THE EFFECT OF AIR ENTRAINMENT IN CENTERWOUND ROLLS

by

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ABSTRACT

Internal stress models for centerwound rolls have existed for over thirty years but no model to date has accounted for air which is entrained due to the web velocity and the viscosity of air. This paper reports the results of an experimental investigation in which the entrained air thickness was monitored on a centerwinding roll. The results confirmed that the air foil bearing theory was adequate for describing the amount of air entrained to a centerwinding roll. Knowledge of the amount of entrained air allowed the derivation of a reduced radial modulus of elasticity for the wound roll which when used with a wound roll model yielded results which compared well to experimental pressure data.

NOMENCLATURE

A	unit area of entrained air, 1 m^2
E_r	modulus of elasticity in the radial direction, Pa
$E_{r,air}$	modulus of air, Pa
$E_{r,stack}$	radial modulus of elasticity of stack, measured, Pa
$E_{r,eq}$	combined stack and air radial moduli, Pa
E_θ	modulus of elasticity in the circumferential direction, Pa
h	web thickness or caliper, m
h_o	air film thickness, m
K_{air}	stiffness of entrained air, N/m
K_{stack}	stiffness of stack, N/m
K_{eq}	combined stiffness of stack and air, N/m
P	pressure of air in the air layer, Pa

P_{atm}	atmospheric or ambient pressure, Pa
P_0	pressure beneath outer layer, Pa
r	radial coordinate of a winding roll, m
r_c	outside radius of core, m
s	outside radius of a roller or a winding roll, m
T	web line tension, N/m
T_w	web tensile stress, Pa
u	deformation within the wound roll in a radial direction, m
v	volume of entrained air, m^3
V	web velocity, m/min
x	radial compression of the air layer due to winding, m
ε_r	radial strain, m/m
σ_r	radial pressure in wound roll, Pa
σ_θ	circumferential stress in wound roll, Pa
μ	dynamic viscosity of air, $3.077*10^{-7}$N-min/m^2 @ 27°C
θ	angle of web wrap about a roller, rad

INTRODUCTION

The quality of wound rolls is highly dependent upon the residual stresses which accrue due to the winding process. Defects such as blocking occur in the winding of plastic film in which the layers ring to one another. Blocking is the result of radial pressures and generally can be prevented by winding at lower winding tension. Telescoping and dishing can result if the radial pressure is not sufficient to prevent lateral movement within the wound roll during the winding process.

There are several wound roll models for determining internal stresses in existence which differ mainly in the manner in which the web material properties are allowed to vary. These models apply only to the center winding technique although recent modifications allow extensions of the previous models to centerwinding with an undriven lay-on roll impinged at the periphery of the winding roll, Good et. al.[1]. Some reference will be made to a machine direction. The machine direction in a web line is the direction in which the web travels through the web line.

Early models, Gutterman [2] and Catlow et al. [3], assumed that a wound roll could be modeled as a linear isotropic material, where the radial modulus was equivalent to the circumferential modulus of elasticity ($E_r = E_\theta$). The next generation of models, Altmann [4] and Yagoda [5], assumed the wound roll could be modelled as a linear anisotropic material, where E_r is unequal to E_θ although both parameters are assumed to be constants. In reality the radial modulus of a wound roll is a parameter which encompasses both structural and material nonlinearities. Paper, plastic film, and other webs have asperities upon their surfaces and when the web is wound or stacked asperities from one surface contact asperities upon the next surface. Thus upon compression the contact area becomes a function of radial or normal pressure and the measured radial modulus, E_r, is a function, typically nonlinear, of radial pressure. Thus the most realistic models of Pfeiffer [6], Hakiel [7], and Willett and Poesch [8] allow for nonlinear anisotropic properties.

Air entrained into the wound roll can drastically decrease the internal stresses as will be shown. Knox and Sweeney [9] established that the amount of air entrained by webs passing over rollers could be predicted using air foil bearing theories which were developed earlier by Blok and van Rossum [10]. The expression which Knox and Sweeney established was:

$$h_0 = 0.65\, s \left[\frac{12\, \mu\, V}{T}\right]^{\frac{2}{3}} \qquad \{1\}$$

The first objective of this publication is to show that relationship {1} provides a conservative estimate of the air layer thickness which is entrained by webs into centerwound rolls.

The second objective of this publication is to show that given expression {1} that wound roll models can be modified to provide accurate results when air is entrained.

AIR ENTRAINMENT IN WOUND ROLLS

The Knox Sweeney relationship {1} was established for a web which passes over a roller as shown in Figure 1. Air at ambient pressure is drawn in at the inlet. If the air entrained is sufficient to cause the web to lift above the roller as shown in Figure 1 the air must attain the pressure required to hold the web in equilibrium above the roller surface. This pressure can be calculated using an equilibrium equation for thin wall pressure vessels, which in terms of the variables chosen becomes:

$$P = \frac{T}{s} \qquad \{2\}$$

The pressure then must decrease back to the ambient level upon exiting the foil air bearing. Expression {1} has been experimentally verified for the geometry shown in Figure 1.

In Figure 2 the geometry of a centerwinding roll is shown. Although the inlet conditions are identical, between the configurations shown in Figures 1 and 2, the exiting conditions appear different. Expression {1} is independent of the angle of web wrap, θ. One argument could be that given the large angle of wrap of the web on a centerwinding roll that perhaps the exiting conditions are inconsequential. However, the winding process is somewhat different in that as a layer is wound into the roll the pressure upon it increases as it becomes wound deeper and deeper into the roll. Thus the interlayer pressures which develop as a function of the winding process would tend to evacuate the air which was entrained at low pressure (T/s in this case).

To verify if expression {1} was applicable to centerwinding, a set of winding tests were devised in which the air layer was measured during the winding process. A displacement sensor which measures the position of a beam of reflected laser light from a target surface, the outer surface of the winding roll in this instance, with a lateral effect photodiode (Keyence 2210) was employed as shown in Figure 3. This sensor can resolve 0.2 µm (7.8 µin) over a measurement range of 6 mm (0.236 in). The sensor was used to determine the air film height beneath the outer layer of a centerwinding roll by using an air jet to periodically deflate the web beneath the sensor. A drum, 60.96 cm in diameter, on a two drum winder as shown in Figure 3 was used as a core shaft due to its low radial runout (5.1 µm). Initial experiments indicated that the air jet was causing air to deplete beneath more layers than just the outer layer. Later experiments were run with a nip roll contacting the centerwinding roll approximately 210 degrees after the web first wound onto the winder, as shown in Figure 3, in an attempt to exhaust the air beneath the outer layer prior to that layer becoming the second layer. Results from experiments under these conditions are shown in Figures 4 and 5. The laser sensors work best on opaque materials and in this case floppy disk media (77 µm in thickness) was used. In Figure 4 the web line tension was 1.30 N/cm and the velocity was 30.5 m/min. Substituting into expression {1} yields an entrained air thickness of 18.1 µm. Experimental measurements of 22 and 27 µm are shown in Figure 4. In Figure 5 the web line tension was 2.77 N/cm and the velocity was 76.2 m/min.. Substituting into expression {1} yields an entrained air thickness of 20.2 µm. An experimental measurement of 20.5 µm is shown in Figure 5. Thus it was felt that expression {1} is valid for estimating the wound-in-air film thickness for centerwinding.

MODELING AIR ENTRAINMENT IN WINDING

When winding films it becomes obvious that at relatively low speeds (15.2-30.5 m/min) that the radial pressure profiles decrease drastically with respect to rolls wound at lower speeds in which there was less entrained air. In Figure 6 the results of such a study are shown along with the result of a winding model which does not account for air entrainment. The input parameters for the model are shown in Table 1. It is evident that models which ignore air entrainment can be grossly in error for non-permeable webs, especially at higher winding velocities. Note that the pressures have declined two to three fold from winding at 15.2 to 30.5 m/min. Note as well that winding at 30.5 and 76.2 m/min produces nearly the same profile in radial pressure.

A study of a input parameters which affect the results from wound roll models revealed two parameters which might be affected by the presence of entrained air. Most models require inputs including web thickness(caliper), core stiffness, inner and outer winding radii, the circumferential modulus (E_θ) and the radial modulus (E_r) as a function of radial pressure, Poisson's ratio and winding tension in the outer layer. Of these parameters by far the most influential upon the radial stress profile are the radial modulus and the winding tension (e.g. the wound-on-tension in the outer layer). One or both of these parameters may be affected by entrained air.

The Effect of Air Entrainment Upon Wound-On-Tension

Good, Pfeiffer, and Giachetto [11] documented how the wound-on-tension in the outer layer could decrease in centerwound rolls of paper. Many of the centerwinding roll models described in the introduction employ an outer boundary condition which is based upon the assumption that the web line tension is equal to the wound-on tensile stress in the current outer layer of the roll. The outer boundary condition typically has the form:

$$\sigma_r = \frac{T_w h}{s} \qquad \{3\}$$

which is derived from the equilibrium expression for a thin wall pressure vessel. It was shown that the pressure beneath the outer layer, σ_r, was less than predicted by expression {3} due to the layers beneath the current layer winding on deforming radially inward and decreasing the wound-on-tension. The expression used for the outer boundary condition in that work was:

$$\sigma_r = [T_w + E_\theta \frac{u}{s}] \frac{h}{s} \qquad \{4\}$$

The radial deformation (u) beneath the outer layer was predicted by the wound roll model and is always a negative number, thus the radial pressure beneath the outer layer predicted by expression {4} was always less than that predicted by expression {3}. The difference between the predicted values was shown to be quite significant for the centerwinding of bond and newsprint grade papers. However work done upon polyester webs wound at speeds at which air entrainment was not a factor showed insignificant differences between the pressures calculated by expressions {3} and {4}. This is attributed to the radial modulus, E_r, of plastic films typically being at least three to five times greater than the radial modulus of paper webs. A larger value of E_r will decrease the radial deformation beneath the outer layer, and as E_r becomes large the pressures computed by expressions {3} and {4} will become nearly identical.

An expression similar to expression {4} to study tension loss due to air entrainment can be generated, provided an expression for the radial deformation (u) can be derived which describes the radial deformation as the air escapes from the winding roll. A conservative assumption was made that perhaps all of the air that was entrained while winding escaped. This allows us to reformulate expression {4} as:

$$\sigma_r = [T_w - E_\theta \frac{h_o}{s}] \frac{h}{s} \qquad \{5\}$$

where h_0 is the thickness of the air film which was entrained and is predicted using expression {1}. The results of such a study are shown in Figure 7. Note that the experimental data plotted in this figure is indicative that significant pressure has been lost in the wound roll due to air entrainment. Note as well that the decrease in wound-on-tension due to the escape of all the air entrained does not provide a decrease in radial pressure which is even a reasonable match to the experimental data. The deviation between what the model predicted with and without air entrainment is insignificant when compared with the radial pressures which were measured in the laboratory.

Another means by which the wound-on-tension might be altered is through slippage beneath the outer layer. A device, known as the Instantaneous J-Line printer, was originally designed for studying the advent of slippage in tension loss was now used to study the possibility of slippage beneath the outer layer of a centerwinding roll with entrained air, Good et al.[11]. A J-Line is a radial line which is struck with chalk upon the end of a winding roll to determine if internal slippage is occurring within the wound roll (Lucas [12]). If the radial line becomes deformed it indicates slippage has occurred. A shortcoming of the technique as previously implemented was that it was difficult to continually strike a line at the upon the outer layer of the winding roll. This technique was improved by attaching an encoder to the winder shaft and using the zero pulse to fire an ink jet head which was aimed at the web just as it contacted the wound roll, refer to Figure 8. In the domain of winding velocity in this study, 15.2-76.2 m/min, there was no deformation in the radial line printed, indicating that slippage was not present and could be discounted as a possible source of tension loss. A J-Line is shown in Figure 9 when winding at 76.2 m/min was typical of the J-Lines at lesser speeds. The pointer in the figure is directed at the radial line printed by the Instantaneous J-Line printer.

Thus this study indicated that the winding tension as affected by tension loss or slippage was not the critical input parameter for wound roll models which required modification if the internal stresses were to be accurately predicted in the advent of air entrainment.

The Effect of Air Entrainment upon the Radial Modulus

In the previous section an assumption was made that in order to maximize tension loss in the outer layer that it would be assumed that all air which was entrained also escaped, presumably from the roll edges. Now it will be assumed that no air escapes and the effect upon the radial modulus and the resulting radial pressure profile within a winding roll will be studied.

If no air escapes it is assumed that layers or pockets of air may be separating layers of web material within the wound roll. Assuming that the trapped air can be modelled as an ideal gas and that this air is entrained and trapped under isothermal conditions the pressure and volume of the trapped air(assuming the gas density is low) is governed by Boyle's Law:

$$[\mathbf{P}\ \mathbf{v}]_0 = [\mathbf{P}\ \mathbf{v}]_1 \qquad \{6\}$$

In application of expression {6} to centerwinding the initial condition represented by the left hand side of the equation corresponds to a pressure and volume of air which could be predicted using expressions {1} and {2}. As this air is wound into the roll the pressure increases due to the winding process and the volume decreases due to the increased pressure. A diagram which portrays the compression of this air is shown in Figure 10. Expression {6} becomes:

$$(P_0 + P_{atm})\, h_0 = (\sigma_r + P_0 + P_{atm})\,(h_0 - x) \qquad \{7\}$$

Solving this expression for x and dividing by the original air film thickness h_0 yields a pseudo expression for the radial strain of the trapped air layer of the form:

$$\varepsilon_r = \frac{x}{h_0} = \frac{\sigma_r}{\sigma_r + P_0 + P_{atm}} \qquad \{8\}$$

The derivative of expression {8} with respect to the radial pressure, σ_r, after inversion becomes the radial modulus of the air per:

$$E_{r,air} = \frac{(\sigma_r + P_{atm} + P_0)^2}{\sigma_r + P_{atm}} \qquad \{9\}$$

It is assumed that the modulus of the trapped air and the stack modulus combine to yield an equivalent modulus much as springs in series combine to form an equivalent stiffness or:

$$K_{eq} = \frac{1}{\dfrac{1}{K_{stack}} + \dfrac{1}{K_{air}}} \qquad \{10\}$$

which becomes after substitution of the variables:

$$\frac{1}{\dfrac{E_{r,eq}A}{h_0+h}} = \frac{1}{\dfrac{E_{r,stack}A}{h}} + \frac{1}{\dfrac{E_{r,air}A}{h_0}} \qquad \{11\}$$

Solving for $E_{r,eq}$, substituting expression {9}, and simplifying yields:

$$E_{r,eq} = \frac{h_0+h}{\dfrac{h}{E_{r,stack}} + \dfrac{h_0(P_0+P_{atm})}{(\sigma_r+P_0+P_{atm})^2}} \qquad \{12\}$$

where $E_{r,stack}$ is measured using a material testing system just as must currently be performed for input to wound roll models which do not accommodate air entrainment.

It is evident that this new modulus is affected both by the amount of air which is initially entrained (h_0) per expression {1} and by the wound-on-tension which affects the entrained air in expression {1} and the initial pressure (P_0) in the air layer per expression {2}.

In Figure 11 a plot showing the stack modulus as measured, $E_{r,stack}$, and the equivalent radial moduli as a function of velocity per expression {12} are shown. It is evident that even at the lowest winding speed tested that the radial modulus has been significantly reduced. The radial pressure profiles which resulted from using a wound roll model in a centerwinding study on a polyester web are shown in Figure 12. In this study all winding parameters were fixed except for the radial modulus which was predicted per expression {12} as a function of various winding velocities, see Table 1. It is obvious that the predicted radial pressures have decreased significantly due to entrained air. It was encouraging that at a given radius that the pressures converge as a function of velocity as was evident in the experimental data shown in Figure 6, especially for the 30.5 and 76.2 m/min winding velocities. This was indicative that a reduced radial modulus, due to entrained air, could be the primary winding model variable needing modification to accurately model the reductions in radial pressure shown previously in Figure 6.

RESULTS

A set of winding experiments were performed on ICI Type S polyester films which were 12.2, 23.4 and 50.8 μm in thickness. Winding velocities included 17.2, 30.5, and 76.2 m/min and the web line stress was held constant at 6.89 MPa. Pull tabs (Monk, Lautner, and McMullen [13]) and force sensitive resistors (Good and Fikes [14]) were used to monitor the radial pressures within the wound rolls. The results of the winding model using the radial modulus per stack tests (equivalent to winding at velocities where no air is entrained) and per expression {12} are shown in conjunction with the experimental data in Figures 13, 14, and 15. The input parameters for the modeling are shown in Table 1. It is evident that at the highest winding velocity of 76.2 m/min that a reasonable correlation is obtained for all web calipers.

The theoretical and experimental results tend to diverge at lower velocities. An explanation for the divergence between the experimental data and the pressures calculated by the model lies in the surface roughness of the web. The derivation of expression {12] relied upon the assumption that the trapped air which had been entrained was sufficient to prevent asperity contact between the web surfaces. In Figure 16 bar charts showing the web roughness in comparison to the entrained air film thickness (h_0) per expression {1} which were calculated at the inside and final outside radii of the wound roll. Per expression {1} the air layer thickness should vary linearly between the values calculated as h_0 is proportional to the current outside radius of the winding roll. After observation of Figures 13, 14, 15 and 16 it is evident that whenever the entrained air film thickness was greater than the surface roughness of the web that the new model predicted the radial pressures quite well.

CONCLUSIONS

The Knox-Sweeney expression {1} provides a reasonable estimate of the air film layer thickness which is entrained into a centerwound roll. In some cases the air film thickness is sufficient to cause separation of the web layers in a wound roll. In these cases a reduced radial modulus, calculated per expression {12}, has been shown to be effective when input to a wound roll model in predicting the radial pressures which result from winding as decreased by air entrainment. Other model inputs such as winding tension were shown not to be significantly effected by the entrained air. Expression {12} is not an accurate form for predicting the radial modulus (E_r) when winding at lower velocities in which the air film is insufficient to prevent asperity contact between the web surfaces. Although expression {12} is not accurate for these cases it is believed that there is some form of reduced modulus which is applicable and should be a topic for continuing research.

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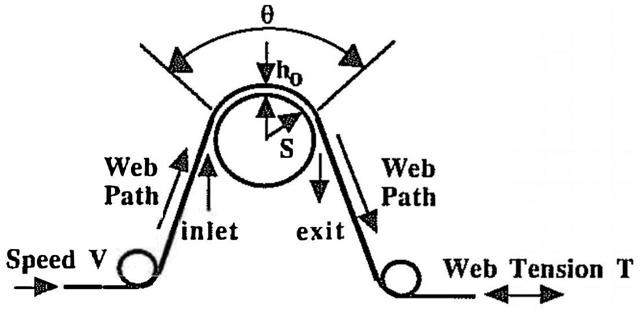


Figure 1. - A Web Encountering an Idler Roll

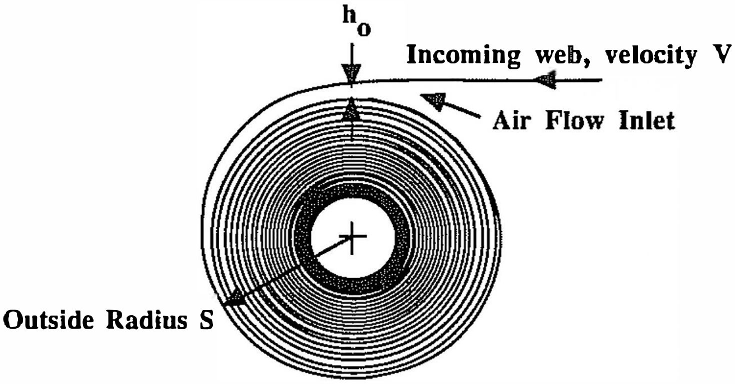


Figure 2. - Air Entrainment in Centerwound Rolls

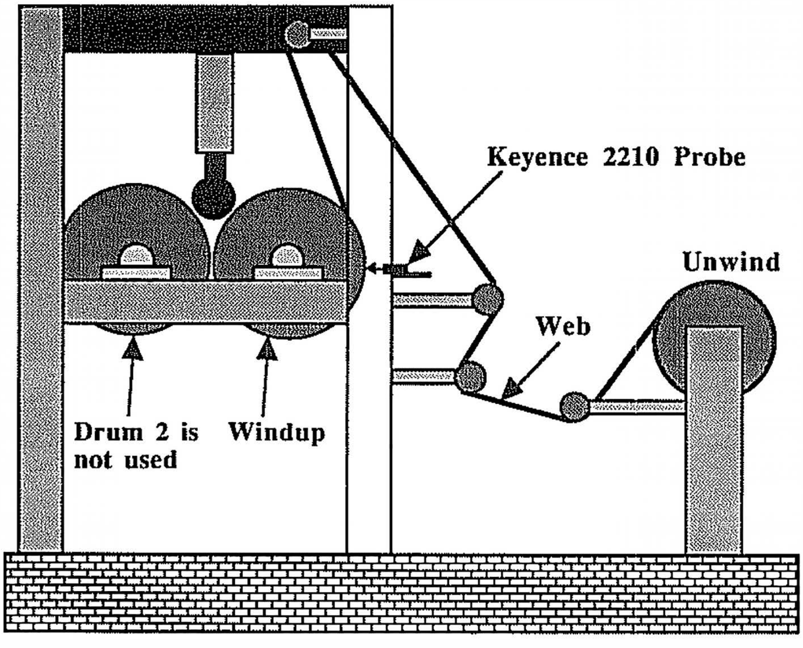


Figure 3. - Two Drum Winder as Modified and Instrumented for Centerwinding Studies

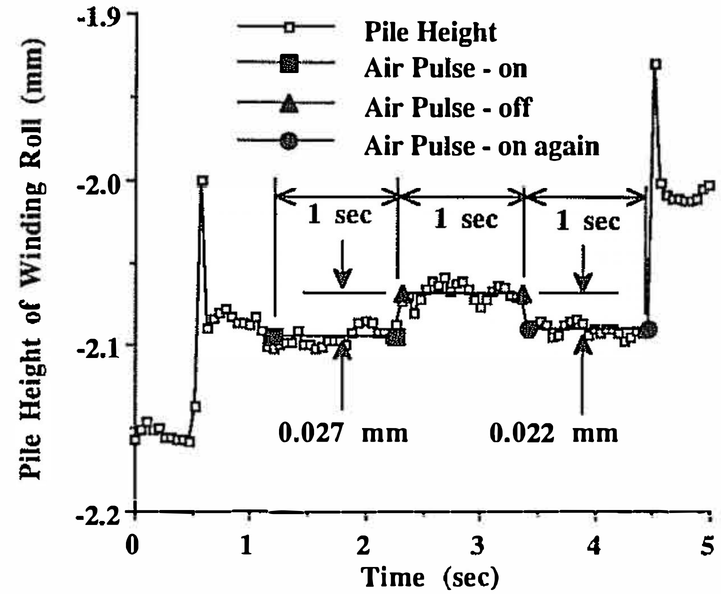


Figure 4. - Air Film Height for Centerwinding Floppy Disk Media at 30.5 m/min

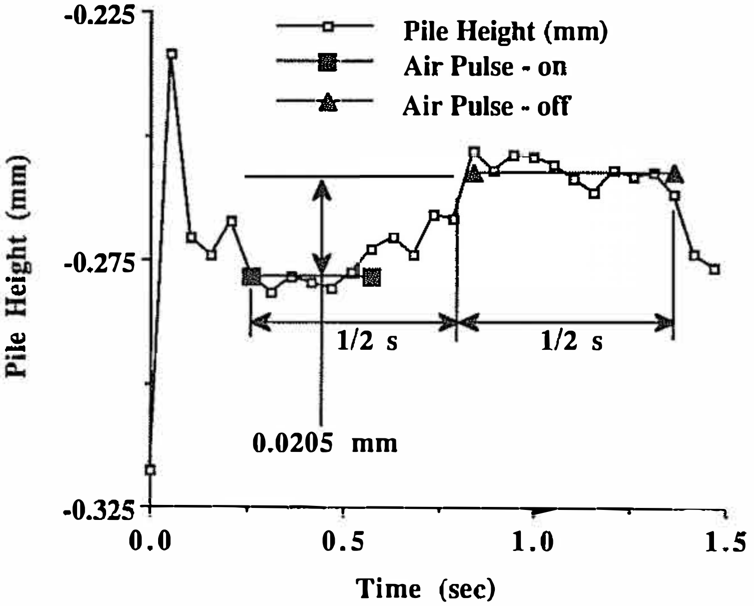


Figure 5. - Air Film Height for Centerwinding Floppy Disk Media at 76.2 m/min

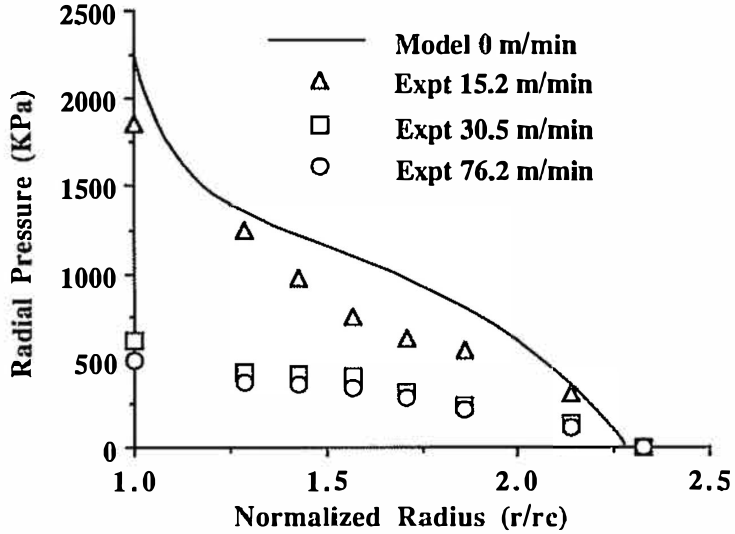


Figure 6. - Experimental Study on the Air Effects upon Centerwinding ICI Type S 23.4 um PET at 6.89 MPa Winding Tension

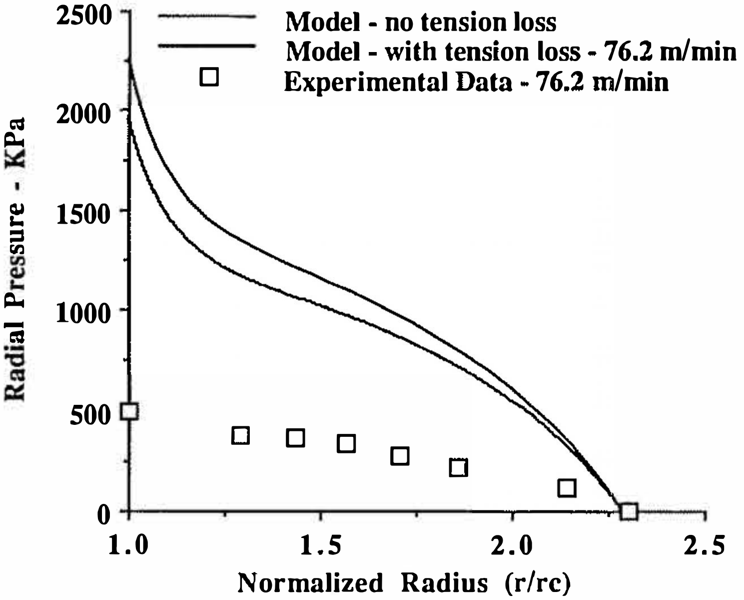


Figure 7. - The Effect of Tension Loss due to Entrained Air upon Centerwinding ICI Type S 23.3 um PET at a Winding Tension of 6.89 Mpa

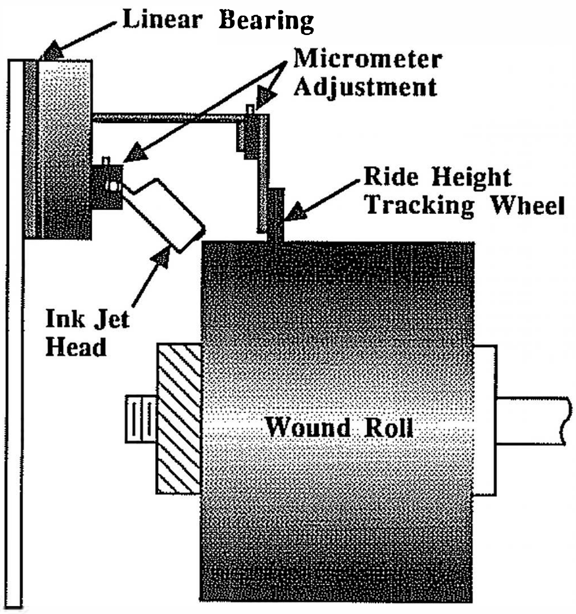


Figure 8. - The Instantaneous J-Line Printer

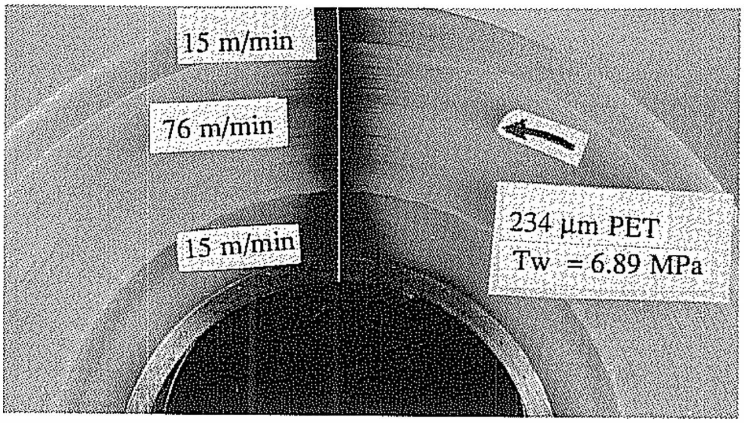
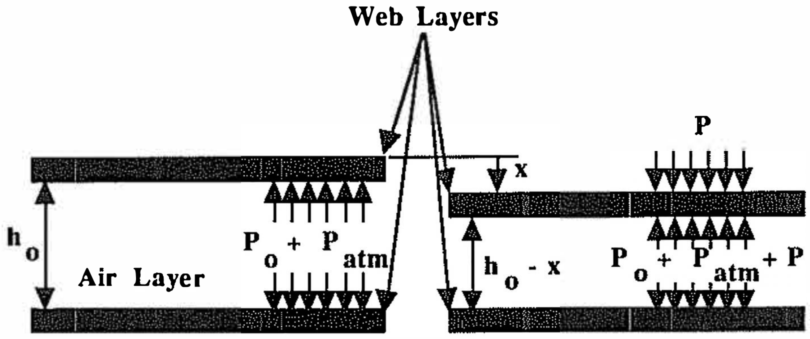


Figure 9. - Instantaneous J-Line Printed upon 23.4 um ICI Type S Film Centerwound at a Winding Tension of 6.89 MPa and a Velocity of 76.2 m/min



Initial Air Layer as the Web is Wound on to the Roll

Final Air Layer after Compression has occurred due to Winding

Figure 10. - The Compression of the Entrained Air due to Winding

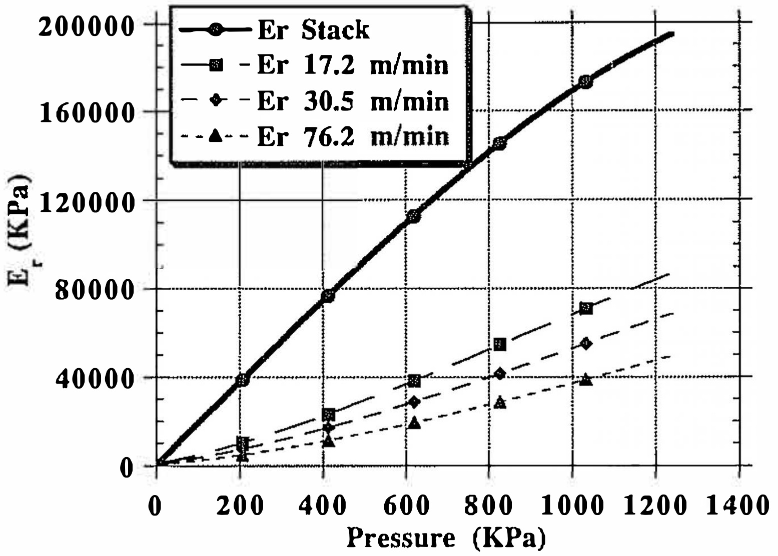


Figure 11. - Radial Moduli for 23.4 um ICI Type S PET - per Test and Expression {12}

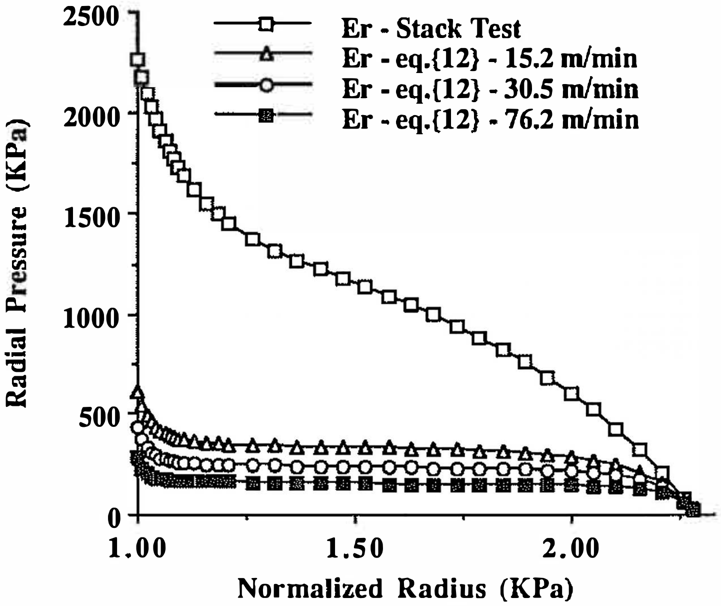


Figure 12. - Radial Pressures Computed from Wound Roll Models for 23.4 um ICI Type S Film Centerwound at a Winding Tension of 6.89 Mpa

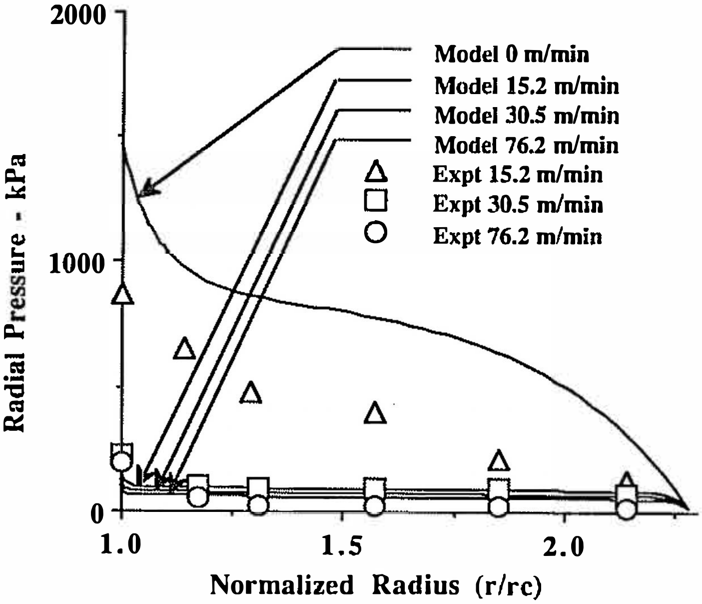


Figure 13. - ICI Type S 12.2 um PET Centerwound at 6.89 MPa

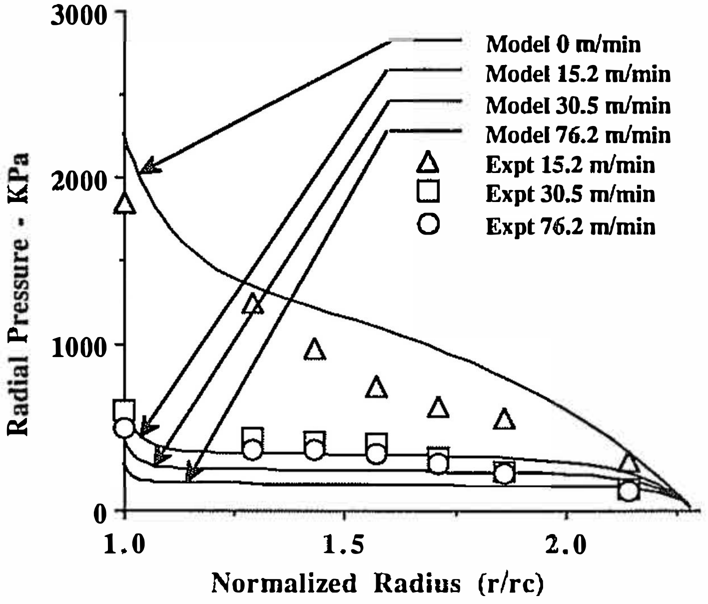


Figure 14. - ICI Type S 23.4 um PET Centerwound at 6.89 MPa

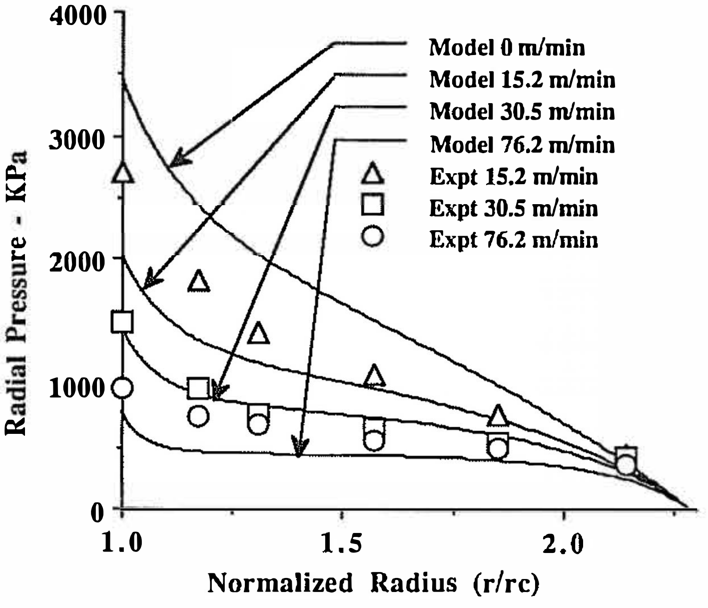


Figure 15. - ICI Type S 50.8 um PET Centerwound at 6.89 MPa

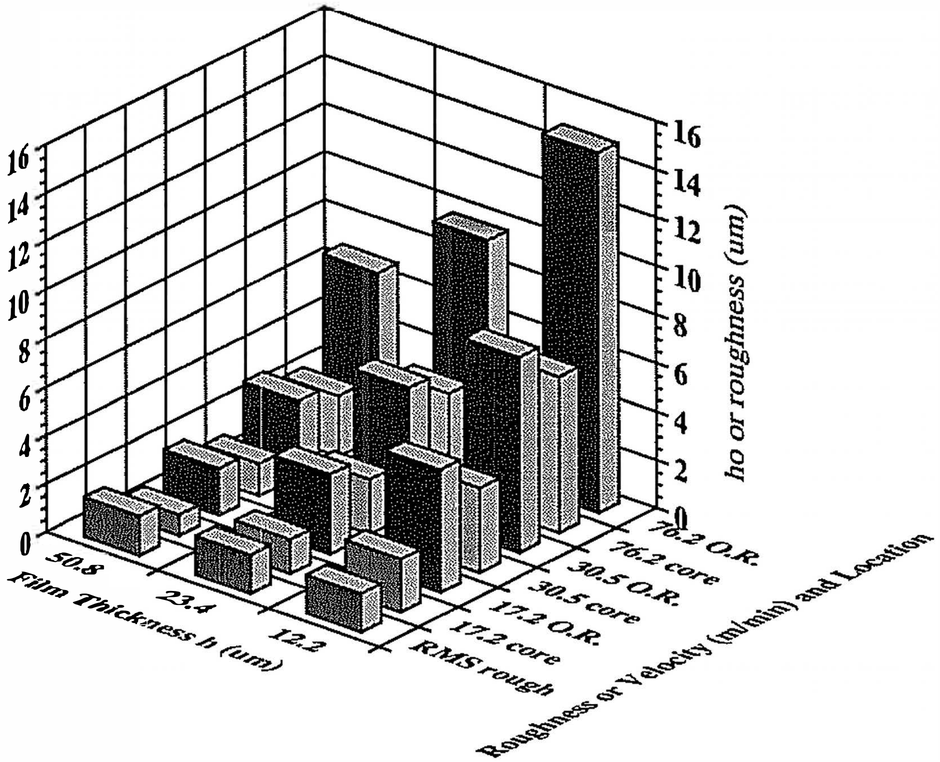


Figure 16. - Comparison of Film Roughness with the Entrained Air at the Core and the Outside Radius as a Function of Velocity

Outer radius of Wound Roll (cm)	10.16
Outer radius of Core - r_c (cm)	4.45
Core Stiffness (GPa)	33.1
Winding Tension - T_w (MPa)	6.89
E_θ (GPa)	4.134
$\nu_{r\theta}$	.01

	$E_r = C_1\sigma_r + C_2\sigma_r^2 + C_3\sigma_r^3$		
E_r	C_1	C_2	C_3
12.2 µm - Stack	138.569	-.430210	-1.6234E-03
12.2 µm - 15.2 m/min	11.234	.065169	4.4159E-04
12.2 µm - 30.5 m/min	8.557	.052570	3.8664E-04
12.2 µm - 76.2 m/min	6.371	.042647	3.2305E-04
23.4 µm - Stack	186.939	.006969	-2.5280E-05
23.4 µm - 15.2 m/min	41.105	.043031	-1.5877E-05
23.4 µm - 30.5 m/min	28.712	.035055	-1.0939E-05
23.4 µm - 76.2 m/min	17.666	.025545	-6.1142E-06
50.8 µm - Stack	301.34	.209999	-1.3999E-03
50.8 µm - 15.2 m/min	125.859	.649888	-1.5655E-03
50.8 µm - 30.5 m/min	89.527	.651621	-1.4028E-03
50.8 µm - 76.2 m/min	52.032	.568327	-1.0639E-03

Table 1. - Winding Properties Required to Model ICI Type S PET Film

QUESTIONS AND ANSWERS

Q. Why did you use the springs in series to model the air entrainment?

A. I think it is reasonable as long as the entrained air layer is insufficient to separate the web layers completely. In the absence of air an asperity on one web surface will contact the adjacent web surface only if all other higher asperities were compressed first. Also the air between the surfaces must be compressed prior to a given asperity making contact, thus this is not the case of having springs in parallel subjected to the same displacements.