OPTIMIZATION OF EQUIPMENT AND PROCESS CONDITIONS FOR FILM WINDING

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ABSTRACT

Mathematical modeling of film winding has progressed to a point where it can offer much insight into the mechanics of this process. However, experience and testing on the actual hardware are still necessary to maximize yields. The purpose of this work is to describe the practice of using both modeling and testing in consort to optimize winding. Modeling is the first step. For the best results, this is done before the winding hardware is fabricated. The use of models for roll stresses, air entrainment, buckling, air leakage and roll aging are discussed. Films are divided into categories based on the predominant defect type. Winding hardware and film surface design requirements are discussed for each of these film groups. An example of this approach is included that describes the process from the concept to on-line testing phases to optimize the process conditions.

NOMENCLATURE

B	Half-width of a roll
E	Elastic modulus of the web
E_r	Radial or stack elastic modulus
f	Added friction factor for air leakage
h_o	Air gap in wound roll
K_1 , K_2	First and second stack compression coefficient, $P = K_1 \exp(K_2 \varepsilon) - K_1$
P	Normalized Air Pressure, $(P_a - P_{atm}) / (P_i - P_{atm})$
P_A	Pressure on surface asperities
P_a	Air Pressure in gaps in wound roll
P_{atm}	Atmospheric pressure
P_i	Initial air pressure between layers
P_o	Wrap Pressure T/r

P_r	Normalized pressure ratio, $(P_i - P_{atm}) / P_{atm}$
R_a, R_z	Surface roughness values, average and peak-to-peak
T	Web Tension
r	Radius of roll
Y	Normalized transverse direction dimension, y/B
y	Dimension from roll center in the transverse direction
ε	Strain
μ	Viscosity of air
σ_r	Radial stress
τ	Normalized time for air leakage calculations
τ_t	Normalizing factor for τ, $12\ \mu\ f B^2 / (P_i - P_{atm}) h_o^2$

INTRODUCTION

A wide range of work has been done in the area of modeling the film winding process. These include calculations for the (1) stresses formed in winding rolls [1-3]*, (2) techniques to predict the formation of defects in the winding rolls [4], (3) the air entrained into the rolls [5-7], (4) the effect of film surface on film winding [8], and (5) roll aging problems related to air leakage and plastic deformation of film [3, 9,10]. Films currently manufactured range from less than 1 micron to greater than 300 microns thick. The surfaces on these films range from very smooth ($R_a < 0.1\mu m$) to very rough ($R_a > 2\mu m$). Rolls of film can be wound that look very good at the end of the winding process, but they may contain undetectable defects or deteriorate over time. For the full range of film thicknesses and types, the control of winding tension, tension taper and air entrainment are crucial to successfully winding high quality rolls of film. Different ranges of film thickness do have unique problems associated with the types of defects that typically occur.

Thick Films (>100 micron): Thick films are the easiest to wind and only present a problem when we have a smooth film surface, poor gage variation or flatness problems. Typical defects include gage bands (stretched lanes in single sheet), blocking (film sticks to itself), telescoping and roll aging. All of these problems are exacerbated by a smooth film surface. Approaches used to enhance winding of smooth films in this gage range include knurling and surface modification by either additives, surface treatment or coatings. The film surface modifications need to prevent blocking (the bonding together of adjacent layers of film) and provide a texture to absorb gage variations of the sheet. Additives for thicker films should be selected to reduce the stack stiffness as much as possible (wide particle distributions, larger particle sizes and low concentrations of additives). For thick films with a smooth surface, consistent roll starts present a serious problem. Here, any imperfection in the roll start is not covered well by the layers added to the roll and a substantial pad of damaged film can result.

Intermediate Gages (25 TO 100 micron): Intermediate gages are slightly more difficult to wind. They are more prone to roll formation defects caused by stresses induced by winding tension. The primary types of defects that can occur include MD ridges (tin canning) and TD ridges and wrinkles. Both MD and TD ridges result in

* Numbers in brackets refer to references included in the Bibliographic References

sinusoidal ripples in the roll with the peaks running in the MD and TD, respectively. Other defects include gage bands (stretched lanes in single sheet), blocking (film sticks to itself), telescoping and roll aging. Additives for intermediate films should be selected to provide a combination of texture for the accommodation of gage variations and higher stiffness to avoid buckles that form MD ridges and TD wrinkles.

Thin Films (<25 micron): Buckle in wound rolls of film due to stresses developed during winding are the primary roll defect for these films. These defects are normally called MD ridges (tin canning) in one direction and TD ridges or wrinkles in the other direction. Here, these defects are difficult to eliminate using ordinary means. Film surface design becomes crucial in this gage range to minimize these buckles [4]. Additives should be provided to make the film as stiff as possible in the stack direction (small particle size distributions and large concentrations [8]).

We have a large volume of both experience and technology to assist us in winding film. How do we use this information to develop windable films, design equipment that can successfully wind them and establish winding conditions to optimize yields? The purpose of this paper is to outline a series of techniques that can be used to develop a successful film winding system. It includes discussions and presentations of (1)key analytical techniques needed, (2) experience factors that can be used and (3) recommendations for means to optimize roll quality.

KEY ANALYTICAL APPROACHES

The key techniques available to analyze film winding involve calculations of (1)stresses in wound rolls, (2) buckling or defect formation in the roll, (3)air entrained in the rolls during winding and (4) aging of the roll due to either air leaking out or plastic deformation of the film or film surface. Each of these will be considered.

Roll Stress Calculations: The standard approach employed for roll stress calculations [1] uses linear superposition to achieve the total stress in the wound rolls. Here, the stress from the addition of each layer of film applied to the roll is determined individually and the total stress is calculated as the sum. This method has been widely used and found to be accurate for most applications. Mathematically, linear superposition is valid only for solutions to linear differential equations. The roll stress equation is nonlinear, however, and strictly speaking this approach is incorrect. Recently, a fully nonlinear solution has been proposed [3]. It does not employ linear superposition. The results are very similar to those achieved using the standard approach for thicker films with higher stack stiffnesses. However, for thinner films with lower stack stiffnesses the results from the two techniques differ widely. The new technique is not yet accepted and needs to be tested for various applications. It is none the less the better choice for films with lower values of stack stiffness (K_2 <100). This approach will be used in the subsequent example included below.

Defect Formation in Wound Rolls: The results of the stress calculations are radial, circumferential and transverse direction stresses inside the roll. These are typically much lower than the yield stresses for the films being wound. So, how do you determine whether a stress distribution is good or bad? For defects related to gage bands, stretched lanes and alike, it becomes very difficult. To model this process fully, you would have to do a full stress analysis of the roll including the width direction and you would have to include gage variations. This is not usually done due to the complexity and limited benefit. The stress work normally done is either a plane stress or plane strain analysis with no gage variations considered. Of these the plane strain is more valuable. It approximates an infinitely wide roll and calculates stresses in the transverse direction which are needed for buckling models that predict the formation of MD ridges.

For thick films you are looking for a stress distribution that (1) does not have a very high maximum radial pressure (say less than 3.5 MPa or 500psi) or (2) does not have a large region of circumferential compression. The pressure should drop monotonically from the core to the surface. The winding hardware should have the capability to taper the winding tension and layon roll pressure in a controlled manner during the winding process. Tension should always decrease during the winding process while layon roll down force can taper up, down or stay the same. A constant layon roll down force is usually adequate.

For intermediate film gages buckling becomes an additional concern. This can be analyzed nicely using the plane-strain stress analysis and the buckling criteria presented in reference [4]. Here, it is shown that the first mode of buckling for a layer of film is a sinusoidal shape. Both MD ridges and TD pattern are sinusoidal buckles. MD ridges are a sinusoidal pattern of buckles where the grooves in the buckles run around the perimeter of the roll. They are caused by transverse direction compression introduced by Poisson's ratio effects acting on the stresses in the radial plane. TD pattern are similar in shape but the grooves run across the roll width. These are caused by circumferential compression inside the wound roll. Two buckling numbers have been defined in reference [4] one for each defect type. These can be evaluated in the roll stress analysis to predict the formation of buckles. By definition, buckling can occur if either buckling number exceeds one. They will be used where appropriate in the included example.

Air Entrapment: Several approaches are available for the calculation of the amount of entrained air entering the roll at the winding nip. These can be divided into two types. Those that consider the surface roughness height of the film[5] and those that don't [6,7]. For the typical winding geometry shown on Figure 1, the layon roll presses the film on the surface of the winding roll. Under the nip there is a contact zone where the stress from the applied nip force is the means of limiting the amount of air that enters the roll. Ignoring the film surface roughness says that this entire force is being supported by air. Including the film surface roughness indicates that the nip load is supported by a combination of air and film surface roughness. After the roll passes, the compressed air expands and the final gap and air pressure defines the air entering the roll.

The approach used to calculate the expansion to the final condition downstream of the layon roll also depends on the film surface assumption used. If no surface is included, it's a simple isothermal expansion (the film determines the temperature) until the pressure is equal to T/r. For the more complex case including surface effects, the expansion becomes

$$P_a(h_o) = T/r - P_A(h_o) \qquad (1)$$

when $h_o < R_z$, the maximum asperity height.

Ignoring the asperity size distribution and tension has to result in problems [10]. Results for two different techniques are included on Figures 2 through 4. All of these are plots of the air gap versus web speed. Two curves are included and points from experimental data. Here, the first curve is from references [6,7] where no surface aspirates are considered (see Table 1 for data used). The second curve uses the approach from reference [5] but here a very small roughness height is used (i.e. $R_z = 0.6$ μm). The predictions compare reasonably well with the data and with the curve from references [6,7]. The final curve which also uses the approach from reference [5] shows very different results when the air gap is below the height of the surface roughness (i.e. $R_z = 1.2$μm). This has to be correct when the air gap is smaller than the maximum asperity height, both terms on the right hand side of equation 1 are needed. Under the nip, where the air flow is being controlled, this is even more true since the normal stress induced by the nip can be very large in comparison and R_z can be much larger than the resulting gap.

The radial elastic modulus used in these calculations is a key issue. The fit shown from calculations performed in reference [6] uses a constant radial modulus (although a more precise means is recommended) to achieve the level of accuracy shown. In order to achieve the fit using the approach with aspirates [5], the radial elastic modulus was obtained from

$$E_r / (P_o + P_{atm}) = \{ (\sigma_r + P_o + P_{atm}) / (P_o + P_{atm}) \}^3 \qquad (2)$$

which is similar to the relationship in Good and Covell [11] but the exponent is different. There are still issues to be resolved here.

Future efforts in this area need to include both the surface roughness and wide ranging experiments. Here, films with different roughness heights and distributions need to be considered. Winding geometries need to be varied and different layon roll dimensions and materials must be considered. Using one film type with a fixed surface roughness can lead to conclusions that don't apply to other films and geometries.

Roll Aging - Air Leaking from Roll: Roll aging is attributed to air leaking out of the ends of the rolls [9] and possibly plastic deformation of the web surface or even the web itself[3,10]. All of these affect either E_r or E. Measurements of the plastic deformation of high performance films typically show little or no plastic deformation in the plane of the web even for long time periods (months). The cases included here will only consider the air leakage and plastic deformation in the stack direction. This does not imply that plastic deformation in the web is not an issue for some films.

Air escaping from the ends of the rolls is a known cause of roll aging. Here, the air is entrained at the winding surface and is compressed as the roll builds. Also as the roll builds, air begins to leak out of the ends of the roll. This process is known to continue for hours. There are several time scales that are important. These include (1) the time for each wrap on the winding roll, (2) the time to wind a full roll, and (3) the time before reprocessing of the roll.

The differential equation describing air leaking out of a very narrow slot is a modified form of an equation from reference [12]. Here, the geometry shown in Figure 5 is employed and the differential equation is simplified by assuming that the slot or gap width is constant. The normalized differential equation is

$$[P + 1/P_r] \partial^2 P/\partial Y^2 + (\partial P/\partial Y)^2 = \partial P/\partial \tau \qquad (3)$$

where the boundary conditions are

$P = 0$ at $Y = 0$ ($y = B$, the outside edge) (4)

$\partial P/\partial Y = 0$ at $Y = 1$ (center of the roll)

Normally, this approach assumes that the flow in the gap between layers is laminar and the roughness of the film layers does not affect the flows and pressure drops. To partially account for the roughness a friction factor, f, is included. We know that measurements of this type of flow friction are very limited. Tests have shown, however, that the wall friction will be higher due to the blockage from surface roughness. This means that a flow calculation using a laminar flow factor of 1 (no extra friction) will yield results where the air leaks out more rapidly than it actually will.

Air leakage results are included on Figures 6 and 7 for the range of normalized variables shown. Figure 6 shows several pressure profiles at different normalized times for a P_r of 1 which corresponds to an initial pressure of 2 atm absolute or 1 atm gage. This is in the range of expected values for air pressures inside the roll [3,8]. Notice that the center portion of the roll does not see the effects of the leakage flow for small normalized times (say $\tau < 0.02$) and that the entire process is virtually over at $\tau = 1$. The next plot, Figure 7, shows the pressure at the half width (center) plotted versus the log of normalized time. This also shows that the center portion of the roll does not see any effect for short times ($\tau < 0.02$) and that the entire process is virtually over at $\tau = 1$.

Now, we need to work back through the normalization to determine how long a typical roll takes to deflate. The properties used for the film and roll are shown on Table 2. Here, $\tau = 0.02$ equates to approximately 70 min. to 0.4 sec. and $\tau = 1$ corresponds to 58.7 hrs. to 21 min. depending on the ratio B/h_o. The value of the normalizing time, τ_t, can be used to determine the rate at which winding rolls will deflate. This is defined as

$$\tau_t = 12 \mu f B^2 / (P_i - P_{atm}) h_o^2 \qquad (5)$$

This is strongly influenced by the assumed value of h_o, the gap height down in the roll. This height should be smaller than that at the surface and the pressure will be higher as indicated. It also should be dominated by the asperity height. The resulting times are usually much larger than the time for an individual wrap of film on the roll but can be larger or smaller than the winding times for a given roll of film. Therefore, substantial leakage can occur during the winding of a given roll of film and/or it could take days for the roll to fully deflate.

Roll Aging - Plastic Deformation in Roll/Film: Plastic deformation of the web has been measured[10,13] and some techniques have been developed to calculate stresses in rolls after aging [10,3]. One area that has been lacking is plastic deformation of films in the stack direction. Figures 8 through 10 show some preliminary data indicating that plastic deformation does indeed occur. The first plot (8) shows raw stack compression results for the compression of a 6 micron PET film. It includes a series of compressions and relaxations. Notice how the film receives a permanent set with each compression and that after several applications a more or less stable condition is reached. The next plot shows a long term stack compression at a fixed pressure of 414 KPa (60 psi) for the same film. Notice here how the film is slowly compressed (creeps) in the stack direction with time. These plots show that a significant level of plastic deformation can occur in the stack direction for films that are resistant to this type of deformation in the plane of the web.

The final plot, Figure 10, shows what happens if a stack of film is subjected to a repeating pulse load. Again, the film plastically deforms in a step-wise fashion due to the repeated load applied. This test approximates the effect of the layon roll on the winding roll surface. It illustrates the second function of the layon roll which is to compact the film in the stack direction.

These plots show that films can creep in the stack direction and that the stiffness in that direction depends on the pressures applied by the layon roll as the film winds. Winding hardware should be designed to provide enough pressure to plastically deform the film surface at the surface of the winding roll. This type of creep is more pronounced for light gage films. A better understanding of this phenomenon could be used to design film surfaces that are more resistant to stack-creep.

EXAMPLE OF ROLL STRESS EVALUATION

This approach indicated that air leakage and plastic deformation of the stack can occur both during and after winding a roll of film. Based on this information, we propose using three solutions for the roll stress to aid in determining the effect of air leaking or aging on roll formation. These include:

1. Calculations of the roll stresses including air pressure assuming no air leakage during winding and the uncompressed stack stiffness (lower value from first compression ignoring the benefit of the layon roll).
2. Calculations of roll stresses excluding the air effect entirely and using the lower stack stiffness value.
3. Starting with the calculation in 1, calculate the effects of all the air escaping from the roll (no net air pressure remaining in the roll).

For a well posed winding system the three solutions will be very similar and none will show potential buckling problems. They also represent a worst case (lower stack stiffness) based on the benefits which the layon roll will produce.

We intend to consider the three solutions described above. Rather than calculate the air entrained during the winding we are going to select a level of air entrainment based on experience. The results of the stress analyses will be used to confirm that the level of air entrainment selected is acceptable. The air exclusion devices needed to achieve this level of air removal can then be determined. This uncouples the calculation to a degree.

The data required for the calculation is included in Table 3. Here, a 5 micron film is described which will be wound at a speed of 600 m/min. Note that results for an air gap that is slightly less than the roughness height is used. Designing for this level of air exclusion is usually sufficient. The results for these calculations are included in Figures 11 and 12.

Figure 11 shows the radial pressure distribution for the three cases and the entrained air pressure for case 1. Note that the pressure distributions are very similar and that the air pressure is much smaller than both the total pressure and the asperity contact pressure (total - air pressures). Figure 12 shows the MD buckling numbers for these cases. They are all well below one (the buckling threshold) and again quite close in magnitude. This approach should work well.

The layon roll device can now be designed based on achieving the required level of air exclusion. The correlation approach without surface roughness [6,7], or the more complicated, full solution [5] that includes surface roughness can be used for this purpose. The conservative approach should be employed here. There are still significant issues around these calculations and a system that will be capable of more air exclusion than might appear necessary should be designed. The requirements introduced by stack-creep also need to be considered. No examples will be included here, since there is still a substantial level of art required to select a good layon roll system and any example included here would necessarily include this art.

OPTIMIZING ROLL FORMATION

The equipment has been designed based on the calculations described above, the measured film properties and a degree of judgment and experience. The capability to adjust and taper tension and layon roll force must be included. Now we need to learn how to wind the film. The calculations and operating experience will give you a starting value, but now the performance needs to be optimized. The statistical test is the best means of accomplishing this.

A flow chart for a statistical test is included as Figure 13. First the control variables must be selected. These should include starting tension, tension taper, winding speed and starting layon roll loading including taper if available. Several types of layon rolls may be tried (different diameters, cover properties and finishes). Different core types and diameter also can be tried. A more extensive test could include variations in the web surface and different levels of skew and gage variation in the film. Note that you don't have to know whether a variable is important or not. The results will tell you that.

The test approach is then selected. You can do an extensive test covering all of the variables in detail or you can start with a scouting test which will identify the key control variables. If you are including more than the standard winding variables, an initial scouting test will be cost effective. Use statistical test software to design the test (for example ECHIP [14]) .

Wind the rolls of film and treat them as standard product. Measure the surface hardness immediately after winding. This can be an important quality check later. The key point here is to let them age unless they are intermediate product that is immediately reprocessed. Remember that the film can age for at least 3 to 4 days. Therefore, wait seven days and evaluate the rolls. Measure everything you normally check and note any abnormalities. Rewind the roll stopping it periodically during the process to recheck quality. Measure the roll hardness at each point during the rewind.

Use statistical test software to fine the optimum winding conditions to minimize your key defects. Then retest the optimum condition to insure that it works. Set the standard operating conditions as indicated and use roll hardness as an indicator to keep the process in control. Periodically save rolls, age them as required and inspect them using the rewind approach used during the test. This procedure almost insures an improvement and establishes a technique to maintain it.

CONCLUSIONS

The number and the quality of the analytical tools available are making film winding more of a science. Techniques are available for calculating internal stresses in wound rolls and predicting the formation of buckles. The level of entrained air can be calculated based on winding conditions and geometry. Plastic deformation of the film can be included and several benefits of the layon roll have been identified. This aids in the design of winding hardware and begins the optimization process for roll quality. Due to current limitations in the analytical tools, however, experience still is required in designing hardware for film winding and experimentation is needed to optimize roll quality.

The roll stress analysis models fall into two types, the layered and body force approaches. The layered approach is the state of the art technique but it uses linear superposition to achieve solutions to a nonlinear problem. The new body force approach does not use linear superposition but is relatively untried. For films with lower stack stiffnesses, the solutions differ [3] and this issue needs to be resolved.

Several areas are still in need of investigation. These center around problems related to roll aging or deteriorating quality with time. The air entrainment still needs work to insure accuracy and take the film surface fully into account. Models exist and experimental techniques are available to measure the entrained air. The data is limited and is not available for a wide range of film surfaces, layon roll geometries, and winding conditions. The results of these can't be relied upon fully as a equipment design tool.

Plastic deformation of films have been measured and quantified in a way that allows for some calculations of roll stresses after the winding process is complete. The existing approach uses the linear superposition method discussed above and potentially has errors. The new body force approach needs to be extended to included plastic deformation and comparisons should be made. Work on the plastic deformation in the stack direction needs to be done to (1) relate this phenomenon to roll aging , (2) include it into plastic deformation models for roll stress, (3) relate to it to film surface design, and (4) quantify the effect of layon roll forces on subsequent radial deformation.

Layon roll systems need to be designed to both remove air and minimize plastic deformation in the radial direction. The entrained air gap should be smaller than the maximum roughness height of the film surface. If the peak pressure under the nip is approximately the same as that inside the wound roll, most of the plastic deformation of the film surface will take place during winding. This combination should minimize aging problems in the wound rolls.

Statistical testing still is required to design films, winding equipment and winding conditions. These tools are powerful and require only limited prior knowledge. They can account for complicated interactions of numerous control and design parameters. They don't tell you what to try, however. The modeling approach is the best means of doing this. Although not fully accurate and complete at this time, the existing models can point out directions and provide insight that would be extremely difficult to achieve using testing alone.

BIBLIOGRAPHIC REFERENCES

1. Hakiel, Z., "Nonlinear Model for Wound Roll Stresses", Tappi, pp. 113-17, May 1987.
2. Pfieffer, J. D., "Predictions of Roll Defects from the Structure Formulas", Tappi, Vol. 62, No. 10, pp. 83-85, 1979.
3. Forrest, A. W., "A Fully Nonlinear Solution to Stresses Inside Wound Rolls", Proceedings of the Fifth International Conference on Web Handling at Oklahoma State University, June, 1999.
4. Forrest, A. W., "Wound Roll Stress Analysis Including Air Entrainment and The Formation of Roll Defects", Proceedings of the Third International Conference on Web Handling at Oklahoma State University, June, 1995.
5. Forrest, A. W., "Air Entrainment During Film Winding with Layon Rolls", Proceedings of the Third International Conference on Web Handling at Oklahoma State University, June, 1995.
6. Taylor, R. M. and Good, J. K., "Entrained Air Films in Center Wound Rolls - With and Without the Nip", Proceedings of the Fourth International Conference on Web Handling at Oklahoma State University, June, 1997.
7. Chang, Y. B., Chambers, F. W. and Shelton, J. J.,"Elastohydrodynamic Lubrication of Air-Lubricated Rollers", ASME Journal of Tribology, Vol. 118, pp. 623-28, July, 1996.
8. Forrest, A.W.,"Film Surface Considerations for Enhanced Winding of Thin Films",Proceedings of the Fourth International Conference on Web Handling at Oklahoma State University, June, 1997.
9. Bourgin, P., "Air Entrainment in Web Handling: to be Avoided or Matered", Proceedings of the Fourth International Conference on Web Handling at Oklahoma State University, June, 1997.
10. Qualls, W. R. and Good, J. K., "A Nonlinear Orthotropic Viscoelastic Winding Model", Proceedings of the Third International Conference on Web Handling at Oklahoma State University, June, 1995.
11. Good, J. K. and Covell, S. M., "Air Entrainment and Residual Stresses in Rolls Wound with a Rider Roll" Proceedings of the Third International Conference on Web Handling at Oklahoma State University, June, 1995.
12. Gross, W. A., Gas Film Lubrication, John Wiley and Sons, Inc. New York, Library of Congress Number, 62-15176.
13. Lin, J. Y. and Westermann, R. A., "Viscoelastic Winding Mechanics", Journal of Applied Mechanics, Vol. 56, December 1989, pp. 821-27.
14. Wheeler, Bob, ECHIP version 6 for Windows, ECHIP, Inc., 724 Yorklyn Road, Hockessin, DE 19707-8703.

Table 1 Properties used for the air entrainment calculations

Radius of Winding Roll = 0.057 m (2.25 in.)
Radius of Layon Roll = 0.051 m (2.0 in.)

Cases	1	2	3
Nip Loadings	= 525.3 N/m (3 pli),	876.6 N/m (5pli),	1400.9 N/m (8 pli)
E_r reference [6]	= 0.689MPa (100 psi),	0.689 MPa (100psi),	0.689 MPa (100psi)
E_r reference [5]	= 0.138MPa (20psi),	0.689 MPa (100psi),	1.723 MPa (250psi)
R_z reference [6] work	= 0	0	0
R_z reference [5] small	= 0.6 microns	0.6 microns	0.6 microns
R_z reference [5] large	= 1.2 microns	1.2 microns	1.2 microns

Table 2 Properties used for the air leakage calculations

h_o = 0.1 micron (3.94 micro-inches) to 10 microns (39.4 micro-inches)
B = 1 m (39.4 inches)
$P_i - P_{atm}$ = 1 atm (14.7 psi)
μ = $1.2\text{x}10^{-5}$ #m/ ft sec
f = 1
τ = t / τ_t
τ_t = $12\ \mu\ B^2 / (P_i - P_{atm})\ h_o^2$ = 352 min. to 0.352 min.

Table 3 Properties used for Wound Roll Example Cases

Film Properties
- Elastic Modulus of Film = 4137 MPa (600 Kpsi)
- Film Thickness = 6 microns (0.24 mils)
- Poisson's Ratio = 0.15
- OD of Roll = 610 mm (24 in.)

Film Surface Properties
- First Stack Coefficient K_1 = 6.895 KPa (1 psi)
- Second Stack Coef K_2 = 80
- R_z = 1 micron (40 μ in.)
- Air Gap at 1 atm = 1 micron (40 μ in.)

Core Properties
- Elastic Modulus = 6140 MPa (890 Kpsi)
- ID of Core = 152.4 mm (6 in.)
- OD of Core = 203 mm (8 in.)

Winding Tension (Linear Taper)	Roll Radius	Web Tension
	101 mm (4 in.)	88 N/m (0.5 pli)
	600 mm (24 in.)	17.5 N/m (0.1 pli)

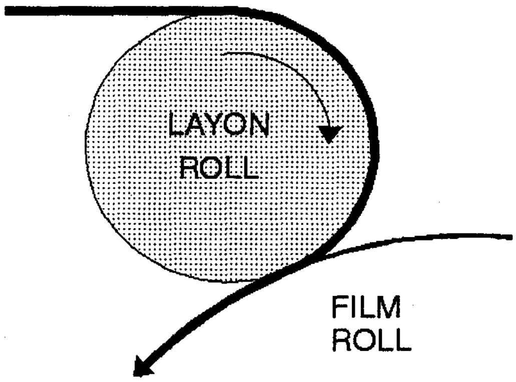

Figure 1 Layon Roll Geometry for Air Entrapment Cases

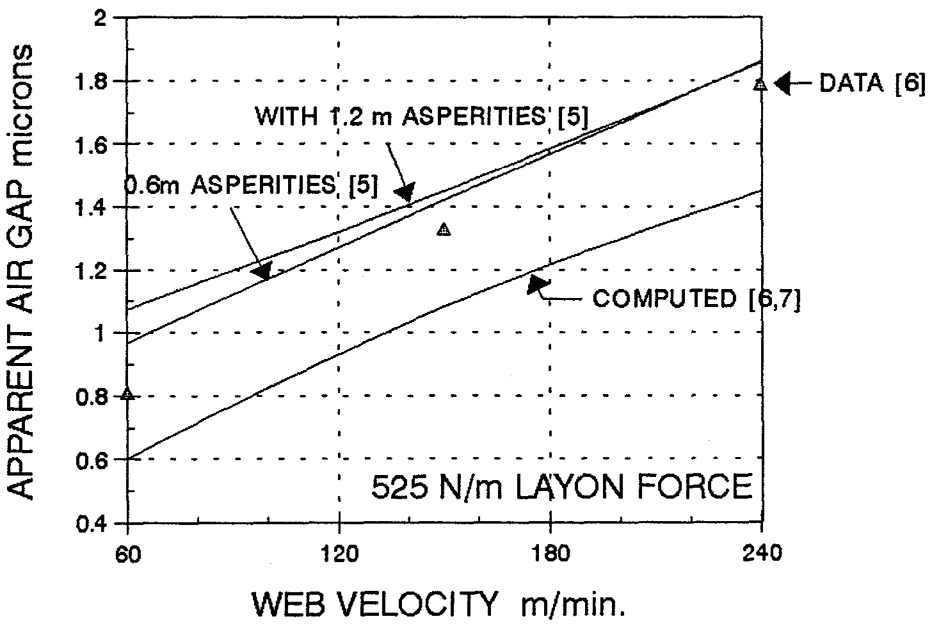

Figure 2 Air Entrapment Case with 525 N/m Layon Roll Down Force

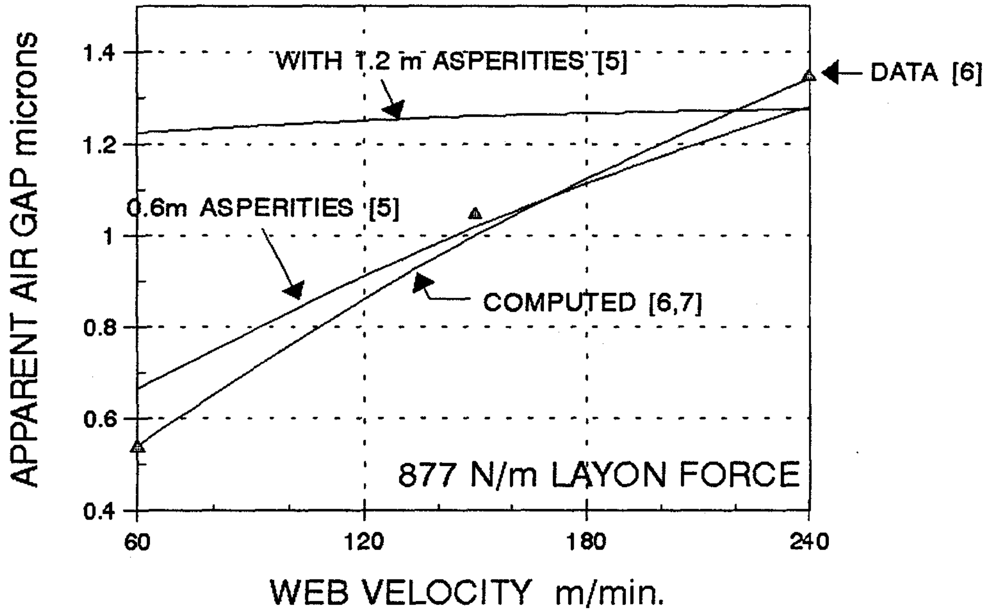

Figure 3 Air Entrapment Case with 877 N/m Layon Roll Down Force

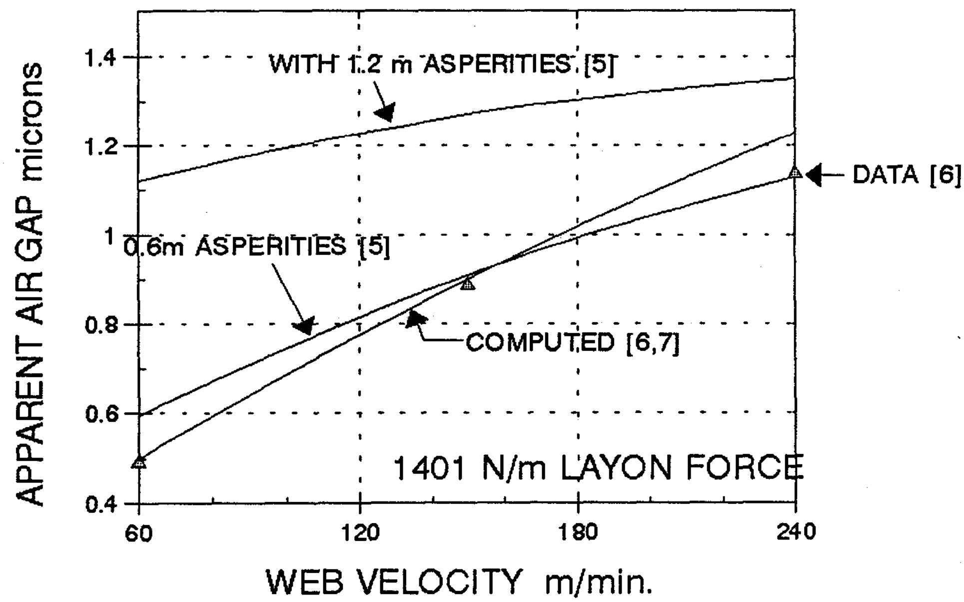

Figure 4 Air Entrapment Case with 1401 N/m Layon Roll Down Force

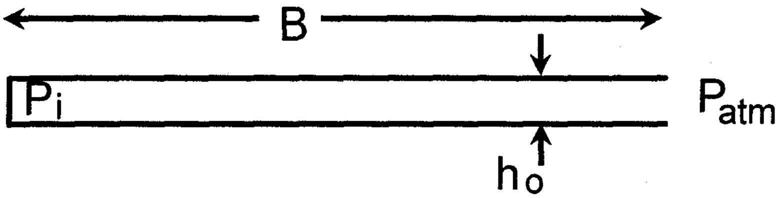

Figure 5 Geometry for Air Leakage Calculation

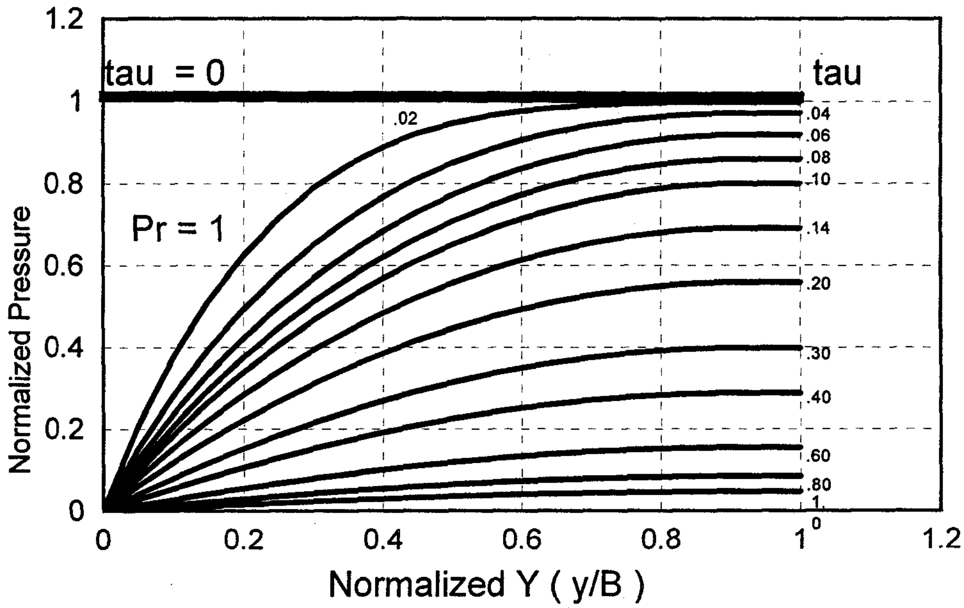

Figure 6 Normalized Air Pressure Profiles for Deflating Roll

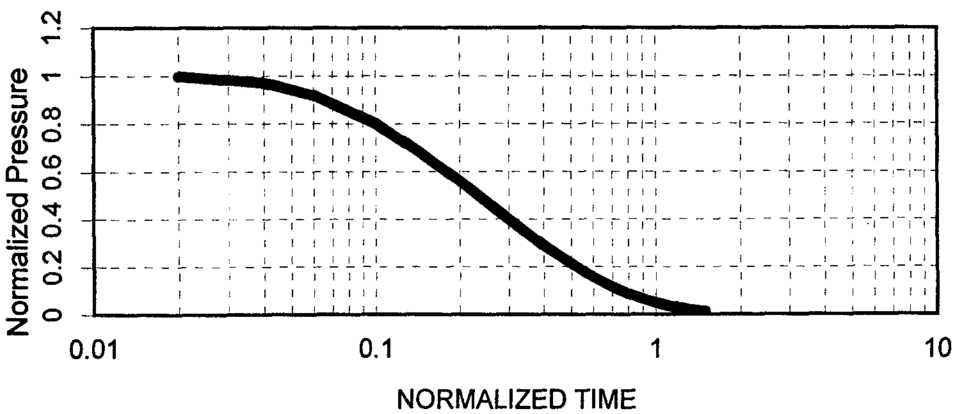

Figure 7 Normalized Pressure at Roll Center Versus Normalized Time

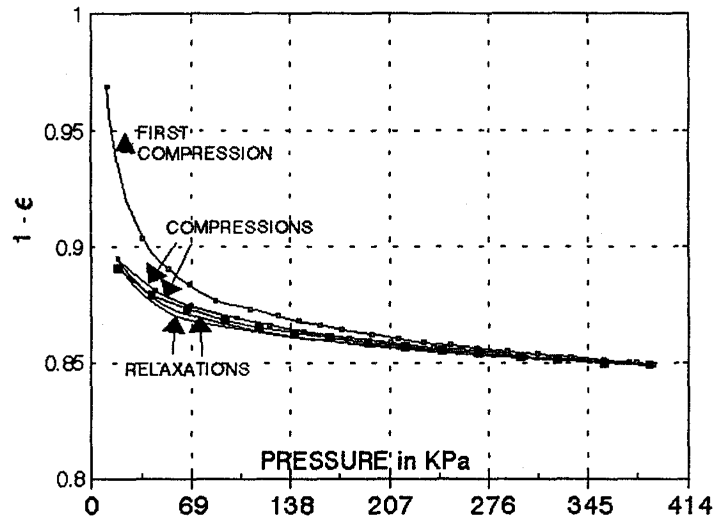

Figure 8 Stack Compression/Relaxation Data

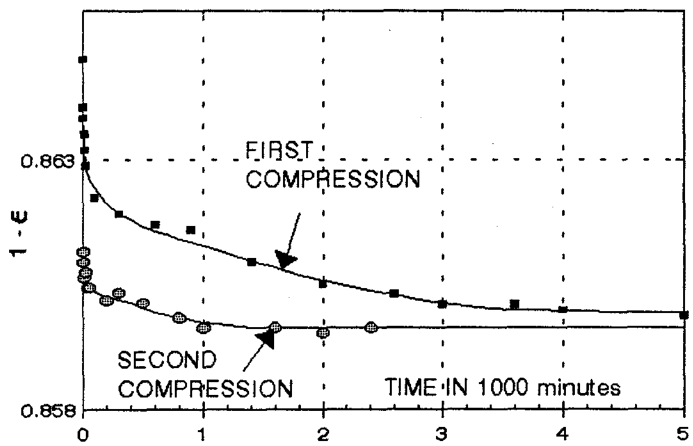

Figure 9 Creep of a Stack of Film

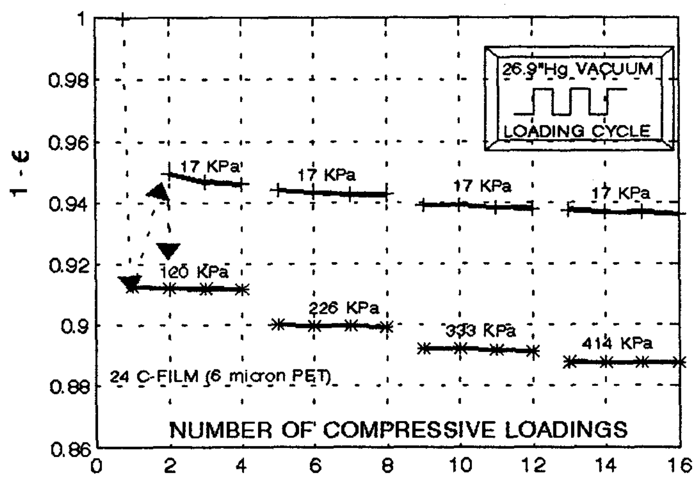

Figure 10 Pulse Loading on a Stack of Film

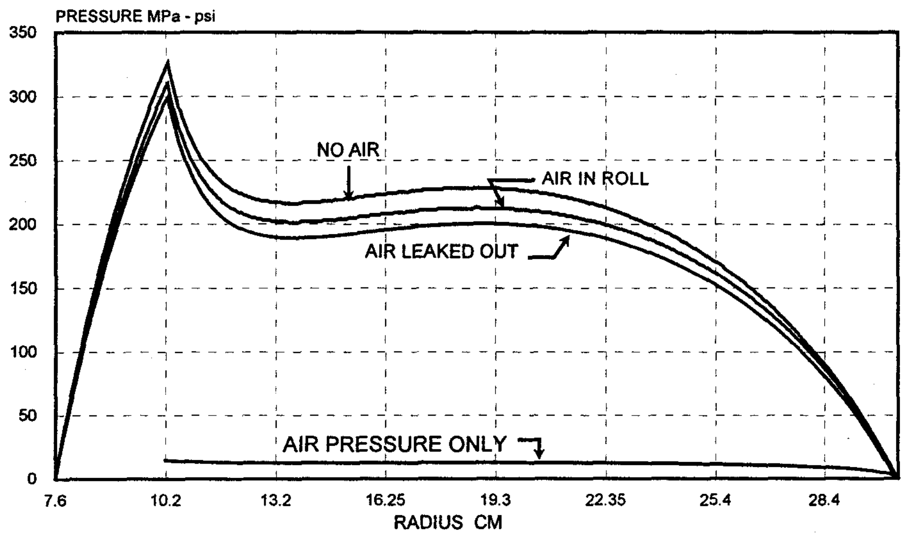

Figure 11 Radial Pressure Distribution for 6 micron Example Film

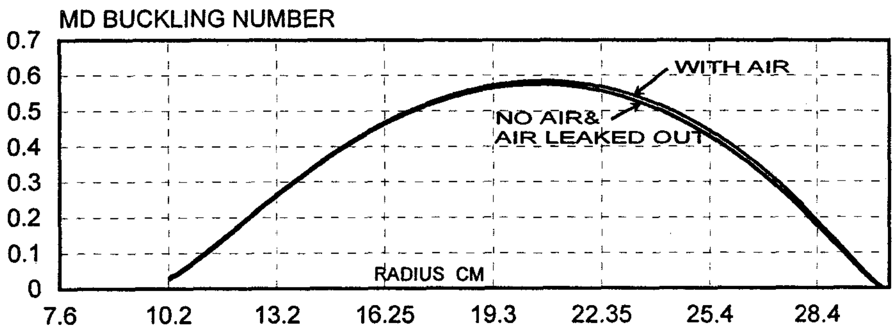

Figure 12 MD Buckling Number for 6 micron Example Film

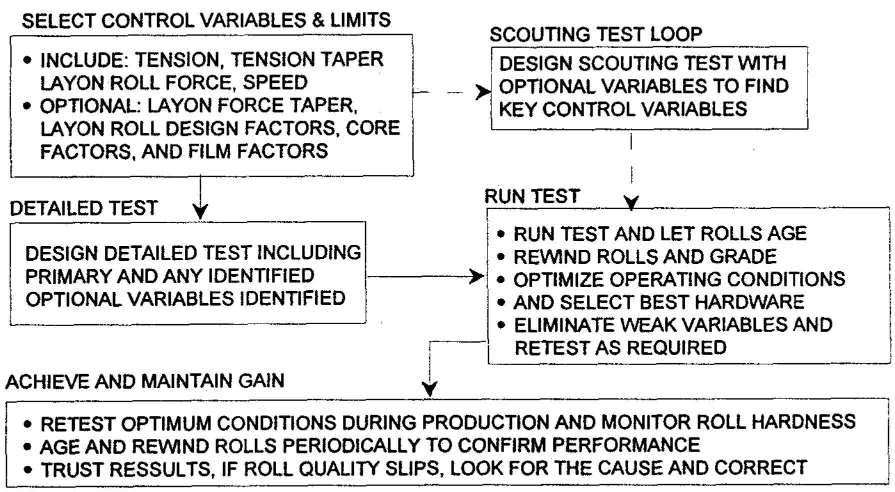

Figure 13 Flow Chart for Statistical Test Sequence

A. W. Forrest Jr.
Optimization of Equipment and Process Conditions for Film Winding
6/7/99 Keynote - Session 1 8:30 – 9:20 a.m.

Question - Bob Lucas, Beloit Corporation
I ask this question as one who has had more experience with paper rather than plastic. Many paper grades that are subjected to a compression test will often return to the original stack height, given time. You were discussing a plastic shake-down, I wanted to ask for a clarification as to differentiating between permanent plastic deformation vs. a viscoelastic response to your load unload cycle. I was hoping you could expand on that.

Answer – Al Forrest, Dupont
My experience is limited to polyester films. We have done only a limited amount of work in this area so what you see is basically what we have done. I think that there is a permanent set and the reason I say that is that if I look at some films that have been wound and set in rolls for a while the stack compression behavior of those films indicated that its been compressed. If I were to take samples from those rolls and let them relax for a month of two, I don't know what they would do. I don't know if they would slowly regain some of the height or not. I think it is permanent set.

Question – Bob Lucas, Beloit Corporation
The purpose of my question is that in some of the paper tests that we have had performed we have been somewhat surprised to find that given time the paper came back a lot more than we thought it would.

Answer – Al Forrest, Dupont
So you witnessed did some recovery in the compression test data?

Question – Bob Lucas, Beloit Corporation
How much time elapsed before you stopped taking data and before you started loading again?

Answer – Al Forrest, Dupont
Probably a few days elapsed, it wasn't a month. We were not necessarily looking for recovery. Maybe that is something I should have looked for.

Question – Wolfermann, Technical University of Munich
How did you measure that hardness during processing?

Answer – Al Forrest, Dupont
We measure the hardness of the rolls after processing for our test. We measured the hardness of the finished rolls on the surface and then for the rolls that we aged we could re-measure the hardness of the surface and then measure the hardness as we wound up the roll. We try to get at least four and maybe five hardness measurements going down through the role and then we could plot the hardness profile through the role. We look for consistency with what we have seen when we were doing that test program. Variations alert us that some change has taken place in our process.

Question – M'hamed Boutaous, University of Louis Pasteur
When we see the slope in your data in Figure 11, where you present rate of pressure decay in the roll, we know that the air plays an important role in stress within the roll. But the difference seen in your pressure data
is very small. How did you explain this?

Answer – Al Forrest, Dupont
How do I explain the small difference due to air? In this case I start out with the asperities contacting. Remember I said that the assumed amount of air getting into the role was basically the height of my asperities. So now I have two things supporting the layers. One is the air pressure within the air film layer or the little air gap between plastic film layers; and the other is the asperity contact. Now asperities are stiffer than air in most cases and for the cases we were observing that was indeed the case. So as you build up the stresses inside the roll it is mostly due to asperity contact. If most of the support is due to the asperities, and the air leaks out, no big deal.

Question:
How did you measure the air gap in Figure 2?

Answer – Al Forrest, Dupont
The way it was measured was an integral measurement and in fact it was reported on at the last IWEB. The rolls are wound and as they are wound, the edges are slit and sealed. Then those rolls are taken after the winding process has occurred, and put under water and unwound and the air is collected from them. You can see it is not easy to get this data. Its very difficult and they have a little rig where you can see them unwinding a roll and the air would bubble out of it and then they would collect the air. Keith Good came up with the approach.