Square One – Observe Your Sheet As It Heats[1]

In the last TF101, we discussed the difference between orientation and shrinkage. Here we continue a portion of this discussion by considering how we can observe the effects of orientation or frozen-in stretching as the sheet is being heated.

Mirror-Image

Consider this thought experiment. Stretch a rubber band and cool it in liquid nitrogen while it is stretched. The rubber band orientation is now frozen in. Now place the rubber band on a table and watch as it slowly reheats. Ultimately all the frozen-in stretch is relieved and the rubber band returns to its original length.

A long time ago, we said that thermoforming was basically an elastic process. The plastic is heated until it is pliable. It is then stretched and "frozen" against a cool mold. If the formed part is reheated to the forming temperature, most or nearly all of it slowly returns to a flat sheet.

Now if we accept this premise, then we should be able to observe any orientation that has been frozen in during the extrusion process. And in fact, we can, as we shall see.

To do this mirror-image thing, we begin at the extruder die exit and follow the thermal history of the sheet, step by step, until it arrives at the thermoformer. At each step, we consider where in the thermoforming process the sheet sees that temperature.

Just Beyond the Extruder Die

The sheet is extruded from the die and is laid onto the middle roll of the roll stack. The top roll may press against the sheet to calibrate its thickness. The molten plastic may be squeezed in the cross-machine direction to achieve a specific final sheet width. The molten plastic is cooling and some of the extrusion stresses are relaxing. Where might this occur in the thermoforming process? The sheet termperature is hottest just as it exits the oven. So sheet sag may be related to the sheet conditions between the extruder die and the roll stack.

As the Sheet Cools on the Rolls

The underside of the sheet is cooled by direct contact with the middle roll of the roll stack. The top surface is only cooled with room air. The uneven cooling can freeze in stresses on only one side of the sheet. Where might these stresses be relieved in the thermoforming process? Since the sheet is now colder than it was a few moments ago, we would expect that this would occur before the sheet exhibited substantial sag. And it would be manifested as a tightening of the sheet as the stresses relieved.

As the Sheet Temperature Approaches a Transition Temperature

Amorphous polymers, such as polycarbonate and polystyrene, go from being rubbery to glassy at their glass transition temperatures. Crystalline polymers, such as polyethylene and polypropylene, go from being nearly fluid to rigid at their melting temperatures[2]. In the extrusion process, this occurs on the rolls for thin to moderately thick sheet. Transitions usually entail density increases. If the sheet is confined, internal stresses occur. These are frozen in by the transition. What would we expect to see as we reheat the sheet in thermoforming" Certainly during reheating, the polymer density decreases. Because the stresses are not locked in uniformly through the sheet thickness, we see the sheet ripple or "swim."

Heat Retention

In extrusion, the sheet is never allowed to cool to room temperature before being cut and stacked on pallets or wound onto rolls. As a result, the rolls or pallets retain heat for extended periods of time. This retained energy can often provide some mild annealing or help relieve some of the locked-in stress. Regardless of extent to which this happens, the concern is that the thermal history of the sheet on the bottom of the pallet is different than one in the middle. And that one is different than the one on the top. The same analysis holds for rolled goods. The extent of this stress relief is observed in the initial tightening of a sheet in the very early heating times. Certainly if this tightening varies throughout the production run, the temperature control of the sheet suffers.

Smoking

Plastics are filled with many small molecule additives – internal and external lubricants, antiblocking agents, UV absorbers, organic dyes and colorants, and so on. Some of these migrate to the sheet surface and some are volatile. In extrusion, the sheet may off-gas or smoke as it leaves the extruder and as it forms over the middle chill roll. In thermoforming, at some place in the oven after the initial sheet tightening, the sheet may smoke.

Moisture

Regardless of how well thin-gauge rolls are wound or heavy-gauge sheet is palletized, air diffuses between the sheet plies in storage. And with air comes moisture. For some polymers such as polycarbonate and polyethylene terephthalate (PET), the moisture is absorbed into the sheet. For others, such as polyethylene, the moisture is simply adsorbed on the surface of the sheet. In thermoforming, where does this moisture exit? In the very early stages of heating, we might actually see the sheet steaming. Keep in mind that steaming is not smoking. These effects occur at different times in the heating process. ■

Keywords: Rippling, tightening, off-gas, stress relief, moisture

[1] ***Thermoforming 101*** is designed to be a tutorial on the basic building blocks of the thermoforming industry. The first series of lessons concluded in TFQ 21:3, 2002. This is the fourth in the second series of lessons that have as their objective to fill in the gaps from the first series of lessons.

[2] Really at their recrystallization temperatures. Perhaps we will consider this concept in a later lesson.