Simulation of Stress Distribution in the Base of Pet Bottles Under Different Processing Conditions

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Abstract—Polyethylene terephthalate (PET) bottles, especially the ones with petaloid shaped base are the most widely used containers for carbonated soft drink (CSD) packaging. Occasionally, cracks develop in the base of the bottles due to the internal stresses generated by the carbonation pressure of the content. To eliminate the stress cracking problem, the process parameters as well as the bottle design need to be optimized. In this study, the effects of process parameters on the distribution of stresses in the bottle base will be studied. In particular, the timing of the stretch rod in relation to the blow pressure activation, the preform temperature and weight will be considered.

Keywords—PET, bottle, simulation, stress.

I. INTRODUCTION

The storage and transport of the carbonated soft drinks via polyethylene terephthalate (PET) bottles offer advantages compared to other materials such as glass and metal. PET is the material of choice for CSD packaging due to its excellent clarity, good mechanical and barrier properties, and ease of processing.

PET bottles used for the CSD packaging are generally made by injection stretch blow molding (ISBM). An injection molded preform is deformed in two directions; radially by the internal pressure and axially by the stretch rod. The air pressure loading consists of two consecutive stages; the pre-blow and final-blow. The pre-blow forms most parts of the bottle with a low pressure while the final-blow exerts a higher pressure to form intricate details such as the petaloid base [1]. Production processing conditions as well as the properties of the PET material affect the final bottle quality, and particularly stress crack performance. The ISBM process parameters, and the preform design, are known to affect the stresses generated within the bottle [2]. The process parameters comprise preform temperature, the timing relationship between the stretching and blowing stages, stretch rod speed, pre-blow and final-blow pressures. Although, there have been quite a few studies related to the effect of process parameters on the bottle properties [3,4,5,6], only a few address directly the cracking/splitting of the base [2,7].

Hanley et al., conducted extensive SAXS studies of the bottle base using a synchrotron radiation source. They have related the stress cracking of the base to the molecular morphology of the PET [2]. They identified an amorphous region in the base center close to the injection gate of the preform with bi-axially oriented, semi-crystalline region in the feet and valleys of the bottle bases. For bottles that had poor crack performance, the transition between these two regions displayed un-axial orientation that would lead to reduced mechanical strength in the circumferential direction. As for Lyu et al, they minimized the stress cracking occurrence at the bottle base by optimizing base parameters: foot length, valley width and clearance. Although, their new base design demonstrated some improvements, stress cracking problem has not been solved completely. Everall et al. proved that the hoop extension differences in the inner and outer surfaces of the bottle combined with the rapid cooling of the outer bottle surface affect the morphological properties; an orientation differential is observed along the bottles thickness [8]. Prevention of the stress cracking in the bottom of the PET bottle depends on the product design as well as processing parameters. In a previous publication, we have focused on bottle base design optimization [9]; here we will consider the process optimization, in particular optimization of the two-stage ISBM process. First stage of the work, the performance of PET bottles will be assessed in terms of stress and thickness distribution in the base of the bottles produced under different processing conditions identified by five different models. Following the initial process optimization, the effect of preform weight and the preform temperature profile will be assessed based on the thickness and stress distribution of the bottle base.

II. EXPERIMENTAL

Material

As for the PET material used, a visco-hyperelastic model was employed.

Bottle mould; stretch rod and preform design

The mold used in this study is a 1.5 lt PET bottle, which is currently used by the packaging industry for CSD applications (Fig. 1). The stretch rod design is shown in figure 2. The preform design, which is generated by Blow-view version 8.2, and its temperature profile are shown in figure 3.

The bottle base is optimized against stress cracking through CATIA V5 R14 Finite Element Analysis software
Process simulation

In this study, a total of five different models were generated; each model has a different set of stretch rod movement and pressure profile as a function of time. Two different preform weight and temperature profiles were considered. Blow View version 8.2 simulation program is used to obtain stress distributions in the base. The processing conditions that result in minimum stress at the base of the bottle were accepted as the optimum process parameters.

The movement of stretch rod is executed under three different regimes:

1. Free-blow is simulated without any stretch rod movement.
2. The stretch rod moves only half way down the bottle.
3. The stretch rod moves all the way down to the base of the bottle.

The pre-blow pressure is kept as low as possible and the final blow pressure is gradually increased.

Pressure profiles as a function of time are varied for two different preform weights (34 and 40 g) and two different preform temperature profiles (93 – 105 °C and 98 – 115 °C) as shown in figure 4 to figure 8 for model 1 to model 5 respectively.

The preform weight and the preform temperature profile was studied for the model 3 which is expected to offer superior stress crack resistance compared to the other models.

The thickness and the stress distribution of the bottle base for the model 3 are compared in figure 13 and 14 respectively; the comparison is based on a single preform temperature profile (93 – 105 °C) and (98 – 115 °C). A relatively low preform temperature profile seems to introduce more uniform base thickness; however, it has little effect on the stress distribution of the base.

The thickness and the stress distribution of the bottle base for the model 3 are compared in figure 11 and 12 respectively; the comparison is based on a single preform weight (40 g) and two different temperature profiles of (93 – 105 °C) and (98 – 115 °C). Although a low preform weight introduces thinner base, it does not seem to effect the stress distribution of the base.

It can be said that the preform weight and the preform temperature profile does not seem to influence stress crack performance of the bottle base.

In the model 3, the pre-blow precedes the stretch rod movement, the final-blow commences after the completion of the stretch rod movement.

The effect of the preform weight and the preform temperature profile was studied for the model 3 which is expected to offer superior stress crack resistance compared to the other models.

The thickness and the stress distribution of the bottle base for the model 3 are compared in figure 11 and 12 respectively; the comparison is based on a single preform temperature profile (93 – 110 °C) and two different preform weights (34 and 40 g). Although a low preform weight introduces thinner base, it does not seem to effect the stress distribution of the base.

The thickness and the stress distribution of the bottle base for the model 3 are compared in figure 11 and 12 respectively; the comparison is based on a single preform weight (40 g) and two different temperature profiles of (93 – 105 °C) and (98 – 115 °C). A relatively low preform temperature profile seems to introduce more uniform base thickness; however, it has little effect on the stress distribution of the base.

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III. RESULTS AND DISCUSSION

ISBM process parameters are very much dependant on each other; a small change in the one of them affects the other; they ultimately affect the final properties of the bottle. If the orientation of the molecules has a significant effect on stress crack resistance of the base, the timing of the stretch rod activation in relation to blow pressure holds the key to the stress cracking problem. The stretch rod movement provides the transportation of the PET material to the base, hence induces orientation of the molecules; it also imparts strain hardening during axial stretching of the material. When the stretch rod movement is too fast, preform ruptures; however if the stretch rod movement is too slow, it causes too much material to be transferred to the bottle base. Therefore, the excessive material transferred to the base reduces the extent of stain hardening of the material. Similarly, the preform temperature profile, which is introduced during the re-heating stage of the two-stage ISBM process, affects blow pressure requirements. That is why for the models 4 and 5 where the effect of the preform weight and temperature profile was studied, a different pressure profile was required.

The comparison of the all five models with respect to the stress distribution of bottle base is shown in figure 9; and figure 10 compares the thickness distribution. The comparison is based on a single preform weight (40 g) and a single temperature profile (98 – 115 °C). Analysis of graphs confirms that the model 3 introduces the minimum stress which is accompanied by the maximum base thickness across the diameter with respect to the other models.
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Figure 3 – The CAD of the preform (in mm)

Figure 5 – Model 2 (a) Pressure profile (b) Stretch rod motion

Figure 4 – Model 1 (a) Pressure profile, (b) Stretch rod motion

Figure 6 – Model 3 (a) Pressure profile, (b) Stretch rod motion
Figure 7 – Model 4 (a) Pressure profile, (b) Stretch rod motion

Figure 8 – Model 5 (a) Pressure profile, (b) Stretch rod motion

Figure 9 – Stress distribution comparison

Figure 10 – Thickness distribution comparison

Figure 11 – Thickness distribution for the 34 and 40 g preforms (preform temp. profile 93-105 °C; model-3).

Figure 12 – Stress distribution for the 34 and 40 g preforms (preform temp. profile 93-105 °C; model-3).

Figure 13 – Thickness distribution for the preform temp. 93-105 °C & 98-115 °C (40 g preform; model-3).
IV. CONCLUSIONS

In this study, a total of five different models were generated; each model has a different set of stretch rod movement and pressure profile as a function of time. Preform weight and preform temperature profiles were also considered. Simulation was used to obtain stress distributions and the thickness distribution in the base.

The stress distribution of the bottle base was minimized when the pre-blow precedes the stretch rod movement and the final-blow commences after the completion of the stretch rod movement.

Under the optimum processing conditions, the preform weight and the preform temperature profile did not seem to influence the stress distribution of the bottle base. It can be said stress crack performance of the bottle base is found to be independent of the preform weight and preform temperature.

In a subsequent study, we will simulate the effect of molecular orientation, biaxial ratio and crystallinity of the bottle base on the stress crack performance of the bottles under the optimum processing conditions.

REFERENCES


