METHOD TO EVALUATE BIAXIAL STRETCH RATIOS IN STRETCH BLOW MOLDING

Masoud Allahkarami1, 2, Sudheer Bandla2, and Jay C. Hanan1
1 Mechanical and Aerospace Engineering, Oklahoma State University, Tulsa, OK 74106
2 Research and Development, Niagara Bottling LLC, Ontario, CA 91761

Abstract

The structural performance of poly (ethylene terephthalate) (PET) films depends on material distribution and microstructural changes in PET from stretching. Biaxial stretching during processes such as blow molding creates a specific thermomechanical history of the film, which determines material properties. The dependence of PET film crystallinity and the resulting mechanical properties on stretch ratios makes them a critical parameter in designing an efficient lightweight design. Therefore, it is important to have a method which can provide accurate material distribution information along with local stretch ratios. Such material efficiency can be applied to container design. In this work, we introduce a method to track material distribution from a “preform” to a “bottle” during a two-step injection stretch blow molding process and evaluate the stretch ratios.

Introduction

Understanding the mechanical behavior of PET and resulting implications in the design of packaging containers has advanced significantly in the past four decades [1], [2], [3], [4]. Successful design initiatives across the industry have reduced the weight of PET bottles by more than 30% while maintaining the performance of the container [5]. Improving the efficiency of targeted material distribution through design and process optimization is crucial for future lightweighting efforts [6]. This necessitates the adaptation of advanced characterization tools as part of the design and development process. In the past, we have shown the application of X-Ray tomography, a non-destructive 3D imaging technique based on the X-ray absorbance of materials, for package design [7], [8], [9]. It is effective in capturing details of complex 3D geometries with micrometer resolution [7], [10].

Stretch crystallization is an important material characteristic of PET. Understanding it is useful in the design of containers. During blowing, PET is stretched bi-axially in both radial and axial directions. Biaxial stretching orients PET chains which induce a form of crystallinity, making the film stiffer and stronger [3]. During blow molding, the wall thickness and diameter of the bottles change along their length, making it a non-uniform correlation with the initial preform thickness profile. In order to find correlations between crystallinity and stretch ratio it is necessary to first develop a method to determine the biaxial stretch ratio and thickness at each segment of the stretched film. Here we introduce an optical microscopy based technique to track material translation and deformation from a preform segment to a bi-axially stretched segment on a bottle. Percent crystallinity at different stretch ratios was measured using micro-X-ray diffraction [11].

Methods

The top section (bell) of a typical water bottle was sectioned using a diamond saw for the thick finish region and a razor blade for the thin wall portion. The cross section was painted with black ink in order to capture a high contrast image. Figure 1(a) and (b) are extracted from 18.0 MP optical images taken using an EOS Rebel T5 DSLR Camera. A Matlab image processing program was used to threshold the black painted cross-section of the image and save the profile as a binary image, illustrated in Figure 1(a). A binary image of the preform section was created as shown in Figure 1 (b). The region of interest starts from the support ledge, a circular ring near the neck for handling the bottles during blow molding and filling stages.

XRD measurements were performed using a Bruker D8 Discover micro-X-ray diffraction system equipped with a 2D detector. Cu Kα radiation (λ = 1.54184 Å) was used for the crystallinity measurements. Crystallinity measurements were performed using a 0.5 mm collimator. PET samples were attached to a Si single crystal (zero background substrate) for data collection in reflectance mode. The maximum detector distance (300 mm) by this system was selected because higher detector distance peaks were better distinguished although their intensity decreases. At 300 mm the detector simultaneously covers the area of 20° in 2θ and 20° in ψ.

SPE ANTEC® Anaheim 2017 / 484
Figure 1: (a) bottle binary cross section image after background and artifact removal, and (b) preform binary cross section image.

Results and discussion

The binary “.tif” images were imported to the Matlab workspace and saved as a matrix of zeros for background and ones for PET. Considering symmetry, only a section of the bottle was used for stretch ratio analysis. The sum of each row in the thickness matrix is equal to number of pixels representing the local horizontal thickness.

![Figure 2: Inner, outer and average radius normalized to the radius at support ledge of the preform and corresponding bottle.](image)

Figure 2: Inner, outer and average radius normalized to the radius at support ledge of the preform and corresponding bottle.

The inner, outer, and average radius of the preform and bottle normalized to thickness below the support ledge, were calculated from the matrix and are shown in Figure 2.

![Figure 3: Accumulated volume and weight for preform/bottle vs distance from the support ledge.](image)

Figure 3: Accumulated volume and weight for preform/bottle vs distance from the support ledge.

Assuming the bottle and preform are symmetric around the z-axis and knowing the inner and outer radius, the volume of cross sectional rings with distance ‘z’ from the support ledge were calculated and plotted, as shown in Figure 3. Considering that the density of PET has not changed for the region of interest, the corresponding accumulated weight of preform/bottle versus distance from support ledge was calculated as shown in Figure 3 (Volume and weight of the bottle are normalized to the volume and weight of the preform).

To get a better idea of material translation from preform to bottle, using conservation of volume we can show in this particular case study the region colored as green on the preform has been stretched into the blue colored region of the bottle as shown in Figure 4.

![Figure 4: Material tracking from preform to bottle.](image)

Figure 4: Material tracking from preform to bottle.

Figure 5 graphically shows the manner in which material has translated from the preform to the bottle wall in both radial and axial directions.
Figure 5: Material tracking from preform to bottle.

Stretch ratio parameters like axial stretch ratio (ASR), circumferential stretch ratios (CSR), radial shrinkage ratio (RSR), and biaxial stretch ratio (Bi-SR) for the region of interest were calculated and plotted against the distance from support ledge, as shown in Figure 6.

Figure 6: Axial stretch ratio (ASR), circumferential stretch ratios (CSR), radial shrinkage ratio (RSR), and biaxial stretch ratio (Bi-SR) vs distance from support ledge.

Crystallinity Measurement

Multiple measurement points, shown in Figure 7(a) were selected on the cross section of the bottle starting from the support ledge. The region close to the support ledge is mainly amorphous while stretched PET indicates strain induced crystallization. 2D XRD frames collected from stretched regions include partial rings while frames from amorphous regions only have the typical hump. Concentrated partial diffraction rings from the two-dimensional frames (shown in Figure 7c), indicate strong orientation of the PET crystallites.

The percentage of crystallinity was measured based on the ratio of the crystalline fraction ($A_c$) to the total area ($A_a + A_c$) under the diffracted curve shown in Figure 8, as represented in Equation 1 [11]. The percent crystallinity was determined by rotating the sample to have orientation independent measurements.

$$X_c = \left[ \frac{A_c}{A_a + A_c} \right] \times 100 \quad (1)$$

Figure 7: (a) Sectioned PET bottle (bell region) having a gradient of crystallinity. (b) Typical 2D X-ray diffraction pattern from the amorphous region. (c) Typical 2D X-ray diffraction pattern from crystalline region.
Figure 8: 1D diffraction pattern for amorphous and semi-crystalline measurement locations (measurement locations are represented by different colors, as shown in Figure. 7).

Table 1: Stretch ratio parameters and percent crystallinity.

<table>
<thead>
<tr>
<th>Measurement location</th>
<th>Axial stretch ratio (ASR)</th>
<th>Circumferential stretch ratios (CSR)</th>
<th>Radial shrinkage ratio (RSR)</th>
<th>Biaxial stretch ratio (Bi-SR)</th>
<th>Percent Crystallinity</th>
</tr>
</thead>
<tbody>
<tr>
<td>(b)</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>5.6</td>
</tr>
<tr>
<td>(c)</td>
<td>1.48</td>
<td>1.98</td>
<td>0.19</td>
<td>3.4</td>
<td>21.0</td>
</tr>
</tbody>
</table>

As seen from Table 1, crystallinity of the PET increased from 5.6% to 21.1% with stretching of the preform.

Discussion

Micro X-ray Computed Tomography (Micro-CT) is effective in quantitatively extracting the thickness information from a package; however there are sample size limitations for Micro-CT [7]. In the case of large containers with sample size limitation for Micro-CT, it is not possible to scan the bottle region of interest. Therefore, by combining digital photography and image processing, the axial and circumferential stretch ratios along with radial shrinkage ratios can be quantified for the bell or other regions of larger water bottles. Using the proposed method, local stretch ratios can be determined and correlated with measured crystallinity values.

The ability to track material translation from preform to bottle with sub-micron accuracy makes it a suitable aid for developing lighter preform and bottle designs. This approach is broadly applicable to many important areas of study where thickness of a complex plastic geometry needs to be quantified. The measurement method can also be implemented to look for correlations of physical properties such as percent crystallinity changes with local thickness.

Conclusions

An algorithm to quantify and correlate the thickness of a preform to the bottle has been demonstrated. Material distribution information between a preform and bottle allowed precise quantification of local stretch ratios which aids in predicting mechanical properties. This is particularly useful for simulating designs.

Acknowledgments

This work was partially possible through foundation grants to the Helmerich Research Center and industry sponsorship.

Bibliography


