AIR ENTRAINMENT DURING FILM WINDING WITH LAYON ROLLS

by

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ABSTRACT

Excessive air entrainment has long been recognized as a cause for telescoping and other forms of wound roll defects. To eliminate a portion of the air, exclusion devices such as layon rolls are often used. Air entrainment calculations in the literature generally do not consider this geometry. When layon rolls are employed, the high pressures under the nip make consideration of the surface roughness necessary. Here, the contact pressure is supported by a combination of the surface roughness and the entrained air pressure. After the nip passes, the entrained air expands and a final winding condition is achieved. This paper describes an analytical procedure that calculates the amount of entrained air considering these effects.

NOMENCLATURE

a	Layon roll contact width
E	Elastic Modulus
F	contact force per unit length, N/m
g	Curvature gap between layon and winding rolls, mm
H	Airy function
h	Air gap for solution to Reynolds' equation, mm
h_c	Maximum asperity height, mm
P	Pressure in air gap, Pa
P_1	Atmospheric pressure, Pa
R	Radius of rolls, mm
u	Dimension along roll surface, mm
v	Displacement of roll surfaces, mm
V	Winding speed, m/min
x	Dimension along gap in Reynolds' equation, mm

ε Strain
Γ Mean free path in air, mm
σ Stress, Pa
θ Theta direction in Airy function

SUBSCRIPTS

f Final conditions after the layon roll passes
r Radial direction indication
z Transverse or z direction indication
θ Circumferential direction indication
1 Layon Roll
2 Winding roll

INTRODUCTION

The final step of film processing involves winding the web into a roll. The film, as shown on Figure 1, forms a nip and the two moving surfaces tend to draw air into the winding roll. Excessive air entrainment has long been recognized as a cause for telescoping and other forms of wound roll deformation. To eliminate the excessive air, exclusion devices such as layon rolls are employed (see Figure 2). These have proven to be effective and they allow us to achieve higher winding speeds and better roll formation. The application of layon or nip rolls during winding has been more of an art than a science, since full understanding of this process has been lacking.

The winding geometry shown in Figure 1, with no nip, was investigated by Knox of DuPont's Circleville Research Laboratory and Sweeney [1]. This work has been widely utilized for both winding and film handling for the last two decades. It does not cover the nipped winding geometry shown on Figure 2 and more work is needed for this and other nipped geometries.

Much of the early work which applies to this situation was developed for either foil bearings or tape recording. Eshel [2-4] was very active in this area and in reference [4] looked at nondeformable rollers in geometries similar to Figure 2. Baumann [5] investigated film wrapping a cylinder with a pressure pad to control the resulting air gap. Baglin and Archard [6] and Hamrock and Dowson[7] looked at the hydrodynamic lubrication of materials of low elastic modulus. Recent work by Chang, Chambers and Shelton [8] are getting much closer to what is actually needed. Here, full solutions of Reynold's equation and deformation of the nip and winding rolls are considered in an iterative fashion. There is one thing that is still missing. None of the investigators to date have included the surface roughness of the film in their analyses. During winding with a layon roll we are trying to achieve film contact between the wrap layer and the top surface of the roll. If we don't achieve this contact the film will float and slide in the transverse direction causing a defect commonly referred to as telescoping. To achieve contact downstream of the nip roll, we must have significant contact under the nip. The purpose of this investigation is to present an analysis of this situation that includes the effects of surface roughness.

AIR ENTRAINMENT GEOMETRY CONSIDERED

The winding geometry considered is the wrapped layon roll configuration shown on Figure 2. Here, air is entrained by viscous forces and passes under the applied layer of film and through the nip. Both the layon (nip) and winding roll deflect at the contact point due to the layon force and a contact pressure distribution results. Between the applied layer of film and the roll surface, asperity contact is made in the nip region. Under the contact area the entrained air and the asperities combine to oppose the layon pressure. For the solution it is assumed that the variation in the film gap under the nip and between the two top layers does not effect the pressure distribution between the layon and winding rolls. This means that the contact pressure distribution solution and the gap height solutions can be considered separately.

The formulation of the problem is presented in three separate parts that cover (1) contact deflection of the rolls, (2) viscous air flow, and (3) asperity contact pressure.

GLOBAL ROLL CONTACT DEFORMATION

The pressure distribution in the nip that is applied to the winding roll of film is dependent on the contact between the layon and winding rolls. It should be mentioned that the stiffness (hardness) of the winding roll is dependent on the amount of air entrained during winding. This makes the entire solution nonlinear and shows that the stress distribution and air entrainment should be considered simultaneously as the roll builds. This type of solution is not discussed here but is part of our current efforts.

The solution employs a stress function defined by

$$H = (F/\pi)\, r\, \theta \sin\theta \qquad (1)$$

to describe the stress distribution due to contact(see Figure 2), and all parameters are defined in the nomenclature. More complicated and accurate stress functions exist but the complexity involved in using them is not justified at this time (see reference [9] for details of this type of analysis).

These stresses defined by the stress function are related to strain by the following relationships:

$$\varepsilon_\theta = \frac{1}{E}\left[\sigma_\theta - \mu(\sigma_r + \sigma_z)\right]; \qquad \varepsilon_r = \frac{1}{E}\left[S\sigma_r - \mu(\sigma_\theta + \sigma_z)\right]; \qquad (2)$$

and $$\varepsilon_z = \frac{1}{E}\left[\sigma_z - \mu(\sigma_\theta + \sigma_r)\right]$$

where S (E/E_r) includes the anisotropic nature of a stack of film. Substituting and reducing leads to a relationship for the surface displacement

$$v(u) = -4\,\frac{S - \mu^2}{E\pi} \int_{-a}^{+a} \sigma(s) \ln|u-s|\, ds + C \qquad (3)$$

Here, v(u) is the surface displacement from the original shape, σ(u) is the surface pressure distribution and u is a dimension along the surface of two rolls starting at the center of contact (see Figure 2). For this analysis, σ is obtained from the hertz form

$$\sigma(u) = \frac{2F}{\pi a^2} (a^2-u^2)^{0.5} \tag{4}$$

Substituting this into equation 3 and solving results in

$$v(u<a) = \frac{4F(S-\mu^2)\, u^2}{\pi\, E\, a^2} + C \tag{5}$$

and $$v(u>a) = \frac{4F(S-\mu^2)}{\pi E}\left(\ln W + \frac{1}{2\, W^2}\right) + C' \tag{6}$$

inside and outside the contact area, respectively, where

$$W = u/a + [(u/a)^2-1]^{0.5} \tag{7}$$

Note that equations 5 and 6 may be applied to both rolls in contact and that C and C' must be determined based on known deflections at some point. The contact half width, a, is obtained from

$$a^2 = \frac{8\,F}{\pi}\left(\frac{S_1-\mu_1^2}{E_1} + \frac{S_2-\mu_2^2}{E_2}\right) \div \left(\frac{1}{R_1} + \frac{1}{R_2}\right) \tag{8}$$

where the subscripts refer to the two rolls in contact.

The air gap dimension between the two rolls at the nip is required to calculate the air pressures as will be discussed. This gap must be calculated prior to the contact region and under that region. The portion prior to contact can be calculated from equation 6 applied to both rolls and a relationship for the gap introduced by roll curvature. The curvature gap is approximately

$$g_c(u) = \frac{(u^2 - a^2)}{2}\left(\frac{1}{R_1} + \frac{1}{R_2}\right) \tag{9}$$

The total gap is obtained by summing the displacements of both rolls and the curvature gap, g_c. This leads to

$$g(u) = g_c(u) + v_1(u>a) + v_2(u>a) + C \tag{10}$$

and C is evaluated from

$$C = h(a) - g_c(a) - v_1(a) - v_2(a) \tag{11}$$

VISCOUS AIR FLOW FORMULATION

The compressible viscous flow for this geometry (see Figure 2) can be described by the appropriate form of Reynolds' equation which is

$$\frac{d}{dx}\left(h^3 P \frac{dP}{dx}\right) + 6\,\Gamma P_1 \frac{d}{dx}\left(h^2 \frac{dP}{dx}\right) = 12\mu V \frac{d(Ph)}{dx} \tag{12}$$

This equation requires that the channel height, h, is known before a solution can be achieved. Since the channel geometry depends on the surface roughness, an iterative solution is necessary.

It is assumed for this formulation that the surfaces are hydrodynamically smooth and that the flow will be laminar. In this case substantial roughness can be tolerated before it significantly effects the results. Under the layon roll, roughness contact is required and some flow blockage may occur which for this calculation is neglected.

The boundary conditions for this equation are defined at the entrance to the nip and at the center of the layon roll contact. Upstream of the contact point at a distance established by trial, the pressure is equal to one atmosphere and the gap is defined by equation 10. The pressure rises from that point until it reaches a maximum under the center of the layon roll. The resulting boundary conditions that describe this are

$$P(\infty) = P_1 \quad \text{and} \quad dP(0)/dx = 0 \tag{13}$$

Equations 12, 13 and a prescribed channel geometry (h(x)) completely define the viscous flow portion of the solution. The differentials in equation 12 are approximated using finite differences with a resulting tri-diagonal matrix. This is solved by a recurrence relationship [10].

The entrapped air will expand isothermally (at the film temperature) from its maximum pressure at x=0 until it reaches a final state after the layon roll has passed. A force balance between the circumferential tension, air pressure, and asperity contact forces is used to obtain the final gap conditions.

ASPERITY CONTACT FORCE FORMULATION

The asperity contact pressure relationship is the exponential form developed by Pfieffer [11] which for this case is

$$P_s(x) = K_1\, \mathrm{EXP}[h_c - h(x)]\, K_2/(t + h_c) - K_1 \tag{14}$$

This relationship is used in the force balance under the nip. Here, pressures from a solution to equations 12 and 14 must sum to those obtained from the global contact stress calculation from equation 4.

SOLUTION METHOD

The solution is achieved in an iterative fashion using the following calculation sequence:

1. The roll contact solution is obtained for given geometrical and physical properties. The roll distortion and nip pressure, $\sigma(x)$, are calculated and used for the remainder of the calculation.
2. The air pressure under the nip is assumed to be one atmosphere to start the calculation.
3. The gap, h(x) under the nip is calculated from

$$\sigma(x) = K_1 \, EXP \, (h_c - h(x)) \, K_2 \, /(t+h_c) - K_1 + P(x) - P_1 \qquad (15)$$

where P(x) is from a solution to equation 12 from the previous iteration.

4. Equation 12 is solved for P(x) using a finite difference solution method and the h(x) from step 3. A recurrence relationship method is used to solve the tridiagonal matrix.
5. The expansion from the minimum air gap to the final gap after the layon roll is calculated from

$$K_1 \, EXP(h_c - h_f) \, K_2/(t+h_c) - K_1 + P_f - P_1 - T/R = 0 \qquad (16)$$

where h_f is the final gap and the final air pressure is

$$P_f = P(o)h(o)/h_f \qquad (17)$$

This is based on the assumption of an isothermal expansion of the entrapped air.

Steps 3 through 4 are repeated until a converged solution is obtained. This usually takes less than 100 iterations and the computer program runs on a personal computer. Step 5 includes the final calculation of the entrained air conditions. Notice that the calculations of the conditions after the final expansion are the first to require a value for the film tension. Therefore, results for a family of film tensions can be obtained rapidly by repeating Step 5.

AIR ENTRAINMENT RESULTS

A parametric study was conducted using the analysis as described. To minimize the number of calculations performed, a base case condition was established and is included as Table 1. At most, several variables were varied at any time to produce the results which are presented.

Typical results for the pressure both in the entrance to and under the nip are included on Figure 3 for the case described in Table 1. Here, the air pressure (gage) curve is the results of the solution to Reynolds' equation and the total pressure is that due to the contact stress. The difference between these two curves is the surface stress or the force generated by asperity contact. The plot starts at the center of the layon roll contact and proceeds through the edge of contact. The largest distance along the film surface represents the point at which the solution to Reynolds' equation begins. The initial iteration used to find the solution assumes that asperity contact is achieved under the entire contact zone. Subsequent iterations allow the air pressure to carry the entire contact load if that is indicated. Solutions with a substantially reduced contact area under the nip often result in no contact downstream of the nip and are of little practical value.

The calculated air gap is plotted for the same case on Figure 4. This plot also starts at the center of contact and proceeds outwardly. Notice the abrupt change in the air gap at the edge of contact.

Figures 5 and 6 show the normalized final air gap (h_f/h_c) plotted versus tension with winding speed included as a parameter for 406.4 mm (16 inch) and 813 mm (32 inch) diameter winding rolls, respectively. Winding speeds of 152 (500), 229 (750), 305 (1000), 381 (1250) and 457 (1500) meters per minute(fpm) are included for each roll diameter. Here, the magnitude of the air gap is inversely proportional to tension as you would expect but the effect is not strong. The gap, also as expected, is directly proportional to winding speed. Speed is a strong factor than tension, however. Notice by comparing the two plots that the air gap increases for the larger winding roll diameter. At higher speeds and/or lower tensions some of the cases show that the normalized air gap exceeds one. This would indicate a potential telescoping problem or a wound roll that is too soft.

Figures 7 and 8 show the entrained air pressure plotted against winding tension with winding speed as a parameter. These results show that the rough film acts with the layon roll to produce a negative gage pressure ($P/P_1<1$) that acts to hold the film down on the winding roll. For the given layon roll conditions and film surface, speed is the dominant factor that sets the magnitude of this negative pressure and it is inversely proportional to this pressure. Higher speeds will tend to pump more air into the winding roll and drive the air pressure up. Entrained air pressure is directly proportional to the winding tension. Here, the higher tension tends to compress the air and asperities after the layon roll passes. This results in the higher air pressure but a constant amount of entrained air.

Comparing plots 7 and 8 shows another interesting effect. The smaller diameter case (7) has twice the wrap pressure due to the outside layer of film since it is given by T/r and the radius is half as big. This tends to drive the entrained air pressure up. On the other hand, the smaller radius should lead to a higher maximum contact pressure. This should result in less air being entrained. The results shown are the combined effect of these and other parameters.

Figures 9 and 10 include the effect of the layon roll diameter. Here, normalized gap and pressure are plotted versus winding tension with layon roll diameter as a parameter. Note that substantial reductions in both gap and pressure are achieved by reducing the layon roll diameter. Here, the peak pressure under the nip goes up for the same nip loading and more air is excluded. This is especially interesting when compared to the effect of nip loading.

Nip loading effects are summarized in Figures 11 and 12. Again, the normalized gap and pressure are plotted versus winding tension with the nip loading as a parameter. All of these are for a layon roll with a 203mm (8 inch) OD. Note that merely increasing the layon roll force has a limited effectiveness. For down forces above 263 N/m (1.5pli) the gains in reduced gap and air pressure are minimal. Here, we see the effect of increasing the contact width which tends to reduce the peak stresses under the nip. This may be coupled with a change in the shape of the air gap under the nip where the air is pumped into the winding roll.

CONCLUSIONS AND RECOMMENDATIONS

Calculations for the air entrainment into winding rolls must include the effects of the film surface. The magnitude of the air gap is controlled by the height of the surface roughness. Here, the asperity contact pressure is of the same order of magnitude as the pressure of the entrained air. This shows that the air gap that meters air into the winding roll is greatly influenced by the film surface. After the nip, the surface acts to expand the air gap until an equilibrium is achieved between the tension induced pressure, the air pressure and the asperity stress.

The air pressure in the gap after the layon roll can be below atmospheric pressure. The layon roll system both compresses the asperities between the top layers of film and limits the amount of air that enters the roll. After the layon roll passes, the asperities expand the air gap which causes the air pressure to drop. This expansion can result in air pressures below atmospheric.

The air pressure and gap are directly proportional to the winding speed. This is expected and it follows the general trend that you have for film wrapping rolls without air exclusion devices. It also emphasizes the importance of improved air exclusion at higher winding speeds. As indicated by the normalized gap exceeding one in Figures 5 and 6, this can result in the film floating on an air layer after the layon roll has passed. This results in a defect commonly called telescoping. Here, the layers of film slide in the transverse direction and protrude out of the end of the wound roll. This usually occurs a few layers below the surface where the layon roll and its contact force are no longer holding the film in place.

Layon roll OD has a significant effect on the amount of air entrained into the winding roll. The smaller contact width that results from the smaller OD leads to a higher peak pressure under the layon roll. This in turn leads to a smaller gap and less entrained air. It also is interesting to note that the pressure of the entrained air can be significantly below atmospheric. This may have benefits in terms of reduced roll aging.

The amount of air entrained is inversely proportional to the layon roll loading. Here, the higher peak pressures under the layon roll introduced by higher loading results in less air entrainment. The interesting point (see Figures 11 and 12) is that above 263 N/m (1.5pli) the effectiveness of additional layon roll loading diminishes. For the configuration, if not in general, there is a point where pushing harder on a layon roll no longer excludes significantly more air. This is probably due to an increasing contact width and its effect on the peak pressure under the layon roll and/or the change in shape in the air gap under the nip.

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Winding Speed	229 m/min (750 fpm)
Winding Roll Diameter	813 mm (32 in)
Film Elastic Modulus	3.48GPa (500 kpsi)
Layon Roll Diameter	203 mm (8 in)
Layon Roll Elastic Modulus	34.8Mpa (5 kpsi)
Film Tension	44 to 350 N/m (0.25 to 2 pli)
Layon Roll Down Force	175 N/m (1.0 pli)
Poisson's Raltion of Winding Roll	0.4
Poisson's Ratio of Layon Roll	0.4
Viscosity of Air	$18.2X10^{-6}$ Pa s
Mean Free Path of Air	0.064 microns
First Stack Compression Coef. K_1	4.82kpa (0.699 psi)
Second Stack Compression Coef. K_2	53.0
Asperity Contact Height	1.5 microns
Thickness of Film	12 microns

TABLE 1. FILM, WINDING ROLL, LAYON ROLL, AIR AND WINDING PROPERTIES FOR CASE 1

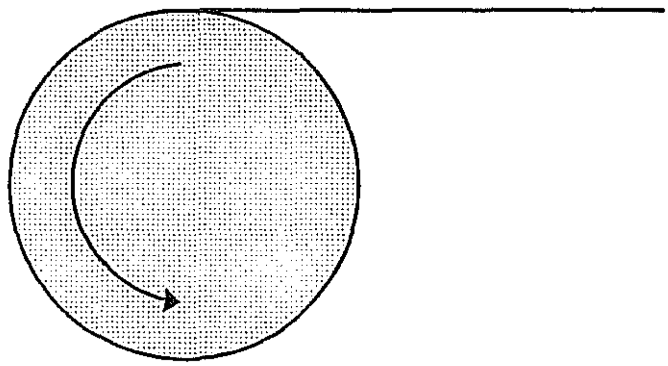

Fig 1 Winding Configuration with no Air Exclusion Device

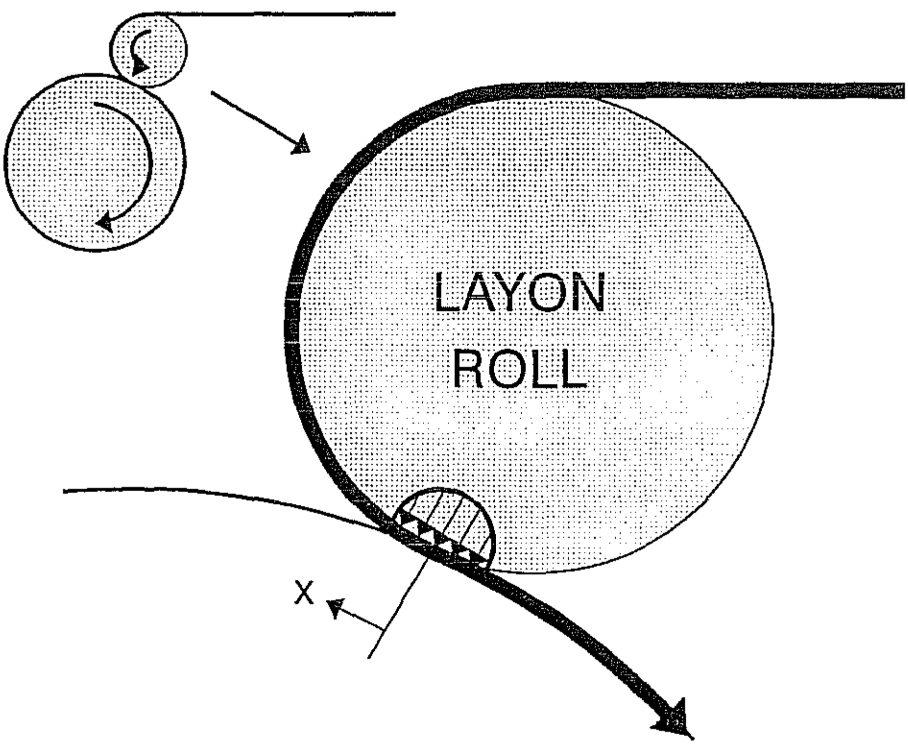

Fig 2 Wrapped Layon Roll Winding Configuration

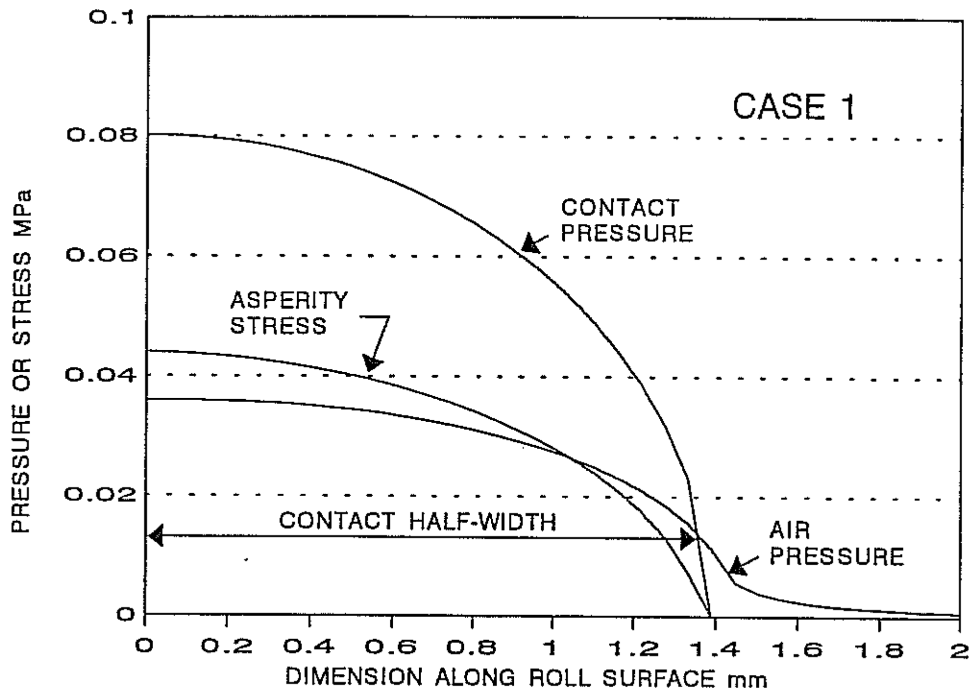

Fig. 3 Plots of Contact Pressure, Air Pressure and Asperity Stress Versus Contact Surface Dimension

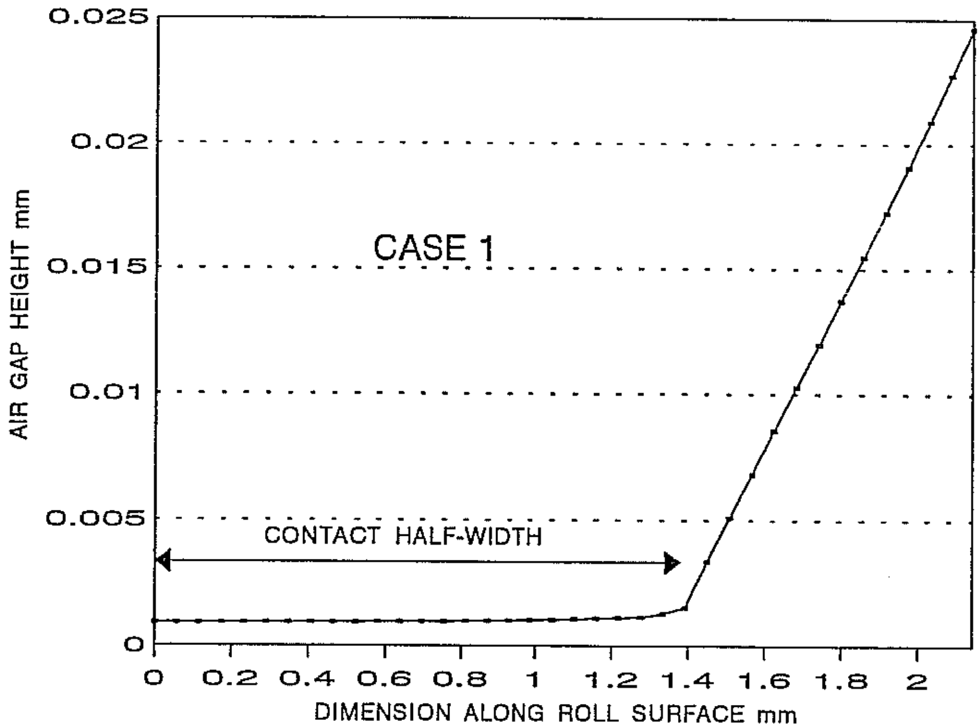

Fig. 4 Gap Under Top Film Layer Versus Winding Surface Dimension

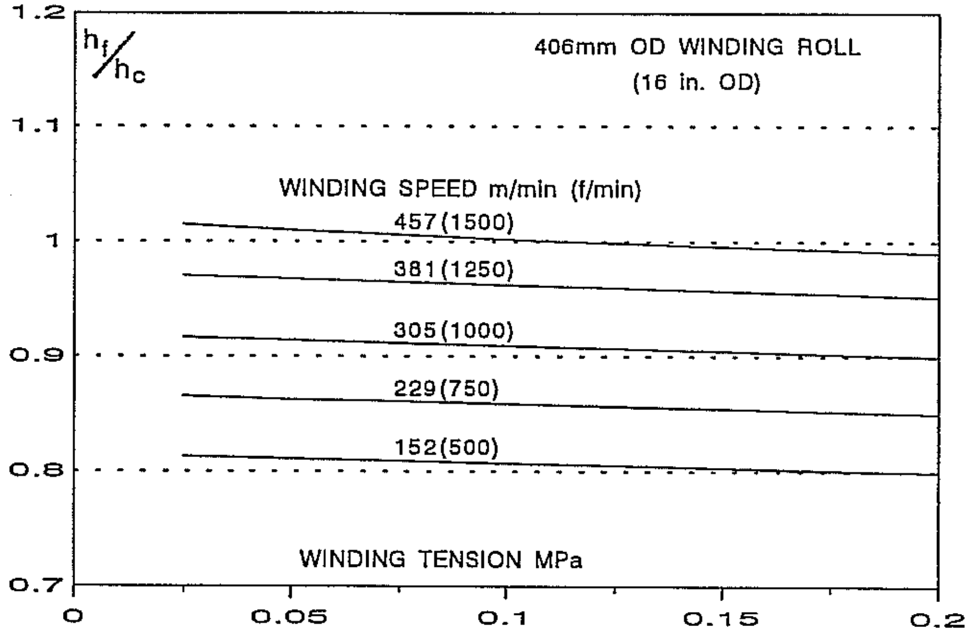

Fig. 5 The Calculated Air Gap Nomalized and Plotted versus Winding Tension with Winding Speed as a Parameter for a 406mm OD Roll

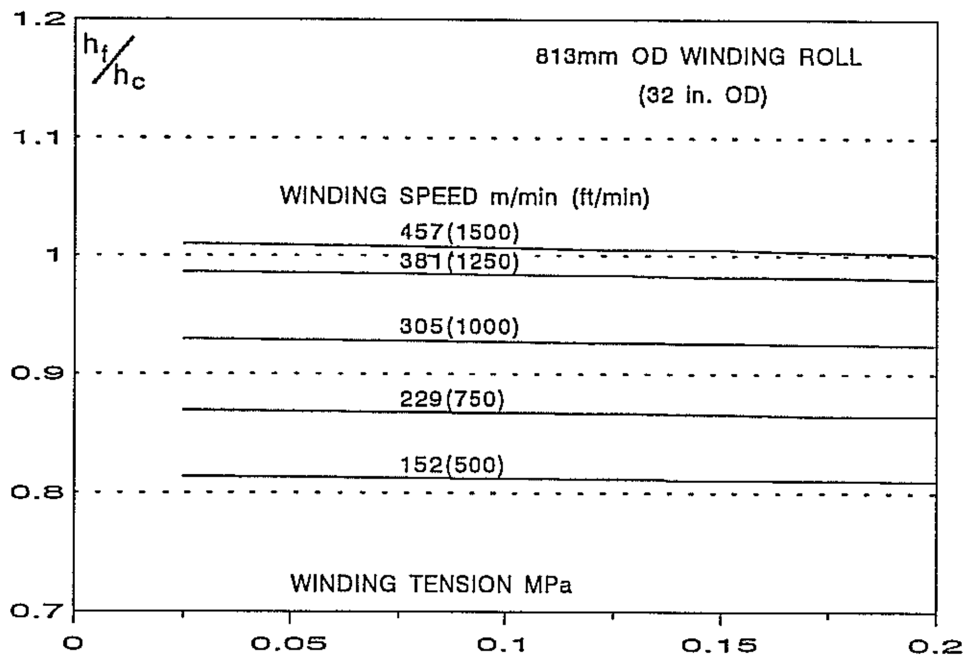

Fig. 6 The Calculated Air Gap Nomalized and Plotted versus Winding Tension with Winding Speed as a Parameter for a 813mm OD Roll

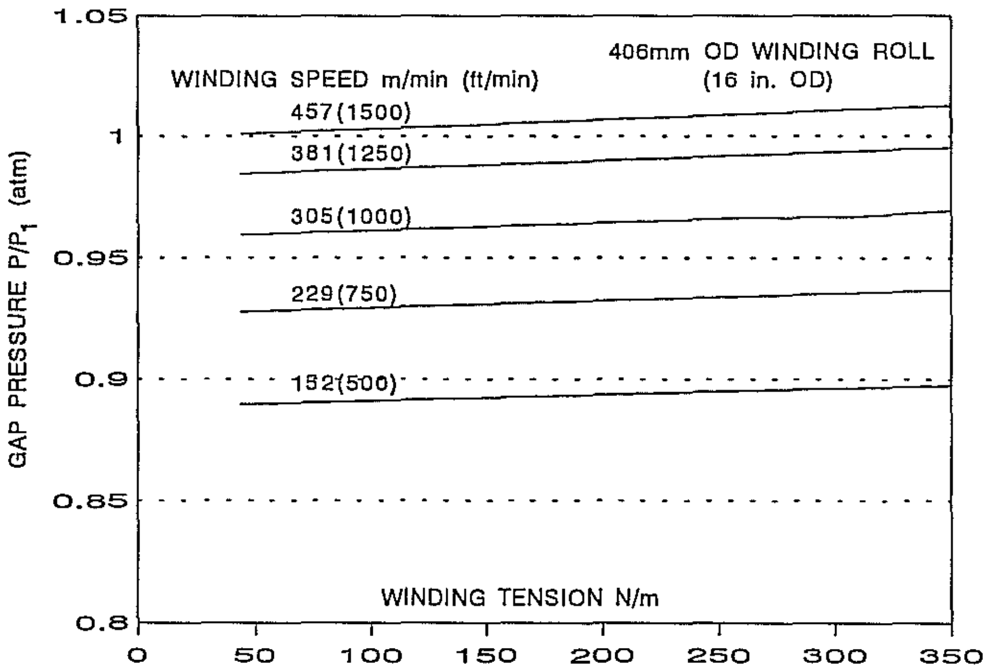

Fig. 7 Calculated Air Pressure in the Gap under the First Film Wrap for a 406mm Winding Roll versus Film Tension

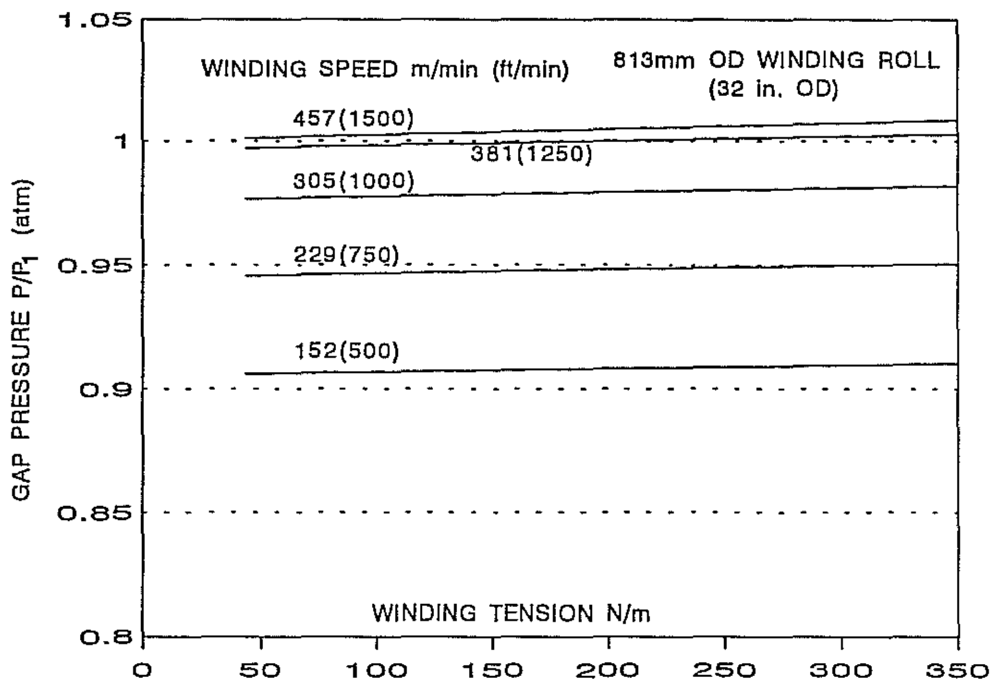

Fig. 8 Calculated Air Pressure in the Gap under the First Film Wrap for a 406mm Winding Roll versus Film Tension

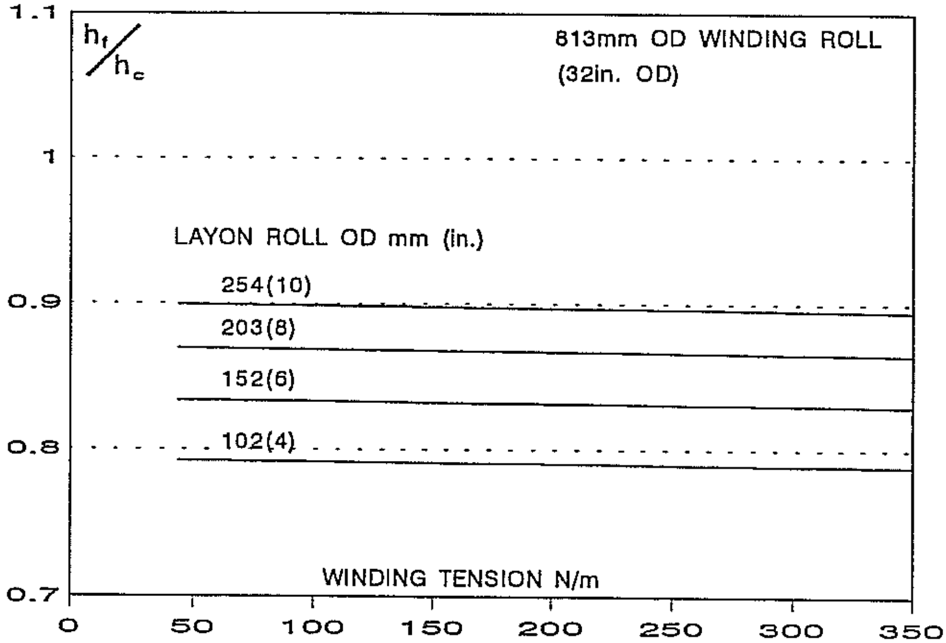

Fig 9 The Calculated Air Gap Normalized and Plotted versus Winding Tension with Layon Roll OD as a Parameter for a 229 m/min. (750ft/min.) Winding Speed

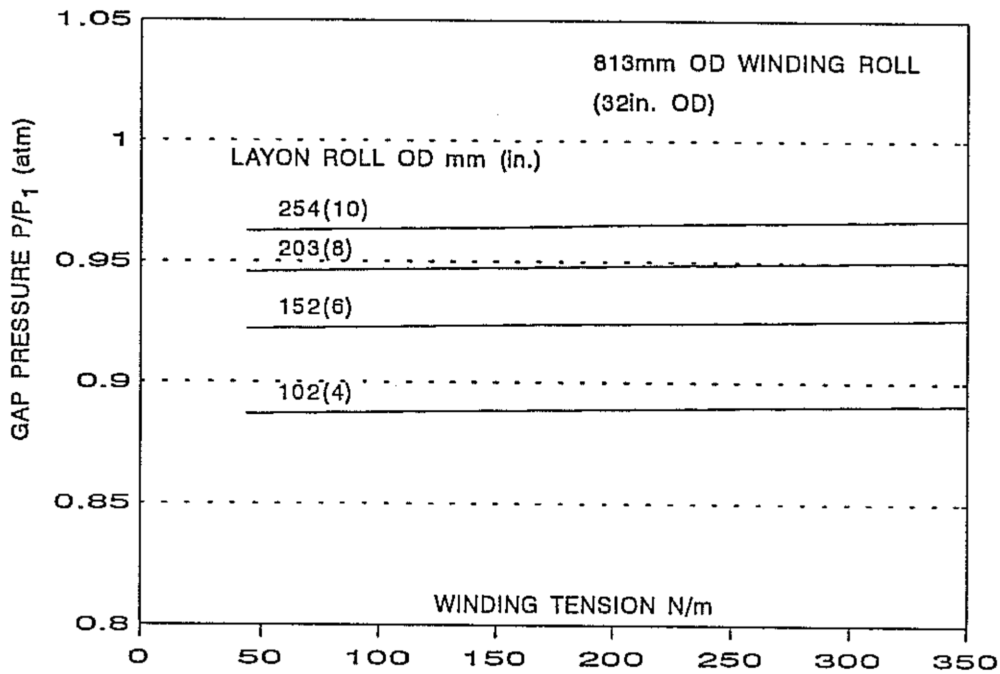

Fig. 10 The Calculated Air Pressure Plotted versus Winding Tension with Layon Roll OD as a Parameter for a 229 m/min. (750ft/min.) Winding Speed

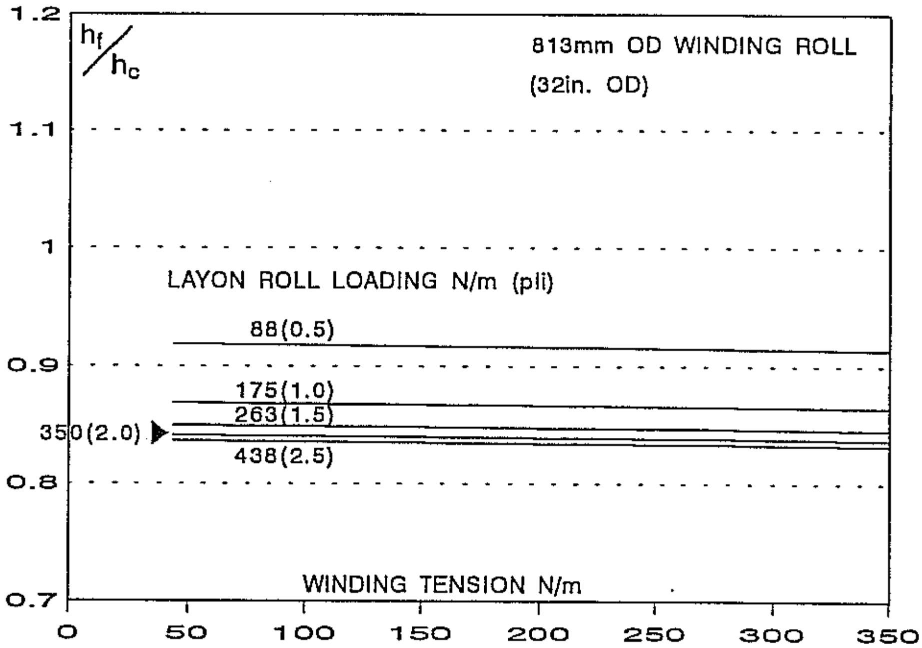

Fig. 11 The Calculated Air Gap Normalized and Plotted versus Winding Tension with Layon Roll Loading as a Parameter for a 229 m/min. (750ft/min.) Winding Speed

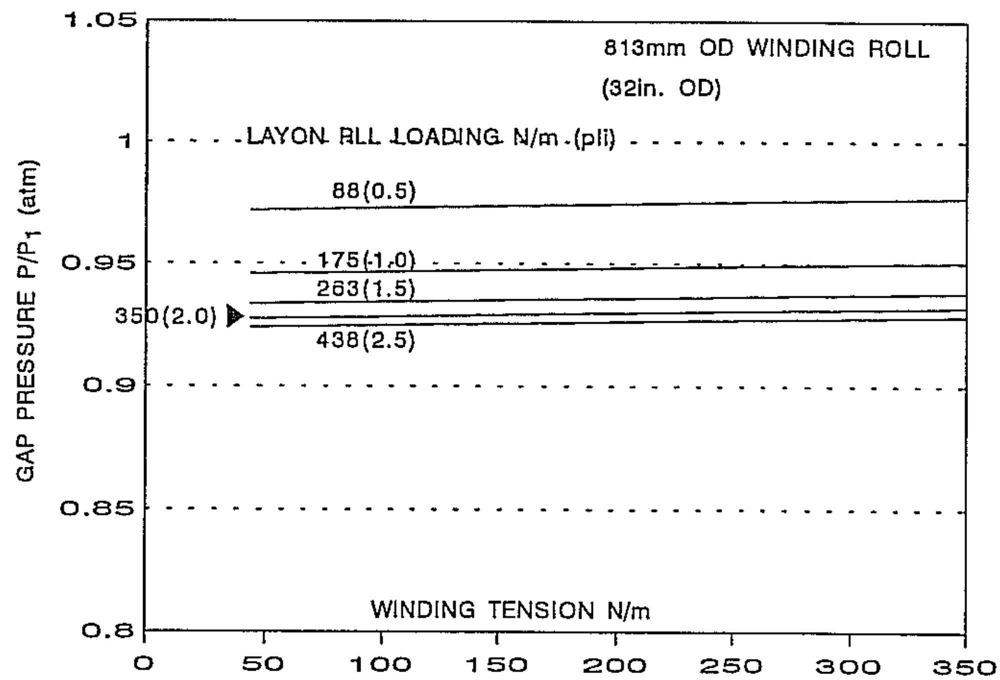

Fig. 12 The Calculated Air Pressure Plotted versus Winding Tension with Layon Roll Loading as a Parameter for a 229 m/min. (750ft/min.) Winding Speed

Forrest, A.W.
Air Entrainment During Winding with Layon Rolls
6/19/95 Session 2 1:10 - 1:35 p.m.

Question - You had some formulas and slides that were not part of your printed preparation. Will those be supplied?

Answer - I think all of that's in there. All of the equations are spread around the report, but everything that's written in those slides is in there. If you find something you don't agree on, give me a call and I'll personally give it to you.

Question - These are some interesting things. Do you have any verification of this stuff? This is all theory. You're making some good conclusions, but I'd like to see some data.

Answer - So would I. It's extremely difficult. to try to measure the pressure under the top layer of a piece of winding film. If anybody has any ideas on how to do that, I'd be delighted to talk to them. I realize that's a limitation.

Question - Do you have a correlation between roll diameter versus the entrainment effect?

Answer - Yes, this is included in the paper and it's a small effect. Typically with the ratio of the layon roll diameter to the winding roll diameter being small in this case. When the ratio is small, the effect is minimal. If they got to be around the same size, I would expect it to make a difference.

Question - Your curves show you end up with basically a vacuum in the film after the lay-on roll. Does this mean that it tries to pull air in after it is wound? Should the roll end up softer?

Answer - That's under the top layer. Down inside after it goes through a compression process by the individual wrap being added to that and it ultimately gets to a positive pressure very quickly.

Question - One suggestion for measuring the amount of entrapped air might be unwinding films per metalization in a vacuum chamber. As you unwind it, a lot of that air has to come out and is pumped down in a vacuum system. So you could probably get a quantitative measure of how much air was in the role by unwinding it in a vacuum.

Answer - There have been some attempts to get a global idea of how much air is in the roll There was one about putting a roll under water and measuring that air that comes out. We've used different techniques where you measure the roll and weigh it . You know the density of the film so you know how much air space is inside. The accuracy of all of those is wanting and needs a step up in thought.

Question - How important would it be to consider roughness in relation to the Reynold's Equation?

Answer - I would be delighted to talk to you about trying to do that. The two things that I'd like to improve is , one, does the Reynold's Equation really apply when we're talking about substantial roughness, and the other thing is, does the Hertz Solution really work well enough. We need to come up with a better stress solution under the nip and improve the Reynold's Equation be verifying that it really works for a fairly rough film.

Question - In your global roll calculations, what do you use for modules in the wound roll? Is that nonlinear only?

Answer - I'm glad you asked that question. We use the radial elastic modules measured in a vacuum and we figure out how much air gets in and we stick that in our roll stress analysis.

Question - That would be nonlinear to the depth, right?

Answer - I use a constant value approximating the conditions on the surface and I realize that's an approximation and that 's probably another factor that needs improvement concerning the roll stress.

Thank you.