WINDING OF INTERLEAVED MATERIAL

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ABSTRACT

The manufacturing of flexible display products has very tight specifications on the dimensional changes between the coating stations or between different passes of a multi-pass coating process. Web stretching and stress relaxation during conveyance and roll storage all contribute to the dimension stability of this product, and therefore are potential concerns. The quality of a flexible display is very sensitive to defects in the films that are used as part of the assembly. Many film components used in the display are very delicate and can be damaged during web handling. To protect the film from damage during the winding process, it can be interleaved with another film, typically one that is softer and significantly cheaper. This paper reports data from a stress relaxation test on a specific polyethylene terephthalate (PET) web, and on the modeling of the stress development, stress relaxation, and dimensional changes of the PET from roll winding and wound roll storage. We also present modeling results and empirical data on the winding of interleaved films.

NOMENCLATURE

σ	Stress
σ_0	Initial stress
t	Time
τ_{ww}	Relaxation time constant
b	Breadth of relaxation spectrum

INTRODUCTION

Many display products consist of repeating small patterns that are made out of several layers of functional materials deposited on a support web. The manufacturing of these products involves a multi-layer coating process, completed either by different coating stations during a single pass event or by a single coating station during a multi-pass event. To maintain pattern registration during the multi-layer coating process, it is critical to control the dimensional stability of the carrier web. As the web is being conveyed in the machine or wound up in a roll between two passes, it stretches and elongates, and part of that elongation becomes permanent deformation, which has a potential to disrupt the registration of the patterns between two layers of the coating. The requirement of the change in web dimension (strain) between sequential coating events can be as low as 2.5E-5. This level of strain can be produced by temperature changes on the order of 1.5°C and humidity changes of 3.5% rH. The elastic strain caused by winding at a typical winding tension of 100-800 N/m far exceeds the allowance for permanent deformation. Besides the dimensional stability, the special coatings on the web are often sensitive to pressures that are developed in the winding process.

This paper studies the dimensional stability of a PET (thickness 122 μm or 4.8 mil) that was coated with a single functional layer. Some samples of the indicated web were obtained to measure its viscoelastic properties. Winding models were applied to predict the pressure and hoop stress developed during the winding of this web. Results of residual strains were computed and compared to the specification requirements. Modeling and experiments were also used to study the winding of the web interleaved with strips of 2.032 mm (80 mil) plastic (low density polyethylene) on two edges. Some discussion is provided at the end of this document.

STRESS RELAXATION MEASUREMENT OF PET

Stress relaxation measurement was carried out at 23ºC/50% rH on an Instron tensile tester, Model 1122. The measurement consisted of different stress relaxation tests at increasing initial stress levels. The results are compared by using the expression $\sigma(t)/\sigma_0$, or simply the ratio of tensile force, $F(t)/F(0)$ for a fixed cross section on the testing sample.

The data from the stress relaxation tests is shown in Fig. 1. The viscoelastic data from the PET is curve-fitted (Fig. 1) to an empirical Kohlrausch-Williams-Watts (KWW) function [1],

$$\sigma(t) = \sigma_0 \exp\left[-\left(\frac{t}{\tau_{ww}}\right)^b\right], \qquad \{1\}$$

where τ_{ww} is a relaxation time constant, and b is the breadth of the relaxation spectrum. The curve fits give the relaxation time constant τ_{ww} = 1.31E9 sec and breadth of the relaxation spectrum b = 0.292 for this specific sample. The stress relaxation parameters of the PET will be used in the following to predict the residual strain developed in the roll winding processes.

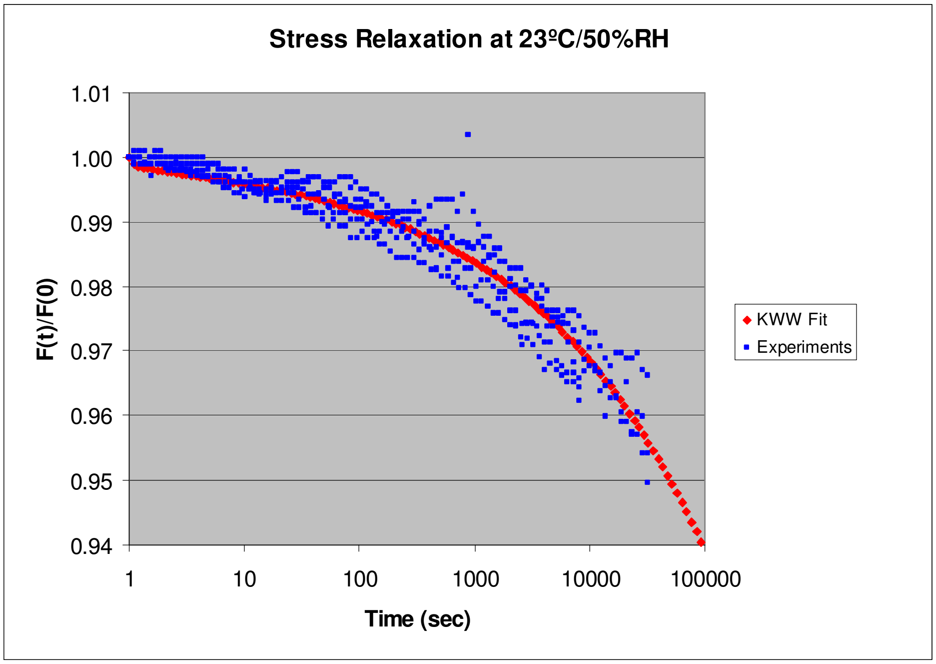

Figure 1 - Data and the Curve Fit of the Stress Relaxation Tests on the PET Screen Coated with a Functional Layer

WINDING MODELS

Stresses that are developed during the winding of the PET film in coating processes can be predicted using a winding model. In this paper, a winding model [2] was used in the study to develop a process window that will enable successful PET roll winding without roll shifting and dishing, and, at the same time, that ensures that the residual strain or dimensional changes in the PET web meets the specification requirements.

Winding of PET Only

As a first approach in understanding the stresses in a wound roll, the PET is assumed to be perfectly flat—any thickness variation on the PET itself and the coating related thickness is neglected. The coating speed of this product is on the order of a few meters per minute or typically slower—slow when compared to traditional film and paper coating operations. The air entrainment during winding can be safely neglected. The roll length is typically short, in the range of several hundred meters, and therefore, only constant winding tension is considered. The extent of roll storage and storage temperature affects the final residual strain in the web. For this study, we chose a storage time of 90 days and a storage temperature of 21ºC.

Table 1 lists the model runs that were executed to study the effect of the roll length and winding tension on wound roll stress and the maximum residual strain after 90 days of roll storage at 21ºC.

Case #	1	2	3	4	5	6	7	8
Winding Tension, N/m	44	88	131	175	44	88	131	175
Roll Length, meter	152	152	152	152	305	305	305	305
Maximum In-Roll Pressure, KPa	7.6	20.5	42.4	72.7	7.6	20.5	42.5	73.4
Residual Strain After storage	1.71E-05	3.39E-05	5.05E-05	6.74E-05	1.71E-05	3.39E-05	5.08E-05	6.84E-05

Table 1. - Model Studies on the Effect of Roll Length and Winding Tension on In-roll Stress and the Max. Residual Strain after 90 Days of Roll Storage at 21°C

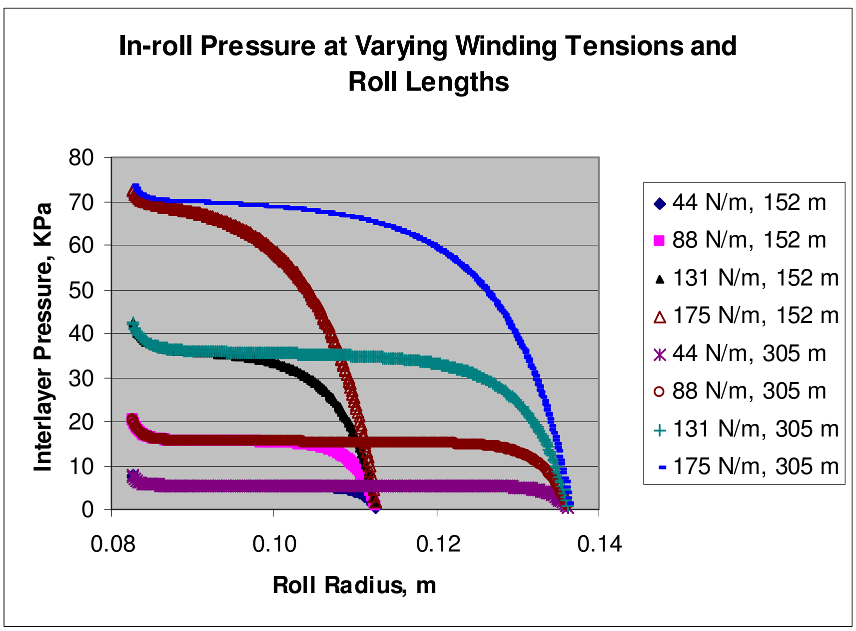

Figure 2 - Model Predictions of the Pressure Distribution in Fresh Rolls Wound at Four Levels of Winding Tension, and to Two Levels of Roll Length.

Model prediction of the in-roll pressure distribution is shown in Fig. 2 for fresh rolls wound at four levels of winding tension: 44, 88, 131, and 175 N/m (0.25, 0.5, 0.75, and 1 pli), and two roll lengths: 152 and 305 m (500 and 1000 ft). In all cases, the web next to the core endures the highest interlayer pressure, and therefore is the most likely place in the roll to suffer pressure-related impressions. Moving away from the core, the pressure tapers and reaches a minimum (0) at the outside of the roll. As indicated in Fig. 2, the maximum interlayer pressure that a roll endures varies with the winding tension—the higher the winding tension, the higher the maximum pressure. It was also noticed that the correlation between the winding tension and the maximum interlayer pressure is nonlinear; the maximum pressure increases more than twofold when the winding tension is doubled. This observation is mainly attributed to the nonlinear stack modulus, and is consistent with previous observations.

Fig. 3 plots the maximum in-roll pressure for rolls wound at different levels of winding tension, for two roll lengths: 152 m vs. 305 m. It indicates that doubling the roll length from 152 m (500 ft) to 305 m (1000 ft) has very minimum effect on the maximum interlayer pressure. Again, this is consistent with previous observations [2] that the pressure near the core is mostly developed from the winding of the first few hundred laps next to the core; extra layers of web wrapped on those have very little effect on the pressure at the core. Results given in Figs. 2 and 3 do not include the effect of gravity on interlayer pressure. Roll storage orientation can change the interlayer pressure dramatically from those shown in Fig. 2, especially when a wound roll is stored horizontally and the weight of the roll is supported on the saddle by two ends of the core, in which case the weight of the roll would add to the interlayer pressure on the top portion of the roll, and subtract from it on the lower portion of the roll. The effect of gravity is dependent on roll size and for large rolls can be a significant factor in terms of roll sag, tenting, and the likelihood of downstream operation failures, such as roll shifting and cinching.

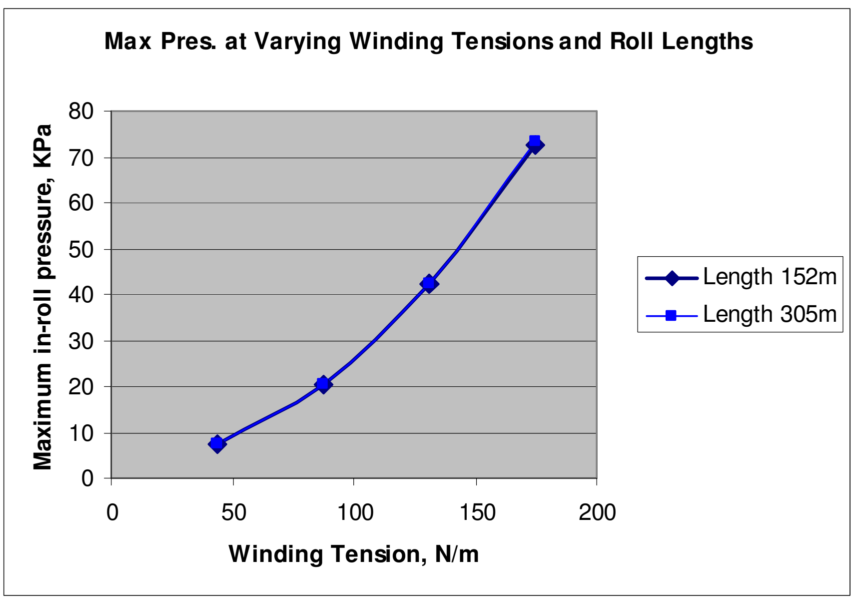

Figure 3 - Maximum In-Roll Pressure at Different Levels of Winding Tension, Roll Length 152 m vs. 305 m

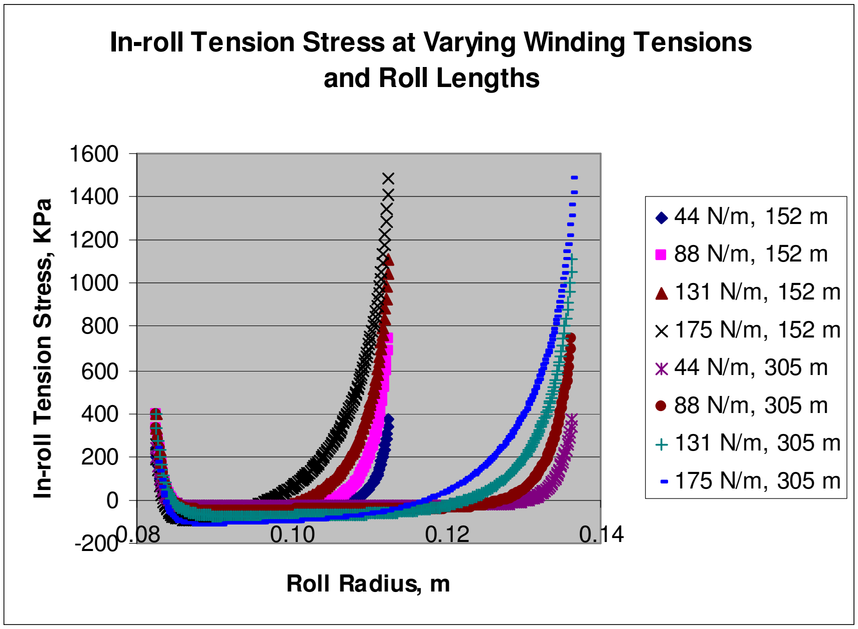

Figure 4 - In-Roll Circumferential Tension Stress of Rolls Freshly Wound at Four Levels of Winding Tension, to Two Levels of Roll Length 152, 305 m (500 vs 1000 ft)

Fig. 4 shows predictions of circumferential tension stress in freshly wound rolls using four levels of winding tension: 44, 88, 131, and 175 N/m (0.25, 0.5, 0.75, and 1 pli), and two levels of wound roll length: 152 and 305 m (500 ft and 1000 ft). The in-roll tension stresses all share a similar shape: starting high at the core, gradually decreasing into the roll to a fairly level section, and ramping back up at the outside. The maximum in-roll tension in a freshly wound roll is located at the outside of the roll, and it is the same as the stress from the winding tension. On the assumption that the circumferential tension stress in a wound roll relaxes following the KWW function given in equation (1) with its coefficients derived from the stress relaxation experiments, Fig. 5 shows the residual strain of the web after being unwound from the rolls that have been in room storage at 21ºC for 90 days. It indicates that large portions of the rolls would have their residual strains less than 2.5E-5, the specification of the residual strain previously stated. The maximum residual strain is located at the outside of the roll. Fig. 6 plots the maximum residual strain of the web vs. the winding tension. Interpolation of the plots indicates that only when the winding tension is less than 61 N/m (0.35 pli) would the maximum residual strain of the web be lower than 2.5E-5. However, the rolls wound at this low tension (61 N/m) are fairly soft and are prone to shifting/telescoping. If the manufacturing process can tolerate some residual strain-related waste at the outside of the roll, winding tension of higher than 61 N/m can be used to avoid roll shifting/telescoping. The winding tension can be optimized to minimize the waste from both roll shifting and registration errors at the outer laps.

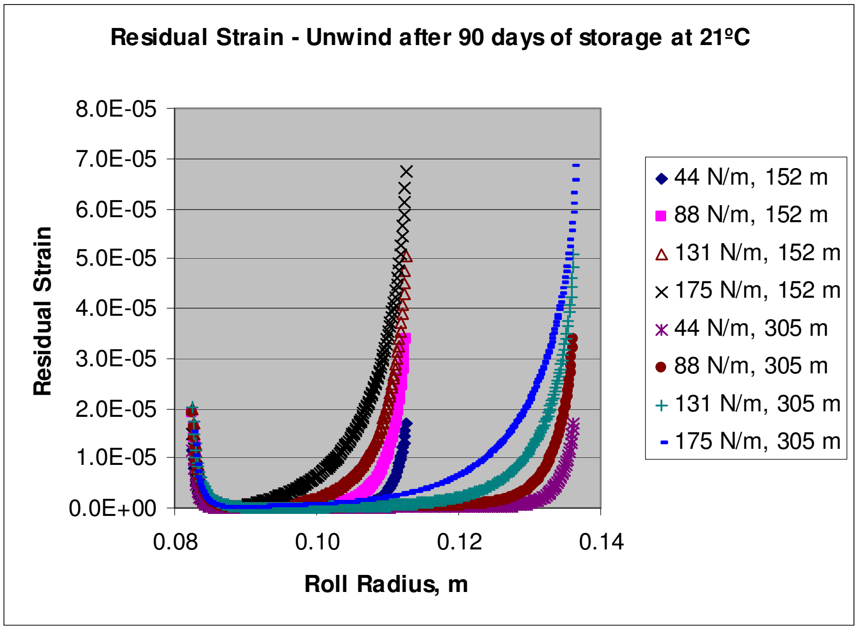

Figure 5 - Residual Strain after 90 Days of Storage at 21ºC and Subsequently Unwound

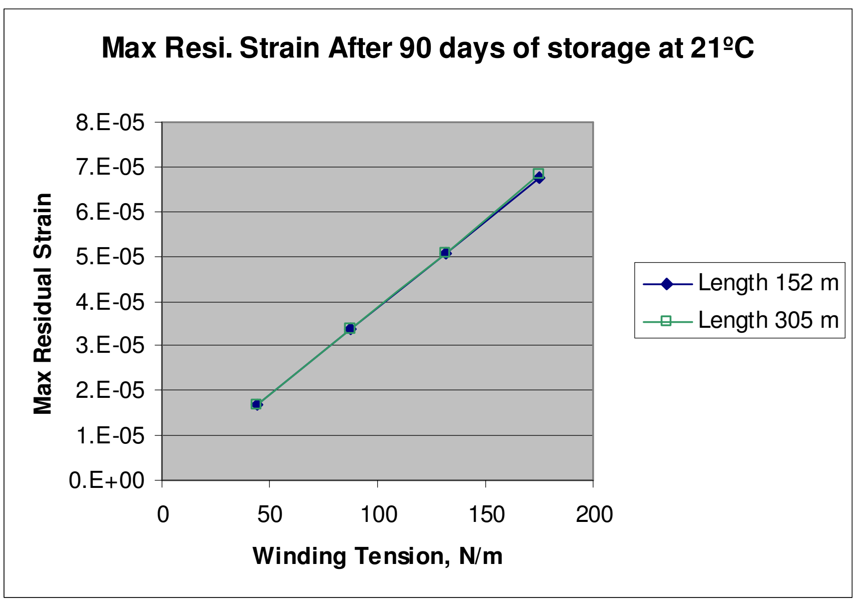

Figure 6 - Maximum Residual Strains after 90 days of Rolls Stored at 21° C

The above predictions are based on the assumption that the PET had no thickness variation across the width. However, a certain level of thickness nonuniformity, either by nature or by intention, is always present in webs. The worst scenario of thickness nonuniformity in roll winding is lengthwise persistent gage bands in the web that are thicker than the surrounding areas of the web, because they can generate hardstreaks. The extra thickness needs to be only a fraction of the average web thickness to cause hardstreaks, depending upon material properties (radially stiff materials will generate hardstreaks more readily than radially compressible materials). The thick streak piles up on top of itself until, in a large roll, one gets a narrow area of the wound roll that stands up above the rest of the roll surface. The hardstreak will generate tremendous interlayer pressure, and also extreme in-roll tension. The extreme in-roll tension causes the web to severely creep, or perhaps even yield, at that location, which then puts a permanent distortion into the web which appears as "roping," or a series of buckles in the web, after it is unwound. Coated areas of web, which for display applications may be applied nonuniformly over the web, will qualify under this criterion as potential hardstreak generators. In winding "normal" webs, it is unusual to have more than one or two hardstreak locations in a roll. With flexible displays, the lengthwise persistent thick spots will be more numerous and consist of a higher fraction of the web width. This will make the resulting hardstreaks less prominent. The total winding tension will be distributed across the surface of the roll—uniformly, if there are no hardstreaks, or preferentially at the hardstreak locations, if there are hardstreaks—but the total force available for distribution is still just the winding tension. So the more hardstreaks there are, each will be less severe. Normally, measurement of lengthwise persistent thickness nonuniformity will indicate the severity of hardstreaks that would be expected in a wound roll. Things that could mitigate the reduction in severity include, for example, one widthwise feature that is thicker than the others. Counteracting this effect is roll length—hardstreaks typically do not begin to show until partway through a "normal size" roll. But if there are hardstreaks, the web at those locations will see a higher interlayer pressure than will the rest of the web. Therefore, one of the side effects in the manufacture of flexible displays could be locally higher interlayer pressure near the outside of the roll in the coated areas.

Modeling of Interleaving with Plastic

Results from the previous section indicate that the coated PET will experience certain levels of pressure and circumferential tension stress in a wound roll. The pressure and tension stress in-roll will be more significant than those presented whenever there is thickness nonuniformity, either from PET support or from subsequent coating. The fact is that the coated web is oftentimes so sensitive to in-roll stress-related defects that it might not tolerate the in-roll stress in a roll wound with even the lowest winding tension developed by a machine.

One possible solution to completely resolve this issue is to emboss raised features, *knurls*, on two edges of the PET, and use the knurls to separate the middle section of the wound roll by supporting the layers on edge knurls only. To achieve this purpose, the knurl height has to be high enough to enable total separation between the layers in the wound roll. The other option to separate the layers is to use interleave material on the PET edges in winding. In the following, we document the use of the winding model to predict the in-roll stresses in a PET roll wound with interleaving materials on the edges.

Stack modulus of a composite PET/plastic. To use the existing winding model, the stack modulus of the composite PET/plastic edges is needed. Low-density polyethylene plastic is a material selected for interleaving since it meets cleanliness requirements for this process. Stack modulus testing of this composite material, 0.122 mm (4.8 mil) thick PET interleaved with 2.032 mm (80 mil) thick plastic, was conducted and the results of stress-strain and stack modulus versus stress are shown in Figs. 7 and 8.

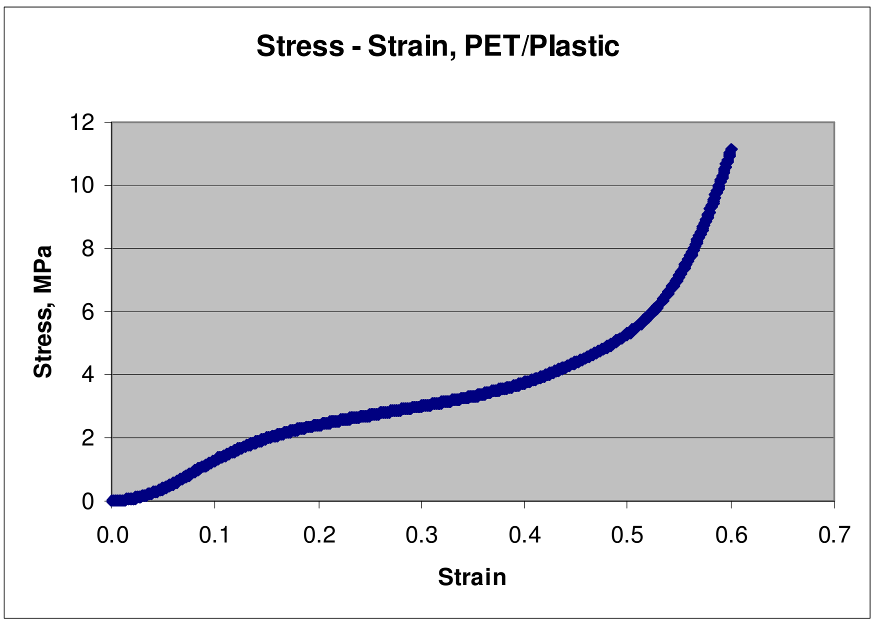

Figure 7 - Stress-Strain Relation of the PET Interleaved with 2.032 mm-Thick Plastic

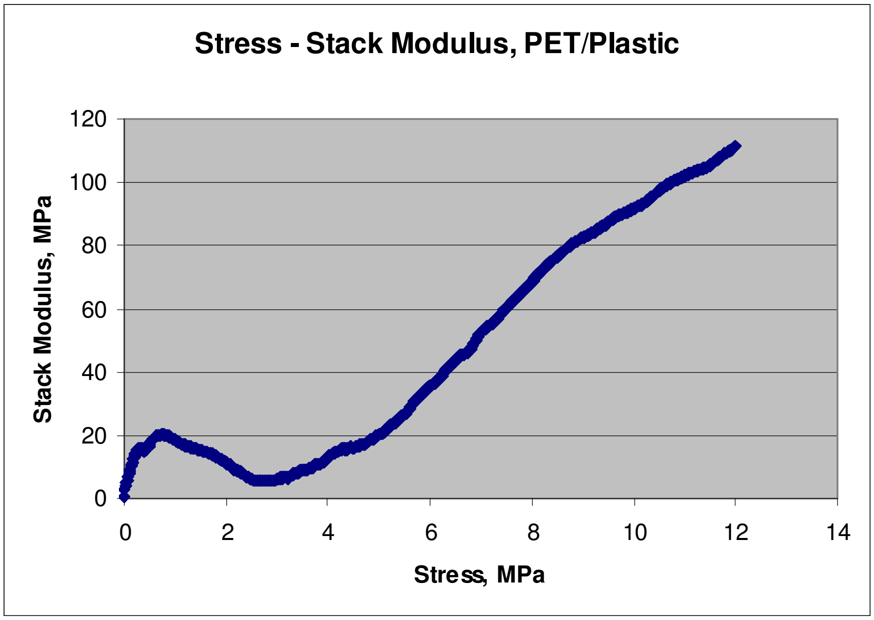

Figure 8 - Stack Modulus vs Stress Relation of the PET Interleaved with 2.032 mm-Thick Plastic

Winding tension approximation. During the interleaved winding of the webs, the tensions on the PET and two strips of plastic can be independently controlled. In this study, the three tensions (Newton) are added up, and the sum is divided by the total width of the PET to provide a single input (N/m) into the model. This approximation has its limitations; for example, the approximation could not predict the effect on in-roll pressure from the plastic strip tension difference side to side. This approximation also neglects the fact that the interleaving web (plastic in this example) and the PET can have very different material properties. They can be stretched to a different extent, and they can carry different loads. New models will need to be developed to fully understand these effects.

Table 2 lists the critical model inputs, which consist of two levels of roll length, 152 m (500 ft) and 305 m (1000 ft), and two levels of winding tensions, 49.25 and 98.51 N/m. The ratio of winding tensions between PET and plastic is held constant, assuming the plastic tension is equally distributed between the two edges. At the winding speed of 15mpm (50 fpm), the air entrainment is minimal; therefore, no air entrainment is included in this study.

Fig. 9 shows the distribution of pressure in a PET roll of 305 m (1000 ft) long and 0.406 m (16 in.) wide interleaved with two (one on each edge) 25.4 mm (1 in.) wide strips of 2.032 mm (80 mil)-thick plastic material. It indicates that the winding tension is distributed only on the edges where the PET is interleaved; the middle section carries no load. As a result, there is no interlayer pressure in the middle section where the PET laps are separated by gaps—a desirable situation for any web that is sensitive to pressure related defects. Circumferential tension stress distribution is given in Fig. 10. The tension stress, similar to pressure distribution, is nonzero only on the interleaved edges of the rolls. In the middle section, there is no tension stress and thus no wound-roll stress related web elongation—another benefit of using interleaving.

Figs. 11 and 12 show the effect of winding tension and roll length to the in-roll pressure and tension in the interleaved edges of rolls. Key observations are:

1. There is no interlayer pressure nor circumferential stress in the middle sections (not shown in the figures) within the range of the parameters used in this study. Pressure and tension stress are distributed only over the interleaved edges.
2. Winding tension has the highest influence on the interlayer pressure and circumferential tension stress. Roll length variation stretches the extent of stress distribution but has very minimal effect on the maximum pressure and tension stress in the wound roll.

Under the circumferential tension stress in the wound roll, the PET in the interleaved edges will relax and develop permanent deformation. When unwound after roll storage, the edges in the areas where the tension stress is positive will be longer than the middle section, and they might develop fluting—a wavy, scallop-like distortion. The fluted edges, if severe, can cause coating disturbances. If there is a slitting operation further downstream, the slit strands from the fluted edge may be cambered as well.

Case #	1	2	3	4
Web Type	PET/Plastic	PET/Plastic	PET/Plastic	PET/Plastic
PET Winding Tension, N	17.79	35.59	17.79	35.59
Plastics Winding Tension (total), N	2.22	4.45	2.22	4.45
PET Width, m	0.4064	0.4064	0.4064	0.4064
Plastic Width (2 edges total), m	0.0508	0.0508	0.0508	0.0508
Total Winding Tension, N/m	49.25	98.51	49.25	98.51
Roll Length, m	152	152	305	305
Core OD, mm	165.10	165.10	165.10	165.10
Effective Thickness, mm	2.304	2.304	2.304	2.304
Roll OD, mm	688.771	688.771	959.976	959.976
Lap Number	149	149	208	208
Winding Speed, mpm	15	15	15	15

Table 2. - Model Inputs of PET Interleaved with Plastic under Each PET Edge

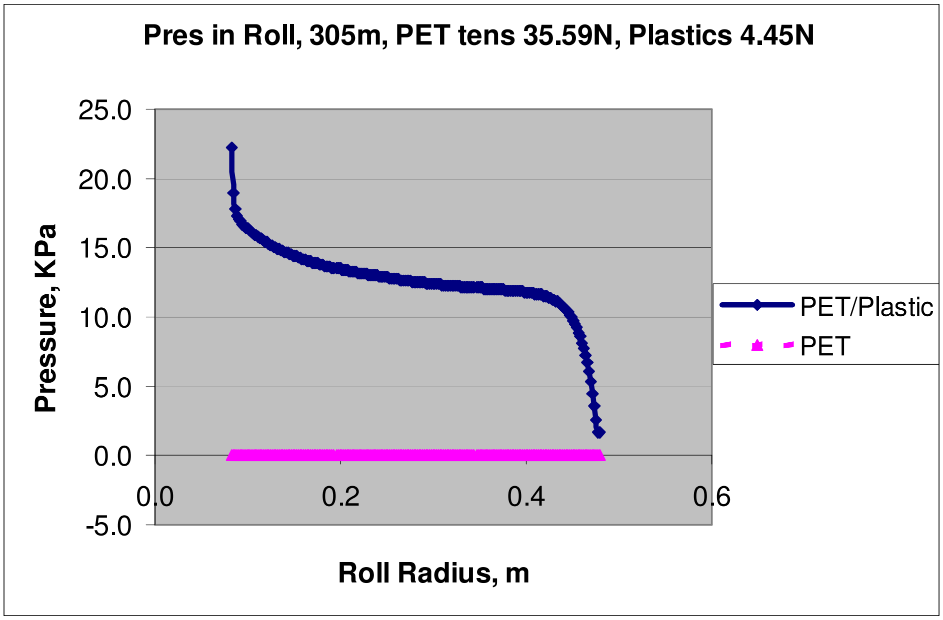

Figure 9 - Pressure Distribution in a 305 m (1000 ft) Roll of PET Using Interleaving of 2.032 mm (80 mil) Plastic. Total PET Tension 35.59 N (8 lb), Total Plastic Tension (over 50.8 mm) 4.45 N

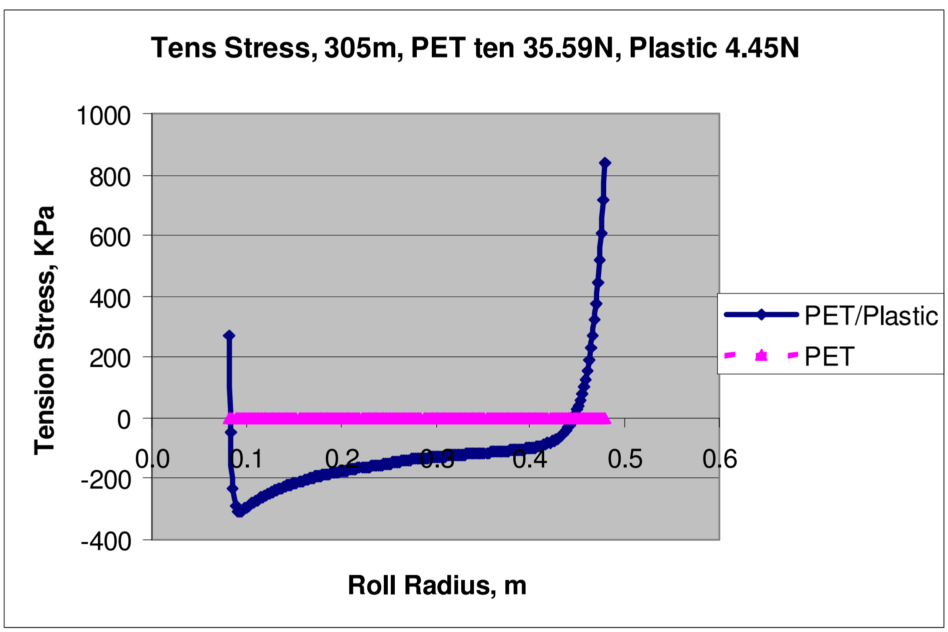

Figure 10 - Hoop Stress Distribution in a 305 m (1000 ft) Roll of PET Using Interleaving of 2.032 mm (80 mil) Plastic. Total PET Tension 35.59 N (8 lb), Total Plastic Tension (over 50.8 mm) 4.45 N

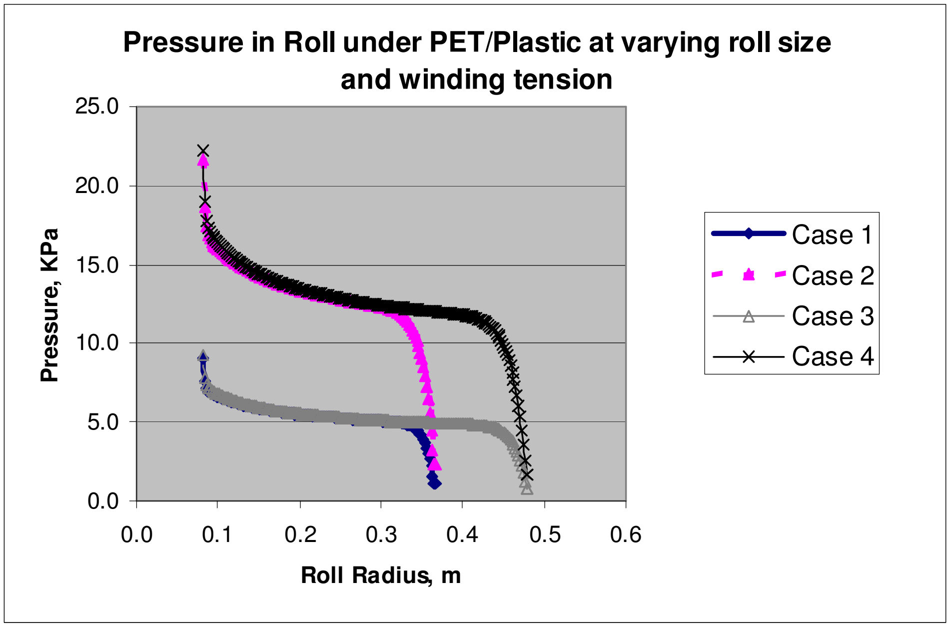

Figure 11 - Pressure in the Plastic Interleaved Sections of PET Rolls

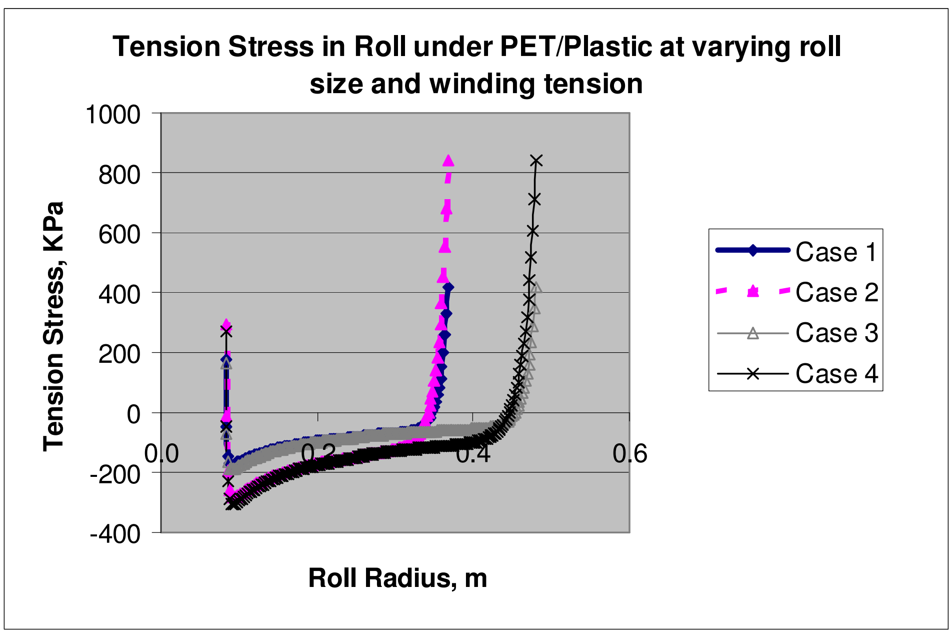

Figure 12 - Hoop Stress in the Plastic Interleaved Sections of PET Rolls

Experiments – interleave winding of PET

To demonstrate the feasibility of interleaving, winding experiments were conducted in the lab using two 25.4 mm (1 in.) strips of 2.032 mm (80 mil) thick plastic material, one on each edge, to interleave 305 m (1000 feet) long, 0.4064 m (16 in.) wide PET. The outer diameter of the core used for this work was 177.8 mm (7 in.). The following process variables were studied in the experiments: (a) tension level (PET, plastic), (b) tension profile (constant; linear taper with diameter from the core to 381 mm (15 in.), then constant to roll finish), and (c) winding speed. The responses in the experiments were: (a) roll quality during winding (roll cylindricity, sidewall straightness) and (b) roll stability after winding.

During the interleaving winding experiments, it was observed that the PET web buckles very easily while it is being wound onto the roll. These buckles initially develop in the web just upstream of the web-roll nip and subsequently result in a buckled winding roll. This problem occurred over many combinations of process settings; hence, this lead us to abandon our initial plan to perform a full-factorial designed experiment and, instead, conduct a screening experiment in an attempt to find combinations of process settings where buckles in the winding roll did not develop.

After process optimization, we were able to wind rolls without buckling. One set of process settings that enabled us to wind a roll without buckling are as follows: (a) winding speed: 15 mpm (50 fpm), (b) product tension: 33.4 to 16.7 N (7.50 to 3.75 lb tapered over 15 in.), and (c) plastic tension: 2.5 to 1.3 N (0.56 to 0.30 lb tapered over 15 in.). These compare to the conditions used for the buckled roll: (a) winding speed: 30.4 mpm (100 fpm), (b) product tension: 26.7 N (6.0 lb constant), and (c) plastic tension: 2.2 N (0.50 lb constant).

From these experiments, we learned the following about interleave winding:

- wind quality was better at lower tensions (both web and plastic),
- wind quality was better using a variable tension profile (both web and plastic), as compared to a constant tension profile,
- wind quality was better at higher speed (because of better drive stability that reduced tension transients),
- wind quality was adversely affected by dynamic tension oscillations (e.g., buckles seemed to form in areas of the roll where tension variations became large, especially in the plastic interleaving material),
- roll integrity was adequate in all cases (e.g., the rolls could be handled with minimal risk of lateral telescoping),

and conclude that interleaving is viable under controlled conditions.

DISCUSSION

To achieve the specification of dimensional stability (2.5E-5 residual strain) of PET, the maximum allowable winding tension is 61 N/m (0.35 pli) if the roll is allowed to be in a 21ºC storage area for a maximum of 90 days. However, higher winding tensions will be allowed if the process can tolerate a percentage of waste at the outside of the roll, where the residual strain from stress relaxation is a maximum. These model predictions are based on the assumption that the web is perfectly flat. Any thickness nonuniformity, either from the carrier PET or from the coating, will have an impact on the results. The severity of that impact can be determined by experiments, or by models, once the thickness variation becomes available.

Winding with interleaved materials is an option to provide gapping in the roll, and thereby eliminate any in-roll pressure-related defects, as well as stress relaxation related dimensional changes in a wound roll. Winding with interleaved materials is subject to web buckling in the free span before the winding nip, as demonstrated in the lab. More studies, both theoretical/modeling and experiments, are needed to optimize a process window that can successfully wind interleaved rolls without buckling.

Knurling of the PET support on both edges is another possible solution for minimizing in-roll pressure-related defects and stress relaxation related dimensional changes in a wound roll. More studies on this approach are needed to achieve a better understanding of the relative merits of this approach.

As stated in the previous section, the current winding model was developed for traditional winding without interleaving. It has limitations when used to provide predictions in an interleaved roll. Further work is needed to make it feasible to provide good predictions in interleaved winding.

ACKNOWLEDGMENT

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