Experimental Study of the injection stretch/blow molding process

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EXPERIMENTAL STUDY OF THE INJECTION STRETCH/BLOW MOLDING PROCESS

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Abstract

The performance of Poly(Ethylene Terephtalate) bottles produced by the injection stretch/blow molding process depends on three main variables: the initial preform shape, the initial preform temperature and the balance between stretching and blowing rates. In order to characterize process parameters, experiments have been performed on a well instrumented mold. In addition, preform free inflation have been processed and a simplified model of an air volum free blowing has been developed.

Introduction

The injection stretch/blow molding process of PET bottles is a three step process (see Figure 1): first the PET resin is injected in a tube-shaped preform, then this amorphous preform is heated above the glass transition temperature ($T_g \cong 80°C$) and transfered inside a mold. Finally the preform is inflated with stretch rod assistance in order to obtain the desired bottle shape. This study will deal only with the last step of the process.

The process parameters will induce the thickness distribution of the bottle as well as the biaxial orientation and cristallinity, which in turn govern the transparency and the mechanical properties of the bottle. Thus, in order to measure process parameters and to characterize the rheology of the material under biaxial stretching, experimental work has been conducted on an instrumented blow molding machine.

A few works refer to the experimental investigation of the kinematic of the blow or stretch/blow molding processes (1 to 5). In a recent paper, Haelly and Ryan (5) have filmed parison free/confined inflation in blow molding of different polymers using high speed video camera. In the case of confined parison inflation, they have designed a transparent acrylic mold. Although this work represents a great contribution to the analysis of parison inflation, the technic still remains limited to simple geometries of mold (high curvatures enhance distorsions of the view). In addition, the design of a speficic mold for each blow molding experiment appears to be costly. The use of contacts sensors at the mold wall which permit to identify the contact time between the polymer and the mold seems to be a good compromise.

Instrumented mold of a stretch/blow molding machine

In order to measure stretch/blow molding parameters, experiments have been performed on a properly instrumented mold at SIDEL COMPANY (6). For the bottle mold and the preform, we have made the choice of simplified geometries (see Figure 2). The dimensions are summarized in Table 1. The instrumented mold is described summarily in figure 3. The displacement of the stretch rod is controlled and the force exerted on the stretch rod is recorded versus time using a force sensor. The blowing pressure is imposed and recorded versus time using a pressure sensor. Nine contact sensors at the mold wall permit to identify the contact time between the polymer and the mold.

The process parameters of the stretch/blow molding step are refered in Table 2 as well as typical values. The parameters associated with the stretching stage are the velocity of the stretch rod v_c which is applied until the preform contacts the bottom of the mold, and Rps the preblowing delay (Rps is the displacement of the stretch rod, in millimeter, without inflation pressure). The parameters associated with the inflation stage are Pps the maximum pre-blowing pressure (low-pressure) imposed during a preblowing time tps for initiating the general trend of the bottle, and Ps the maximum blowing pressure (high-pressure) which is applied during a blowing time ts in order to flatten the polymer against the mold wall. The preblowing flow-rate Qps and the blowing flow-rate Qs are not measured.

In previous papers (7, 8), we have pointed out, by plotting the stretching force versus time, that the increasing part and the decreasing part of the stretching force are corresponding respectively to the elastic and viscous response of the PET.

The location of the contact sensors (from n° 1 to n° 9) on the mold wall is indicated in figure 2. Recorded contact times versus number of contact sensors are plotted in figure 4 using the process parameters which are refered in Table 2. When the preblowing delay Rps is increased from 1 mm to 40 mm, all the contact times between the polymer and the mold increase and the contact times are more homogenous in the central part of the bottle. In addition, if we plot the measured thickness distribution versus longitudinal coordinate at the end of the process for the two values of Rps (see figure 5), we note that an increase in the preblowing delay induces more material displacement from the neck to the bottom of the bottle.

Measurement and calculation of the internal pressure

Let us now study the free inflation of a preform without stretching rod. The preform (cf. figure 2) is heated in a silicone oil bath in order to obtain an uniform temperature distribution, this for three different values of temperature (T=95°C, 100°C, 105°C). An inflation pressure $p_a(t)$ is applied on the internal surface of the bottle and the differential inflation pressure $\Delta p_a(t) = p_a(t) - p_o$ (p_o atmospheric pressure at ambient temperature) is recorded versus time using a pressure sensor. For each temperature, free inflations have been filmed using video camera. In figure 6, different steps of preform free inflation are presented for T=105°C. In addition, the recorded differential pressure is plotted versus time for three different values of temperature (see figure 7). All the curves are composed of three different parts:

. a first part where the pressure rises to a maximum (less than 3 bars), during which the polymer is not inflated (the internal volume of the preform remains constant);

. a second part where the pressure decreases continuously to a minimum because the internal volume increases;

. the last part of the curve where the pressure increases in order to force the “strain-hardening” phenomenon of the material, which in fact is related to the development of cristallinity under biaxial stretching.

This experiment demontrates that the evolution of the internal pressure and the inflation of the preform are highly coupled. It is to be noticed that the recorded internal pressure is significantly different from a constant “nominal” pressure. In order to better understand this pressure evolution, we develop hereafter a simple thermodynamic model. As sketched in figure 8, we consider that air, at temperature T_a, flows in the "control volume" $V_a(t)$ at a specific flow-rate q with entry velocity field $\vec{w}_e$, pressure p_e and temperature T_e. The specific flow-rate q is constant (cf. pre-blowing stage), so it results in the following relationship between the air mass $m_a(t)$ (occupying the volume $V_a(t)$) and q:

$$q = \frac{dm_a}{dt} = cte \Rightarrow m_a(t) = m_o + qt \quad (1)$$

where m_o is the air mass at time t = 0. Using the following assumptions:

. no heat transfer between the air volume and the surrounding medium,
. air is an ideal gas,

the global energy balance during the time step dt over the volume $V_a(t)$ may be simplified as:

$$\frac{d}{dt}\left(Ln(p_a V_a^{\gamma})\right) = \frac{d}{dt}\left(Ln(m_a^{\gamma})\right)\frac{T_e}{T_a} \quad (2)$$

where γ = 1.4 for the air. It is noteworthy that a very similar relationship has been determined by G. Louiz (9). In order to obtain a simplified relationship, we make the more criticizable assumption $T_a \cong T_e$. Using (1) and $m_a = \rho_a V_a$, equation (2) reduces to:

$$\frac{p_a(t)}{p_o} = \frac{1}{\rho_o^{\gamma}}\left(\frac{m_o + qt}{V_a(t)}\right)^{\gamma} \quad (3)$$

where ρ_o is the air specific mass at time t = 0. Knowing the increase of volume $V_a(t)$ (due to parison inflation), this relation should provide the pressure value $p_a(t)$. However, the experimental determination of the specific flow-rate q is very difficult. In order to overcome this difficulty, we suggest that q should be determined through an inflation test at constant volume V

Erreur !. Deriving eq. (3) with respect to time, at initial time t = 0, we obtain :

$$q = \frac{\rho_o V_o}{\gamma p_o} \left.\frac{dp_a(t)}{dt}\right|_{t=0} \quad (4)$$

Once the specific flow-rate q has been experimentally determined, it is possible to express the differential inflation pressure $\Delta p_a(t)$:

$$\frac{\Delta p_a(t)}{p_o} = \left(\frac{V_o}{V_a(t)}\right)^{\gamma} \left(1 + \frac{t}{\gamma p_o} \frac{dp_a(t)}{dt}\bigg|_{t=0}\right)^{\gamma} - 1 \quad (5)$$

This relationship has been introduced in the stretch/blow molding finite element code BLOWUP (10) in which the rheological behavior of the PET is represented by a viscoelastic constitutive equation of Oldroyd-B type. For the calculation of $\Delta p_a(t)$ using the relationship (5), we proceed as follows:

. inflation at a given specific flow-rate of a preform which has not been heated and measurement of the initial slope of the recorded pressure curve,

. computation of the initial internal volume of the preform V_o ,

. computation of the internal volume of the preform $V_a(t)$ at each time step and application of (5).

Application of preform free inflation

From the first results of preform free inflation issued from numerical simulation it appears that the expansion of the preform and especially the radial expansion is unlimited. This problem, which is not observed experimentally, occurs because the strain-hardening phenomenon of the material is not taken into account in the numerical model. Strain-hardening is related to the development of cristallinity under biaxial stretching. The problem of coupling between microstructural evolution and thermomechanical history still remains an open issue. It is not the goal of the present article to discuss such problems. However, a simple model which is able to take into account “in a certain sense” the strain-hardening phenomenon has been tested. The relation proposed by G’Sell (11) is based on the assumption that the viscosity depends on the generalized strain. The computed differential inflation pressure and the measured one at T=105 °C are plotted in Figure 9. We note that the agreement is fair between the two curves except in the last part. Experiments have shown that anisotropy occurs during the development of cristallinity. That’s why axial expansion still continues while radial expansion is blocked. The proposed model induces isotropic strain-hardening. It results that the expansion of the bubble is limited in the same manner in all directions. If the volume of the preform remains constant, the pressure increases according to the relation (5).

Conclusion

Experimental work has been conducted on an instrumented blow molding machine. Process parameters such as the preblowing delay and the velocity of the stretch rod have exhibited a significant influence on the thickness distribution in the final product. In addition, the use of contacts sensors has permitted to identify the kinematic of confined preform inflation .

A simplified model of an air volum free blowing has been developed and introduced in a finite element code. Due to results issued from numerical simulations, it appears that coupling between microstructural evolution and thermomechanical history should be the next issue of this work.

Acknowledgments

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Figures with captions

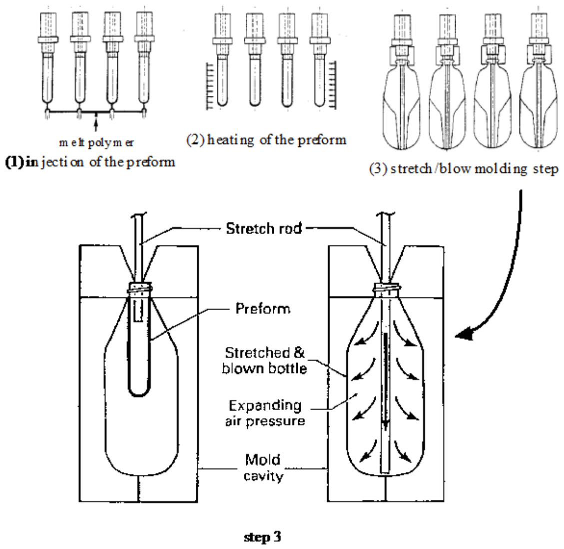

Figure 1: Description of the injection stretch/blow molding process

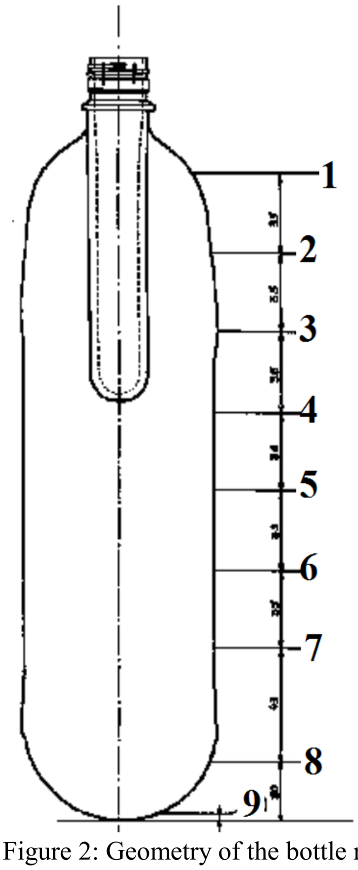

Figure 2: Geometry of the bottle mold and initial preform

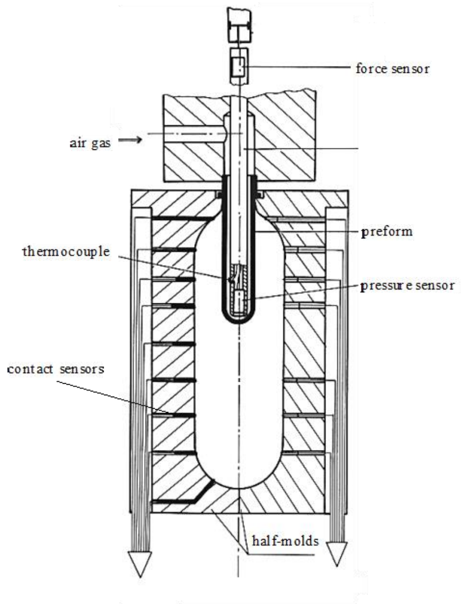

Figure 3: Description of the instrumented mold of a stretch/blow molding machine

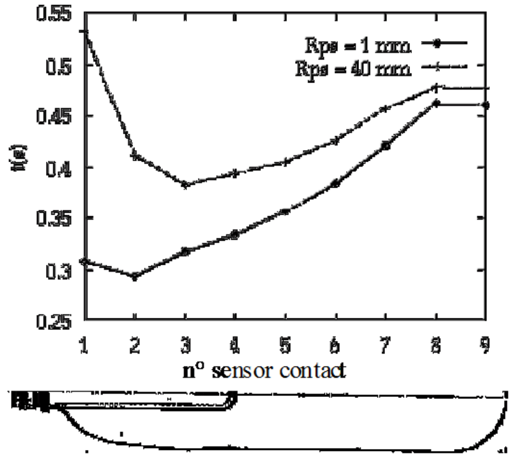

Figure 4: Contact times versus number of contact sensors

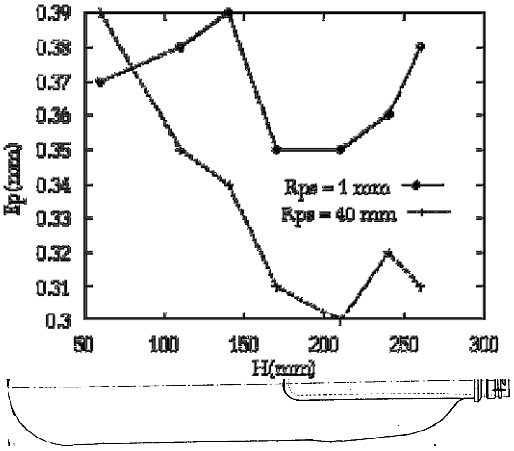

Figure 5: Thickness distribution at the end of the process

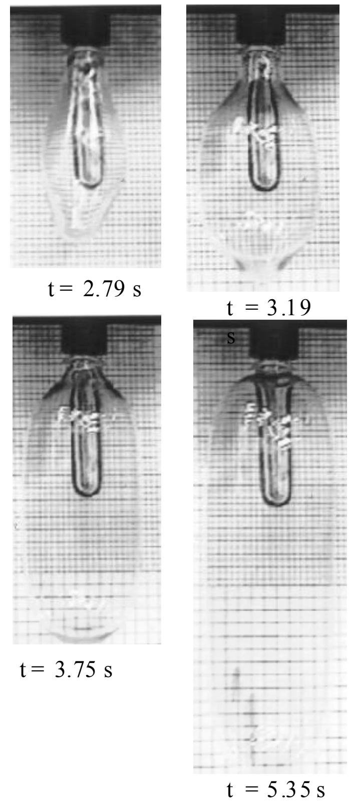

Figure 6: Preform free inflation (T=105°C)

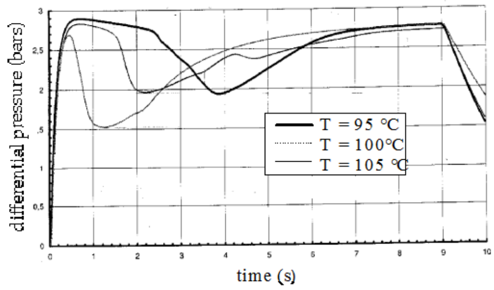

Figure 7: Differential inflation pressure versus time

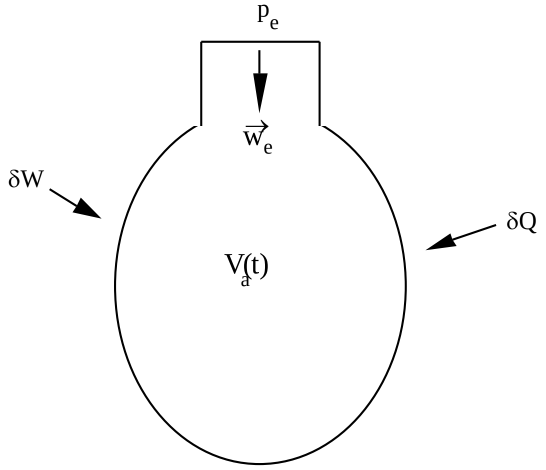

Figure 8: Volum free blowing

at a constant flow rate

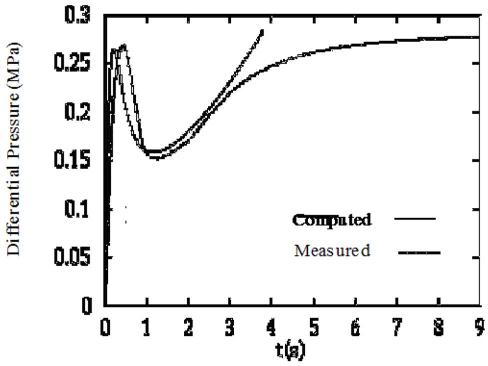

Figure 9: Measured and computed differential inflation pressure versus time (T=105°C)

Tables with captions

	Length (mm)	Inner radius (mm)	External radius (mm)
Preform	125	9.275	13.025
Bottle mold	310	44.3	44.3

Table 1: Dimensions of the bottle mold and the preform

Stretching stage	v_c (mm/s)	500
	R_{ps} (mm)	1
Preblowing stage	P_{ps} (Pa)	5.10^5
	D_{ps} (s)	0.3
	Q_{ps} (kg/s)	-
Blowing stage	P_s (Pa)	40.10^5
	D_s (s)	1.5
	Q_s kg/s)	-

Table 2: Process parameters

Keywords

stretch/blow molding; experimental investigations; air volum free blowing model; calculation of internal pressure