PEELING PROCESS DEVELOPMENT FOR THIN FLEXIBLE WEBS

by

Herong Lei[1] and Kevin A. Cole[2]
[1]Eastman Kodak Company
[2]Grid Computing Solutions, LLC
USA

ABSTRACT

Many consumer products are manufactured from continuous media. When the media is thin and flexible, it is referred to as a web. Webs are typically manufactured by extrusion or casting; however, for some applications, a coating process onto a sacrificial carrier web, followed by a peeling process, provides a more robust means to achieve the functional requirements of thin webs. One example of this is with the protective cover sheet for LCD polarizers. Conventional casting is impractical because of the thickness and tear- sensitivity of the preferred support material. The coating and peeling processes, however, are not without their own problems. This paper describes work aimed at developing a robust coating and peeling process for the manufacture of protective cover sheets for LCD polarizers. First, we describe the general process method. Next, we focus our discussion on the development of the web peeling process and review in detail the peeling imperfections, such as ripping and tearing defects, that negatively impacted our ability to successfully peel the thin webs from the carrier webs. Web handling findings from this work will also be shared.

INTRODUCTION

Transparent “resin films” are used in a variety of optical applications [1]. For example, resin films are used in protective cover sheets for light polarizers in a variety of electronic displays, including Liquid Crystal Displays (LCD).

The structure of LCDs may include a liquid crystal cell, one or more polarizer plates, and one or more light management films. Liquid crystal cells are formed by confining liquid crystal materials between electrode substrates. Polarizer plates are typically a multilayer element comprising resin films. In particular, a polarizer plate can comprise a polarizing film sandwiched between two protective cover sheets. Polarizing films are normally prepared from a transparent and highly uniform amorphous resin film that is subsequently stretched to orient the polymer molecules and then stained with a dye to produce a dichroic film. An example of a suitable resin for the formation of polarizer films is fully hydrolyzed polyvinyl alcohol (PVA). Because the stretched PVA films used to form polarizers are very fragile and dimensionally unstable, protective cover sheets are normally laminated to both sides of the polarizing film to offer both support and abrasion resistance.

Protective cover sheets of polarizer plates are required to have high uniformity, good dimensional and chemical stability, high transparency, and low birefringence. Originally, protective cover sheets were formed from glass but a number of resin films are now used to produce lightweight and flexible polarizers. Of the many options available, the fully substituted polymer, triacetyl cellulose (TAC) is the one that is most commonly used, owing to its superior performance.

Historically, the optimum method for manufacturing resin films for protective cover sheet applications has been casting. This method involves first dissolving the polymer in an appropriate solvent to form a dope having a high viscosity and then applying the viscous dope to a highly polished metal band or drum through an extrusion die, peeling the partially dried film from the metal support, and conveying the partially dried film through an oven to more completely remove solvent from the film. Cast films typically have a final dry thickness in the range of 40–200 µm. Thinner films, although desirable, are very difficult to produce by this method because of the fragility of wet film during the peeling and drying processes.

The protective cover sheet also normally requires a surface treatment to ensure good adhesion to the PVA dichroic film. Generally, the film is treated in an alkali bath to saponify the TAC surface. However, this method is very messy and time consuming. A preferred alternative is to combine the adhesive functionality into a cover sheet multilayer construction where the composite or multilayer film includes additional functional layers, such as an antiglare layer, antireflection layer, antismudge layer, compensation layer, or antistatic layer.

An alternate method for manufacturing resin films for protective cover sheets, which overcomes the obstacles of the casting method as described above while enabling multilayer construction, is to utilize multi-slot slide coater technology in combination with a removable carrier substrate manufactured from lower viscosity polymer solutions than are normally used to prepare cast films. In the work described in this paper, poly (ethylene terephthalate) (PET) film was used for the carrier web. During manufacturing, the disposable substrate/multilayer resin film is wound into rolls and the resin film is peeled from the substrate prior to lamination to the polarizer plate. Successful implementation of this method of construction requires that a minimum level of adhesion between the film and carrier be maintained to avoid premature delamination while, at the same time, a maximum level be maintained to avoid damage during the subsequent peeling operation.

In the remainder of this paper, we review findings obtained during the development of a peeling process for resin film manufacturing using multi-slot slide coater technology and a removable carrier substrate. First, we describe the structure of two variations of resin film used during the course of this development. Next, performance observations made from peeling experiments are discussed. A theory is then presented that qualitatively explains the performance differences between the two variations of resin film in terms of physical properties of the films and the peeling geometry. Finally, we present practical web path design approaches for maximizing peeling robustness for this application. The value of this work is that it highlights a surprisingly strong link between conveyance process and design features and product properties in such a way as to illustrate the need for a disciplined development effort to overcome the problems and achieve the benefits of a new manufacturing method.

EXPERIMENTS

Peeling experiments were conducted on two samples manufactured using multi-slot slide coater technology [2]. From the results of these experiments, we learned that peeling performance is correlated with the material formulation and peeling geometry. While the impact of formulation on performance was not unexpected, it was quite surprising to learn how large an impact peeling geometry had on performance. In this section, we describe sample preparation and experimental results.

Sample Preparation

Two sample rolls were coated (see Figure 1), and then peel tested during this experiment. In the first sample, a 100 µm thick PET carrier substrate having an antistatic backing layer (backside) is coated on its front surface with a PVA adhesive (Celvol 205 polyvinyl alcohol) having a dry coating weight of ~750 mg/m^2 and NeoRez R-600 (polyurethane dispersion from NeoResins) having a coating weight of ~250 mg/m^2. The dried layer is then overcoated with a triacetyl cellulose (TAC) formulation comprising three layers: a surface layer comprising CA-438-80S (triacetyl cellulose from Eastman Chemical Company) having a dry coating weight of ~2080 mg/m^2, diethyl phthalate having a dry coating weight of ~208 mg/m^2, and Surflon S-8405-S50 (a fluorinated surfactant from the Asahi Glass Company) having a dry coating weight of ~210 mg/m^2; a mid layer comprising CA-438-80S having a dry coating weight of ~18,990 mg/m^2, Surflon S-8405-S50 having a dry coating weight of ~295 mg/m^2, diethyl phthalate having a dry coating weight of ~1900 mg/m^2, TINUVIN 8515 UV absorber (a mixture of 2-(2'-Hydroxy -3' -tert-butyl-5'-methylphenyl)-5-chloro benzotriazole and 2-(2'-Hydroxy -3' ,5'-ditert-butylphenyl)-benzotriazole, available from Ciba Specialty Chemicals) having a dry coating weight of ~840 mg/m^2, and Parsol 1789 UV absorber (4-(1,1-dimethylethyl)-4'-methoxydibenzoylmethane, available from Roche Vitamins) having a dry coating weight of ~90.4 mg/m^2; a lower layer as the tie layer comprising a mixture of 95:5 cellulose acetate trimellitate (Sigma-Aldrich) and trimethyl borate, having a dry coating weight of ~1000 mg/m^2. The TAC formulation was applied with a multi-slot slide coater using a mixture of methylene chloride and methanol as the coating solvent. The cellulose acetate trimellitate has an acid number of 182.

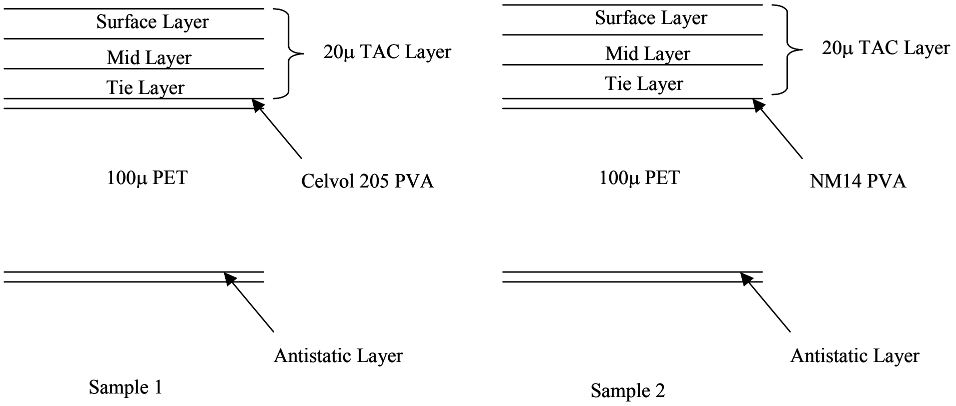


Figure 1 – Sample Structure

Sample 2 was a very similar formulation to that of the sample 1, except that the Celvol 205 PVA was replaced with another kind of PVA (NM 14 polyvinyl alcohol) to promote adhesive strength.

The composite films described above, 1330 mm in width, were wound into supply rolls. The outer diameter of each supply roll after winding was 300 mm on 152 mm cores. For each roll, the dried TAC coating was peeled from the PET carrier substrate at the interface between the front side of the carrier substrate and the adhesion-promoting layer of the PVA film.

Peeling Observations

Early during the peeling trial using sample 1 rolls, it was noticed that the TAC layer separated nicely from the PET carrier web. However, when this sample was used as the cover sheets for the polarizer film, the package failed during an environmental test conducted at high temperature and humidity. Once the adhesive formulation was switched to sample 2, the final product performance in the environmental test was enhanced; however, it was noticed the TAC film was having difficulty being peeled from its carrier web. In some cases, the TAC broke easier, and in worse cases, the PET was torn apart. Figures 2 and 3 show the film salvaged from the peeling location. The samples indicate that the TAC was separating with great difficulty from the PET substrate. At some locations, the TAC even took PET with it and left a hole in the PET. Figure 3 shows chatter lines that appeared on the TAC and PET films after they were separated.

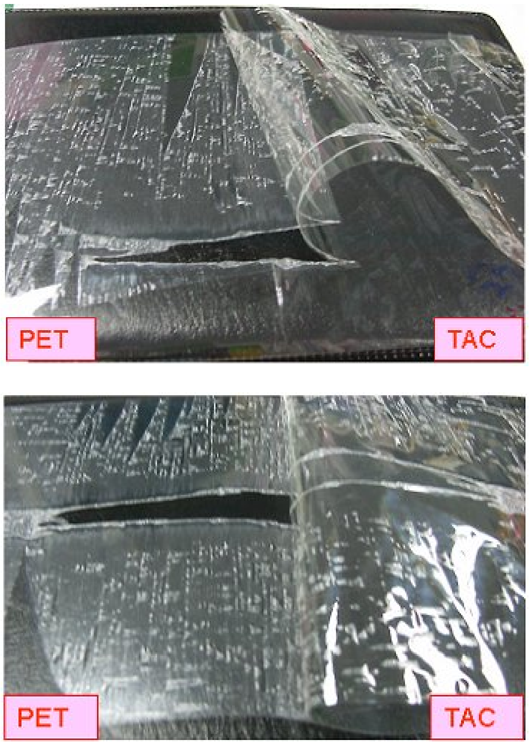


Figure 2 – Sample 2 Peeling Defects: PET Tearing

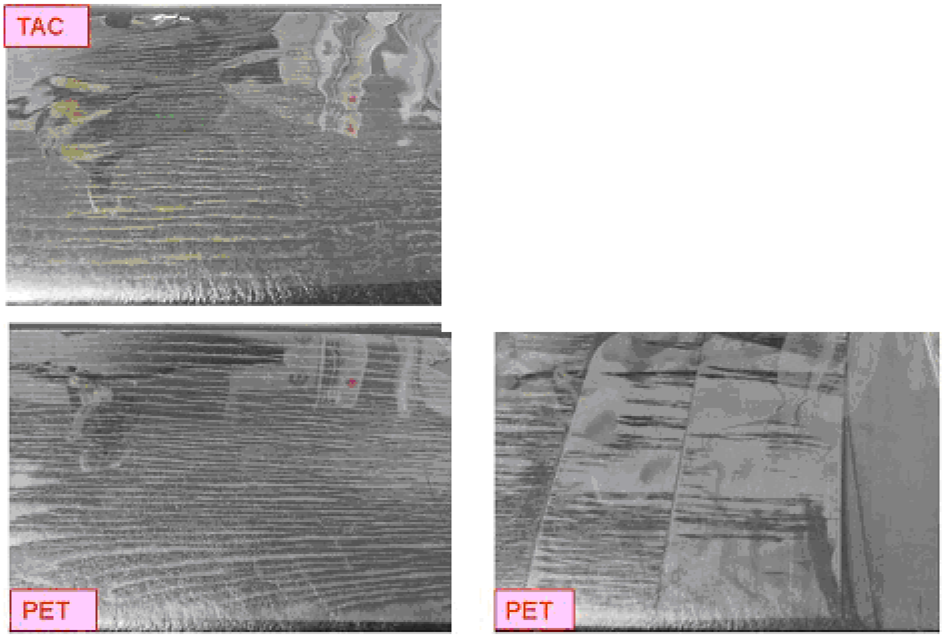


Figure 3 – Sample 2 Peeling Defects: Chatter Lines

Further testing indicated that the difficulty in peeling the film made from sample 2 was functionally related to the bending geometry of the web at the peeling location. When this film was peeled over a four-inch-diameter roller with a web path configuration as indicated in Figure 4 (i.e., the PET wrapped around the peeling roller so that it was bent away from the TAC film during peeling), the peeling was very unreliable. However, if the roller before this roller was used as the peeling roller (as indicated in Figure 5), the peeling proceeded without difficulty.

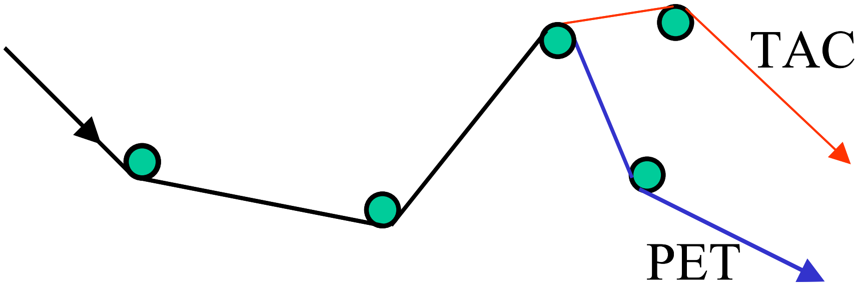


Figure 4 – “Bad” Peeling Geometry for Sample 2

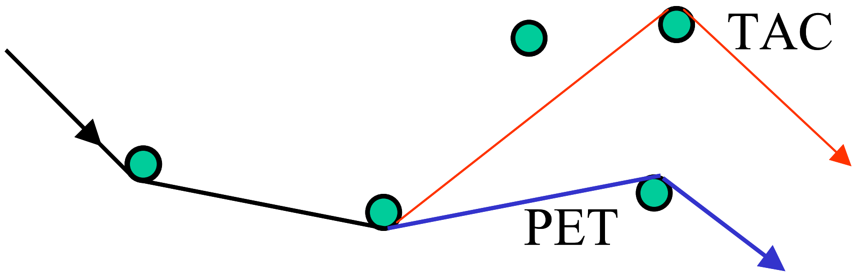


Figure 5 – “Good” Peeling Geometry for Sample 2

Further experimental study indicated that for sample 2, the quality of peeling is positively impacted by the radius of curvature at the peeling location and, consequently, if the four-inch-diameter roller is changed to a larger diameter peeling roller, the performance will improve. Practically, it was determined that a diameter larger than 6 in. yielded acceptable peeling using the “bad” peeling geometry shown in Figure 4 during steady-state operation of the web conveyance path. More will be said concerning the non-steady-state operation shortly.

Peeling Force Measurements

Subsequent to the peeling experiments, peeling force was measured on samples 1 and 2 using apparatus conforming to ASTM test standard D 3330 [3]. It was found that the peel force of sample 2 averaged 6.2 Newton/meter (16 gm/in.) while that of sample 1 averaged 1.5 Newton/meter (4 gm/in.). Based on these results, it seemed likely that peeling performance was correlated to adhesive force between the adhesive layer and the PET substrate. However, it was unknown whether or not the improvement in environmental performance of the polarizer package was causally related to adhesive force or just to the adhesive chemistry. An attempt was made to modify adhesive force by conducting peeling force measurements at increased temperatures and simultaneously measuring peel quality by conducting a simple hand peel test. It was found that, in fact, peel performance was not improved by increasing temperature, and additionally, that peel force for sample 2 was substantially higher than that for sample 1 over a reasonable temperature range (see Figure 6). Based on these results, the decision was made to optimize peeling quality by improving the geometry of the conveyance web path.

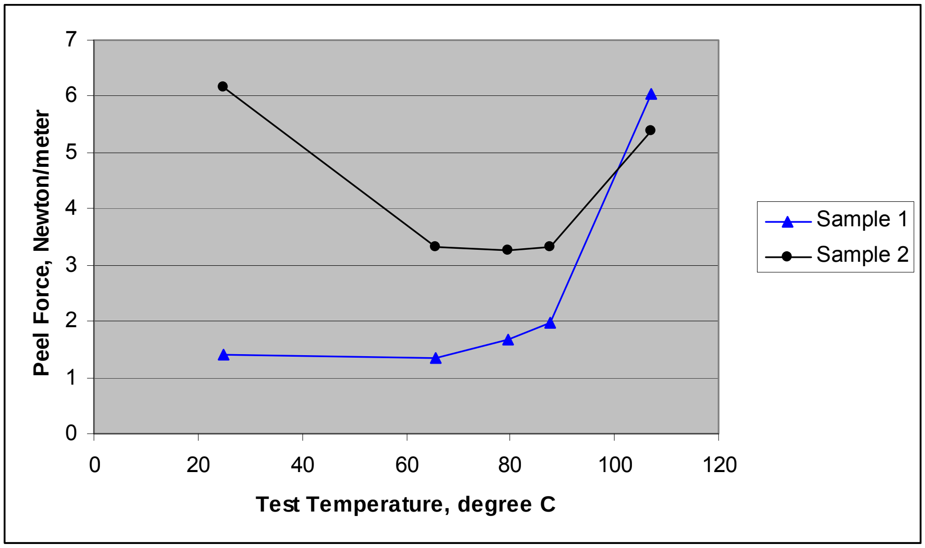


Figure 6 – Peeling Force Measurement vs. Temperature

THEORY

A fundamental understanding of the root cause of the peeling defects is not known at this time; however, some plausible theories have been postulated. One of the theories relates to how the cracks and separation lines between the TAC and PET would propagate while the TAC is being separated from the underlying substrate.

When the adhesive force between the TAC and the PET substrate is relatively low, as in the film made from sample 1, the TAC can be easily separated from the substrate without difficulty in all geometries tested. However, when the adhesive force between the TAC and its substrate PET is high, as in the film made from sample 2, the quality of peeling depends on peeling geometry.

To develop a plausible theory for this performance difference, it is insightful to consider the material characteristics of the PET substrate. The substrate used in the preparation of the two samples was first drafted in the machine direction and then tentered in the width direction during manufacturing. Its strength along the machine direction and cross direction is therefore much greater than its strength in the thickness direction. One way to approximate its anisotropic strength is to model the PET as consisting of many slabs, as shown in Figure 7. When the PET substrate is relatively flat, the cohesive strength of the PET is higher than the adhesive strength between the PET and the TAC. As long as the PET substrate stays flat while the TAC is being peeled, the separation line would propagate along the PET/TAC interface because of its lower adhesive strength, as shown in Figure 7.

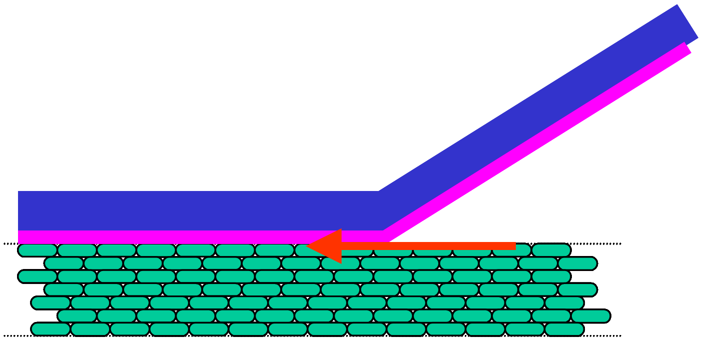


Figure 7 – Heuristic Peeling Model: Adhesive Failure
(Separation Line Propagates along Interface)

When the PET substrate is no longer flat and is bent away from the TAC film, stresses will develop in the PET film as a result of bending. Because the TAC film is much thinner than the PET film (20 μ vs. 100 μ), tensile stress will develop at the TAC/PET interface, and compressive stress will develop on the bottom of the PET layer. Once the PET is bent to a radius of curvature lower than a critical value, tensile stress at the TAC/PET surface will be high enough to pull the slabs slightly apart so that micro-cracks will develop in the PET near the interface. The formation of these micro-cracks reduces the cohesive strength between slabs to a level lower than the adhesive strength at the PET and TAC interface, and as a result, at the peeling location, rather than staying at the PET/TAC interface, the separation line would propagate into the PET substrate through the micro-cracks, making the peeling operation difficult and resulting in ripping and tearing defects.

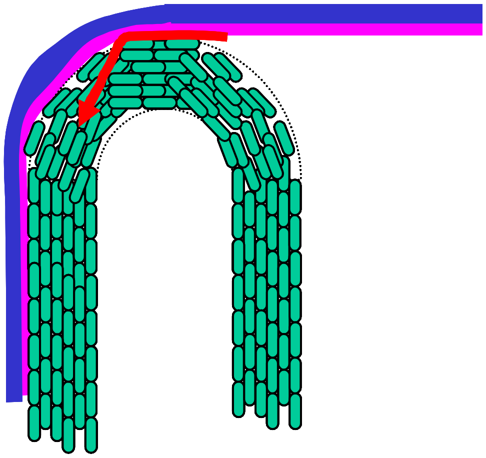


Figure 8 – Heuristic Peeling Model: Cohesive Failure
(Separation Line Propagates into PET)

RESULTS AND DISCUSSION

One potential solution to enable a smooth peeling operation, and to avoid the frequent web tearoffs that would develop, is to have the TAC wrapped around the peeling roller (as shown in Figure 9). Note that this is essentially the “good” geometry shown in Figure 5. This peeling configuration worked well as long as the machine was running at steady state; e.g., no tension transients allowing the web to go slack (Figure 9a). In a roll-to-roll continuous process, however, tension transients can arise, such as when a splice passes through the machine. During the experiments, the PET did occasionally go slack, as indicated in Figure 9b. As a result, the PET/TAC separation line would move downstream of the peeling roller, thereby creating a large curvature in the PET at the separation line. Sudden reapplication of tension on the PET would then create ripping and tearing. Therefore, this option is not a robust option.

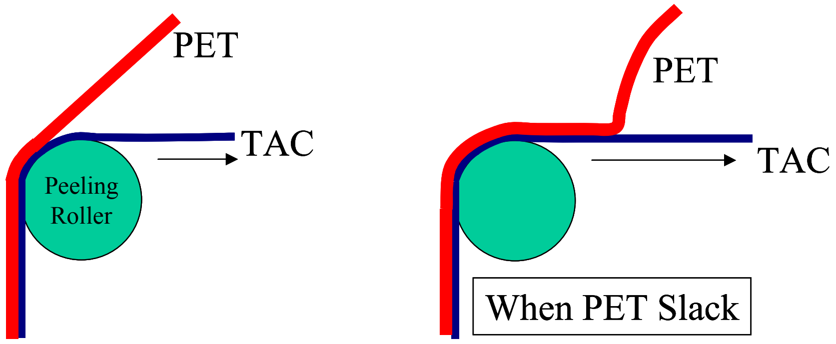
The other option is to have PET wrapped around a peeling roller that has a radius larger than the critical radius of curvature (Figure 10). This peeling configuration, while acceptable during steady-state operation (Figure 10a), still experiences problems during non-steady operation (see Figure 10b), and therefore is not robust for roll-to-roll continuous operation.

An alternative configuration is to replace the peeling roller in Figure 10 with a vacuum roller. As shown in Figure 11, the PET is wrapped around the vacuum roller, whose radius should be larger than the critical radius of curvature. In this configuration, the PET would be drawn down tightly to the roller surface even when the PET becomes slack during transient operation, therefore avoiding the development of a small radius of curvature that would bend the PET away from the TAC. This thereby avoids the risk of non-steady operation causing a small radius of curvature in the PET and the resulting ripping and tearing defects.

When peeling with a vacuum roller, the vacuum level being supplied to the roller becomes critical to the success of the process in a continuous roll-to-roll operation. Too low of a vacuum level will not draw the PET down onto the peeling roller surface, so if the PET becomes slack, it will travel with the TAC, causing ripping and tearing. Too high of a vacuum level will avoid these defects, but will also cause operational issues, such as making the initial machine threading more difficult. Too high of a vacuum level would also cause the web to wrap around the vacuum roller if the web breaks in the machine.

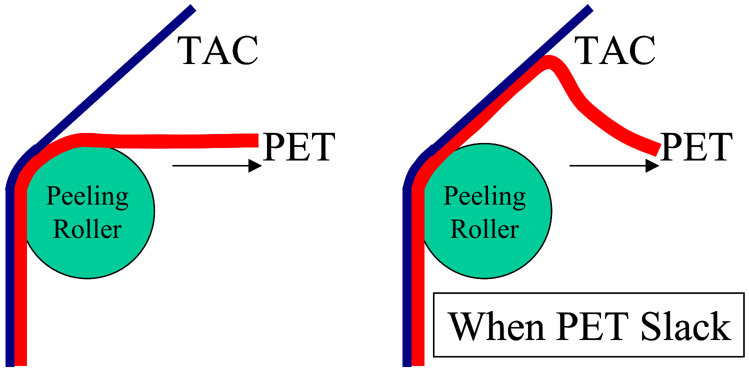
To reduce the air volume needed for the vacuum roller during the continuous operation, a ported vacuum roller is preferable. A ported vacuum roller would also avoid the web’s wrapping around the roller in the case of a web break. However, the tension loss in a ported vacuum roller, caused by internal friction, would be higher than in an unported vacuum roller, and therefore it may need to be driven to avoid too excessive a tension loss during conveyance.

During a lab trial, an unported vacuum roller with surface grooves for vacuum distribution was used. In the lab trial, excellent peeling performance was observed. Successful peeling was achieved even when the tension was lowered to a level significantly less than required to prevent the composite web, the TAC, and the PET webs from going slack. Vacuum roller peeling was also successful when splices went through the machine.



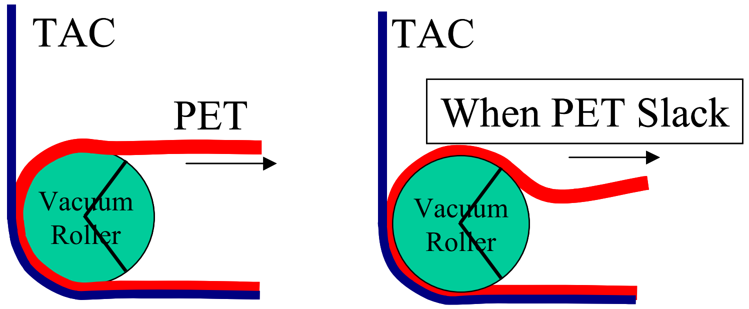
(a) Steady-State Operation (b) Non-steady Operation

Figure 9 – Peeling Geometry: TAC Wrapped on Roller



(a) Steady-State Operation (b) Non-steady Operation

Figure 10 – Peeling Geometry: PET Wrapped on Roller



(a) Steady-State Operation (b) Non-steady Operation

Figure 11 – Vacuum Roller Peeling: PET Wrapped on Roller

ACKNOWLEGMENTS

The authors thank Roland Bruyns of Eastman Kodak Company for providing the experimental data on peeling force measurements.

REFERENCES

1. Fuchigami, S., "Challenges and Opportunities in Flat Panel Industry," Proceedings of the Eighth International Conference on Web Handling. Web Handling Research Center, Oklahoma State University, Stillwater, Oklahoma, 2005, pp.183-202.
2. Cohen, E. D. and Gutoff, E. B., Modern Coating and Drying Technology, Wiley, 1992, pp.119-120.
3. ASTM, Standard Test Method for Peel Adhesion of Pressure-Sensitive Tape, ASTM D 3330/D 3330M, 2004.

Peeling Process Development for Thin Flexible Webs

H. Lei[1] **& K. Cole**[2]**,** [1]Eastman Kodak Company and [2]Grid Computing Solutions, LLC, USA

Name & Affiliation	**Question**
Keith Good, Oklahoma State University	Why not waste twice as much vacuum air instead of relying on web tension to pull one web away from the peel zone? Why not have vacuum pull roll on both sides of the web and try to separate them apart on the two vacuum pull rolls?
Name & Affiliation	**Answer**
H. Lei, Eastman Kodak Company	That could work too. Since this was to be implemented in industry the cost element must also be considered.
Name & Affiliation	**Question**
Kevin Cole, Grid Computing Solutions	If we had used two rollers, the top roller may damage the film.
Name & Affiliation	**Answer**
H. Lei, Eastman Kodak Company	If the contact force was small and did not damage the top web two vacuum pull rolls may provide an acceptable solution.
Name & Affiliation	**Question**
Steve Lange, Proctor & Gamble	Do you have to use PET film or can you use something like polypropylene that has a lower surface energy where you might get enough adhesion, but not too much?
Name & Affiliation	**Answer**
H. Lei, Eastman Kodak Company	After seeing these defects, using a different type of carrier was one of many ideas discussed. We can coat on paper or other films. Paper would not be clean enough for this industry. But we did not examine those ideas further.
Name & Affiliation	**Question**
Kee Shin, Konkuk University	If the transient tension was the problem, why didn't you try solving the problem with tension control rather than consuming a lot of energy?
Name & Affiliation	**Answer**
H. Lei, Eastman Kodak Company	We tried our best to get the web straight all the time. The trouble is this film can be wide, like 50, 60, 70 inches wide. It is okay during the steady state operation, but the defect would appear again when the splice comes through – you can never make a perfect splice on the machine. The splice will always be slack on one side and tight on the other. The tight side would be okay, but the slack side would not. We did try to improve tension control, but that alone did not provide a solution.
Name & Affiliation	**Question**
Keith Good, Oklahoma State University	Continuing on the thought of two rollers at the peel point: Maybe the second rooler doesn't even need to be a vacuum pull roll, perhaps it could be a roller with a soft cover. You could try to get both surfaces in tensile stress that way.

Name & Affiliation	**Answer**
H. Lei, Eastman Kodak Company	Actually, we could put a vacuum roller on the top, but I don’t think it is necessary.
Name & Affiliation	**Question**
Keith Good, Oklahoma State University	But that allows that TAC web to wrap it.
Name & Affiliation	**Answer**
H. Lei, Eastman Kodak Company	The roller on the top is not necessary because we are afraid of the PET web developing a small radius of curvature. For the TAC film, we don’t care – the TAC film can go slack and go wherever they want. Whenever the tension comes back, the TAC is okay. It doesn’t develop those ripping and tearing defects.
Name & Affiliation	**Question**
V. Niebuhr, Ruhr-University Bochum	I think the problem is you need a definite point where one web is taken from the other one and perhaps two rollers provides that whether vacuum is applied or not. The point of separation needs to be defined.
Name & Affiliation	**Answer**
H. Lei, Eastman Kodak Company	You bring up a very good point. Early on in the project, we tried all kinds of things. We tried a peeling knife – basically it is a stationary knife. The first disadvantage was that the peeling knife will generate a lot of particles, and it is not good for a clean environment which is required for these products. Although a peeling knife would work in steady state, transients will result when a splice comes through the machine. We did try a small diameter roller - about 1” or ½” diameter, but that did not help. The only one that really works well in both the transient and steady state conditions was the vacuum roller.
Name & Affiliation	**Question**
Bob Lucas, Winder Science, LLC	If the PET web cannot be replaced by another carrier film, is there a way you can modify the electrostatic or molecular attraction by an ionizing process at the point of entry to pre-condition the surface of the PET so it doesn’t have such a strong bonding effect?
Name & Affiliation	**Answer**
H. Lei, Eastman Kodak Company	We did not try this. We don’t want too strong an adhesion, but we don’t want too weak an adhesion either in the process.