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 re-heats. 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 temperature 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.

**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.

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