HOW TO OPTIMIZE PERFORMANCE AND MINIMIZE COSTS IN REFRIGERATOR AND FREEZER LINERS

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Introduction - Liner Fabrication Technology and Resins

The extrusion/thermoforming process is accepted within the industry as the most effective and versatile manufacturing technology for the fabrication of refrigerator liners. Thermoforming is a low-temperature low-pressure process when compared to other processes like injection molding and blow molding, and allows the use of relatively inexpensive and light mold materials and thus rapid tool construction at low costs.

The liner manufacturing and subsequent assembly is as follows: The plastic is first extruded or co-extruded into a cut sheet of 3-5mm in thickness. Sheets are subsequently stacked and allowed to further cool down before being transferred to a vacuum thermoformer, where they are heated to allow forming around a mold. The liner is cooled and then proceeds to the trimming and punching station to remove excess plastic and to make holes for wiring and tubing. The liner is then transferred to an assembly line, where it is fixed to the steel outer cabinet, and where the refrigerant system, electrical wiring, etc., are mounted. The assembled unit subsequently proceeds to the foaming unit where a mold matching the shape of the liner is used to maintain the liner shape while polyurethane foam is injected in the cavity between the steel cabinet and the plastic liner. After foaming, the compressor and internal accessories are installed and the unit undergoes final inspection.

Styrenic resins such as High Impact PolyStyrene (HIPS) and Acrylonitrile Butadiene Styrene (ABS) copolymer are used to manufacture liners. These amorphous polymers offer a wide processing window and meet critical application requirements such as stiffness, ductility, chemical resistance, good aesthetics and dimensional stability. Although ABS is typically more expensive compared to HIPS, the enhanced stiffness and strength allow the use of less resin per liner, which can make the overall cost penalty versus HIPS significantly smaller. Most refrigerators in Europe are made from a type of polystyrene which has an improved resistance to environmental stress cracking, commonly known as Environmental Stress Cracking Resistant (ESCR) HIPS.

Refrigerator manufacturers are continuously optimizing their liner manufacturing operation to improve the overall refrigerator quality but also to reduce costs. One approach to achieve this is to manufacture liners from sheet with reduced thickness. This results in a reduction of raw material costs and an additional reduction in associated utility and labor costs during extrusion/thermoforming. Figure 1 depicts a typical split in manufacturing costs for a refrigerator liner. However, there are limitations to the minimum liner thickness that can be employed since a too thin liner could result in poor liner appearance and even liner cracking.

Reducing the liner wall thickness

Several factors influence the minimum achievable liner thickness, such as the quality and flexibility of the extrusion and thermoforming equipment as well as the operational discipline and experience of the operators. In addition, there are resin and liner design related aspects.

Liner integrity and shelf guide stability

The liner has to provide sufficient robustness to support pre-assembly and to accommodate the PU foaming process. Stiffness is also required to withstand dimpling of the liner. This is a phenomenon created by voids at the foam/plastic liner interface. The void pressure can decrease significantly due to blowing agent condensation under normal refrigerator operating conditions and due to carbon dioxide diffusion out of the foam. Local deformation of the liner occurs when this pressure difference can no longer be sustained by the liner integrity and this will be visible as dimples, which typically occurs at the end of the PU foam flow path or in details protruding from the liner surface, such as shelf guides.

The deformation of a liner section, as a result of a differential pressure is approximately a function of the resin stiffness and the liner thickness:

$$y \propto \frac{p}{Et^3}$$

With y is the maximum deformation in m, p is differential pressure in N/m^2, E is elastic modulus in N/m^2 and t is thickness in m.

For small deformations, the maximum deflection can be estimated using standard stress and strain formulas for plates. For instance, the deflection will rapidly increase below 0.6 mm liner thickness for a 10 mm wide and deep HIPS refrigerator hollow shelf guide with an underpressure of 0.2 bar (Figure 2).

Therefore, in case liner deformations occur at reduced liner thicknesses, the first parameters to modify would be the PU foam quality and/or the liner stiffness.

Resistance to stress cracking - mechanical

A liner breakage may occur during assembling due to excessive flexing when pressing the liner into the steel cabinet. More problematic is liner cracking when the refrigerator is in use. This is often related to thermally induced stresses caused by different shrinkage and expansion behaviour of the liner, the foam and the metal cabinet. The section of the liner facing the metal evaporator plate may cool down rapidly and cyclic, thermally induced strains and stresses can be up to 0.35% and 4.5 MPa respectively as can be seen in Figure 3. This is well below the critical levels for ESCR HIPS and ABS resins. However, there are examples of complex geometries (shelf guides, corners) where finite element modeling can demonstrate stresses exceeding the resin's yield point.

In addition, voids in the PU foam may cause extra stresses which can be modeled using Roark's stress and strain formulas for a fixed flat circular plate:

$$\sigma_{\max} = \frac{6pr^2(1+\nu)}{16t^2} \quad \text{and} \quad y_{\max} = \frac{-pr^4 12(1-\nu^2)}{64Et^3}$$

With $\sigma_{\max}$ is the maximum stress in N/m^2, p is pressure in N/m^2 , r is the radius of the void in m , ν is the Poisson's ratio, t is the liner thickness in m, and E is the modulus in N/m^2.

As can be seen in Figure 4, stress levels will rapidly increase with PU void size which demonstrates the importance of a good PU foam quality.

Resistance to stress cracking - environmental

Blowing agents, cleaning agents and food stuffs can deteriorate the physical properties of the liner. The plastic may locally soften which can macroscopically result in liner cracking, especially when combined with a stress. The fraction of cracked refrigerators being returned from the market is in the tenths of one percent range. Nevertheless, the risk of a potential cracking issue is often the largest obstacle to liner thickness reduction. Some refrigerator producers have therefore developed a test that involves covering the refrigerator interior with a vegetable oil and applying a temperature cycle (for instance from -10°C to +50°C) for several weeks and monitoring the time to develop cracks, the number of cracks and their growth rate. It is generally accepted that this test is not optimal in view of the poor reproducibility and the costs and time required, as well as the fact that it may not be representative for the refrigerator performance when in use.

Very thin areas and liner stress concentrations must be avoided in order to prevent an increased risk of liner cracking with a reduced liner thickness. The liner design is therefore very important. The higher the draw ratio (which is calculated by dividing the total surface area of the formed part by the length times width of the part) the more difficult it will be to form the part and the thicker the initial sheet needs to be. Special care must be taken to design critical areas like corners and shelf guides. Design rules can be found in thermoforming design guides and thermoforming simulation software is available to address potential design issues upfront. Furthermore PU foam imperfections, such as voids and cracks, should be minimized and suitable resins resistant to stress cracking should be selected.

Aesthetics

In contradiction to ABS, which typically has a glossy appearance, ESCR HIPS resins have a matt appearance. This can be overcome by co-extruding a thin layer of general purpose polystyrene (GPPS) or high gloss HIPS. Both resins may limit liner thickness downgauging since they do not contain a specially designed rubber phase for improved (environmental) stress crack resistance. Figure 5 shows the difference in ESCR performance between a standard HIPS resin, a glossy HIPS resin and an ESCR HIPS resin. The ESCR HIPS resin remains ductile during the entire test, where cracking occurs after 1 day for the standard and glossy HIPS resin.

As can be seen in 6, the onset of cracks and crack growth for a vegetable oil exposed liner sheet with and without a glossy HIPS resin cap layer. The crack initiation will occur at slightly lower strains for gloss layer capped sheets and the crack depth is higher at similar strain levels.

This negative effect is layer thickness dependent, therefore, if a glossy appearance is requested, it is recommended to obtain a thin as possible glossy cap layer, preferably using glossy HIPS and not GPPS.

Regrind

Liner thickness downgauging is also impacted by the amount and quality of regrind used. Regrind should be clean and free from dust and other foreign particles since contaminated regrind is one of the most important contributors to thermoforming rejects. If done properly, the physical properties of natural resin and regrind material will be quite similar as can be seen in the table below.

Table 1: Comparison of natural ESCR HIPS and industrial post thermoforming regrind

		ESCR HIPS natural	ESCR HIPS industrial regrind
Tensile Yield Strength	MPa	14.5	14.2
Tensile Rupture Strength	MPa	22.2	21.9
Elongation	%	70	56
E-modulus	MPa	1620	1620
ESCR (% elongation loss after 10 days at 1% strain in corn oil)	%	66	85

In case a glossy cap layer is used it should be noted that the capping layer resin will accumulate in the core layer according to the formula below.

$$Fraction\_capping\_layer\_material\_in\_core\_layer = \frac{R}{1-R} * \frac{t_{cap}}{t_{core}}$$

With R is the fraction regrind in the process, t_{cap} is the cap layer thickness in mm and t_{core} is the core layer thickness in mm.

An example of capping layer resin accumulation in the core layer can be found in Figure 7. Again it is recommended to use a thin as possible capping layer and additionally, have a constant thickness over the width of the sheet.

Thermoforming

Both ABS and HIPS have large thermoforming windows. ESCR HIPS resins can be formed using temperatures ranging from 125°C to 175°C. Often liners are thermoformed at too high temperatures leaving little orientation resulting in less than optimal overall strength, toughness and stress cracking resistance. Table 2 shows the strength and stiffness of refrigerator liners (back side) versus the sheet forming temperature

Table 2: Influence of forming temperature on physical properties of a liner produced from a developmental ESCR HIPS resin

Forming Temperature	Average Strength (MPa)	Average Modulus (MPa)	Shrinkage after 10 minutes at 130°C (%)
135°C	25	2160	45
150°C	20	2050	33
165°C	16	1820	11

For improved strength and stiffness, the sheet forming temperature should therefore not exceed 150°C. Proper orientation can easily be checked by performing shrinkage tests on samples cut from liners.

Type and quality of resin used

The key requirements for a refrigerator liner resin are thermoformability and stress cracking resistance. Resin improvements, both in HIPS and ABS, have been focused upon enabling the use of thinner sheets and this trend continues. The variables such as molecular weight, rubber content, rubber particle size and plasticizer type and content are available to improve mechanical properties after thermoforming and/or to obtain a better thickness distribution as is represented graphically in Figure 8, without reducing the processing window and ESCR.

Thermoformability: a thermoformable liner resin may allow a lower average liner wall thickness through improved resistance to excessive thinning in areas such as corners and shelf guides. Resin designers will therefore develop resins which allow a uniform deformation during sheet heating as well as prestretching and draping.

Improved Mechanical Properties: a stiffer and stronger resin allows a reduction in overall liner wall thickness because the same performance can be achieved with less material. When comparing two materials, as a rough estimate, for equivalent stiffnesses, the following relationship can be used:

$$\frac{t_1}{t_2} \propto \sqrt[3]{\frac{E_2}{E_1}}$$

with t_l and t_2 are the average wall thicknesses of liners made from material 1 and 2 respectively and E_1 and E_2 are the moduli of material 1 and 2 respectively.

For equivalent strength at different liner thicknesses, a linear relationship is valid:

$$\frac{t_1}{t_2} \propto \frac{\sigma_2}{\sigma_1}$$

with σ_l and σ_2 are strengths in N/m^2 of materials 1 and 2 respectively

A resin with higher strength and stiffness typically shows a reduced resistance to environmental stress cracking. Researchers are developing technologies to break this relationship by modifying the resin's composition and morphology.

Conclusions

Significant resin and process cost savings are in many cases still achievable in refrigerator liner manufacturing by optimizing the fabrication process, the sheet and liner designs and selecting proper resins. There should be a focus on removing fluctuations in the fabrication process and on avoiding contaminations when handling process regrind. 6Sigma defect reduction methodology is an excellent tool to achieve this. In addition, improved liner properties and reduced energy consumption can be achieved by avoiding thermoforming at too high temperatures. Finally, resin selection plays an important role as well. Commercially available refrigerator liner resins can differ in terms of physical properties, more notably, the thermoformability and stiffness and strength after forming and thus have a strong influence on the ability to reduce the liner thickness.

Biography

Roel Vossen is a Senior Application Development Specialist for Styron, a division of The Dow Chemical Company, leading application and resin developments for STYRON Polystyrene resins and MAGNUM ABS resins for Appliance and Sheet & Profile applications

SUPPORTING GRAPHIC MATERIAL

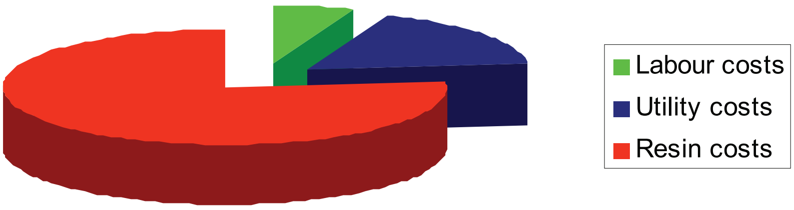

Figure 1 : Typical costs build up for a refrigerator liner

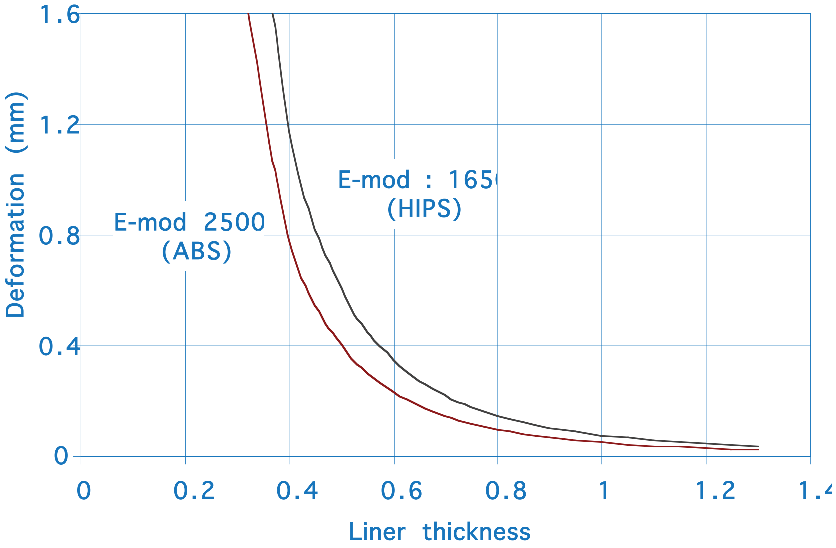

Figure 2: Calculated maximum deformation of a 1 cm wide shelf guide as a function of liner thickness with 0.2 bar differential pressure

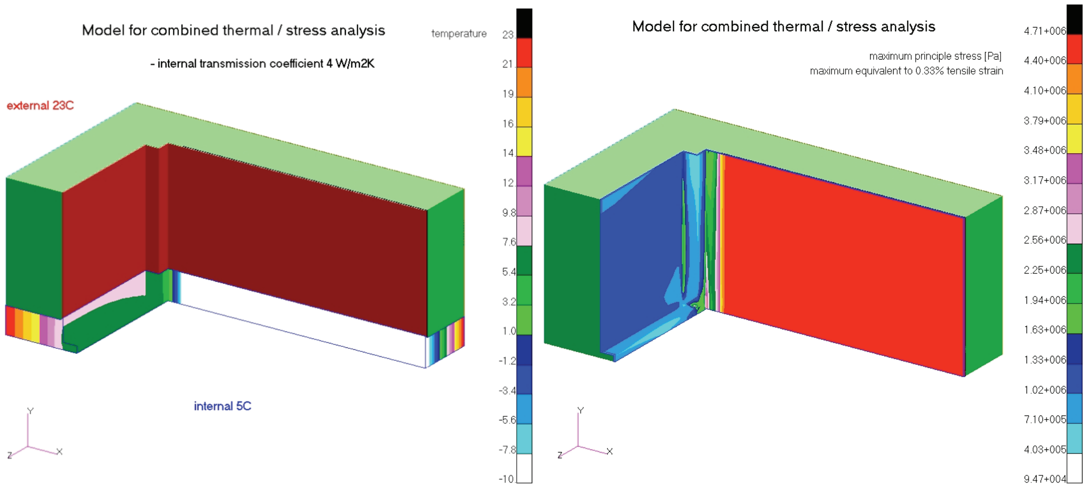

Figure 3: Temperatures and principal stresses in a liner with the evaporator plate at -10°C and refrigerator interior at 5°C. Maximum stresses are found at the cooling plate and in the corners

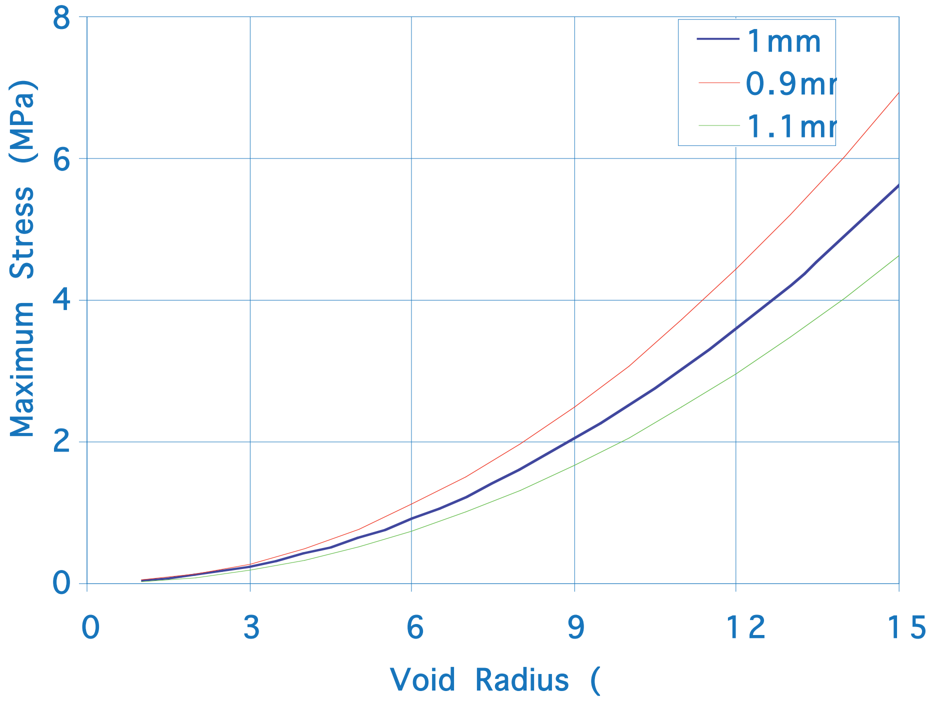

Figure 4: Maximum stress as a function of void radius and liner thickness at a pressure differential of 0.5 bar assuming that the thickness and pressure is uniform and the sheet is fixed at the edges

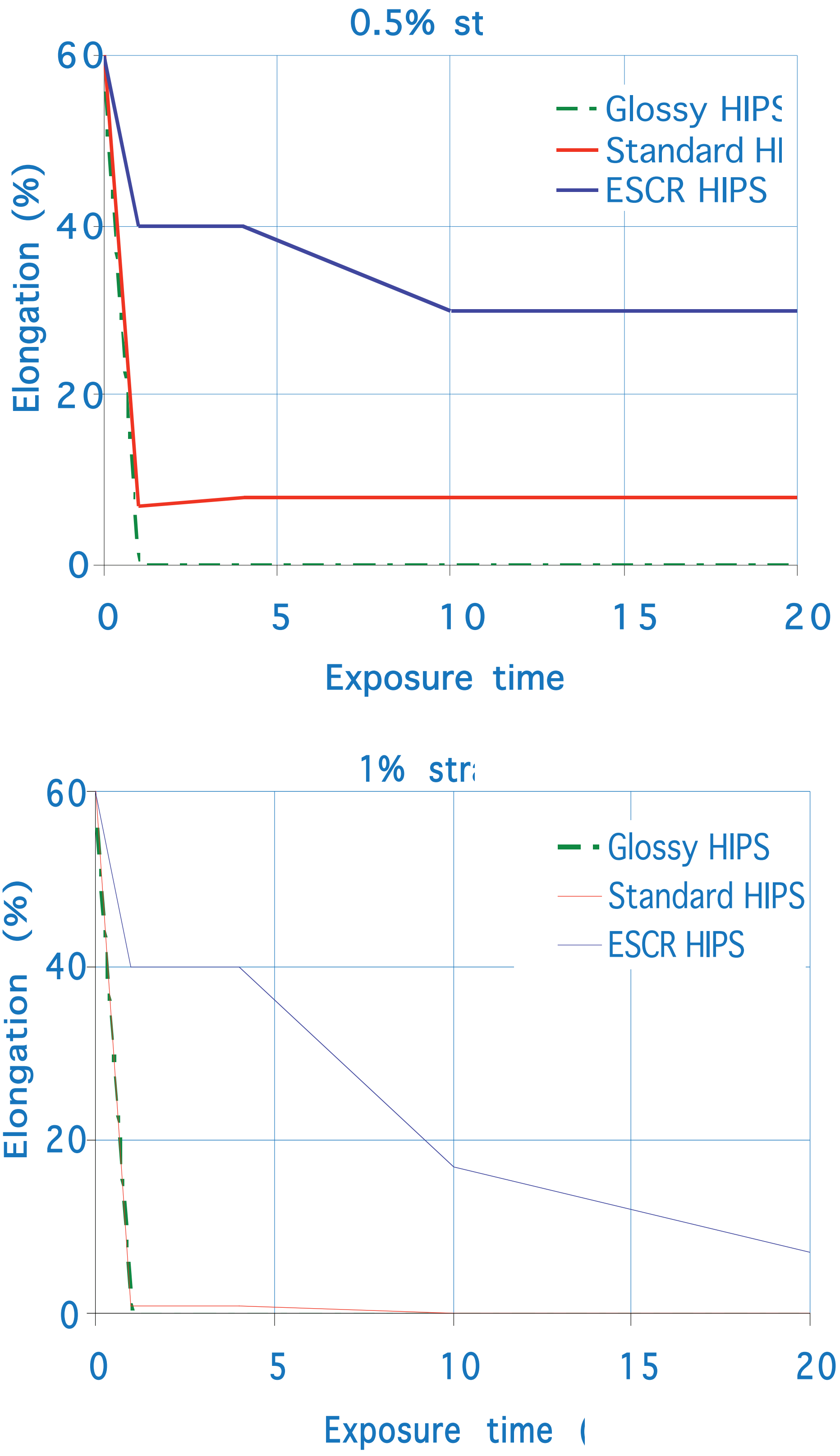

Figure 5: Residual elongation of injection molded ISO bars as a function of exposure time to corn oil and 0.5% and 1% strain

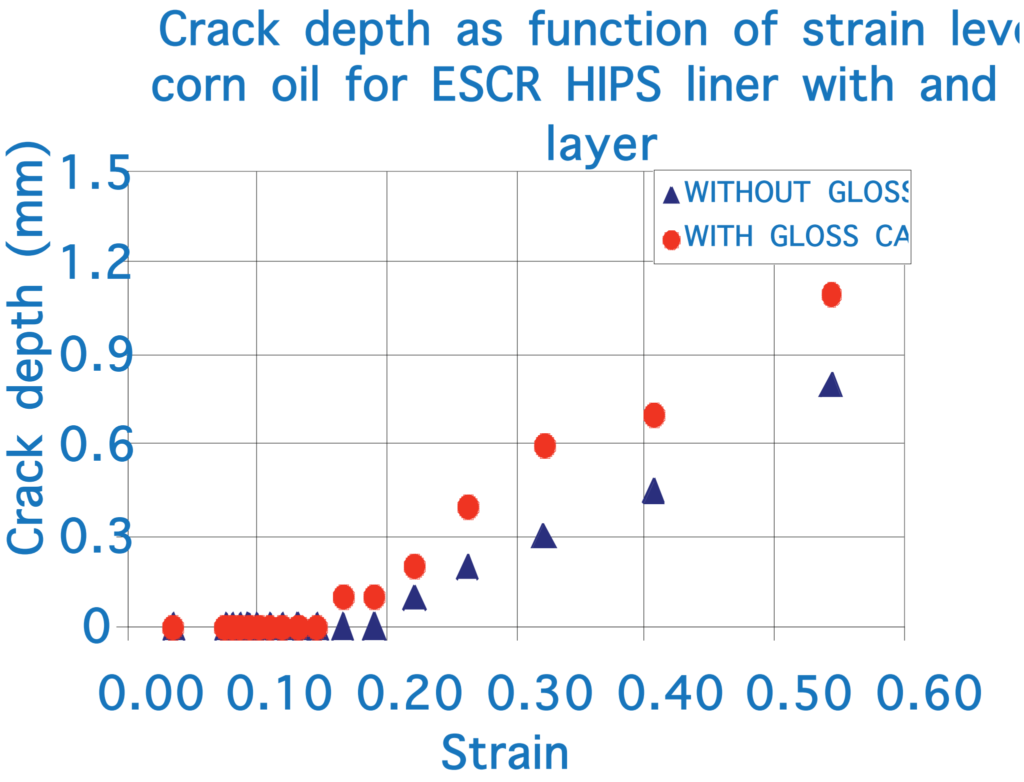

Figure 6: Crack depth as function of strain level after exposure to corn oil for 3 days for a 1.4 mm thermoformed ESCR HIPS liner with and without glossy HIPS layer

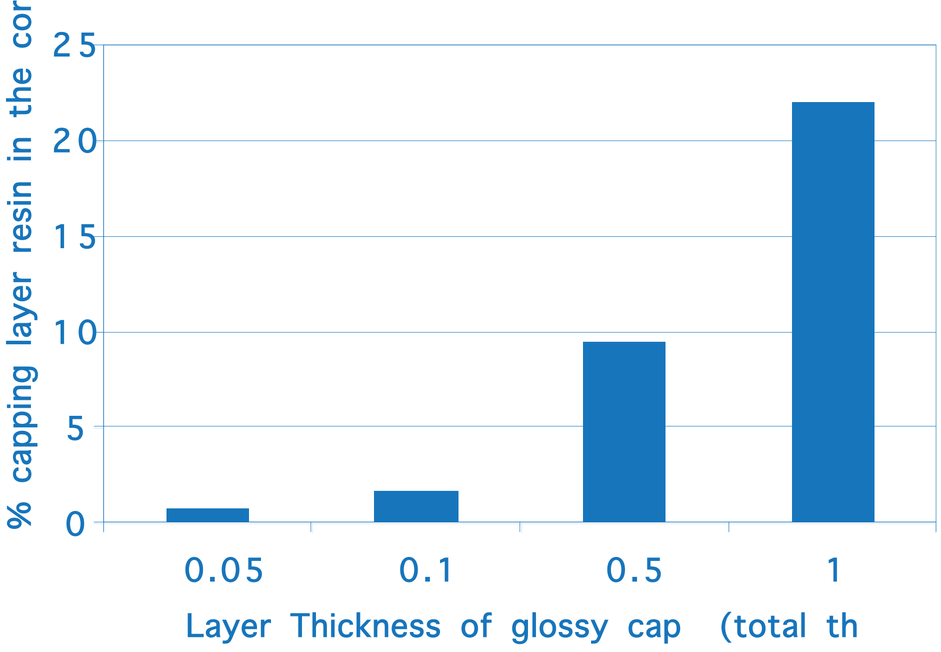

Figure 7: Percentage of top layer resin in the core layer with 40% regrind in the process

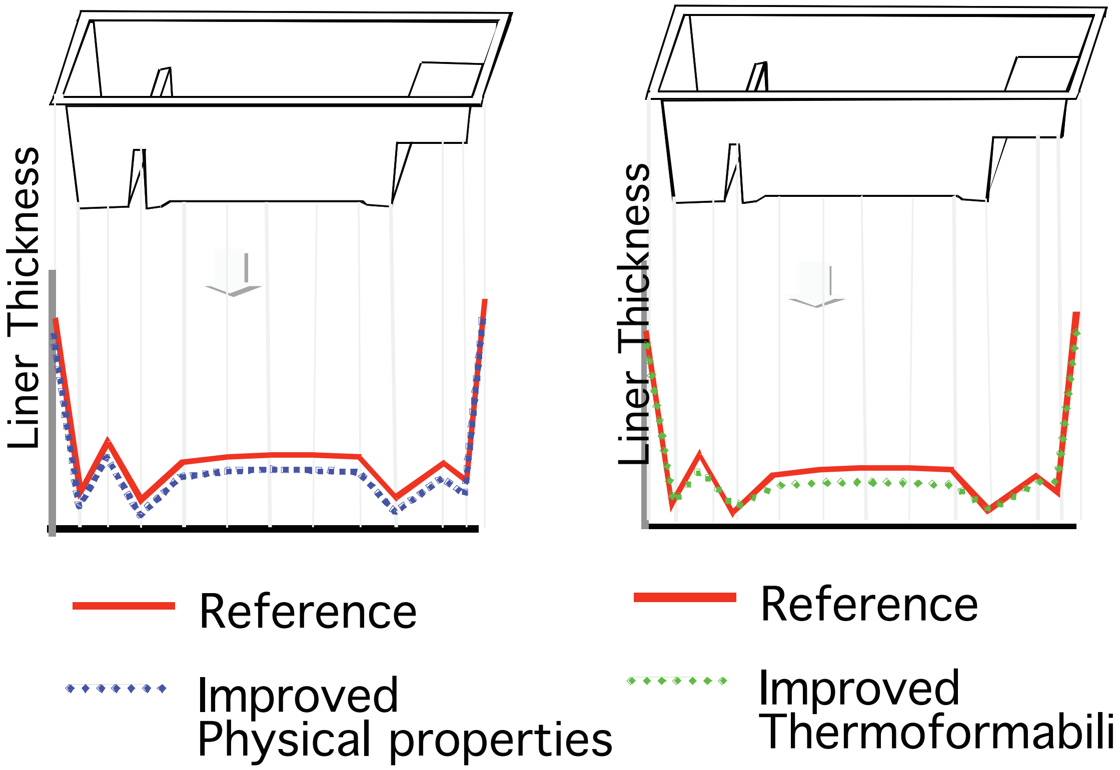

Figure 8: Sheet downgauging by increasing the resin's stiffness and strength (left) or by improving thermoforming allowing more narrow liner thickness distribution (right)