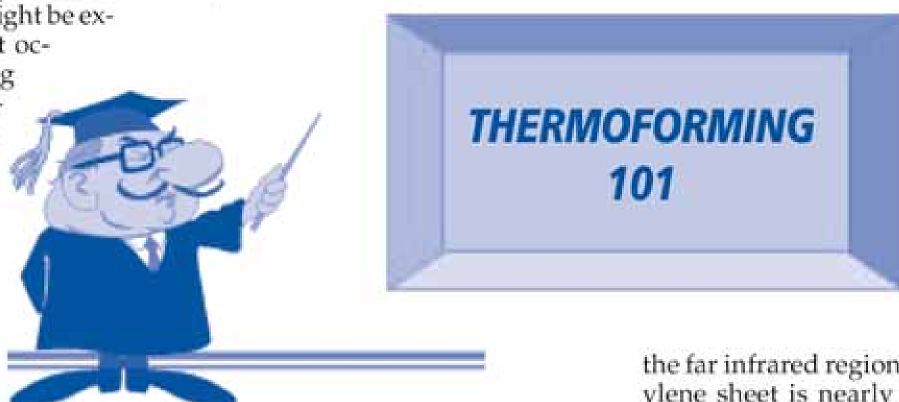
Stretching The Sheet - I

This is a three-part tutorial in sheet behavior during heating and forming. This part focuses on sheet behavior while it is still in the oven. The second part considers pre-stretching. And the third part considers draw-down into or onto the mold.

Sheet Behavior In The Oven

It is common for a sheet to exhibit periodic shape changes, including waffling or swimming, tautness and sag as it is being heated to its forming temperature. In many cases, the sheet is relieving stresses[1] that were imparted during the cooling portion of the extrusion process. As might be expected, shape changes that occur early in the heating process are the result of conditions imposed late in the extrusion process. Shape changes occurring late in the heating process are the result of changes imposed in the roll stack portion of the extrusion process. Orientation or stresses that are frozen in during the extrusion of the sheet are typically relieved relatively late in the heating process when the sheet is becoming quite soft. Annealing of this residual orientation causes the sheet to contract. The effect is seen as a tightening of the sheet between the clamps. Excessive orientation can cause the sheet to pull free of the clamps.



The Nature of Sag

In addition to relaxation of imposed stresses, the heating sheet is also experiencing a rapid reduction in physical properties, such as modulus and tensile strength. As the sheet approaches its transition temperature, the polymer is no longer strong enough to support its own weight. The sheet begins to sag or droop under its own weight. As expected, the extent of the sag increases with increasing sheet temperature. For all but the very earliest sag, the sheet is being stretched in tension. Therefore, the hot tensile strength of the polymer is very important in determining the extent of sag. However, the viscous character of the polymer is now considered to be a contributing factor to the rate at which the sheet sags.

Although sag is an anticipated aspect of sheet heating, it is difficult to deal with. Sag can cause nonuniform thinning in the sheet prior to forming. As the sheet sags, it becomes "salad bowl"-like. As a result, the local heating efficiencies, top and bottom, are altered, although the effect is apparently not as dramatic as one might expect[2]. The sagged sheet may rub against the lower oven wall as it exits, although ovens are designed with drop sides to accommodate the sag. And certain polymers simply tear away during sagging. Technically, substantial strides are being made in mathematically modeling sag using finite element analysis and linear viscoelastic models for the polymer.

Heating Rate

Many things influence the rate at which a sheet heats to its forming temperature. Certainly the dominant factors include heater temperature, the thermal properties of the sheet and its thickness. Other factors include the efficiency of heat transfer between the heaters and the sheet, the energy absorption characteristics of both the sheet and the heaters (better known as their emissivities), air temperature and movement around the sheet while it is heating, and the sheet dimensions relative to the heater dimensions. More subtle factors include the color, texture, and transparency of the sheet. Shiny or polished sheet is thought to reflect more energy than roughened or matte sheet. The technical aspects of this effect may focus on the spectral rather than diffuse nature of the reflection of incoming rays of energy. Dark sheets are thought to heat more rapidly than white sheets. This may be due to the absorbing characteristics of the pigments near the sheet surface. Sheet transparency refers to transparency in the far infrared region. Thin polyethylene sheet is nearly transparent to IR energy and so heats quite slowly. Thin PTFE sheet on the other hand is nearly opaque in the IR region and so heats quite rapidly.

Newer heating technologies use short IR wavelength energy. According to ported gas burner and halogen heater manufacturers, the high heater temperature generates short wavelength energy that is absorbed in the volume of the sheet rather than just at the surface, as is the case for far infrared radiative heaters. This provides for more uniform heat, lower sheet surface temperature, and more rapid heating rates. This technology appears most effective for thick sheets with relatively low pigmentation levels.

Keywords: sag, finite element analysis, viscoelasticity, tensile strength, extrusion process, heating rate, infrared region

[1] Residual stress, orientation and shrinkage are addressed in a future tutorial.
[2] A. Buckel, "Comparison of American and European Heavy-Gauge Thermoforming Machines", TFQ 18:3, 1999, p. 13.

Stretching The Sheet - II

This is a three-part tutorial in sheet behavior during heating and forming. The first part focused on sheet behavior while it is still in the oven. This part considers draw-down into or onto the mold. The last part considers pre-stretching.

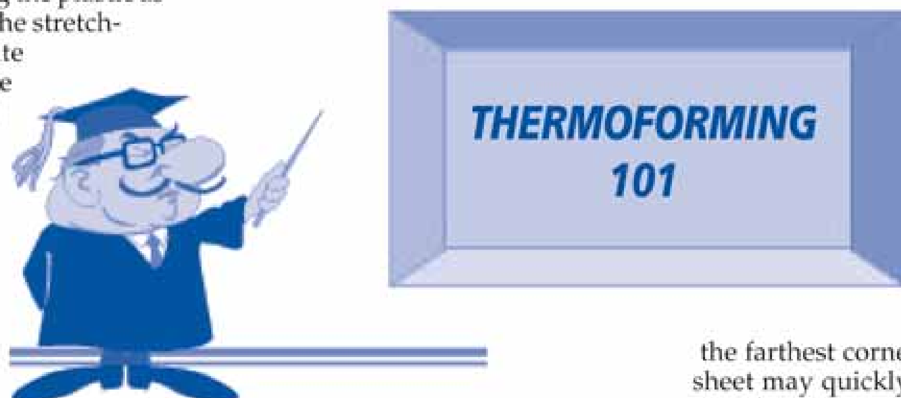
Simple Draw-Down

As noted earlier, thermoforming is technically deformation of a rubbery mostly-elastic membrane. In simple terms, we are stretching the plastic as if it is a rubber sheet. The stretching mechanism is quite easy to explain. Imagine a simple drinking cup female mold. The hot plastic first contacts the rim of the cup, then sags uniformly into the cup. Vacuum is applied to the cup cavity and the sheet begins to stretch into the cavity[1], forming a dome. Then a portion of the plastic contacts the cup edge. For all intents, the friction between the hot sheet and the mold surface holds that portion against the mold throughout the rest of the draw-down. As vacuum continues, an additional portion of the plastic contacts an additional portion of the cup wall. This plastic is also immobilized against or "stuck on" the mold wall. Since some of the original plastic is already on the mold wall, this additional plastic must come from the dome that is still free of the mold surface. And since some of the original plastic is already on the mold wall, it is only logical that the additional plastic must be thinner than the original plastic. As draw-down or stretching continues, more and more plastic is drawn from the hot plastic dome that is free of the mold surface and is deposited on the mold wall. And it is apparent that both the thickness of the plastic in the dome and that of the plastic just deposited on the mold wall must decrease as draw-down continues.

In other words, the wall of the cup gets progressively thinner toward the bottom of the cup. And as expected, as the plastic draws into the last portion of the cup mold, the corner, it becomes even thinner.

Stress-Strain Related To Draw-Down

In an earlier tutorial, it was stated that:



When force is applied to any material, it stretches or elongates. The amount that it stretches depends on the amount of force per unit area, or "stress," applied to the sheet, the nature of the material and its temperature. The amount that the material stretches is elongation or "strain."

We can now relate the material behavior to applied load, or stress-strain, to the draw-down of a plastic sheet into the cup mold. The shape and magnitude of the stress-strain curve of any polymer depends on the nature of the polymer and its temperature. Typically, in the forming temperature region, the polymer stretching initially increases slowly with increasing stress, then increases more rapidly as the applied stress increases. Typically, at low temperatures, the polymer stretches a relatively small amount before rupturing. As the polymer temperature increases, the polymer "elongation at break" or its ability to stretch further and further without breaking, increases dramatically. At very high temperatures, this stretching limit begins to drop abruptly, indicating that the polymer molecular structure is too weak to support load.

Initially, the sheet sags into the mold without the application of vacuum[2]. The stress being applied to the sheet is just its own weight per unit area. As vacuum is applied or the stress on the sheet increases, the sheet elongates. This is recognized as "thinning." So long as the applied stress increases, the sheet will stretch and thin as it is deposited against the cup mold wall.

There are many reasons why a sheet may not fully stretch into the farthest corner of the mold. The sheet may quickly cool as it is being stretched. As a result, the amount of stress or equivalently, the applied force, may not be enough to stretch the sheet beyond a certain point. The initial sheet temperature may be too low, and the sheet resistance may be too high to allow the sheet to fill the cavity. Certain plastics "strain harden," that is, beyond a certain strain level, the force needed to stretch the plastic further may quickly increase. If the force is not enough, the plastic stops stretching. Crosslinked polyethylene is an example of such a plastic. For filled and short-fiber reinforced plastics, the force required to stretch the sheet even a modest amount may be so high that forming may require pressures higher than those used in simple vacuum forming. Pressure forming will be considered in a subsequent tutorial.

Keywords: stress, strain, differential pressure, elongation, elongation at break, thinning, strain hardening

[1] The pressure difference between atmospheric pressure on one side of the sheet and vacuum on the other is referred to as "differential pressure".

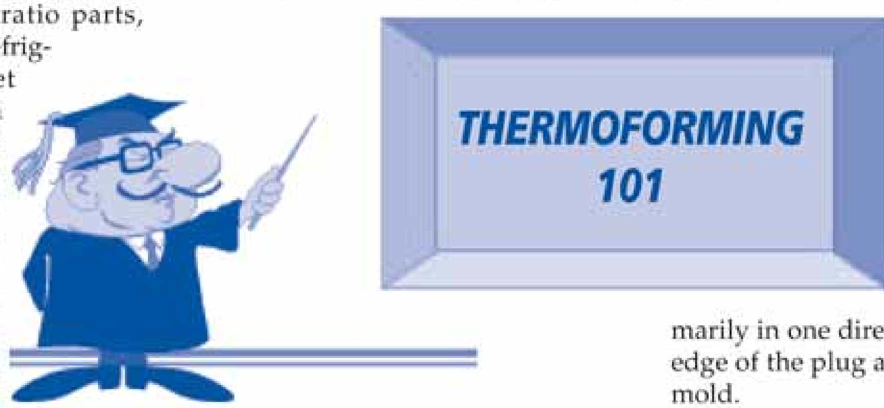
[2] The shape of the sheet is similar to the shape taken by a freely hanging chain or rope held by both ends.

Stretching The Sheet - III

This is a three-part tutorial in sheet behavior during heating and forming. The first part focused on sheet behavior while it is still in the oven. The second part considered draw-down into a mold and its relationship to the stress-strain behavior of the plastic. This part considers pre-stretching.

Why Pre-stretch?

As we saw in Stretching The Sheet-II, the sheet gets progressively thinner as it is stretched deeper into the mold. For large draw-ratio parts, such as drink cups and refrigerator liners, the sheet may be thinned so much at the bottom of the part that the part may fail there. Redistribution of sheet from thicker regions to thinner regions must be done to provide useful, functional parts in both thin-gauge and thick-gage thermoforming. This redistribution is called "pre-stretching." There are two general ways to do this – stretching the sheet with air pressure and stretching the sheet with mechanical means. These are considered here.



Pneumatic Pre-Stretching

This is a technical way of saying that the sheet is pre-stretched using differential air pressure. One way is to clamp the sheet over a "blow box" and blow low-pressure air into the box. Air pressure of 3 to perhaps 10 psi is usually sufficient to "inflate" the sheet into a dome. The mold is then raised into the inflated sheet. Pneumatic pre-stretching is used mostly in thick-gauge thermoforming. Another way is to clamp the sheet over a "draw box" and apply a vacuum to the draw box. Again, a soft vacuum of 5 to 15 inch Hg is usually sufficient to "draw" the sheet into a dome. The mold is then immersed in the drawn sheet. Regardless of whether the sheet is blown into a bubble with air pressure or drawn into a dome with vacuum, the forces acting to pre-stretch the sheet are differential forces, due entirely to the unbalanced air pressure across the sheet. Vacuum pre-stretching is used in both thin- and thick-gauge thermoforming.

As experienced thermoformers know, there needs to be a careful balance between the stretching characteristics of the plastic, the sheet temperature, the extent of differential pressure, the rate of pre-stretching, the extent of pre-stretching, and the timing between inflation and mold immersion. For example, ABS and PMMA can be greatly pre-stretched, even into hemispheres. PS and PC are more difficult to pre-stretch extensively. RPVC and PET are quite resistant to extensive pre-stretching. Further, RPVC will pull apart and PET will locally draw if pre-stretched too quickly. The sheet is nearly uniformly stretched across its surface in pneumatic pre-stretching. Stretching in mostly one direction occurs only where the sheet is clamped to the frame.

Mechanical Pre-Stretching

Mechanical pre-stretching relies on a solid object called a plug or a pusher. This device is mechanically or pneumatically driven into the heated sheet before it touches the mold cavity. Plugs are used extensively in both thin- and thick-gauge thermoforming. In general, two things happen when the solid object contacts the sheet. The first is that the sheet is impaled on or sticks to that portion of the plug that contacts the sheet. As a result, that portion doesn't stretch and it cools by transferring its energy to the cooler plug. This can lead to objectionable "plug markoff" on the part. And then stretching takes place in the sheet free of the mold surface and between the edge of the plug and the edge of the mold. This can lead to an objectionable ridge or "witness line" at the edge of the plug. Unlike pneumatic pre-stretching, plug stretching is primarily in one direction, between the edge of the plug and the edge of the mold.

As with pneumatic pre-stretching, in plug assist pre-stretching, there needs to be a balance between polymer stretching properties, sheet temperature, rate of stretching, and extent of stretching. As with pneumatic pre-stretching, polymers such as ABS and PMMA are easily pre-stretched with plugs and PVC and PET are more difficult to pre-stretch with plugs.

Plugs are more versatile than air for redistributing plastic across a mold surface, particularly as the part becomes more complex. But plug design and shape remain mostly trial-and-error.

Keywords: pre-stretching, blow box, draw box, plug assist