Some Rheological Aspects of Fracture in Thermoforming

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This paper focuses on several aspects of drawability, including the interactions between material parameters, operating temperatures, and frictional properties of the material. The deep draw process for a molten plastic sheet can be described by a simplified model using the characteristics of the normal stress as a lumped parameter. A rapid evaluation of the maximum draw ratio and mold closing speed can be obtained by systematically drawing a series of three draw ratios. The fracture mode should then be examined to determine the appropriateness of molding temperatures. Therefore the maximum attainable draw ratio can be calculated from the elongational viscosity data. To support the analysis, data is provided on the formation of a cup with polystyrene sheets and using Maxwell extensional model as an example.

INTRODUCTION

Thermoforming is a two-stage process in which a sheet is heated near its melting point and molded to obtain the desired shape. Deformation kinematics becomes important because elongational deformation plays a major role in the molding stage. This influences the selection of materials and processing parameters.

A number of studies of the elongational flow of molten polymers have been reported in the literature (1-5). The work of Vinogradov (1), Meissner (2) and the studies of Stevenson (3) may be classified as controlled deformations, since the sample is deformed at a controlled rate. On the other hand, a host of data was obtained under the non-uniform deformation occurring in fiber spinning (6-7) and blown film extrusion (8-9). With the combined information, we are able to account for the instability in fiber spinning and blown film extrusion.

The results obtained under controlled flow conditions have generally been presented as plots of apparent extensional viscosity versus time of deformation for a series of constant extension rates. For low extension rates, the extensional viscosity increases with time until an equilibrium value is attained equal to three times the shear viscosity at zero shear rate. With increasing extension rate, however, a rapid stress growth is generally observed. If the stress exceeds some critical value of about 10^6 N/m^2, the material ruptures.

In thermoforming, the drawing performance of a material is influenced by factors that control the draw limit and the uniformity of deformation. The evaluation of drawability is difficult since strain distributions, material properties, and instability criteria all must be modeled correctly. Strain uniformity in thermoforming is governed by three types of variables:

- Design variables—shape, curvature
- Process variables—mold speed, pressure, temperature, friction, mold alignment
- Material parameters—thickness, elongational viscosity, sheet orientation, thermal stability

The design variables are determined in accord with product requirements. The process variables are the most important ones in manufacturing. However, these are always adjusted to yield maximum production rates at minimum cost and, hence, require the utmost from material properties. In practice, thermoformed parts are likely to be thin in various locations. The thickness ratio of a part can reach 10 to 1. A material of high rupture stress processed at a uniform profile at low extensional strain rate would give an optimum drawing performance.

A number of papers have considered the performance of thermoplastics in the deep drawing of cups from a sheet (10-15). Comparisons of the observed performance with theory have been made in terms of parameters found to be relevant for metals. It appears that the viscometric functions generated during rheological characterization are not fully utilized in industrial applications, especially in the thermoforming operation.

This paper describes the rheological aspects of sheet deformation, including the interactions between material parameters, operating temperatures, designed parameters, and the deformation rate. The objectives of this paper are 1) to construct a simple model so that the processing variables can be readily optimized; and 2) to develop a qualitative test to assort the drawing performance of different polymers.

MODEL FOR THE PREDICTION OF MAXIMUM DRAWING

We shall restrict attention to the case where an initially flat sheet is forced into the shape of an axisymmetric shell. As indicated in *Fig. 1*, the deformation can be described by a cylindrical polar coordinate system with the polar-axis along the center cup line. The sheet is assumed to undergo a deformation with a typical particle initially at (r, θ, z) moving to (ρ, θ, ψ) at time $t > 0$. The principle stretch ratios may be written as:

$$\lambda_1 = \left\{\left(\frac{\partial\rho}{\partial z}\right)^2 + \left(\frac{\partial\psi}{\partial z}\right)^2\right\}^{1/2} \tag{1}$$

$$\lambda_2 = \psi/r \tag{2}$$

$$\lambda_3 = 1/\lambda_1\lambda_2 \tag{3}$$

where λ_3 is determined by the assumption of incompressibility. The stress equilibrium in the flange at a radial position is:

$$(\partial\tau_{rr}/\partial r) - (\tau_{\theta\theta} - \tau_{rr})/r = 0 \tag{4}$$

where τ_{rr} and $\tau_{\theta\theta}$ are the radial and circumferential stress components.

Forces acting in the material can be represented by (12):

$$F_t = F_p + F_c + F_f \tag{5}$$

where F_t = the tension actually measured at the rim
F_p = the mechanical force acting in the direction of punching
F_c = the compressive and bending forces
F_f = the frictional force

Integration of these equations requires the assumption of a specific plastic stress-strain relationship. The mathematical modelling of molding a cold sheet has been analyzed, notably by J. Williams (14), but the full equations are difficult to handle without extensive computational facilities, and require detailed knowledge of material functions and constitutive equations which are not always readily available. The following treatment is a semi-empirical approximation which may be used for qualitative comparison of the draw down behavior of different plastic sheets.

Let us define the average strains as a logarithm of draw ratios. Orientation is probably the major cause of non-machine related problems in thermoforming. To check frozen-in-strains, a test should be made by immersing samples in a hot oil bath for 10 minutes.

$$\begin{array}{c}\text{Shrinkage ratios}\\ \text{at the axial direction}\end{array} = \alpha_i = \frac{S_{rd}}{S_r} \tag{6}$$

$$\begin{array}{c}\text{Shrinkage ratios}\\ \text{at the circumferential direction}\end{array} = \beta_i = \frac{S_{\theta d}}{S_\theta} \tag{7}$$

where S_r, S_θ, and S_{rd}, $S_{\theta d}$ are shrinkage ratios before and after molding in the correspondent directions.

$$\text{The average draw ratio} = \bar{D} = \sum_{i=1}^{n} (\alpha_i^2 + \beta_i^2)^{\frac{1}{2}}/n \tag{8}$$

where n is the number of samples in various locations.

$$\text{The time scale of process} = t = \frac{\text{mold depth } (m)}{\text{punch speed } (V_p)}$$

$$\text{Then, the elongational rate} = \frac{V_p}{m} \ln \bar{D} \tag{9}$$

For the first approximation one can estimate the stress exerted on the sheet for the thermoforming operation with given rheological characteristics. These can be either in terms of experimental data or a hypothetical plot of extensional viscosity vs. extensional rates as reported by Everage and Ballman (5). *Figure 2* shows the construction of an operating line using three or more draw ratios. Based on the maximum principle stress theory (16), which states that the material will fail when the numerically largest principle stress equals the failure stress in uniaxial tension, the maximum draw ratio, D_m, can be obtained:

$$\ln D_m = \frac{\tau_m}{\bar{\eta}_e(V_p/m)} \tag{10}$$

where τ_m is the rupture stress of the materials.

This result suggests that for a given material the maximum draw ratio attainable decreases with an increasing elongational viscosity, and with an increasing mold speed. The elongational viscosity increases as the sheet temperature, T, is decreased, following the Eyring-Frenkel relation.

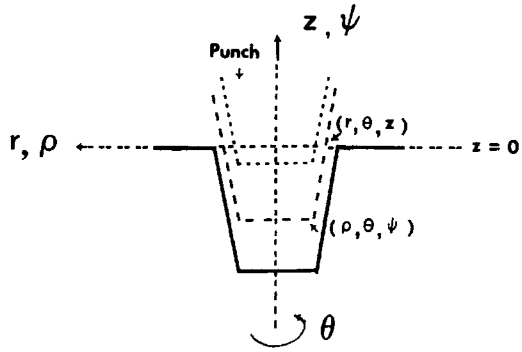

Fig. 1. Deformed configurations for cup drawing.

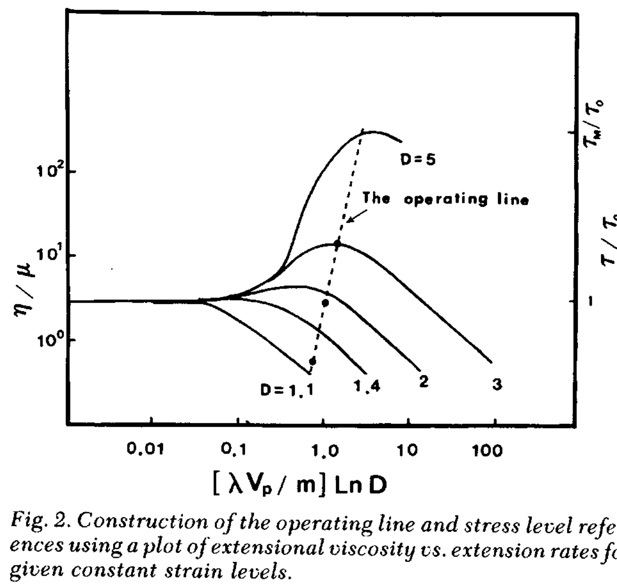

Fig. 2. Construction of the operating line and stress level references using a plot of extensional viscosity vs. extension rates for given constant strain levels.

$$\bar{\eta}_e(T) = \bar{\eta}_e(T_o) \exp (E/R) [(1/T) - (1/T_o)] \quad (11)$$

where E is the activation energy, and R is the gas constant.

Using the Lodge elastic liquid (17) model, the draw ratio can be expressed as:

$$\ln D_m \simeq \frac{m}{V_p} \left(\frac{1}{2} \left(\frac{1}{\lambda} \right) + \left[\left(\frac{1}{\lambda} \right)^2 + \frac{4\, T_m}{3 \eta_o \lambda} \right]^{\frac{1}{2}} \right) \quad (12)$$

where λ is the effective relaxation time. This result points out the important role of the relaxation time in thermoforming. We should note that *Eq 12* was obtained for the total elongational strain less than 5.0, which is within the normal range of thermoforming.

OPERATION PARAMETERS AND DISCUSSION

Failure Due to Necking

Figure 3 shows the thickness distribution of a vertical section of the molded part. The thickness variation is a reflection of the inhomogeneity in strains on the sheet. This inhomogeneity may be due to non-isothermal conditions across its thickness and area as well. As the sheet is drawn into the mold, it initially contacts the mold at the rim and then at the bottom center of the male mold. As the molding progresses, the material in contact with the cold surface will drop in temperature resulting in a higher elongational viscosity in the area. Therefore, very little additional thinning takes place at the rim or in the region around the plug nose. As a result, the total amount of material available for drawing decreases, and the cup wall thins.

A measurement in thickness distribution will locate the neck-down region. For many realistic operations, the maximum drawability predicted from *Eq 10* may be cut in half, depending on the extent of necking.

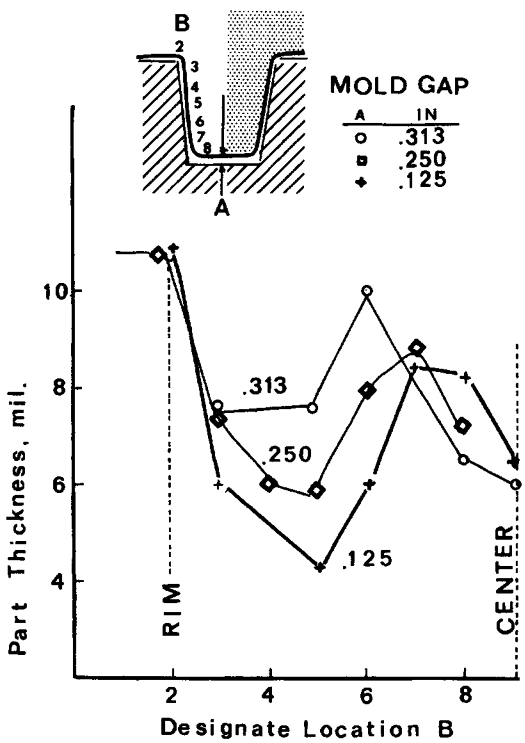

Fig. 3. Thickness variations of thermoformed part with different alignments of the mold.

Failure Due to Crack Initiation

Table 1 shows the effects of heating on the performance of forming a polystyrene cup. The temperatures of the sheets are proportional to the heater temperature and heating time. The failure mode occurring at the lower temperatures was due to crack initiation and growth at the corners of the cups. Studies of normal stress yielding in polystyrene film subjected to uniaxial load have shown the craze region to be occupied by drawn fibrils and voids. In a glassy polymer, crazes initiate cracks that are responsible for the overall brittle fracture at 5 percent level elongations. Consequently, a higher sheet temperature is required to eliminate the cracks. *Table 1* shows that the draw ratio increases with an increasing sheet temperature up to the point where the sheet will not have enough melt strength to hold its place.

Effect of Friction on Molding

The role of sliding friction between a sheet and a mold in the molding operation was evidenced in the following experiment: A series of runs were made to thermoform cups of various depths while all other thermoforming conditions were kept constant. The side walls began thinning at a medium draw ratio and a sheet fracture occurred at a higher draw ratio. At this point, vacuum assistance was employed on the female mold so that the friction between the sheet and the male mold is reduced, producing a good thermoformed part.

It should be noted that the friction between a sheet and a mold is a function of temperature. Data determined from sliding friction in *Table 2* shows that the friction increases drastically near the glass transition temperature. In the molding process when the sheet is over-heated or when the mold is too hot, frictional force would be extremely high in the area where contact first occurred, thus the sheet loses its overall mobility and results in localized elongation at the side wall or wherever the friction force is minimum.

From *Eq 5* and *Table 2* it can be seen that a lower sheet temperature results in less stress variation due

Table 1. Effects of Heating on the Performance of Forming

Sample no.	Heater temp °F	Heating time, sec	Sheet temp °F	Draw ratio*				
				1.2	1.4	1.8	2.4	3.0
1	800	6	—	X	X	X	X	X
2		8	—	0	0	X	X	X
3		10	—	0	0	0	0	X
4	900	4	170	X	X	X	X	X
5		6	226	0	X	X	X	X
6		8	286	0	0	0	X	X
7		10	308	0	0	0	0	0
8	1000	3	180	X	X	X	X	X
9		4	225	0	0	X	X	X
10		6	268	0	0	X	X	X
11		8	306	0	0	0	0	0
12		10	348	X	X	X	X	X

* An impact polystyrene sheet of 20 mil thick was used.
X—Failure.
0—Pass.

Table 2. Sliding Friction of Polystyrene Sheets on the Mold Surface

Temperature °F	80	140	180	190	200	210
Friction Factor	0.30	0.32	0.35	0.40	0.58	0.85

to friction. In most cases, it is necessary to conduct the drawing process above the glass transition point. Because of friction characteristics, the thickness distribution of thermoformed part can be manipulated by mold temperature profiles with vacuum and/or pressure assistance.

CONCLUSION

The deep draw process for a molten plastics sheet has been successfully described by a simplified model which was developed using the characteristics of elongational viscosity. Using this model, a rapid evaluation of the maximum draw ratio and mold closing speed can be obtained by systematically conducting three draw ratios. The fracture mode should then be examined to determine the appropriateness of molding temperatures. The maximum attainable draw ratio can therefore be calculated from the elongational viscosity data. This study is not suitable for the deep drawing of ductile thermoplastic sheets below the glassy state since the plane compression yield strength becomes dominant in solid-phase forming.

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