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► **To cite this version:**

Fabrice Schmidt, Jean François Agassant, Michel Bellet, G. Denis. Numerical Simulation of Polyester Stretch/Blow Molding Process. Numerical Methods in Industrial Forming Processes, 1992, sophia-antipolis, France. hal-02017895

HAL Id: hal-02017895

<https://hal.science/hal-02017895>

Submitted on 11 Mar 2019

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Numerical simulation of polyester stretch-blow molding process

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ABSTRACT : Finite element simulation of the stretch-blow molding process to make Polyethylene (PET) bottle has been carried out using an axisymmetric code BLOWUP2, derived from FORGE2[®], first developed to model the large viscoplastic deformations. The use of numerical simulation to optimize process parameters is a major challenge. Various parameters such as displacement of the plunger, blowing pressure, polymer temperature distribution, have to be adjusted in order to improve the process. The numerical model is based upon an updated-lagrangian finite element method together with a penalty treatment of mass conservation . Such a method leads to mesh degenerescence, and an automatic remeshing technique has been used. Preliminary numerical results have been obtained with a Newtonian behavior. They have been compared with short shots bottle blowing experiments.

1 INTRODUCTION

Many blow-molding processes for plastic bottle production have been developed in industry, such as extrusion blow-molding, extrusion stretch-blow molding, injection stretch-blow molding. The last one enjoyed large developments during the last decade , corresponding with the production of thin walled Poly(Ethylene Terephthalate) bottles for carbonated beverages (Rosato 1989).

There are two steps to the process. In the first step, the PET resin is injected in a tube-shaped mold. In the second step (as shown in Figure 1), the amorphous preform is heated in an infrared oven above the glass transition temperature ($T_g = 80^\circ\text{C}$), then simultaneously stretched with the assistance of a plunger and blown up with high-pressure air inside a mold to obtain the desired bottle shape, appropriate transparency and mechanical properties.

The performance of PET bottles produced by the injection stretch-blow molding process depends on three main variables : the initial preform shape, the initial preform temperature

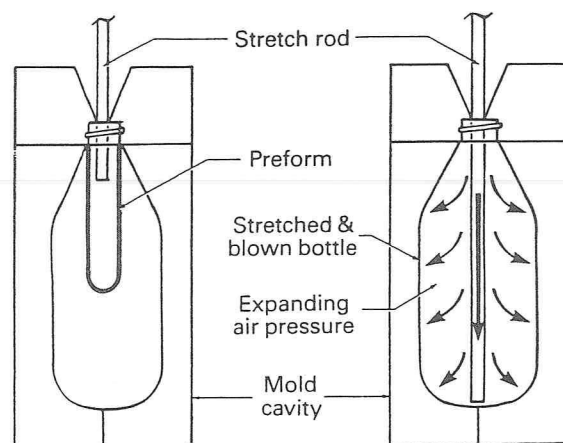


Figure 1 Description of stretch-blow molding step

and the balance between stretching and blowing rates .

These 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.

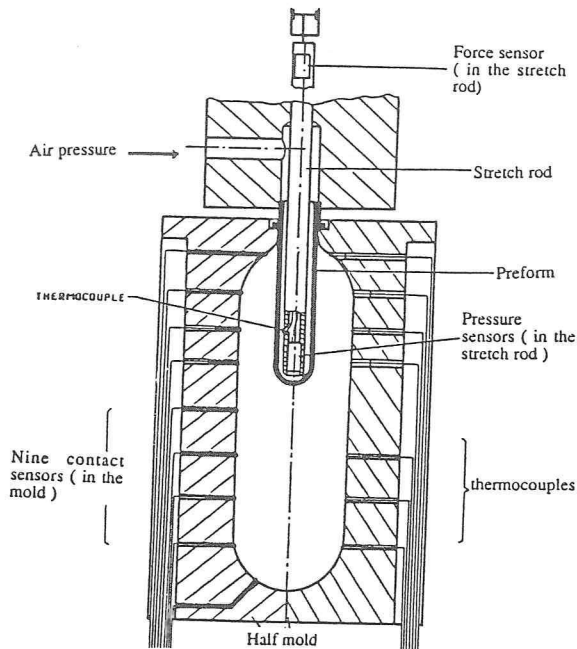


Figure 2 Instrumented mold of a stretch-blow molding machine

Optimizing the stretch-blow molding process is an art based on trial and error which consume significant amounts of material and time. A great deal of work (see Chung 1975, Warner 1984 and Cakmak 1985) refers to the investigation of the kinematics of stretch-blow molding PET bottles. More recently, numerical models have been proposed assuming elasto-visco-plastic behavior (Chung 1989) or nonlinear-elastic constitutive equation (De Lorenzi 1990). They lead to reasonable thickness distribution predictions, but they are not able to predict accurate stress distribution.

In fact, it is difficult to determine the true behavior of PET during the stretch-blow molding process. The rheology is highly rate sensitive during the stretch-blow molding process (Cakmak 1985). The initial injected preform is quite totally amorphous, and a viscous or liquid-like viscoelastic behavior has to be considered above the glass transition temperature at the beginning of the process. Crystallinity develops progressively during the process and, at the end, a solid-like viscoelastic behavior has to be taken into account.

In this paper, a finite element simulation of the stretch-blow molding of a newtonian isothermal fluid is proposed. Numerical results

are compared to experiments performed by Sidel Company on a well instrumented mold (Thomas 1991).

2 EXPERIMENTAL INVESTIGATIONS

The preform is heated in an infrared oven at a temperature around 120°C, the most uniform as possible (the temperature at the center of the preform is higher), and then transferred into a well instrumented mold. Once the preform is set up in the mold, the real value of the temperature is inferior (15°C less).

The instrumented mold is described summarily on Figure 2. The displacement of the plunger is controlled and the force exerted on the plunger is recorded. The blowing pressure is imposed and recorded, and contact sensors at the mold wall permit to identify the contact time between the polymer and the mold. In addition, short shots blow molding experiments have been performed . The thickness distribution of the bottle has been measured.

3 MECHANICAL FORMULATION

3.1 The virtual work principle

At each time step, the virtual work principle may be written on the domain Ω_t occupied by the polymer :

$$\int_{\Omega_t} \underline{\sigma} : \underline{\dot{\epsilon}}^* d\Omega = \int_{\Gamma_f} \tau u^* ds - \int_{\Gamma_p} \Delta P n \cdot u^* ds \quad [1]$$

where $\underline{\sigma}$ is the Cauchy stress tensor, $\underline{\dot{\epsilon}}^*$ the virtual strain rate tensor connected with the virtual velocity field u^* , τ the friction vector along the mold wall, Γ_f the part of the boundary contacting the mold, Γ_p the part of the boundary where inflation pressure ΔP is applied.

3.2 Material behavior

The material is assumed to be isotropic and incompressible. As above mentioned, the temperature was assumed to be constant during the process and a liquid-like behavior (Newton's law) was used in this analysis. The

deviatoric stress tensor \underline{s} is then related to the strain rate tensor $\underline{\dot{\epsilon}}$ by :

$$\underline{s} = 2\eta \underline{\dot{\epsilon}} \quad [2]$$

where η is the viscosity of the material.

3.3 Penalized functional

As a classical result of the variational calculation, the kinematic constrained velocity field \mathbf{u} solution of the weak form of the equilibrium equation [1] is equivalent to the minimization of a functional $\Phi(\mathbf{u})$:

$$\Phi = \int_{\Omega_t} \eta (\underline{\dot{\epsilon}} : \underline{\dot{\epsilon}})^2 d\Omega + \int_{\Gamma_f} \frac{\alpha_f}{p+1} \|\Delta \mathbf{u}_t\|^{p+1} ds + \int_{\Gamma_p} \mathbf{n} \Delta P \mathbf{u} ds \quad [3]$$

where α_f is the friction coefficient and p the friction rate sensitivity parameter (taken equal to 1 in the newtonian case), $\Delta \mathbf{u}_t$ the tangential velocity along the mold interface.

To enforce incompressibility, a penalty method is used. Finally, the penalized functional Φ_p to be minimized is written :

$$\Phi_p = \Phi + \frac{\rho}{2} \int_{\Omega_t} \eta (\nabla \mathbf{u})^2 d\Omega \quad [4]$$

where ρ is a large positive number called penalty coefficient.

4 NUMERICAL RESOLUTION

Using an updated lagrangian finite element method (ULFEM), the whole process is divided into small time steps Δt on which the mechanical problem [4] is solved.

For each time step, the fixed domain of calculation (a section of the axisymmetric preform) is meshed with quadratic triangles. Thus, the unknown function \mathbf{u} can be approximated throughout Ω_t , in each increment, by the relationship :

$$\mathbf{u} = \sum_{i=1,q} N_i \mathbf{u}^i \quad [5]$$

where q is the number of nodes of the element, N_i the shape function related to the i^{th} nodal point and \mathbf{u}^i the nodal velocity.

The minimisation of the discretized functional gives a banded set of linear algebraic equations, which is solved by a direct Crout decomposition.

A forward Euler integration scheme is then used to update the configuration :

$$\Omega_{t+\Delta t} = \Omega_t + \mathbf{u}(t) \cdot \Delta t \quad [6]$$

5 AUTOMATIC REMESHING

It is well known that, in an updated langrangian formulation using a convective mesh, the degeneracy of the mesh occurs very rapidly. An automatic mesh generation procedure checks at each time step the distortion of elements and the accuracy of the mesh boundary (penetration of peripheric meshes into the mold, free surface curvature,...) and decides itself to remesh or not according to prescribed tolerances (Coupez 1992).

6 APPLICATION TO THE STRETCH-BLOW MOLDING PROCESS

6.1 Validation test

A constant pressure Δp is applied on the internal surface of a tube of PET and a constant velocity v_0 at the bottom side. Under some kinematic assumptions (see Figure 3), it is possible to obtain an analytic solution for the newtonian behavior. Let R_0 be the initial internal radius and L_0 the initial length of the tube. The internal radius R can be expressed as:

$$\frac{R(t)}{R_0} = \sqrt{\frac{\left(\frac{S_0}{R_0}\right)^2 - 1}{\left(1 + \frac{v_0 t}{L_0}\right) \left[\left(\frac{S_0}{R_0}\right)^2 e^{-\frac{\Delta P t}{\eta}} - 1\right]}}$$

The comparison between the analytic thickness distribution and the numerical one versus time is presented on Figure 4. The agreement is fair.

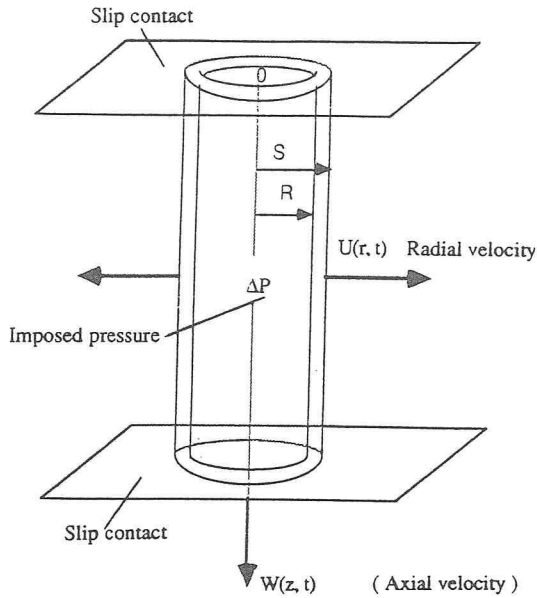


Figure 3 Boundary conditions

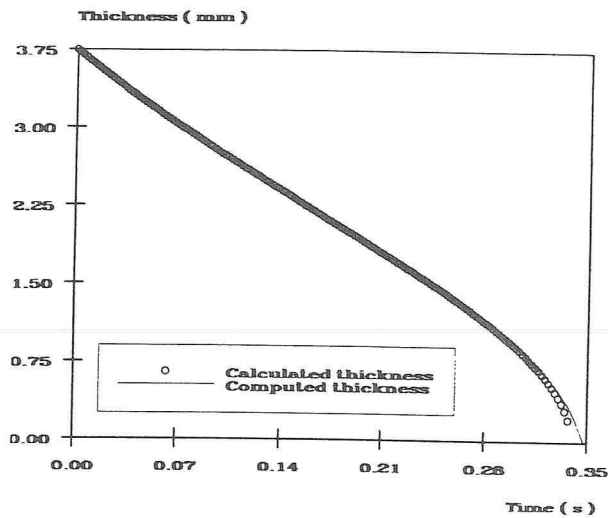


Figure 4 Thickness versus time

6.2 Set up of real stretch-blow molding process

The cross-section of the preform and bottle are shown in Figure 5. Dimensions of the bottle mold are 310 mm length and 44.3 mm radius. The wall thickness of the preform is 3.5 mm, its height 125 mm. This yields a radial stretch ratio of 4.5 and an axial one of 2.5. The speed of the plunger is 400 mm/s.

The imposed pressure is presented as a function of time in Figure 6: a pre-blowing stage for initiating the general trend of the bottle (maximum pressure 1 MPa), during which the preform is stretched and blowup; a blowing

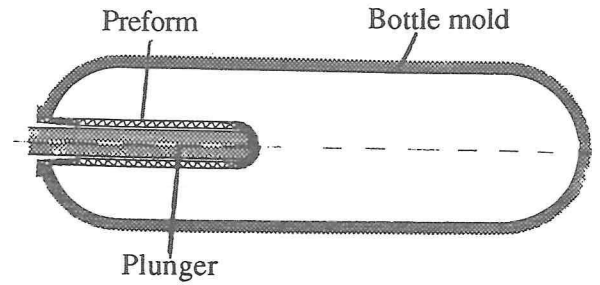


Figure 5 Preform and bottle shape

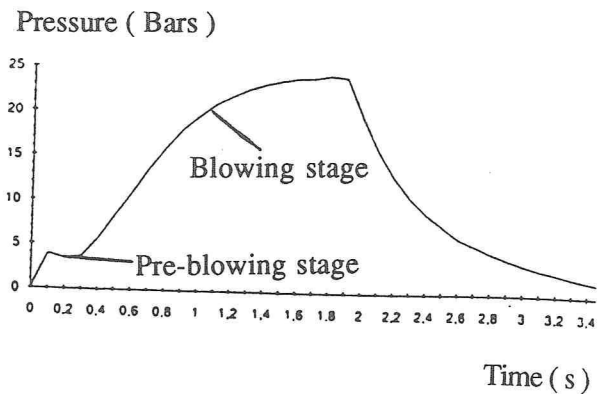


Figure 6 History of pressure versus time

stage in which higher pressure (2.1 MPa to 4.5 MPa) is applied in order to flatten the polymer against the mold wall.

6.3 Computation and results

Intermediate shapes from the initial preform to the final bottle were obtained for the target process. These shapes are plotted in Figure 7 as a function of time. It is interesting to compare the evolved bottle shapes with short shots bottles produced for the target process (see Figure 8). There is a qualitative agreement between computation and experiments.

The thickness distribution obtained from the simulation is compared in Figure 9 with experimental values. It shows a relatively good agreement except on the center of the bottle. This can be related to the non-uniform temperature distribution in the initial preform.

The measured force of the plunger versus time (Figure 10) starts from zero, then the curve rises to a maximum and decreases continuously. The numerical curve obtained for $\eta = 0.2 \text{ MPa}\cdot\text{s}$, starts directly from a maximum

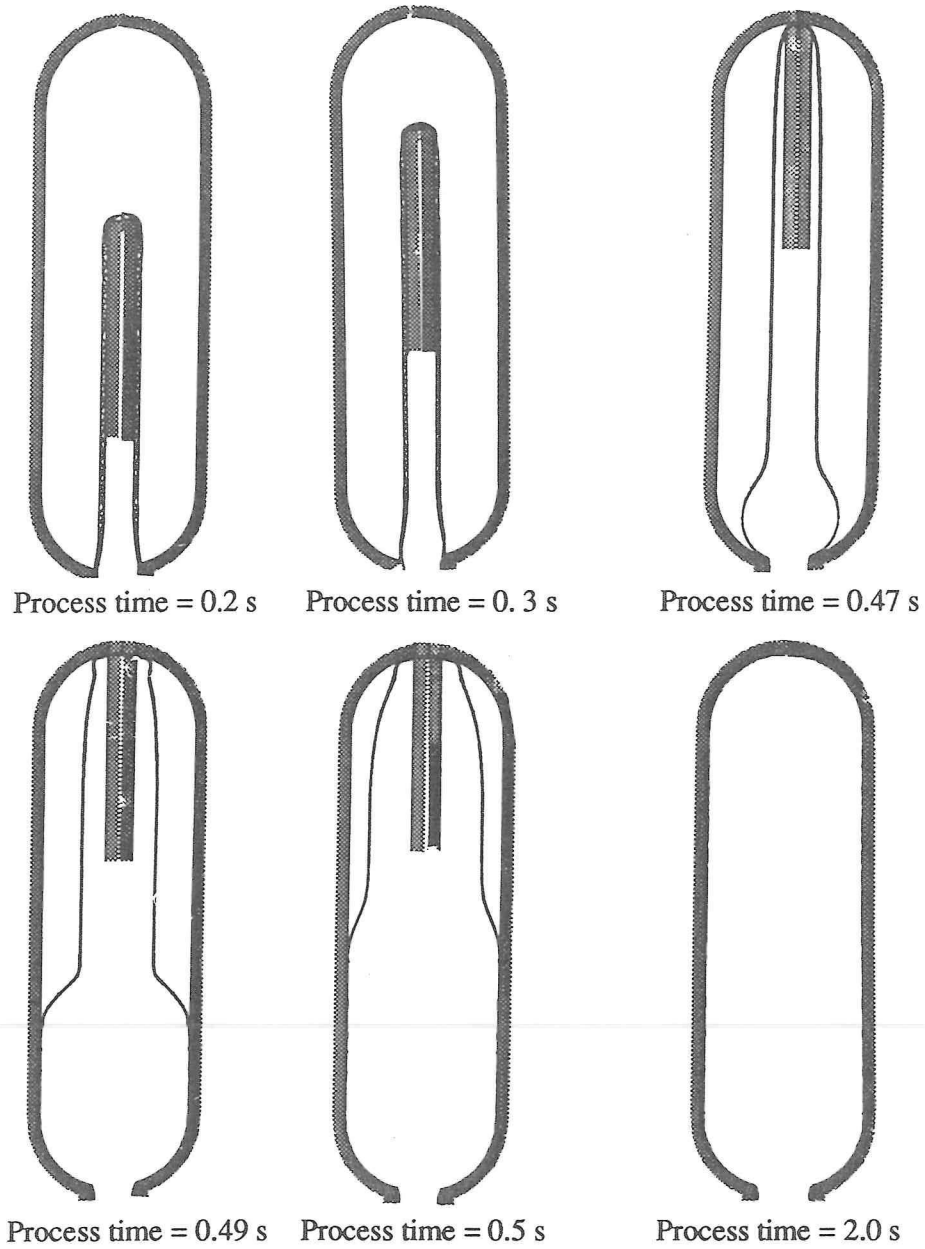


Figure 7 Intermediate bottle shapes

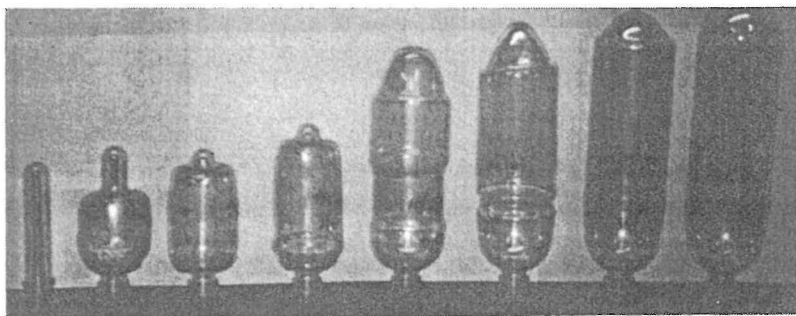


Figure 8 Short shot bottles produced

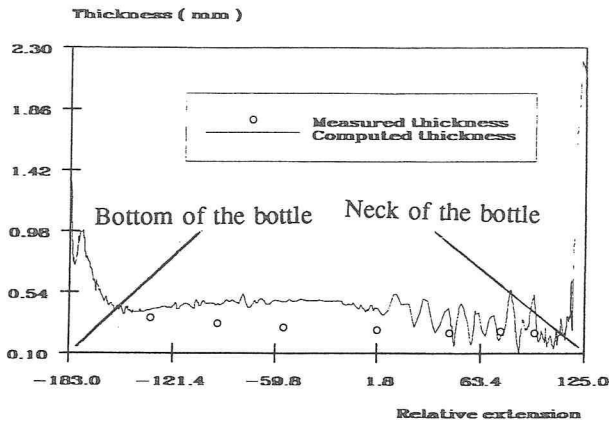


Figure 9 Thickness distribution versus extension of the bottle

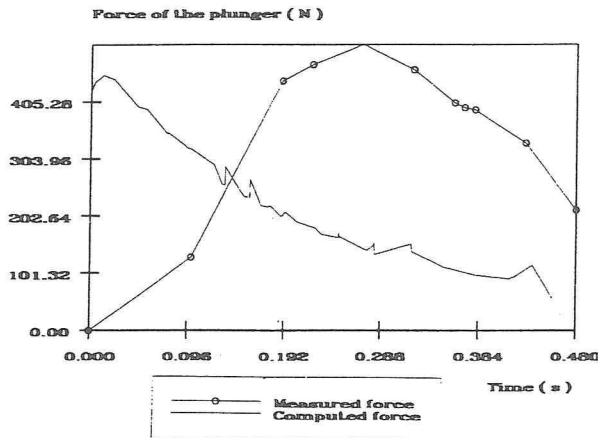


Figure 10 Force of the plunger versus time

but decreases with a similar slope. This seems to be a clear indication that the newtonian behavior is a crude approximation.

7 CONCLUSION

Successful simulations of stretch-blow molding processes have been carried out using ULFEM. The automatic remeshing technique has permitted to simulate the inflation of large stretch-ratio PET bottles.

In this first approach, a viscous constitutive equation for PET rheological behavior was chosen. Realistic intermediate shapes of the bottle and thickness distribution have been obtained as well as order of magnitude of the stretching force.

Next step of the work is to include viscoelastic behavior taking into account memory phenomena like stress retardation and relaxation, shear recovery, as well as temperature dependent phenomena.

ACKNOWLEDGMENT

The research is supported by Sidel Company and the French Ministère de la recherche et de la Technologie (MRT n° 90A 136). Special thanks go to R. Hudebine and R. Roussel at Sidel Company for the experimental work.

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