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# Minimizing wrinkling of thermoformed polymer films

**G. Prasath Balamurugan, Rohan N. Pukadyil, Michael R. Thompson, Kent E. Nielsen, and Frank A. Brandys**

*Biaxial stretching of laminates during thermoforming relieves stored compressive stresses and produces decorative parts with improved surface appearance.*

Decorative multilayered films are used increasingly within industry as a replacement for paints and coatings in commercial, construction, automotive, and aerospace applications. These films give the finished products a high-quality appearance, but do not involve workplace safety issues (i.e., associated with volatile organics) or the necessity for high-cost fabrication equipment. To use the films, they can be directly laid onto finished parts that have simple geometries. Alternatively, the films can be laminated over a sheet substrate (made of metal or plastic) and then deformed into more complex shapes through the in-mold forming (IMF) technique.[1–3] However, wrinkling is a common defect that arises from radiant heating during the IMF process (particularly when using high-gloss decorative laminates) and that is difficult to prevent. The wrinkles are a mode of buckling that results from mismatched strain between the layers of the laminate as they thermally expand to different degrees.[4] With this recent development of processes such as IMF, it has therefore become necessary to study wrinkling of all-polymer laminate constructions (i.e., in which all the layers are polymeric), but this field has only been sparsely studied until now.[5–7]

To date, it has been shown that both the amplitude and wavelength of wrinkling in all-polymer laminates are time-dependent.[8] This is very different from the spontaneous nature of elastic constructions (e.g., metal foils). In addition, viscous or viscoelastic models have been proposed to describe the mechanical behavior and explain the time-dependent evolution of wrinkles as a function of the system temperature.[9, 10] None of the current models, however, accounts for the effect of the heating rate. This is an important parameter because higher temperatures are often used for polymer processing than in other industries.

The purpose of our study,[7] therefore, was to examine the effect of temperature—especially heating rate—on wrinkling in a laminate of a decorative polymer film substrate. We thus hoped to identify a preferred approach for vacuum thermoforming of such materials that prevents the occurrence of wrinkling. In particular, we studied an automotive-grade blackout film (FBO)—composed of a polyethylene-polypropylene (PE-PP) copolymer base layer and polyester topcoat—which was supplied by 3M Canada. In addition, we used an acrylic-based pressure-sensitive adhesive to adhere the film to a thick (505$\mu$m) PP substrate.

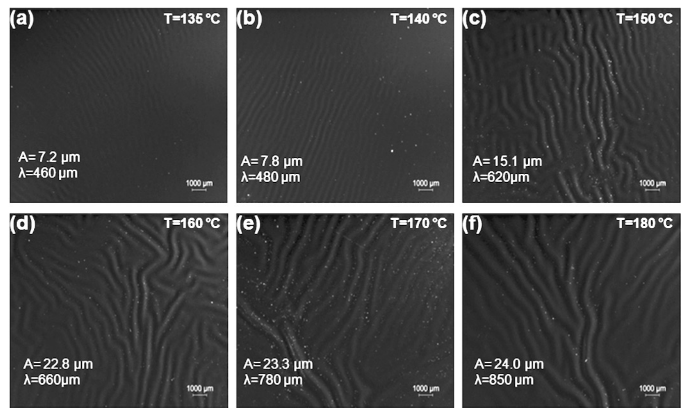


***Figure 1.*** *Optical images of the wrinkled blackout film/polypropylene (FBO/PP) laminates that were heated, at a rate of 70°C/minute, to a temperature (T) of (a) 135°C, (b) 140°C, (c) 150°C, (d) 160°C, (e) 170°C, and (f) 180°C. A and $\lambda$: Amplitude and wavelength of wrinkles, respectively. Scale bars indicate 1000$\mu$m.*

In the first part of our study, we investigated wrinkling with the use of a specially designed bench-top unit (BTU) thermoformer. This equipment consisted of a radiant heating unit and a blowing unit that were coupled with a sample clamping assembly. We mounted the FBO/PP laminates in the blowing unit and then heated them to a specific temperature (between 120 and 180°C) at a chosen heating rate (45–85°C/minute). Our results showed that, irrespective of the heating rate in the BTU, wrinkling always occurred on the film's surface when the laminate temperature exceeded 135°C (see Figure 1). The intensity of wrinkling differed, however, depending on the operating conditions. This temperature threshold lies between the thermal transitions of the

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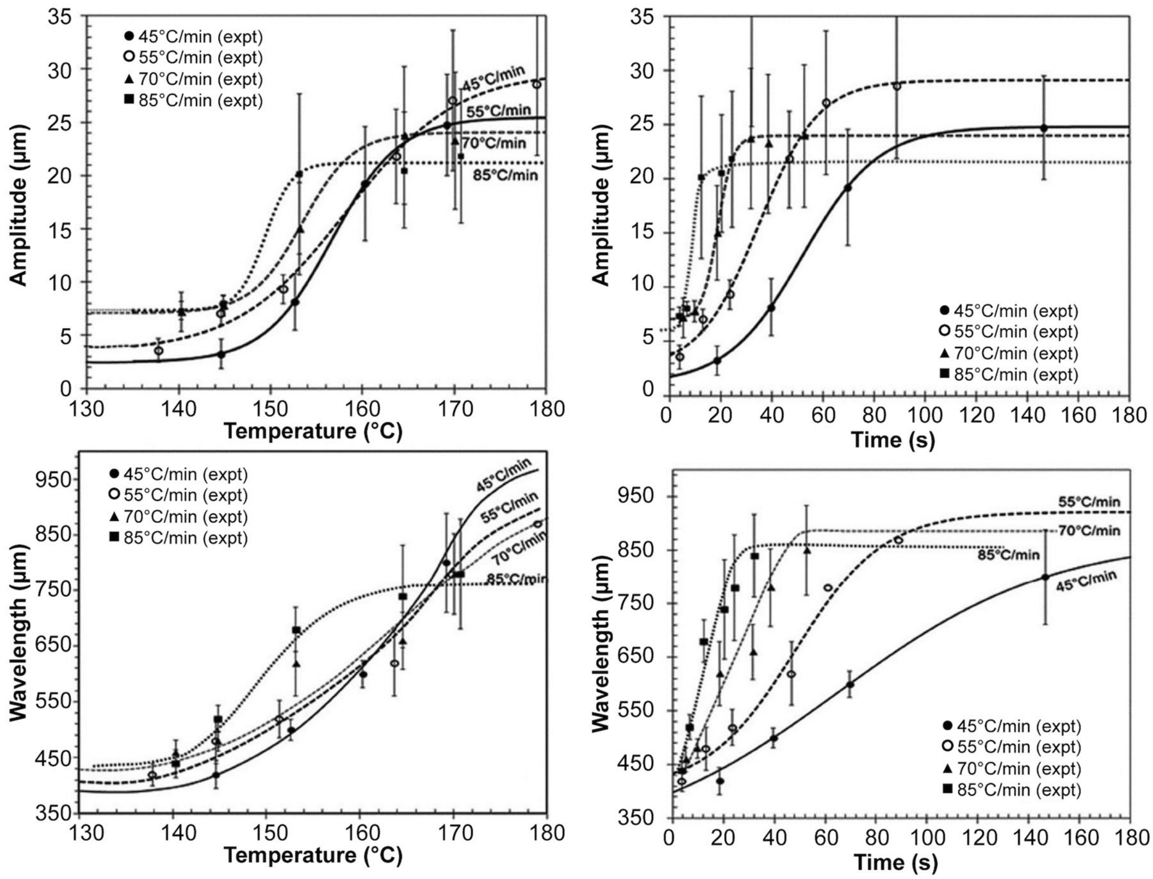


*Figure 2. Variation in the amplitude (top) and wavelength (bottom) of the wrinkles on four FBO/PP samples (those heated at rates of 45, 55, 70, and 85°C/min) as a function of temperature (left) and time (right). Expt: Experimental.*

PE-phase film and that of the PP (120 and 160°C, respectively, as determined by dynamic mechanical analysis). In addition, the threshold is the same as the temperature for the onset of wrinkling when the film was laminated to stainless steel. These findings indicate that the film controls this buckling mode.

We used a 3D surface profilometer to measure both the wavelength and amplitude of the wrinkles on our samples. We found (see Figure 1) that both parameters increased with laminate temperature and that the wrinkles become more intense with higher heating rates. This progression in wrinkling is also illustrated in Figure 2, which shows that both the amplitude and wavelength of wrinkling follow a sigmoidal trend with increasing system temperature. The nature of this trend is related to the three distinctive stages of thermal expansion that we identified from optical strain measurements of the laminate. Thermoforming equipment is generally operated at heating rates that are similarly high (or even higher) to those we used in our study. Parts that are made from a similar decorative laminate material will therefore consistently exhibit wrinkles unless thermal stresses can be relieved. In the next stage of our work we therefore subjected the FBO/PP laminate to biaxial stretching by bulging in the BTU (under controlled heating). In this way, we were able to counter the compressive thermal stresses that give rise to the wrinkles and thereby control the undesirable phenomenon. We found that an applied biaxial strain, equivalent to the critical compressive strain[11] that produced the wrinkles, was sufficient to remove all the distortions. The wrinkles reoccurred, however, once the applied strain was removed, and a much greater applied strain was necessary to permanently remove the wrinkles.

To scale our approach so that it is applicable to a vacuum thermoformer (from Belovac Inc.), it was necessary to fit a bellow under the clamping assembly. The vacuum box was thus enclosed so that compressed nitrogen could be applied to bulge the mounted laminate sheet. We tested two different methods to counter the compressive strain that forms the wrinkles. In the first approach—the isothermal bulge method

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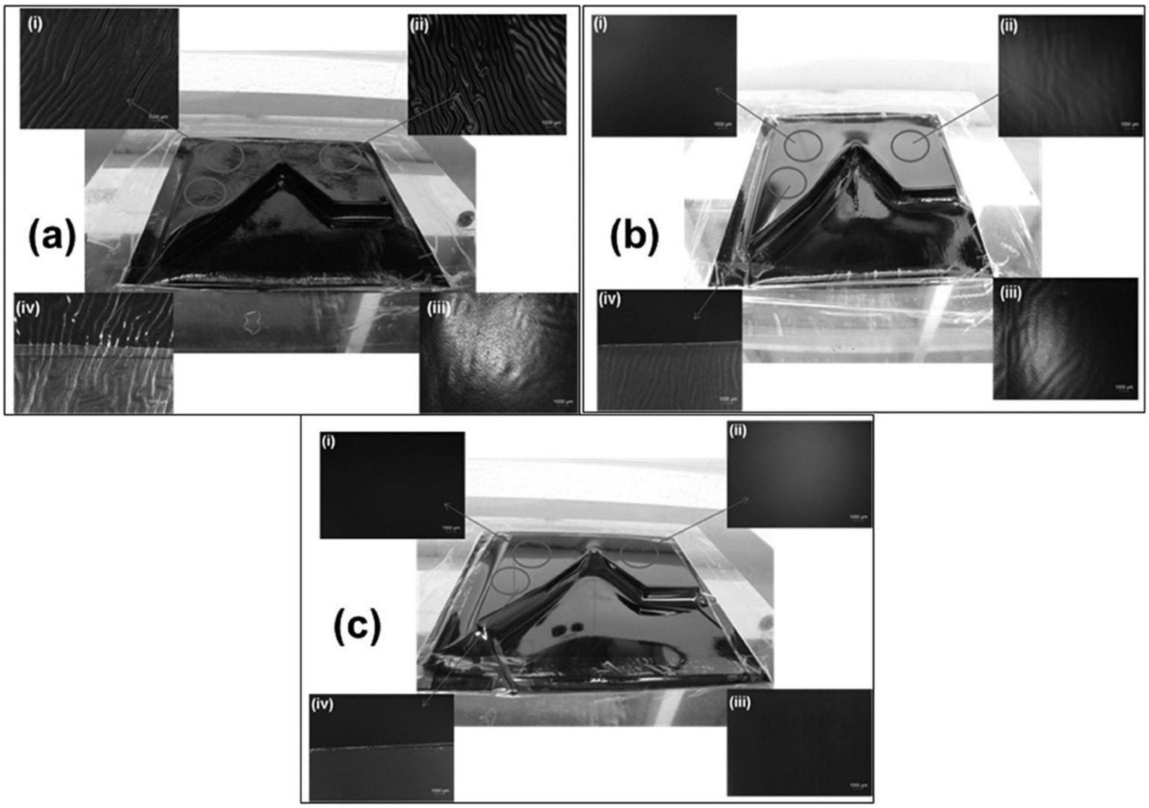


***Figure 3.*** *Images of FBO/PP laminate samples that were thermoformed using (a) conventional vacuum forming, (b) the isothermal bulge method, and (c) the dynamic bulge method. Insets show the (i) top sample surface, (ii) top surface at 35° inclination, (iii) back side of the laminate, and (iv) visible portion of the PP substrate where the film has been partly peeled away.*

(IBM)—we heated the sample to a high temperature before conducting the bulging. In contrast, in the second approach—the dynamic bulge method (DBM)—we continually strained the sample while it was heated. Although we apply the same strain in both methods, the difference between them is that the film is stretched after the wrinkles form in the IBM, whereas the continuous stretching during the DBM prevents the wrinkles from forming at all. Images from the laminate samples that were produced from our two different methods (as well as conventional vacuum forming) are shown in Figure 3. From color measurements, we found no significant difference between the original, pristine FBO/PP sample and those produced from any thermoforming method. The results of gloss measurements (at incidence angles of 20 and 60°), however, were substantially lower for the samples produced via the standard forming technique and IBM. In the IBM samples the wrinkles were not visually apparent, but faint distortions were visible on the substrate when we peeled back the film. The DBM sample exhibited a smooth 'class-A' finished surface with no distortions. In addition, we observed a very small reduction in gloss for this sample, but it remained above 60 gloss units.

In summary, we have investigated the formation of wrinkles during thermoforming of an FBO/PP laminate. We have tested the decorative films at a number of different temperatures and heating rates in a model environment, and applied our findings to thermoforming via three different forming methods (conventional vacuum forming, IBM, and DBM). We found that only with biaxial stretching during the DBM was it possible to retain a class-A surface finish for the formed product. Both our new methods (i.e., IBM and DBM), however, can be used to remove wrinkles from the laminate. In our ongoing research, we have transitioned toward using shape-memory polymers as decorative films because they show greater resistance to wrinkling.

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**References**

1. J. L. Throne, **Understanding Thermoforming**, Hanser, 2008.
2. S. Engelmann, **Advanced Thermoforming: Methods, Machines, and Materials, Applications and Automation**, Wiley, 2012.
3. Y. W. Leong and H. Hamada, **Introduction to Film Insert Injection Molding**, Lambert Academic Publishing, 2009.
4. E. P. Chen, Q. Lin, and C. M. Stafford, *Quantifying the elasticity and viscosity of geometrically confined polymer films via thermal wrinkling*, **J. Polym. Sci. Part B: Polym. Phys. 50**, pp. 1556–1561, 2012.
5. S. K. Basu, A. M. Bergstreser, L. F. Francis, L. E. Scriven, and A. V. McCormick, *Wrinkling of a two-layer polymeric coating*, **J. Appl. Phys. 98**, p. 063507, 2005.
6. A. Auguste, L. Jin, Z. Suo, and R. C. Hayward, *The role of substrate pre-stretch in post-wrinkling bifurcations*, **Soft Matter 10**, pp. 6520–6529, 2014.
7. G. P. Balamurugan, R. N. Pukadyil, M. R. Thompson, K. E. Nielsen, and F. A. Brandys, *Wrinkling in polymer film-polymer substrate systems and a technique to minimize these surface distortions*, **Polym. Eng. Sci.**, 2016. doi:10.1002/pen.24382
8. R. Huang and Z. Suo, *Wrinkling of a compressed elastic film on a viscous layer*, **J. Appl. Phys. 91**, pp. 1135–1142, 2002.
9. E. P. Chen, Q. Lin, and C. M. Stafford, *Quantifying the elasticity and viscosity of geometrically confined polymer films via thermal wrinkling*, **J. Polym. Sci. Part B Polym. Phys. 50**, pp. 1556–1561, 2012.
10. R. Huang, *Kinetic wrinkling of an elastic film on a viscoelastic substrate*, **J. Mechan. Phys. Solids 53**, pp. 63–89, 2005.
11. R. Huang, *Kinetic wrinkling of an elastic film on a viscoelastic substrate*, **J. Mech. Phys. Solids 53**, pp. 63–89, 2005.