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HIGH IMPACT POLYSTERENE(HIPS) ELASTICITY MODULUS DETERMINATION IN STRETCH DEGREE FUNCTION BY VACUUM FORMING

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Abstract. *High-Impact Polystyrene (HIPS) have been used in several industry application due to impact-resistant properties, versatility and economic factors, otherwise mechanical properties after vacuum forming process are not fully known. This paper presents correlation between HIPS strength modulus after manufacturing vacuum forming process and stretch degree. Elasticity modulus was analysed through tensile test in ASTM D638-10 and the specimens were obtained by cutting a refrigerator lining which presented different stretch degree in two orthogonal direction, determined by a grid measurement before and after manufacturing process. At first, a isotropic approach was used to describe HIPS mechanical behavior but experimental results showed that elasticity modulus varies in different regions and directions. A second approach correlated stretch degree to strength modulus, presenting that increasing stretch degree results in elasticity modulus increasing, as well. In most stretched region it was obtained the larger values to strength modulus such 2778.00 MPa. A quadratic surface was interpolated to fit experimental results and the difference between elasticity modulus in two orthogonal direction was analysed obtaining about 12% of value difference to regions that present most anisotropic behavior.*

Keywords: *High Impact Polystyrene, Elasticity Modulus, Stretch Degree*

1. INTRODUCTION

High impact resistance of styrenic polymers is achieved by incorporating a rubber phase dispersed in polysterene rigid matrix. In particular, High Impact Polysterene (HIPS) is generally produced by free radical polymerization of styrene in presence of polybutadiene (PB) variable amounts, usually 5 - 12% weight fraction. The resulting material can be described as a multiphase material. Due to this multiphase structure, HIPS present improved fracture resistance (impact strength and elongation at break) in comparison to polysterene (PS). However, it presents reduced modulus and tensile strength compared with the unmodified (Vilaplana *et al.*, 2011). Due to it's properties, low cost and ease fabrication HIPS have been used in food packaging, drinking cups, toys, refrigerator linings, audio and video equipment. (Demirors, 2002).

In thermoforming process, a HIPS sheet is clamped in it's edges and heated. Due to heating process, the sheet becomes less rigid and expand. Once the heaters are removed, pressure is applied to the upper face of the sheet or by evacuating the volume between the sheet and the mould, configuring a vacuum forming process. Since the mould is cooler, the sheet that comes in contact with the mould freeze and take the moulding shape. The pressure is maintained while the walled structure is cooled, finally the pressure is removed and the structure is blown off the mold. Due to springback, the structure may have it's final shape changed (Warby *et al.*, 2003). Thermoforming is used to produce thin-walled parts with large surface area, presenting mold and equipment low coast in comparison to other plastics processes, once the forming forces are smaller, and high production rates (Ghobadnam *et al.*, 2014).

In complex products such a refrigerator lining, thermoforming presents a large range of deformation along the part during forming process. Since material presents internal structure orientation and different deformation due to manufacturing process it is expected different elasticity modulus in different directions and different regions. However, a first approach considered strength modulus to an isotropic material and independent to stretch degree. This approach presented strength modulus variation in function to direction analysed and in refrigerator lining position, what led to a approach correlating stretch degree to strength modulus longitudinal and transversal to manufacturing deformation.

Sandwich construction is commonly used in structures where strength, stiffness, and weight efficiency are required (Arias *et al.*, 2001). Typically, this structure is present in refrigerators using a polyurethane rigid foam as core, steel and HIPS as skins. The sandwich beam rigidity is dependent of both skins and core strength modulus (MINES *et al.*, 1994), being important to know all these material properties. To determine skins material strength modulus is common to take tensile tests.

2. EXPERIMENTAL PROCEDURE

Two different regions were chosen to obtain specimens in order to perform tensile tests: refrigerator lining back and top. Also, a fixed coordinate system was defined to describe main refrigerator direction.

2.1 Isotropic Approach

At first, 19 specimen were obtained by cutting refrigerator lining in both regions and orthogonal direction as presented in Fig. 1. The specimens were cut according to type I ASTM D638-10 standard and tensile test were realized in 5 mm/min speed test using a 1000 N load cell and a clip gage as presented in Fig. 2.To perform these test, appropriate grips were developed to avoid specimen slipping.

$$S_a = W \sum_{i=1}^{3} \frac{t_i}{3} \tag{1}$$

$$\sigma = \frac{P}{S_a} \tag{2}$$

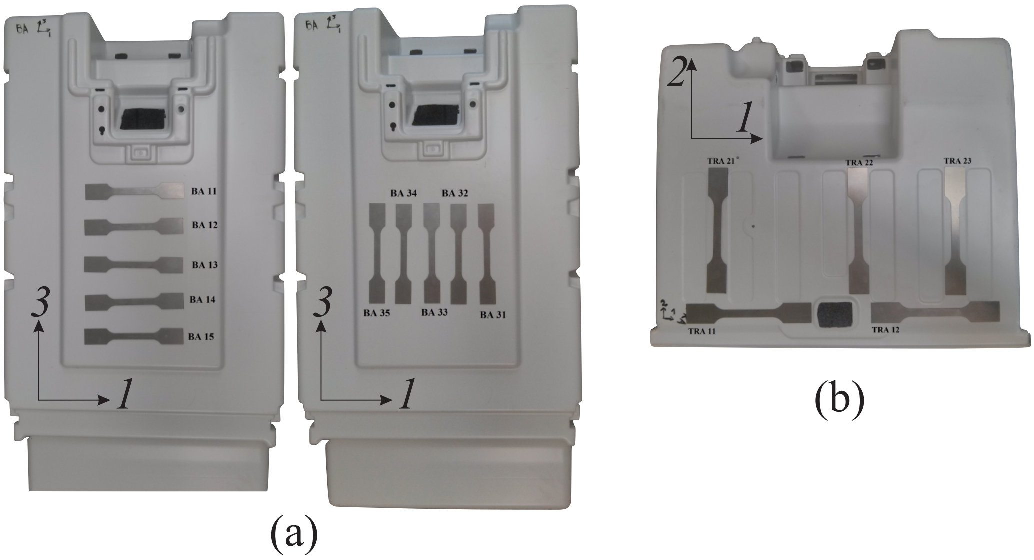

Figure 1. First Specimen regions and direction. (b) Refrigerator lining back (c) Refrigerator lining top

Once material present different thickness, strength is calculated by average area of three thickness measurement t_i (mm) and width W (mm) as presented in Eq. 1 and 2, being S_a (mm^2) the average area and P (N) is the applied load. Strain-Stress curves, as presented in Fig. 7, were obtained to all specimens test. Linear fit for the first region of curve determine the elasticity modulus. Tensile tests realized in these specimens presented different results to strength modulus as presented in Table 2.

2.2 Stretch Dependent Approach

A second approach consider to use stretch degree in longitudinal direction, ε_L (mm/mm), and transversal direction, ε_T (mm/mm), correlated to elasticity modulus E (MPa). This way is determined a function f that describes elasticity modulus as presented in Eq. 3. Consider HIPS elasticity modulus a function dependent of manufacturing stretch degree is a valid assumption once there are stretching of polymer chain in preferred direction. Stretched materials typically present larger strength modulus in stretching direction (Roynce, 1995).

$$E = f(\varepsilon_L, \varepsilon_T) \tag{3}$$

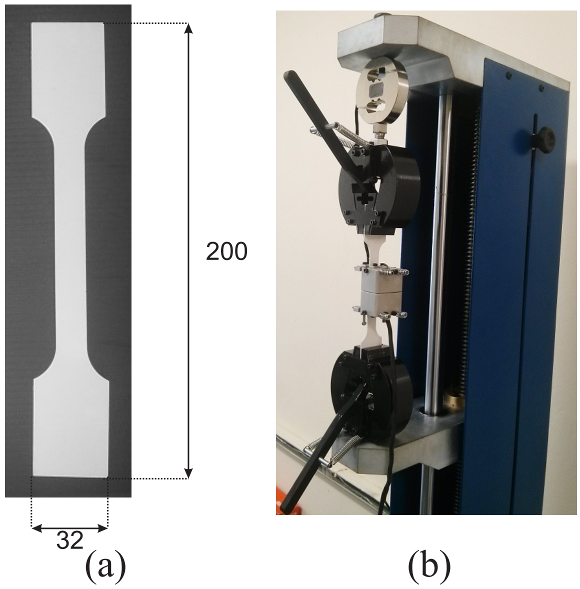

Figure 2. (a) ASTM D638-10 Specimen. (b) Grips and clip gage.

To an area element as presented in Fig. 3, stretch degree in both direction is defined as presented in Eq. 4 and Eq. 5. Subscribe $L0$ and $T0$ denotes area element before vacuum forming in longitudinal and transversal direction, respectively, to tensile test load σ. Subscribe Lf and Tf denotes final element area after vacuum forming to longitudinal and transversal direction, respectively, to tensile test load.

$$\varepsilon_L = \frac{L_{Lf} - L_{L_0}}{L_{L0}} \tag{4}$$

$$\varepsilon_T = \frac{L_{Tf} - L_{T0}}{L_{T0}} \tag{5}$$

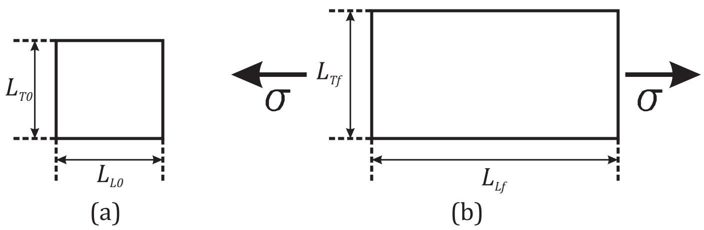

Figure 3. Area element. (a) Before vacuum forming (b) After vacuum forming

To determine stretch degree ε_L and ε_T a 10 x 10 mm measuring grid was draw in the HIPS sheet before vacuum forming process. Due to manufacturing process there are material flow in different directions leading to a range of deformation as presented in Fig. 4. This deformation was measured using image analysis through ImageJ software and the stretch degree was determined to all 26 specimens according to type I of ASTM D638-10 standard. Three measurements were taken in longitudinal and transversal direction to all specimens and the stretch degree was assumed as the average of this measurements in both directions.

These specimens were obtained by cutting a refrigerator lining in such way that tensile test load is applied longitudinal or transversal to main manufacturing process deformation in specimens as presented in Fig. 5. The distribution of specimens along to longitudinal stretch degree and transversal stretch degree is presented in Fig. 6.

Tensile tests were taken to these 26 specimens in 5 mm/min test speed, using average area S_a to determine strength modulus.

3. RESULTS

Using a linear fit to initial part of Stress-Strain curves, it was possible to determine the strength modulus to all specimens, as presented in Tab. 2 and Tab. 3 for the first and second approach respectively. In Tab. 3 values correspond to

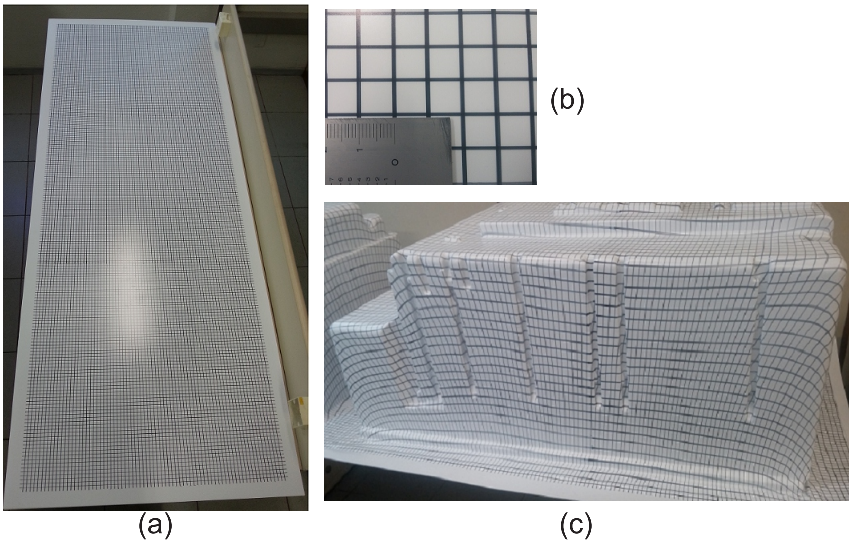

Figure 4. Grid to determine stretch degree. (a) Before vacuum forming. (b) Detail in grid before vacuum forming(c) After vacuum forming.

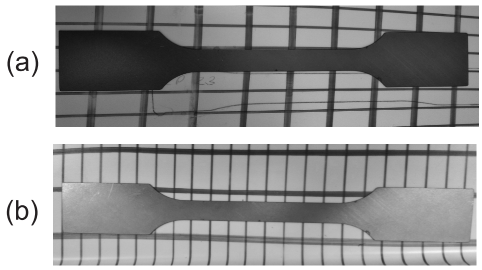

Figure 5. Specimens (a) Major longitudinal stretch degree (b) Major transversal stretch degree

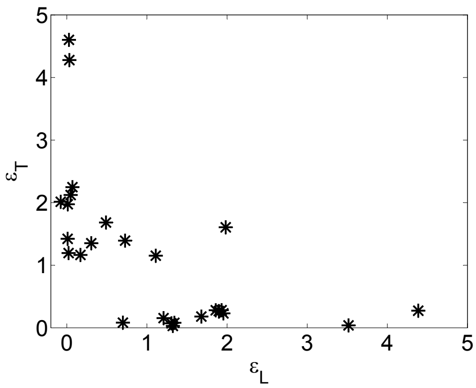

Figure 6. Specimens distribution along $\varepsilon_L - \varepsilon_T$ plane.

elasticity modulus in the direction of load.

Using Student's t-test to unequal samples size and unequal variances to the orthogonal directions in both analysed regions, a $P\ value$ test presented 2.35% probability to refrigerator lining back elasticity modulus being the same in both direction, and 1.07% probability to refrigerator lining top elasticity modulus being the same. Using 10% as tolerance to $Pvalue$ test the null difference hypothesis was discarded. Therefore the strength modulus must be different in the orthogonal taken directions.

To verify a non-homogeneous hypothesis along the refrigerator lining, Student's t-test was also realized between refrigerator lining back direction 1 and refrigerator lining top direction 1, resulting in 4.89% $P\ value$, back direction 1 and top direction 3, resulting in 11.72% $P\ value$, back direction 2 and top direction 1, resulting in 2.69% $P\ vaalue$,

Table 1. Stretch degree to specimens.

Specimen	ε_L (mm/mm)	ε_T (mm/mm)	Specimen	ε_L (mm/mm)	ε_T (mm/mm)
L01	1.342	0.080	T01	0.070	2.248
L02	1.306	0.072	T02	0.047	2.123
L03	1.207	0.155	T03	-0.076	2.015
L04	1.323	0.030	T04	0.489	1.683
L05	1.898	0.269	T05	0.305	1.352
L06	1.859	0.281	T06	0.170	1.164
L07	1.932	0.282	T07	0.010	1.423
L08	1.954	0.231	T08	0.022	1.195
L09	1.679	0.180	T09	0.012	1.974
L10	4.386	0.274	T10	0.027	4.602
L11	3.516	0.039	T11	0.032	4.279
L12	0.700	0.083	T12	1.110	1.153
L13	1.983	1.607	T13	0.727	1.393

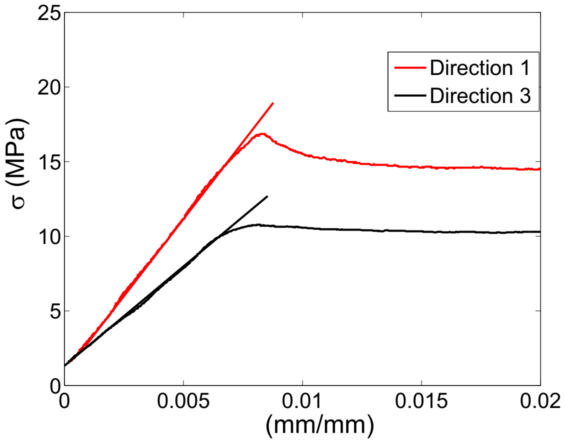

Figure 7. General Strain-Stress curve to HIPS

Table 2. Experimental results for tensile test on specimens for isotropic approach.

	Ref. Lining Back		Ref. Lining Top	
	Elasticity Modulus (MPa)		Elasticity Modulus (MPa)	
Axis Direction	1	3	1	2
Specimen 1	1781.55	1632.26	1396.92	1705.59
Specimen 2	1737.77	1628.05	1332.02	1987.27
Specimen 3	1684.83	1612.66	1487.16	1487.92
Specimen 4	1698.94	1690.35	1337.05	1857.79
Specimen 5		1654.55		2065.28
Average	1725.77	1643.57	1388.27	1820.78
Standard Deviation	43.40	30.14	72.18	230.74

and back direction 3 and top direction 2, resulting in 4.71% $P\ value$. Once only the test between back direction 1 and top direction 3 was inconclusive to a 10% tolerance, it is possible to assume that HIPS presents a non-homogeneous mechanical behavior in refrigerator lining regions. In this way, a more sophisticated model is necessary to describe HIPS mechanical behavior.

A quadratic function was chosen to properly describe HIPS strength modulus in stretch degree function, as presented in Eq. 6. Using MATLAB fitting curve tool, coefficients $a_0,\ a_1,\ \ldots\ a_5$ were determined to fit experimental data. Obtained values can be found at Tab. 4. A graphic representation to elasticity modulus in load direction in function to stretch degree can be found in Fig. 8.

$$E(\varepsilon_L, \varepsilon_T) = a_0 + a_1\varepsilon_L + a_2\varepsilon_T + a_3\varepsilon_L\varepsilon_T + a_4\varepsilon_L^2 + a_5\varepsilon_T^2 \tag{6}$$

Table 3. Experimental results for tensile test on specimens to stretch degree dependent approach.

Specimen	Elasticity Modulus (MPa)	Specimen	Elasticity Modulus (MPa)
L01	2001.34	T01	1743.74
L02	1876.43	T02	1722.50
L03	1768.62	T03	1719.94
L04	1817.78	T04	1971.80
L05	1955.15	T05	1912.03
L06	1978.76	T06	1871.49
L07	1984.49	T07	1801.98
L08	1940.68	T08	1620.10
L09	1922.65	T09	1669.43
L10	2622.33	T10	2696.54
L11	2591.01	T11	2322.21
L12	1775.21	T12	1799.32
L13	2032.40	T13	1949.55

Table 4. Coefficients to Eq. 6.

Equation Coefficient	Value
a_0	1726.00
a_1	89.76
a_2	-86.88
a_3	12.31
a_4	30.24
a_5	58.80

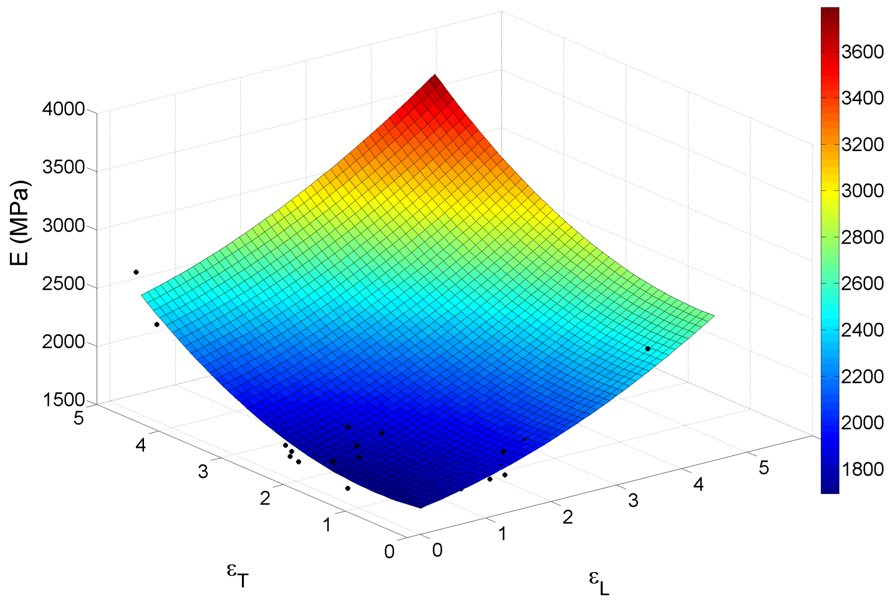

Figure 8. Graphical representation to Eq. 6 describing strength modulus

Coefficient of determination, R squared denoted by R^2 was determined to surface, obtaining a value of 0.8797, which was considered an acceptable value to the quadratic interpolation model, once there is no error greater than 10% to any of 26 specimens, as presented in Tab. 5. Error was calculated as presented in Eq. 7.

$$Error = \left| \frac{E_{exp} - E_{surf}}{E_{exp}} \right| 100\% \tag{7}$$

Table 5. Error comparing Eq. 7 to experimental results.

Specimen	Error (%)	Specimen	Error (%)
L01	5.28	T01	5.30
L02	0.73	T02	5.20
L03	5.66	T03	3.56
L04	4.28	T04	8.33
L05	1.91	T05	8.40
L06	0.27	T06	7.93
L07	0.74	T07	4.41
L08	3.34	T08	5.45
L09	1.53	T09	6.92
L10	2.84	T10	4.49
L11	6.84	T11	4.88
L12	1.26	T12	3.19
L13	2.06	T13	7.01

Once there are a a surface that properly describes strength modulus in function of stretch degree is it possible to obtain elasticity modulus to a longitudinal and transversal stretch direction to any region of refrigerator lining affording to consider an orthotropic model. Observing Tab. 1 it is possible to verify that the minor stretch degree average to all specimens is about 0.2. Fixing to this value one of the stretch degree in eq.3 is it possible to find E_L (MPa) and E_T (MPa) as eq. 8 and eq. 9. The behavior of ratio $\frac{E_L}{E_T}$ in function to ratio ε is presented in Fig. 9 to a minor stretch degree of 0.2 which was the average of minor deformation of specimens.

$$E_L = f(\varepsilon, 0.2) \tag{8}$$

$$E_T = f(0.2, \varepsilon) \tag{9}$$

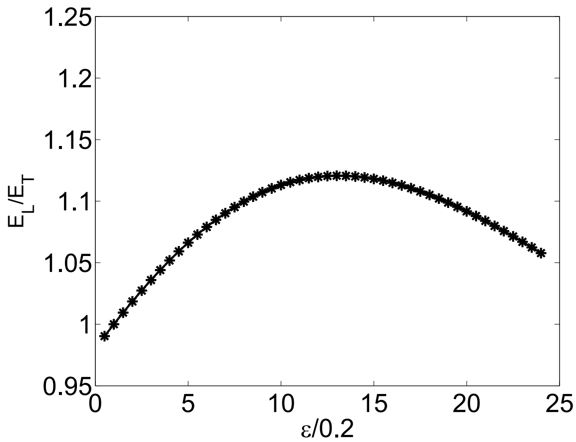

Figure 9. Relation between E_L and E_T to stretch degree ratio to minor stretch degree valuing 0.2

4. CONCLUSION

Specimens were obtained by cutting a refrigerator lining according to ASTM D638-10 standard. A division in regions and general direction was taken to a isotropic approach. This isotropic approach was inconsistent once the values obtained to strength modulus were statistically different in region and direction.

A second approach consisted to correlate stretch degree caused by manufacturing deformation to elasticity modulus, which eliminates the region correlation and introduced a physical factor to correlation. To this approach a measuring grid had to be drawn before vacuum forming and stretch degree was determined to 26 specimens through image analyses.

Finally, a quadratic fitting equation was interpolated to describe elasticity modulus in function of stretch degree to load direction application. In this way it was possible to analyse the correlation between stretch degree ratio and longitudinal-transversal elasticity modulus ratio.

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