement curve for determining the critical load P_Q.

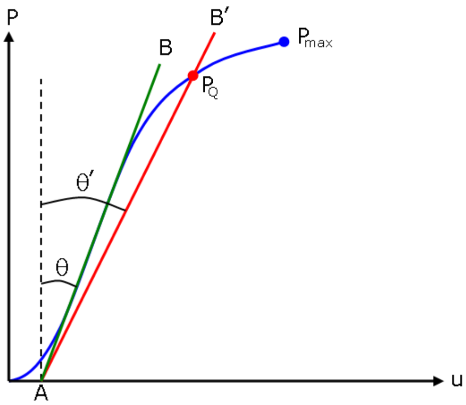


Fig. 1. Force-displacement curve for determining the critical load P_Q.

Determining the critical load is as follows: Draw a best straight line (AB) to determine the initial compliance, C (*C=tanθ; 1,05C=tanθ'*). C is given by the reciprocal of the slope of line (AB). Draw a second line (AB') with a compliance 5 % greater than that of line (AB). If the maximum load that the specimen was able to sustain, P_{max}, falls within lines (AB) and (AB'), use P_{max} to calculate K_Q. If P_{max} falls outside line (AB) and line (AB'), then use the intersection of line (AB') and the load curve as P_Q. Furthermore, if P_{max}/P_Q < 1.1, use P_Q in the calculation of K_Q. However, if P_{max}/P_Q > 1.1, the test is invalid [11].

For a specimen that meet the condition, L/W=4, K_Q is determined by the following the relation:

$$K_Q = \left(\frac{P_Q}{BW^{1/2}}\right) f\left(\frac{a}{W}\right), \text{ with: } 0 < \frac{a}{W} < 1 \tag{1}$$

with f(x) a non-dimensional function given by:

$$f\left(\frac{a}{W}\right) = 6\sqrt{\frac{a}{W}}\,\frac{\left[1.99 - \frac{a}{W}\left(1-\frac{a}{W}\right)\left(2.15 - 3.93\frac{a}{W} + 2.7\left(\frac{a}{W}\right)^2\right)\right]}{\left(1+2\frac{a}{W}\right)\left(1-\frac{a}{W}\right)^{3/2}} \tag{2}$$

where:

P_Q - force acting on the specimen;
b - specimen thickness;
W - specimen height;
a - crack length;
S - span length.

In order for a result to be considered valid according to these test methods, the following size criteria must be satisfied:

$$a, B, (W-a) \geq 2.5\left(\frac{K_Q}{\sigma_{ys}}\right)^2 \tag{3}$$

where σ_{ys} is the yield stress of the material for the temperature and loading rate of the test.

In case that the condition (3), the critical stress intensity factor, K_{IC}, is considered to be equal to the calculated stress intensity factor, K_Q, so:

$$K_{IC} = K_Q \tag{4}$$

2. EXPERIMENTAL PROCEDURE

Experimental tests for determining the static fracture toughness were made on the Strength of Materials Laboratory from the Faculty of Mechanical Engineering from Timisoara on a tension-compression Zwick Roell 005 testing machine of 5 kN, (Figure 2).

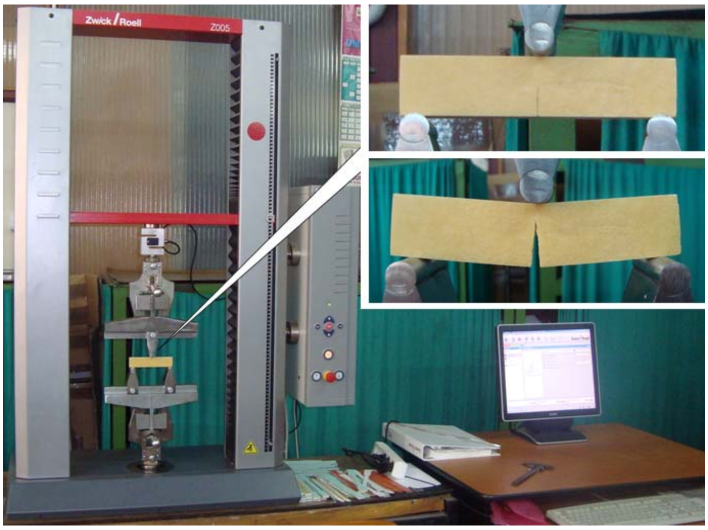


Fig. 2. Zwick Roell 005 testing machine used for 3PB tests.

Tests were performed at room temperature, (20 ± 2 ºC), using specimens with the shape and dimensions shown in Figure 3. For determining the fracture toughness of studied materials we used notched specimens loaded in three point bending.

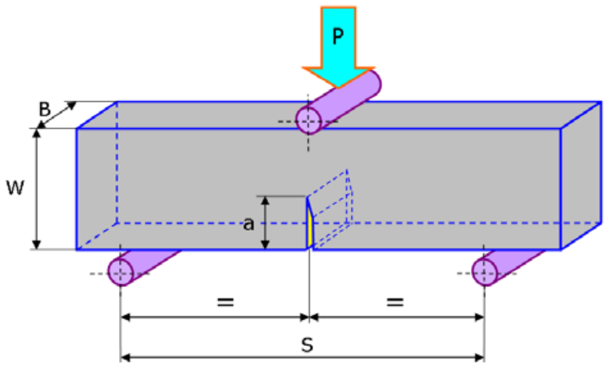


Fig. 3. Shape and dimensions of the used specimens for 3PB tests.

In the experimental program was used rigid polyurethane foam with 40 and 140 kg/m^3. Figure 4 presents the shape of the specimens used for experimental tests. Both specimens and notches were cut from one and the same rectangular plate with a blade thickness of 0.6 mm.

a) b)

Fig. 4. Shape of the specimens used for 3PB tests:
a) ELR; b) DF.

The specimens were subjected to 3PB. The loading speed was 2 mm/min for determining the influence of direction of formation, and 2, 20, 200 and 400 mm/min for determining the ELR.

For each type of test 5 specimens were used, and the tests were performed according with ASTM D 5045-99 (*Standard Test Methods for Plane-Strain Fracture Toughness and Strain Energy Release Rate of Plastic Materials*), and were taken into account the fact that the load must act exactly on the notch direction.

2.1. The effect of loading rate (ELR)

The mean values of the fracture toughness obtained from the experimental tests for rigid polyurethane foam with 140 kg/m^3 density, according to loading rate, are listed in Table 1.

Table 1. Mean value of the mechanical characteristics for analyzed foams after 3PB tests.

Density ρ, [Kg/m^3]	Samples dimensions				Loading rate, [mm/min]	Critical load, P_Q [N]	Fracture toughness, K_{IC} [MPam$^{0.5}$]	$2.5\left(\frac{K_Q}{\sigma_{ys}}\right)^2$ [mm]
	Widt B [mm]	High W [mm]	Span length S [mm]	Crack length, a [mm]				
140	13.9	24.9	100	12.5	2	34.70	0.156	7.9
	13.1	25.0			20	30.64	0.149	6.9
	14.6	25.1			200	28.50	0.137	4.7
	12.8	24.9			400	25.06	0.130	4.9

Figure 5 presents the load-displacement curves for studied foam and Figure 6 showed the variation of fracture toughness versus loading rate.

2.2. The effect of loading direction (DF)

The fracture toughness of anisotropic foam depends on the direction in which the crack propagates. This is the best defined with two subscripts, the first indicating the normal to the crack plane, the second the direction of crack propagation, [1].

In Figure 7 is shown the sampling of the 3PB specimens from a rectangular SF plate, and Figure 8 shown the influence of this training plan and direction of the load on the mechanical characteristics at 3PB.

Loading direction emphasizes anisotropic behavior of the foam. Mean value of fracture toughness obtained are listed in Table 2.

Table 2. Mean values of fracture toughness versus loading direction.

Density ρ, [Kg/m^3]	Samples dimensions				Loading direction	Critical load, P [N]	Fracture toughness, K_{IC} [MPam$^{0.5}$]	$2.5\left(\frac{K_Q}{\sigma_{ys}}\right)^2$
	Width B [mm]	High W [mm]	Span length S [mm]	Crack length, a [mm]				
40	25.5	49.4	180	25.0	(2)	16.4	0.0279	20.1
	25.1	50.2			(3)	14.2	0.0276	15.1

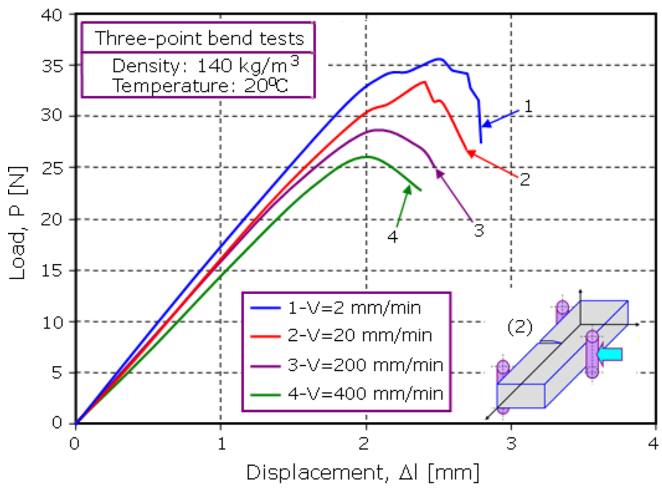


Fig. 5. Load-displacement curves for ELR.

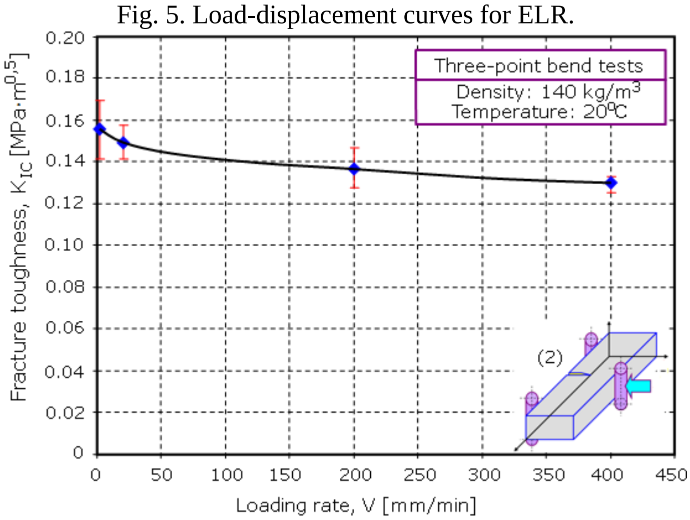


Fig. 6. Variation of fracture toughness versus loading rate.

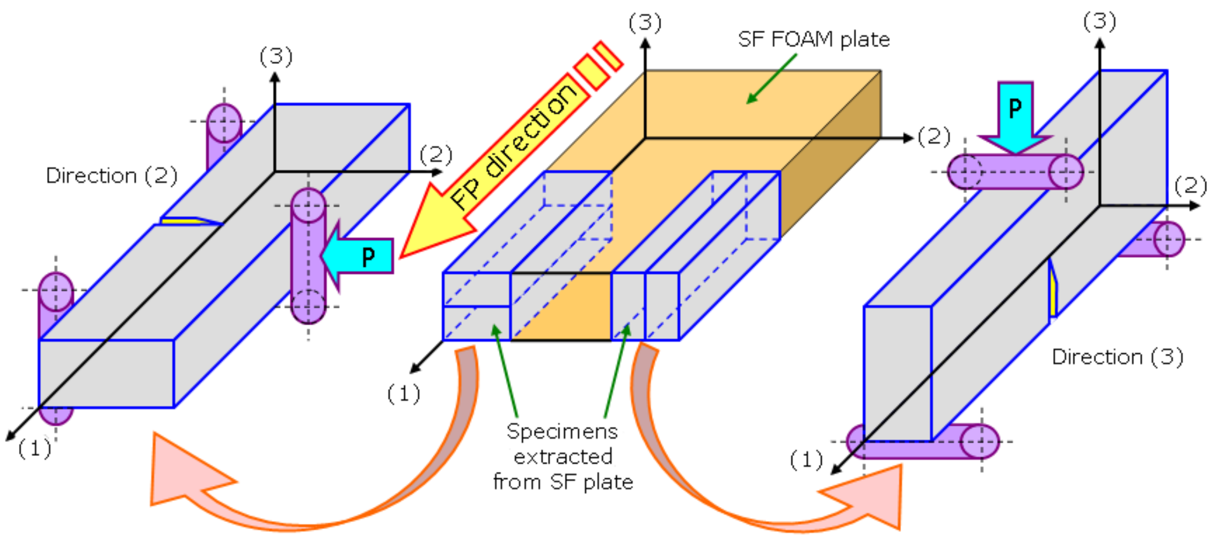


Fig. 7. The sampling of the 3PB specimens from a rectangular SF plate.

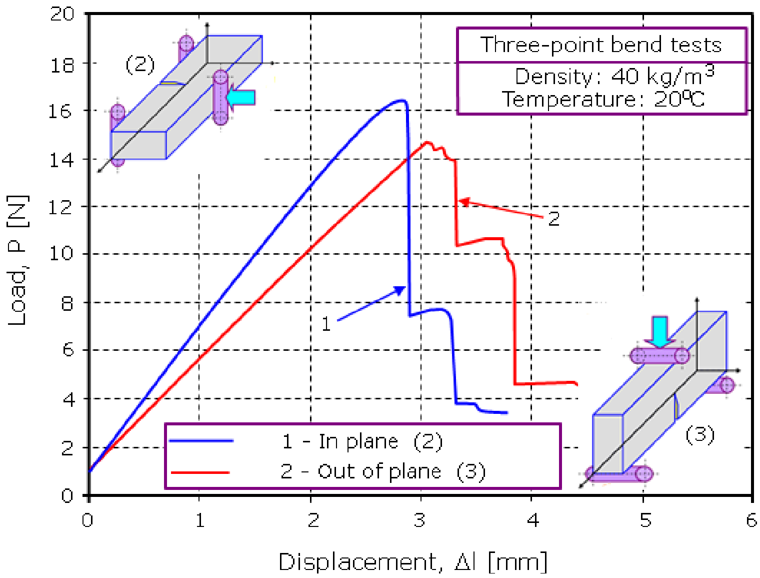


Fig. 8. Load-displacement curves for 3PB tests. Effect of loading direction.

For all tested specimens plane strain condition (3) was fulfilled.

From the Table 2 it can be observed that the variation of fracture toughness with load direction is insignificant, (for this type of foam).

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 [3].

3. MICROSTRUCTURAL ANALYSIS OF INITIAL AND BROKEN SURFACES

For analysed foams has made a micro structural analysis. The analysis was done for both before, (initial surface), and after, (broken surface), 3PB tests on the Laboratory from the Faculty of Building and Architecture at Lublin University of Technology, Lublin, Poland.

Initial and broken surfaces of rigid polyurethane foam used in 3 PB experimental programs are presented in Figure 9. Also, in same figure is shown the cellular structure of foam having closed cell with ρ = 40 kg/m^3 respectively 140 kg/m^3 density.

All tested specimens show a quasi-brittle fracture without plastic deformations and cushioning.

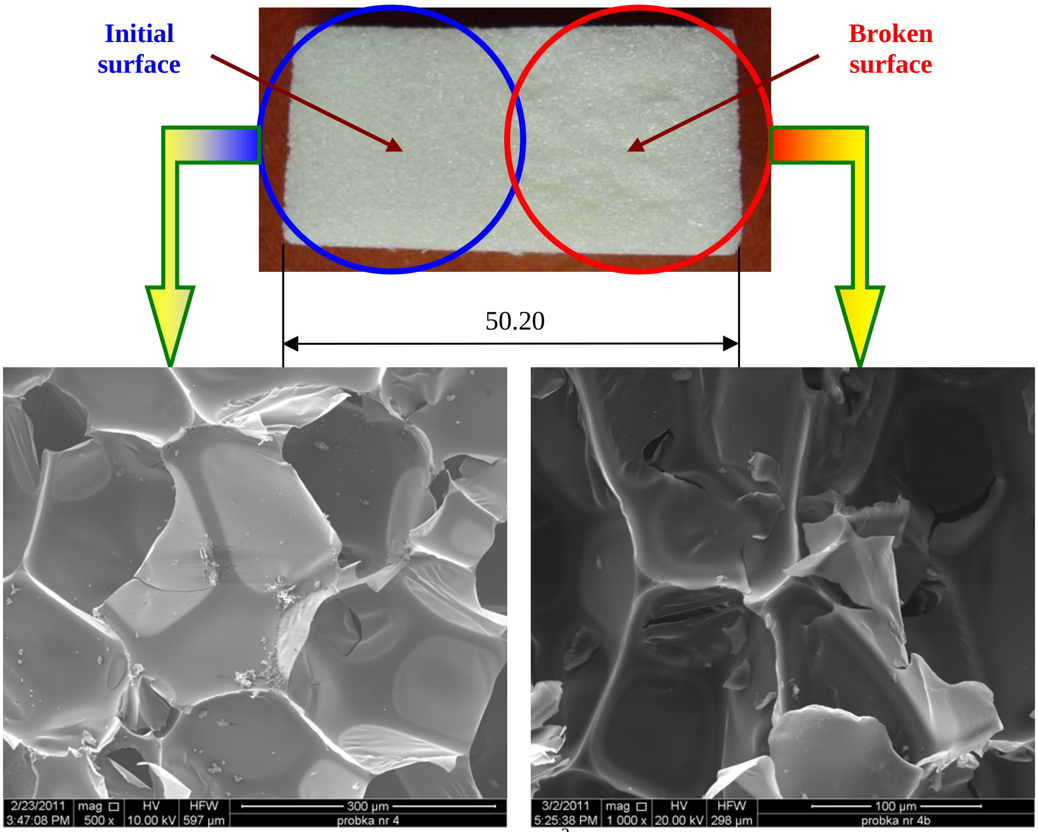
4. CONCLUSIONS

This paper presents two parameters which influence the fracture toughness of rigid polyurethane foams: effect of loading rate (ELR) and effect of loading direction (DF).

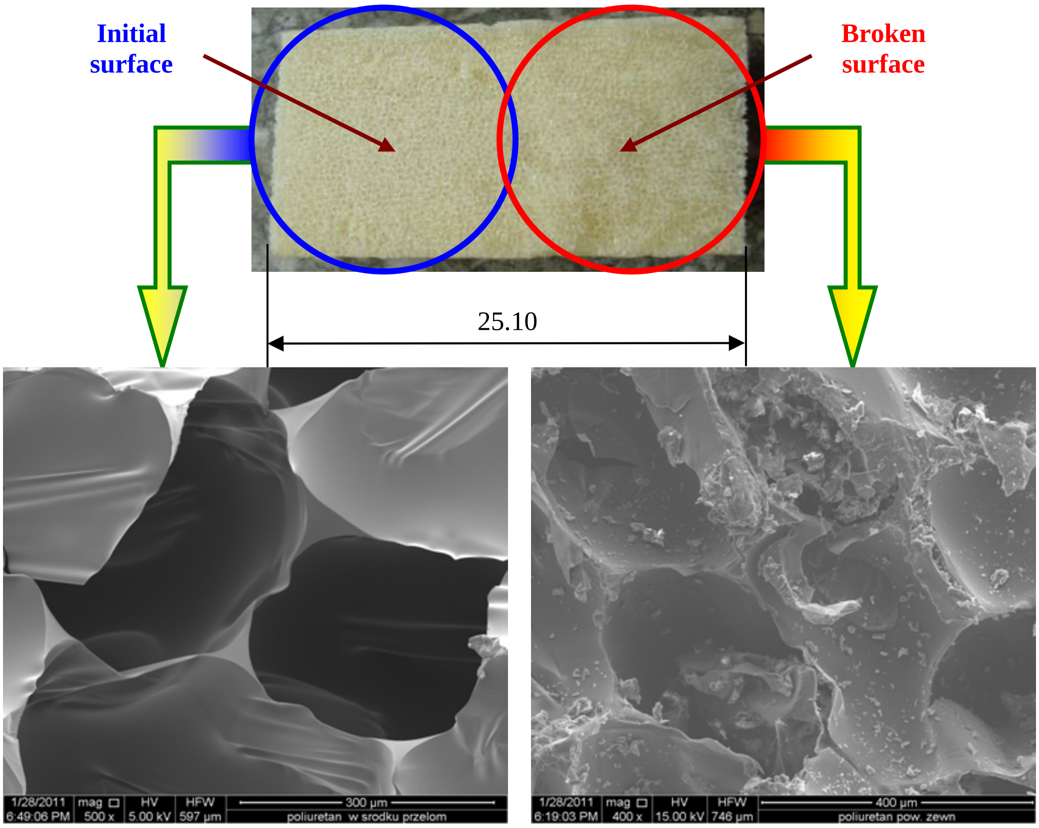
The values of fracture toughness for PUR foams are in the range 10^{-2} - 10^{-1} MPa m$^{0.5}$. Fracture toughness decrease with increasing of loading speed (Figure 6 and Table 1).

Loading direction emphasizes anisotropic behavior of the foam. For this type of polyurethane foam with 40 kg/m^3 density, was obtained approximately the same fracture toughness (Table 2).

All the specimens present brittle failure without plastic deformation.



a) 40 kg/m^3 density;



b) 140 kg/m^3 density;

Fig. 9. The microstructure of polyurethane foams used for compression tests.

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