Material Behaviour

Influence of chemical nature, expansion ratio and cellular morphology on the fracture behaviour of flexible polyolefin-based foams assessed by the Essential Work of Fracture (EWF)

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Abstract
Several commercial polyolefin-based flexible foams produced by extrusion foaming were characterized in terms of their cellular morphology and fracture behaviour using the concept of the Essential Work of Fracture (EWF), focusing on the influence of foam’s chemical nature, expansion ratio and cellular structure on the values of the fracture parameters. Correction procedures were proposed in order to take into account the complexity of foams in the obtained fracture parameters, particularly a correction procedure based on their expansion ratio, and a second one based on the fraction of polymer present in the foams determined from cellular structure characterization. Although doubts remain about the applicability of the EWF methodology to LDPE foams, the correction procedure based on the expansion ratio seemed to provide more accurate results than that based on polymer fraction, with EWF effectively distinguishing between polyolefin foams having different chemical nature. Comparatively, foams based on a P-E copolymer presented the highest values of the essential work of fracture in the MD direction, while significant differences were only observed in the TD direction for foams having a highly oriented cellular structure. All PP-based foams showed similar non-essential work of fracture values in both MD and TD directions.

Keywords: flexible polyolefin foams; cellular morphology; Essential Work of Fracture (EWF)
1. Introduction

Polymeric foams, multiphase materials in which a gas is dispersed in a polymer continuous matrix, have found increasing industrial interest in sectors such as building (typically used as thermal insulators), automotive (weight reduction) or packaging (impact protection). Although the mechanical response of these materials has been extensively studied under compression [1-3], there is still lack of knowledge about their fracture behaviour, with the scarce work focusing on rigid foams.

Most of rigid polymer foams show linear-elastic behaviour under tension, and hence their fracture analysis may be treated using the concept of linear-elastic fracture mechanics (LEFM) [4-8]. Nevertheless, this linear-elastic approach is not applicable to flexible polymer foams, as in the case of films or thin sheets of polyolefin foams, as a significant extent of plasticity is developed. In this sense, the concept of the Essential Work of Fracture (EWF) has been successfully applied in the fracture characterization of films and thin sheets of several polymers [9]. The EWF concept is based on the fact that the total energy required for crack propagation ($W_f$) may be divided into two components: one related to the energy required to generate new fracture surfaces in the process zone (so-called essential work of fracture, $W_e$), and a second related to the energy dissipated in the surroundings of the crack plane by plastic deformation (non-essential or plastic work of fracture, $W_p$). The total energy for crack propagation ($W_f$) is commonly normalized according to the geometric characteristics of the analyzed samples, with both the essential and non-essential terms being presented in the form of specific values ($w_e$ and $\beta w_p$, respectively) [10]:

$$w_i = \frac{W_f}{lt} = w_e + \beta w_p l$$  (1)

The units of these fracture parameters are usually kJ·m$^{-2}$ ($w_i$, $w_e$) and MJ·m$^{-3}$ ($w_p$) where $l$ and $t$ are the ligament length and thickness (both in mm) of the sample, respectively, and $\beta$ is an a dimensional shape factor that accounts for the geometry of the plastic zone.
However, there are some problems in directly applying the EWF concept to foams resulting from their multiphase complexity, as not all their ligament length and thickness is formed by polymer. In fact, an important volume fraction is composed of air, especially in the case of low density foams, where air accounts for more than 90 vol.% of the material, making it a requirement to correct the ligament length of the sample. In a previous work [11] we proposed two different approaches in order to correct the values of the EWF parameters of several polypropylene (PP) foams. The first one was based on the expansion ratio, \( ER \) (reciprocal of relative density, \( \rho_r \)), which consisted of dividing the specific work of fracture \( (w_f) \) by the relative density of the foam, giving a new parameter termed \( w_f^{c,ER} \), according to the following expression, using the same units for the fracture parameters as expressed above:

\[
w_f^{c,ER} = \frac{w_f}{\rho_r} = \frac{w_c + \beta w_p l}{\rho_r} = w_c^{ER} + \beta w_p^{ER} l
\]

The second correction procedure was based on the fraction of polymer present in the foamed material \( (f_s) \) by analyzing the cellular morphology of each foam and assuming four different cell shape approximations. The specific work of fracture determined this way was termed \( w_f^{c,cs} \) (\( cs \) standing for cellular structure), using the same units for the fracture parameters as expressed above:

\[
w_f^{c,cs} = \frac{w_f}{f_s} = \frac{w_c + \beta w_p l}{f_s} = w_c^{cs} + \beta w_p^{cs} l
\]

The EWF results were correlated with the density and thickness of the foams, and they seemed to ascertain the feasibility of the corrected procedures.

Whereas that previous work dealt with the influence of density on the fracture behaviour of PP foams, the present work applies the corrected EWF methodology to a broader set of polyolefin-based foams, trying to ascertain its applicability and correlating the fracture parameters with the characteristic cellular morphology of the
foams, ultimately evaluating the possibility of differentiating between foams with different chemical nature.

2. Experimental

2.1. Materials

Rolls of several commercial flexible polyolefin-based foams kindly supplied by Sekisui Alveo were used in this study. These foams, produced using a vertical chemical foaming process by the thermal decomposition of a chemical blowing agent (CBA) inside especially designed ovens placed after the extruder, differ in chemical nature and present similar expansion ratios (around 13.5).

In order to study the possible effect of the expansion ratio on the final fracture parameters, an additional foam with an identical chemical nature as one of the previous ones was selected with a significantly lower expansion ratio (around 8.0). A preliminary analysis of the chemical nature of the foams is presented in section 3.1, alongside their assigned codes.

2.2. Testing procedure

Differential scanning calorimetry (DSC) was carried out in order to assess the polymer chemical nature of all tested foams by analyzing their characteristic melting and crystallization peaks using a Perkin Elmer, Pyris 1 model with a glycol-based Perkin Elmer Intracooler IIP calorimeter, with samples weighing around 5.0 mg. The following program was used applying a constant rate of nitrogen: heating from 40 to 180 ºC at 10 ºC/min and holding for 1 min to erase the thermal history before cooling at 10 ºC/min from 180 to 40 ºC.

Additionally, infrared spectra of the several foams were obtained in order to complement DSC analysis. An FT-IR detector (Nicolet Thermo Scientific 6700) in FT-IR/ATR, i.e., Fourier-Transform Infrared in the Attenuated Total Reflection Mode (Smart Orbit), was used with a spectrometer operating in continuous scan mode. Spectra were collected with an 8 cm⁻¹ spectral resolution in the 2000-400 cm⁻¹ range using 32 scans.
The density of the foams was measured according to standard procedures (ISO 845) and their respective expansion ratios were calculated by dividing the density of the respective base solid material by the density of the foam. The cellular structure was assessed using a JEOL JSM-5610 scanning electron microscope. Samples were prepared by cryogenically fracturing the foams using liquid nitrogen and sputter depositing a thin layer of gold onto their surface. The average cell size ($\phi$), cell nucleation density ($N_0$, in number of cells per volume of unfoamed material) and cell density ($N_f$, in number of cells per volume of foamed material) were obtained from micrographs using the intercept counting method [12]. $N_0$ and $N_f$ were calculated assuming an isotropic distribution of spherical cells according to:

$$N_0 = \left( \frac{n}{A} \right)^{\frac{1}{2}} \left( \frac{\rho_s}{\rho_f} \right)$$  \hspace{1cm} (4)

$$N_f = \frac{6}{\pi \phi^3} \left( 1 - \frac{\rho_f}{\rho_s} \right)$$  \hspace{1cm} (5)

where $n$ is the number of cells per area of analyzed micrograph ($A$ in cm$^2$), and $\rho_s$ and $\rho_f$ are the solid and foam densities, respectively.

Alongside the two considered foam orientations, i.e., the extrusion flow direction (MD) and that transversal to the flow (TD), two cell sizes were determined depending on the preferential foam growth direction: $\phi_{VD}$, where VD is the vertical direction of foaming, i.e., the direction of foam growth at the exit of the extrusion die, and $\phi_{WD}$ (WD: width direction). The cell aspect ratio ($AR$) was determined as the quotient between both cell sizes using a representative cell population ($AR = \phi_{WD}/\phi_{VD}$). According to Gosselin and Rodrigue [13], and assuming that the cells are ellipsoids of revolution with their longest axis in the width direction and their shortest axis in the direction of foam growth, it was possible to determine the real cell density in number of cells per volume of foamed material ($N'_f$). This approximation was possible after checking that differences between cell sizes measured in the VD direction were negligible when compared to those in the other transversal direction, which enabled considerable simplification of
cell density determination. So, considering that the cells are ellipsoids of revolution with their longest axis in the WD direction and their shortest axis in the VD direction, the cell nucleation could be determined according to:

\[
N_f = \frac{6(1 - \frac{\rho_f}{\rho_s})}{\pi \phi_{WD} \phi_{VD}^2}
\]  

For fracture testing, rectangular samples (90 × 60 mm) were cut from the extruded foam rolls in the directions parallel (MD) and perpendicular (TD) to the extrusion flow direction. The samples were side notched using a razor blade, generating Deeply Double Edge Notched Tensile specimens (DDENT). For MD specimens, the notches were perpendicular to the extrusion flow direction, whereas TD specimens had the notches aligned in the extrusion direction. Following the proposal of the European Structural Integrity Society (ESIS) [14], samples were notched in order to leave ligament lengths ranging from 5 to 25 mm. Ligament lengths were measured after mechanical testing by fracturing each sample and using an optical travelling microscope. A minimum of 20 samples were tested for each material at room temperature using a universal testing machine Galdabini Sun 2500 at a constant crosshead speed of 2 mm·min\(^{-1}\). The energy consumed during fracture was determined as the total area under the force-displacement curve. According to Eq. 1, the linear fitting of the values of the specific work of fracture versus ligament length provides the essential and non-essential work of fracture parameters. This linearization was applied using the two mentioned correction procedures, i.e., the one based on ER according to Eq. 2 and the correction procedure based on the fraction of polymer present in the foamed material, determined from cellular structure analysis assuming simplified cell shape geometries (Eq. 3).

3. Results and discussion

3.1. Analysis of the chemical nature of the foams

As previously stated, the chemical nature of all tested foams was analyzed by DSC and FT-IR/ATR. The combined analyses revealed the existence of three types of
polyolefin-based foams according to their chemical nature: a low density polyethylene (LDPE) foam, so-called for now “TAS”; several polypropylene-based foams, particularly two propylene-ethylene copolymer foams (coded “TPVF” and “TPLPM”) and a foam based on PP homopolymer (“TPEE”); and a third type of foam, coded “TEE”, having an important fraction of ethylene-vinyl acetate (EVA). DSC and FT-IR results are respectively presented in Fig. 1 and Fig. 2.

As previously stated, the foam coded TAS is an LDPE foam, as revealed by the melting peak found at 108 ºC and onset of crystallization of 102 ºC (see Fig. 1), as well as the characteristic intense methylene rock and scissor infrared absorbance peaks, respectively found at 717 and 1467 cm$^{-1}$, and a less intense peak corresponding to methylene symmetric bending at 1375 cm$^{-1}$ [15] (see Fig. 2).

Of the two propylene-ethylene copolymer foams, TPVF is composed of a mix of a random P-E copolymer and a fraction of LDPE, as assessed by the presence of melting and crystallization peaks at, respectively, 145 and 107 ºC, characteristic of a random P-E copolymer, and the melting peak found at around 117 ºC (together with an almost unnoticeable crystallization peak that overlaps with the end of the crystallization of the random P-E copolymer fraction) characteristic of LDPE. On the other hand, TPLPM foam is formed by a block copolymer, as not only the higher temperature melting peak appears at a higher temperature than that of TPVF foam, but the crystallization temperature is much higher (onset at around 126 ºC), showing a second peak corresponding to the crystallization of the ethylene block (at around 110 ºC), both characteristic of a P-E block copolymer instead of a random one. Both foams show intense infrared absorbance peaks related to methylene symmetric bending (1375 cm$^{-1}$), characteristic of methyl side groups of propylene [15] (see Fig. 2).

TPEE is also a PP-based foam, although composed of a mix of a PP homopolymer (characteristic melting peak at 158 ºC and high onset of crystallization, probably induced by the presence of nucleating agents) with a high amount of a low melting point polyolefin (melting peak at 95 ºC), most probably an $\alpha$-olefin. FT-IR/ATR spectrum of TPEE is almost identical to that of TPVF and TPLPM foams, indicating that there is no presence of any type of ethylene copolymer having carbonyl or ester groups.

Finally, TEE foam is based on a low melting point polyethylene (melting peak at 92 ºC and onset of crystallization slightly below 90 ºC) with a fraction of ethylene-vinyl
acetate (EVA), as revealed by the infrared absorbance peaks related to the C=O (1737 cm\(^{-1}\)) and C-O (1283 cm\(^{-1}\)) bonds of the acetate group [15] (see Fig. 2).

3.2. Cellular structure characterization

Micrographs showing the typical cellular structure of all analysed foams in both TD and MD orientations are presented in Fig. 3. The cellular structure characterization results in terms of cell size (\(\phi_{\text{VD}}\) and \(\phi_{\text{WD}}\)), cell aspect ratio \(AR\), cell nucleation density \(N_0\) and cell density \((N_f\) and \(N_f')\), as well as the fraction of solid \(f_s\) determined assuming different cell shape approximations, particularly ellipses, regular hexagons and elongated hexagons (further details about \(f_s\) determination can be found in reference [11]), are displayed in Table 1.

3.2.1. Influence of chemical nature

TEE foam was the one that showed a finer cellular structure (globally smaller cell sizes), and thus higher cell density (see Figs. 3(g) and (h)). Nevertheless, like almost all the analyzed foams, it still presented a certain cellular anisotropy in the TD orientation when compared to MD, a direct result of the relatively lower values of the average cell size in the vertical direction when compared to the cell size in the WD direction (see values presented in Table 1). As the cell size in the WD was smaller in MD orientation than in TD, this foam presented a cell nucleation density that was a bit higher in MD orientation, still in both cases much higher than \(10^7\) cells/cm\(^3\).

As with almost all analyzed foams, TPLPM foam presented a considerably higher cell aspect ratio in TD orientation when compared to MD, a direct result of the combination of the smaller cell size values in the vertical direction of foam growth and much higher cell sizes in WD in the case of TD orientation (see values presented in Table 1 and compare Figs. 3 (i) and (j)). As a consequence of its more isotropic and finer cellular structure in MD orientation than in TD, TPLPM foam presented a globally higher cell nucleation density and cell density in MD orientation.

As already presented in a previous article [11], TPVF foam presented a similar cellular structure morphology to TPEE, TEE and TPLPM foams, with a more anisotropic cellular structure in TD orientation than in MD (reaching an \(AR\) value of
1.6), in this case due to the much higher cell size in the WD direction in the case of the first (around 200 µm, compared to ≈ 150 µm in MD orientation). As a result of these important cell size differences, TPVF foam showed considerably higher values of \( N_0 \), \( N_t \) and \( N'_t \) in MD orientation.

Interestingly, TAS foam was the only one that displayed a higher cell aspect ratio in MD orientation when compared to TD, thus being the only foam that presented improved fracture properties in terms of both the essential and non-essential work of fracture in TD orientation than in MD (see results presented in section 3.3). These differences are the result of a much higher difference between the cell size in the VD direction compared to that in the WD direction between TD and MD orientations. While in TD the average cell size in the vertical direction was only slightly lower than that in the opposite direction, in MD orientation there was a big difference (see Fig. 3), especially resulting from the increase of the cell size in the WD direction, a direct result of the deformation of the cells due to stretching of the material during processing.

### 3.2.2. Influence of the expansion ratio

As previously mentioned, an additional foam with the same chemical nature as one of the selected foams (TPEE, a PP homopolymer-based foam with a high amount of an \( \alpha \)-olefin) with a lower expansion ratio (\( ER \approx 8.0 \)) was selected in order to study the possible effect of this parameter on the final fracture parameters of the foam. In order to distinguish between foams, TPEE foam with \( ER \approx 13.0 \) was designated as “TPEE thin”, while TPEE foam with \( ER \approx 8.0 \) was coded “TPEE thick”.

Starting out by comparing the cellular structure parameters obtained in TD orientation, TPEE thick foam (\( ER \approx 8.0 \)) presented a considerably higher average cell size in the VD direction when compared to TPEE thin foam (around 125 µm, compared to around 80 µm of TPEE thin foam), while the cell size in the WD direction was almost the same for both foams (≈ 150 µm). As a result, the cell aspect ratio (\( AR \)) was much higher for TPEE thin foam than for TPEE thick foam. In fact, the aspect ratio of TPEE thin foam in TD orientation was the highest of all analyzed foams, while TPEE thick foam presented what is considered to be a typical cell aspect ratio for this type of foamed rolls. These differences are quite interesting and will have a direct effect in the fracture analysis of these foams, especially taking into account that, albeit having
considerably higher expansion ratio, TPEE thin foam presented globally smaller cell sizes than TPEE thick foam, which was related to a restriction of foam growth in the vertical direction during processing. As TPEE thin foam presented a combination of smaller cell sizes and higher expansion ratios than TPEE thick foam in TD orientation, both cell nucleation density as well as cell density were much higher in the case of the first, reaching a value higher than $10^7$ cells/cm$^3$ of solid material ($N_0$), and higher than $10^6$ cells/cm$^3$ of foamed material ($N_f$ and $N'f$), i.e., a > 150% increment when compared to TPEE thick foam.

Although TPEE thick foam still presented higher cell sizes in both VD and WD directions than TPEE thin foam in MD orientation, these differences were much smaller than in TD orientation as, on the one hand, TPEE thick foam presented significantly smaller cells and, on the other hand, TPEE thin foam showed a cellular structure that was much more isotropic than in TD orientation but with no significant modifications in terms of the absolute value of cell size. In fact, the significant anisotropic cellular structure observed for TPEE thin foam in TD orientation almost disappeared in MD orientation, with this foam displaying a similar cell aspect ratio to TPEE thick foam, which, on the other hand, kept the slightly higher than 1 cell aspect ratio already observed in TD orientation. As a consequence of these morphological cellular structure differences, the number of cells per volume of solid or foamed material was much closer between the two foams, though TPEE thin foam still presented slightly higher values.

3.3. Fracture characterization

As can be seen from the typical force-displacement experimental curves displayed in Fig. 4, quite good self-similarity was found for all foams, with a force maximum being reached followed by stable crack propagation. In all cases, except for TAS foam, the load-displacement traces with similar ligament lengths yielded maximum force values higher in the machine direction than in the transversal direction. However, it is worth pointing out that these curves showed higher instability than those reported in a previous work of our research group for unfoamed ethylene-propylene block copolymer films/sheets [16], which was related to the successive processes of cell deformation and orientation along the axial axis, material yielding, cell collapse and ultimate material
rupture in the foams. Additionally, full ligament yielding took place before crack propagation. Following the last ESIS protocol, the stress state of the samples was also checked, with the experimental points that deviated more than 10% from the average value of the net stress determined for all tested samples, represented as stars in the several graphs presented in Fig. 5, being disregarded from the EWF analysis.

From the linearization of the values of the specific work of fracture vs. ligament length and applying the corrections based on the values of the expansion ratio and the fraction of polymer present in the foam assuming different cell shape approximations, particularly considering cells to be regular or elongated hexagons (the geometric approximation of assuming cells to be ellipses was disregarded, as estimated $f_s$ values resulted negative for all foams - see values presented in Table 1), the fracture parameters could be obtained, being represented in Fig. 6 and summarized in Table 2. The linear fittings provided correlation coefficients close to 1 for all foams, except for the LDPE-based one (coded TAS), whose correlation coefficients were quite far apart from 1 (see Fig. 6). This gives some uncertainty about the applicability of the EWF methodology to this foam and, as a consequence, about the validity of the values of the obtained fracture parameters shown in Table 2.

It has to be pointed out that in the cases where the value of the fraction of polymer in the foam resulted negative (see values presented in Table 1) the corrected fracture parameters could not be determined (indicated with “nd” in Table 2).

3.3.1. Influence of chemical nature

As can be seen by the values presented in Table 2, in the MD direction (notches placed in the samples perpendicular to the extrusion flow direction) the foams that displayed the highest values of the specific essential work of fracture corrected taking into account the expansion ratio ($w_{\text{c,ER}}$) were those based on a propylene-ethylene copolymer (TPVF and TPLPM foams). The substitution of ethylene by a low melting point $\alpha$-olefin as co-monomer in TPEE foam led to a reduction of $w_{\text{c,ER}}$, with this reduction tendency being even more marked with increasing $ER$, as TPEE thin foam presented lower values than TPEE thick foam. While TEE foam showed similar values as TPEE foams, TAS foam (LDPE-based) showed the lowest value of the specific essential work of fracture.
In the TD direction (notches placed in the samples aligned in the extrusion direction), no significant differences were found between PP-based foams and TEE foam, with the only exception of TPEE thin foam, which displayed higher values, a direct result of its combination of highly oriented cellular structure in the extrusion flow direction and small cell sizes (see section 3.2.2). Due to its particular cellular structure, characterized by a higher cell aspect ratio in MD orientation than TD, TAS foam presented the highest value of the specific work of fracture in TD direction of all analyzed foams.

It is worth mentioning that the specific essential work of fracture values corrected considering the fraction of polymer present in each foam (\(w_{c,cs}\)), assuming two geometric cell shapes (regular and elongated hexagons), was considerably different to those determined based on \(ER\).

Concerning the specific non-essential work of fracture (\(\beta_{wp}^{c,ER}\)), all PP-based foams showed similar fracture values in both MD and TD, with only small differences attributable to experimental error and, in the case of TPEE thick foam, to its lower expansion ratio. On the other hand, while TEE foam displayed a lower value of the specific plastic work of fracture than PP-based foams, especially in the MD direction; LDPE-based TAS foam clearly yielded the lowest values of the plastic term.

The specific non-essential work of fracture values corrected considering the fraction of polymer present in each foam (\(\beta_{wp}^{c,cs}\)) were much closer to those calculated based on \(ER\), especially when assuming cells as elongated hexagons, demonstrating that this geometric cell approximation may be useful for comparing the fracture parameters of foams having oriented cellular structures.

3.3.2. Comparison between correction procedures

While the correction of the common experimental procedure of the essential work of fracture by using the expansion ratio could be applied to all studied foams, the correction based on the polymer fraction present in the foams calculated from cellular structure characterization could only be applied in some cases (positive values of \(f_s\)). As a result, these two approaches could only be compared for some of the analyzed foams.

Both procedures were fully applicable to foams based on a propylene-ethylene copolymer (TPLPM and TPVF foams). Comparatively, the values of the fracture
parameters of these foams were lower when using the polymer fraction correction, independently of the testing direction (MD or TD), with this effect being more marked in TPVF foam. LDPE-based TAS foam showed the opposite trend, with higher fracture parameter values being obtained when using the polymer fraction correction.

4. Conclusions

Preliminary analysis of the chemical nature of the studied foams allowed classifying them in three types: an LDPE-based foam, PP-based foams and a third one containing an important fraction of EVA.

All PP-based foams and that containing EVA (TEE foam) presented higher cellular anisotropy in TD orientation when compared to MD, a direct result of the stretching applied during foaming in the direction of the extrusion flow. Comparatively, TEE foam was the one that showed a finer cellular structure, and TPEE thin foam the one with a higher aspect ratio in TD orientation. On the contrary, the LDPE-based foam displayed a higher cell aspect ratio in MD orientation than in TD.

Due to the instability at the end of the fracture tests and the great dispersion on the linear EWF fittings, doubts remain about the applicability of the EWF methodology to LDPE foams. On the contrary, the EWF methodology could be adequately applied to PP-based foams, though generally speaking small differences (within experimental error) were found between the values of the fracture parameters for these foams. Significant differences were found between PP-based foams, the LDPE-based foam and that containing an important fraction of EVA, showing the effectiveness of EWF methodology in distinguishing between polyolefin foams with different chemical nature.

In terms of the fracture parameters, foams based on a P-E copolymer presented the highest values of the specific essential work of fracture in the MD direction, as the addition of an α-olefin led to the reduction of this fracture parameter, with additional decrease being observed with increasing expansion ratio. No significant differences were observed in the TD direction, except for TPEE thin foam, a consequence of its particular cellular structure developed during extrusion foaming. All PP-based foams showed similar non-essential work of fracture values in both MD and TD directions.
Comparing the two applied correction procedures, the one based on the expansion ratio seemed to provide more accurate fracture parameters results than the polymer fraction correction procedure, which could not even be applied to all studied foams. Moreover, the polymer fraction correction approach requires more analysis time due to the complexity behind the calculation of the polymer fraction present in each foam from cellular structure analysis and assumption of idealized cell geometries.

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**References**


Table 1. Cellular structure characterization results and fraction of solid determined assuming different cell shape approximations for the several foams. MD and TD accounts orientation respect to the machine direction, parallel (MD) or transversal (TD). VD and WD accounts for the direction of cell measurements (vertical, VD or width WD).

<table>
<thead>
<tr>
<th>Foam code</th>
<th>ER</th>
<th>Orientation</th>
<th>$\phi_D$ (μm)</th>
<th>$\phi_{VD}$ (μm)</th>
<th>$N_o$ (cells/cm$^3$)</th>
<th>$N_t$ (cells/cm$^3$)</th>
<th>$N'_t$ (cells/cm$^3$)</th>
<th>AR</th>
<th>$f_s$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TAS</td>
<td>13.2</td>
<td>MD</td>
<td>116.7 ± 6.9</td>
<td>164.4 ± 0.5</td>
<td>8.78 x 10$^6$</td>
<td>6.35 x 10$^7$</td>
<td>7.88 x 10$^7$</td>
<td>1.4</td>
<td>-14.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TD</td>
<td>111.7 ± 7.6</td>
<td>137.1 ± 4.8</td>
<td>1.27 x 10$^7$</td>
<td>9.17 x 10$^6$</td>
<td>1.03 x 10$^6$</td>
<td>1.2</td>
<td>-17.2</td>
</tr>
<tr>
<td>TPEE thick</td>
<td>8.3</td>
<td>MD</td>
<td>110.5 ± 7.4</td>
<td>130.8 ± 3.5</td>
<td>9.41 x 10$^6$</td>
<td>9.57 x 10$^6$</td>
<td>1.05 x 10$^6$</td>
<td>1.2</td>
<td>-23.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TD</td>
<td>124.8 ± 0.6</td>
<td>152.1 ± 1.7</td>
<td>6.31 x 10$^6$</td>
<td>6.33 x 10$^6$</td>
<td>7.09 x 10$^5$</td>
<td>1.2</td>
<td>-24.5</td>
</tr>
<tr>
<td>TPEE thin</td>
<td>13.1</td>
<td>MD</td>
<td>82.5 ± 7.7</td>
<td>100.3 ± 4.2</td>
<td>2.68 x 10$^7$</td>
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<td></td>
<td></td>
<td>TD</td>
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<td>150.1 ± 5.4</td>
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<td>1.14 x 10$^6$</td>
<td>1.78 x 10$^6$</td>
<td>1.8</td>
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<td>TEE</td>
<td>13.7</td>
<td>MD</td>
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</tr>
<tr>
<td>TPLPM</td>
<td>13.3</td>
<td>MD</td>
<td>124.5 ± 0.6</td>
<td>149.9 ± 3.5</td>
<td>8.56 x 10$^6$</td>
<td>6.84 x 10$^5$</td>
<td>7.60 x 10$^5$</td>
<td>1.2</td>
<td>-9.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TD</td>
<td>118.6 ± 3.5</td>
<td>180.7 ± 12.6</td>
<td>6.27 x 10$^6$</td>
<td>5.27 x 10$^5$</td>
<td>6.94 x 10$^5$</td>
<td>1.5</td>
<td>-1.9</td>
</tr>
<tr>
<td>TPVF</td>
<td>13.8</td>
<td>MD</td>
<td>123.1 ± 7.6</td>
<td>153.1 ± 2.0</td>
<td>8.02 x 10$^6$</td>
<td>9.50 x 10$^5$</td>
<td>7.64 x 10$^5$</td>
<td>1.2</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TD</td>
<td>125.9 ± 4.2</td>
<td>197.1 ± 2.2</td>
<td>5.80 x 10$^6$</td>
<td>8.88 x 10$^5$</td>
<td>5.67 x 10$^5$</td>
<td>1.6</td>
<td>0.3</td>
</tr>
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Table 2. Specific essential and non-essential EWF fracture parameters for all studied foams corrected taking into account the expansion ratio ($ER$) and cellular structure ($cs$).
Figure captions

Figure 1.  (a) Heating and (b) cooling DSC thermograms of all studied foams obtained applying a heating/cooling rate of 10 °C/min.

Figure 2.  FT-IR/ATR spectra of all tested polyolefin-based foams showing the main infrared absorbance peaks.

Figure 3.  Micrographs showing the typical cellular structures of the studied foams: TAS (a) TD and (b) MD; TPEE thick (c) TD and (d) MD; TPEE thin (e) TD and (f) MD; TEE (g) TD and (h) MD; TPLPM (i) TD and (j) MD; and TPVF (k) TD and (l) MD orientations.

Figure 4.  Experimental force-displacement curves of the studied foams: TPEE thick (a) MD and (b) TD; TPEE thin (c) MD and (d) TD; TAS (e) MD and (f) TD; TPLPM (g) MD and (h) TD; TEE (i) MD and (j) TD; and TPVF (k) MD and (l) TD orientations.

Figure 5.  Stress-state of the studied foams. Hollow symbols: MD orientation; filled symbols: TD orientation. Solid (MD) and dashed (TD) lines represent the average values of the maximum net stress +/- 10%.

Figure 6.  EWF linearization results for all studied foams applying the expansion ratio correction procedure. Hollow symbols: MD orientation; filled symbols: TD orientation.