THE EFFECTS OF NON-IDEAL WEBS ON ROLL WINDING

by

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ABSTRACT

In typical winding processes, webs are rarely (if ever) ideal but instead thickness non-uniformity and distortions (two examples) are the norm. These deviations from ideal have significant ramifications to both predictive model development and to winding equipment design configurations. This paper will present methods for quantitative measurement of some of the important non-ideal web characteristics. Typical results will be presented for film and paper webs. Also presented will be examples of modeling enhancements needed to generate predictions of the winding behavior in systems comprised of non-ideal webs. Finally, examples will be given of hardware modifications that are driven, to a large extent, by the reality that webs are not perfect. The objective of this paper will be to enlighten the winding process development community regarding a very challenging and relevant area for future research.

NOMENCLATURE

Greek:

ε_0	initial unstressed longitudinal strain
ε_{0c}	maximum unstressed longitudinal strain
η	thickness variation parameter
κ_z, κ_θ	axial, circumferential web curvature
θ	circumferential position
ν	Poisson's ratio of the stack

Roman:

D	flexural rigidity of the web
E	Young's modulus of the web
g	gap between the roll before loading and the bottom of the web after loading
h	web thickness
h_a	average web thickness
k	roll foundation stiffness
l	web length
l_0	nominal web length
L	web width

H	camber displacement
M_z	axial face bending moment
N_θ	circumferential stress
Q_z	axial face transverse shear force
q	external loading applied to the web
R	untensioned reference radius, averaged across the width
R_c	camber radius of curvature
R_{pm}	surface roughness parameter, average of the five highest peaks in a sample, measured from the mean plane
R_z	surface roughness parameter, difference between the five highest peaks and the five lowest valleys in a sample, measured from the mean plane
r	unloaded roll radius
S	untensioned reference radius, width dependent
T	total web tension
u	outer lap radial displacement, measured with respect to the centerline of the roll
w	outer lap radial displacement, measured with respect to the average reference radius
w_0	difference between the width dependent reference radius and the average reference radius
x	length position
z	lateral web position

INTRODUCTION

A web is defined as a structural member with length much greater than width and with width, likewise, much greater than thickness. Webs are used throughout industry in many varied applications. For instance, webs are used in the manufacture of such diverse consumer items as photographic film and paper, carpet and linoleum, and automobile components such as hoods, doors, and other parts. Webs are manufactured in a number of ways, ranging from extrusion, coating, and drafting to tentering and calendaring. One common aspect in the manufacture of webs is the process of winding, whereby webs are wound into rolls. The winding process enables transport of the web from one operation to the next in a very compact and cost effective fashion.

It is important to understand that while wound rolls are a very convenient way to transport webs, this ease does not come without risk. As those of you who have had many years of experience with winding can attest, it is very often a difficult task to ensure that the quality of the web emerging from the wound roll is acceptable. The quality depends on several factors, including the process-parameter settings used during the winding of the roll, the handling and environmental conditions that the web is exposed to during its time in the wound roll, and the process conditions the roll experiences during unwinding. In addition to these influences, the overall web quality can also be degraded depending on the initial quality of the web prior to winding.

Web quality is a very general concept. In this paper, we seek to better qualify what this means. To begin, we first define what is meant by an "ideal web," e.g. a web with perfect quality. We define as an ideal web one which has both geometric and material spatial invariance. Figure 1 shows such an idealized web. A cross section of the web (a perpendicular cut across the width) is perfectly rectangular with constant thickness, h, which is independent of lateral position, z, and length position, x. Further, the width of the web, L, is a constant, independent of length position. In addition, an ideal web is one devoid of any distortions. Thus, we see from Figure 1 that the ideal web is perfectly flat over its entire width and length. Also, in the stress-free state, the web is straight in the length (no camber) and the out-of-plane curvature is infinite (no curl). The ideal web also possesses material invariance. The simplest statement of this fact is that the ideal web can be characterized as a linear isotropic material and there are only two material properties, Young's modulus, E, and Poisson's ratio, ν, and they are independent of orientation and position throughout the web.

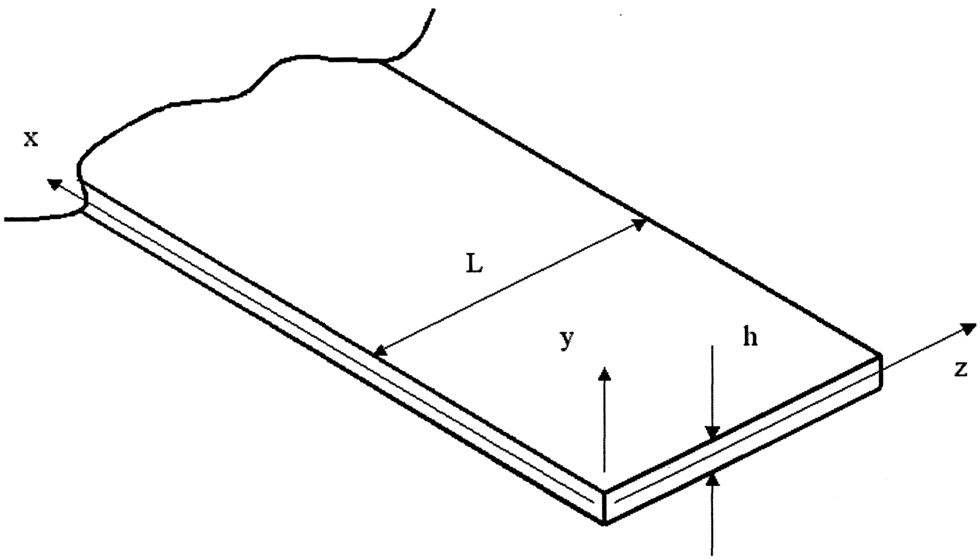


Figure 1 - Ideal Web

In reality, an ideal web is just that, an ideal; in practice, the ideal web does not exist. Instead, all of the characteristics just mentioned are violated to varying degree because no web manufacturing process is perfect. In this paper, we begin by discussing methods to measure, or quantify, these deviations from ideal, e.g., imperfections, and proceed to show some typical examples of different types of webs. This is followed by a general discussion of methods whereby some of the current predictive winding models can be extended to incorporate web imperfections to enable quantitative prediction of their effect on wound roll stresses. Finally, a few examples will be cited to demonstrate the practical implication of imperfections on the design of winding hardware. This will serve to link the modeling enhancements to the practical aspects of not only winding-process optimization but also to winding equipment design.

IMPERFECTION MEASUREMENT

We begin by discussing methods to characterize geometric web imperfections. We will discuss thickness, camber, curl, web distortion and web roughness, which can be rightly viewed as a geometric metric. We will then discuss how stack modulus, an imperfection characterizing compressive stiffness, is measured. In the next section, we will see how these imperfections impact winding, how these effects can be treated in winding models and where more work is needed.

Web thickness, as stated previously, is often not constant but, in fact, is a function of widthwise and lengthwise position within the web. This is due to the very nature of how webs are made. For instance, often plastic webs are manufactured using a process whereby polymer is extruded at high temperature through a fixed dye onto a casting wheel and is subsequently stripped from the wheel for conveyance to the winder. The very nature of this process practically guarantees that widthwise thickness nonuniformity will be present and, further, that this nonuniformity will tend to persist in the lengthwise direction of the web. The manufacture of paper and metal webs often contains another process whereby webs, once formed, are reduced in thickness by a process called calendaring. This step is done to not only reduce thickness but also to establish surface characteristics. However, this step, by its very nature, is prone to creating thickness nonuniformity, which can be a function of both widthwise and lengthwise position. In all these cases, it is desirable to be able to measure thickness to establish the dependence of thickness on width and length. It is important to be able to do this to insure that adequate specifications can be established and confirmed for actual web production. Web thickness measurement methods fall into two categories: offline and online. In the first category, there exist both contact and noncontact techniques. Contact techniques generally consist of a pair of perpendicularly oriented gauges that often have spherical metal tips attached to insure smooth tracking as the web is transported between them. Usually, one gauge is rigid while the other is free to translate in the presence of variable thickness web passing through the interface. The translating gauge is often lightly spring loaded to insure intimate contact between the metal tip and the web. Additionally, the displacement is measured using a type of displacement sensor, an LVDT being a typical example. Finally, these systems will possess a drive system capable of accurately driving the web at a fixed speed through the measurement assembly and a data acquisition system to collect the data for subsequent quantification and characterization. Figure 2 shows the thickness measurement system used at Eastman Kodak Company to characterize web thickness.

Figure 2 - Eastman Kodak thickness gauge

Figures 3 and 4 show typical thickness results for film and paper webs. These results very clearly indicate the widthwise and lengthwise dependence of web thickness. Noncontact, offline thickness techniques are very similar to the aforementioned system except that the thickness is measured by noncontacting means such as capacitance, ultrasonic, and photonic gauges. These systems have the benefit of not causing unwanted compression of the web being measured; however, depending on the gauge selected, other difficulties can arise. Some examples, which affect accuracy, are material variability (capacitance) and web orientation (ultrasonic, photonic). In practice, the contacting method provides the best compromise between accuracy and cost. This is especially true when the main concern is relative thickness differences within the web.

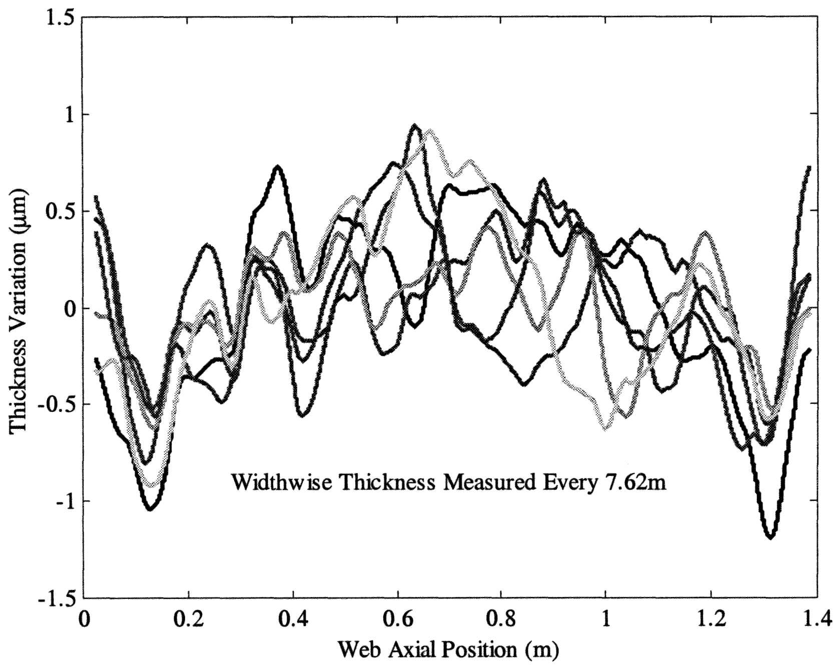


Figure 3 - Web thickness, typical PET web

Online thickness measurement means measurement while the web is being transported through the web conveyance line. This method is usually used as a part of a larger system, which controls online thickness through a thickness control algorithm. Depending on the type of web being considered either contacting or noncontacting gauges can again be used. For most webs, it is preferable to use noncontacting gauges because contacting elements can give rise to unwanted web damage. Typical examples include the aforementioned capacitance, ultrasonic and photonic gauges. Another commercially available technique to measure thickness on plastic, paper, and metal webs relies on the webs ability to transmit radioactive particles in proportion to thickness. In all cases, online systems are comprised of either a translating gauge or an array of fixed gauges to enable collection of both widthwise and lengthwise thickness data.

Web camber is a web imperfection characterized by a lack of straightness in the lengthwise direction. Figure 5 shows the geometry of this type of web imperfection. Web camber is typically specified either in terms of the radius of curvature, R_c, or in terms of a

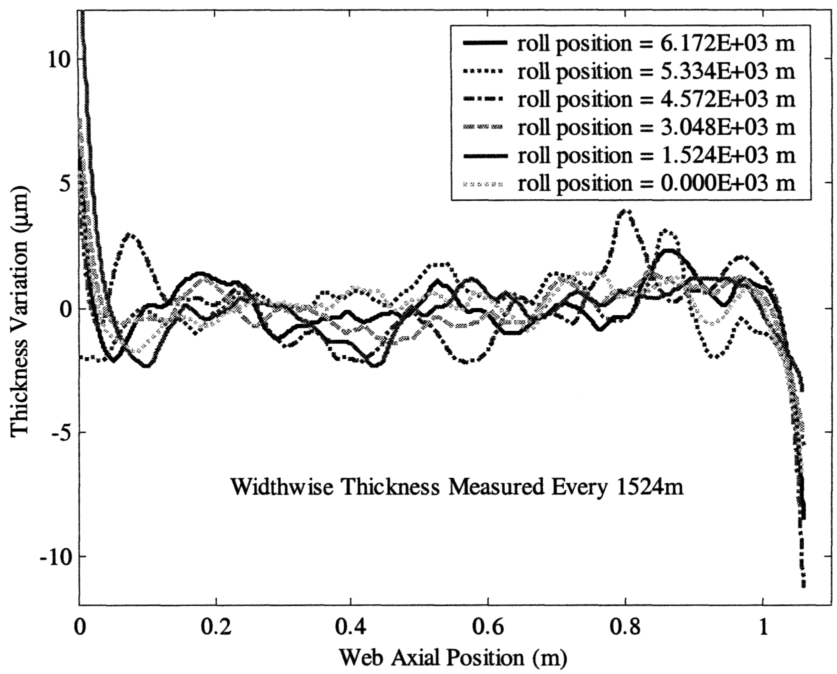
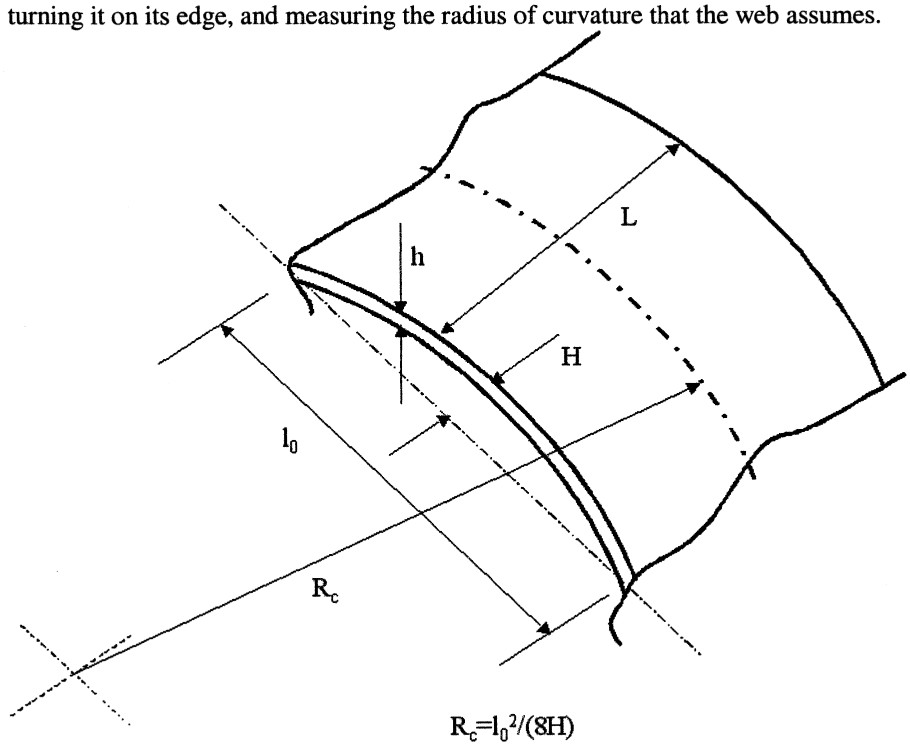


Figure 4 - Web thickness, typical paper web

given amount of displacement, H, over a fixed lengthwise distance, l_0 (see Figure 5). Camber can be either constant with length or periodic. If a web has long edges or a long center, the process of slitting will create a web with constant camber. Conversely, if a web is slit while the slitter unwind is moved back and forth axially in response to stock roll edge variations, then the slit webs will have periodically varying camber. In general, web camber is not easy to measure. One way is to measure the reaction forces in both bearings of a roller wrapped by the web. Because a curved web has a nonuniform tension distribution, the difference in the reaction forces is a measure of web camber. However, this measurement is also affected by web distortions, thickness variations, and web tracking as discussed by Graff [1]. Another way of measuring camber is to lay out a relatively long sample under no tension. The goal is to put the web down so that it is flat. The curvature can then be measured. Figure 5 shows how to relate the distances H and l_0 to the radius of curvature.

Web curl is defined as out-of-plane distortion along either the lengthwise or widthwise direction. More general out-of-plane distortion is referred to as distortion. Curl can arise from multiple effects. First, if the web has been bent for some time, for example, in a wound roll, relaxation of the bending stresses may cause it to remain bent even after the original bending moment is removed. Curl produced by this mechanism is called "core set" and is about the widthwise direction. Second, if the web consists of layers of different materials and the materials respond differently to changes in temperature or in humidity, the differential expansion or contraction in the layers cause the web to become nonflat, e.g., curl. In this case, the curl, theoretically speaking, is isotropic; however, practically because the web length is typically much greater than the width, the curl will align about the lengthwise direction. The measurement of curl is performed following standard procedures as described in ISO Standard 18910 [2] and consists of cutting a web sample, turning it on its edge, and measuring the radius of curvature that the web assumes.



$$R_c = l_0^2/(8H)$$

Figure 5 - Cambered web geometry

Web distortion is a more general out-of-plane distortion, and many different terms are used to denote it, depending on the characteristic distortion. Examples include, bagginess (excess local length at central locations across the width of the web), fluting (a waviness of the web edge caused by roller misalignment, thickness nonuniformity, or moisture absorption, and edge swelling in rolls of wound paper), cockle (a particular type of bagginess produced when a web buckles while wrapped on a cylindrical object and having a waffle-like pattern), and core impressions (distortions caused by the web end being pressed against the web layers at and near the core in a wound roll). Web distortion has always been a difficult characteristic to measure. In this discussion, we cite an example of a novel offline method developed by Eastman Kodak Company to perform this measurement [3]. Figure 6 shows a schematic of the measurement system. This system consists of an optically flat surface that is vented to a vacuum system. A sample to be measured is placed on the flat surface, a vacuum applied, and the sample trimmed to an appropriate size. Next, the vacuum is removed and the web is positioned for measurement. An overhead gantry is traversed along the length of the sample by means of a stepper motor attached to linear slides. Attached to the gantry is a series of detectors that measure the distance between the gantry reference and the undisturbed web at fixed spatial increments. Noncontacting ultrasonic transducers are used to detect distance and work well with any nonporous web. Using a numerical algorithm, the system computes normalized web length as a function of lateral position. Finally, the results are presented graphically. Figures 7 and 8 show some typical results for film and paper. In closing, it should be stated that a good online method for measuring web distortion does not yet exist, even though there is demand for such a system.

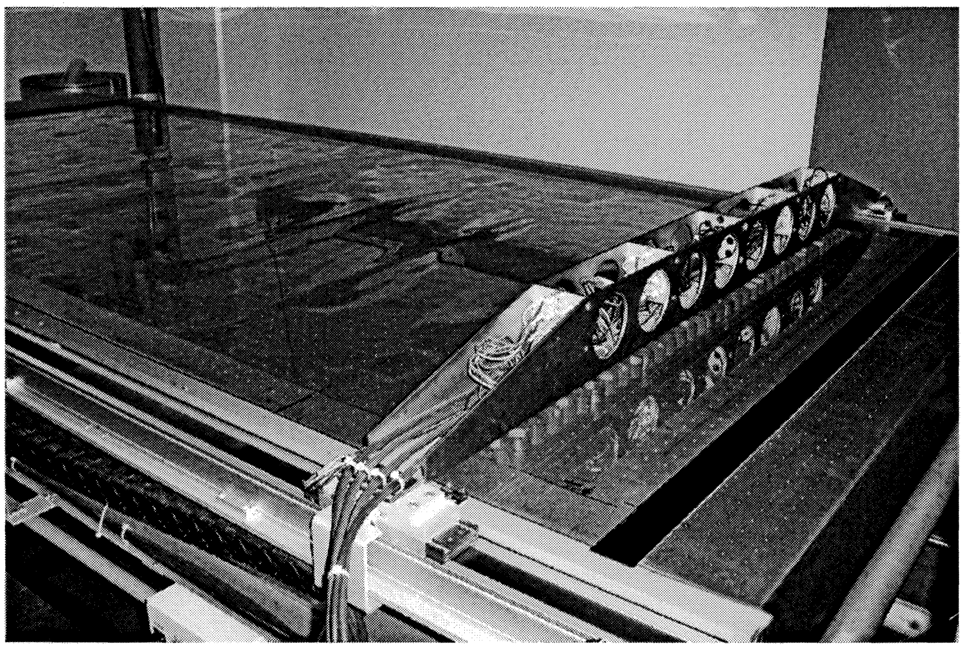


Figure 6 - Eastman Kodak web distortion gauge

Surface roughness is also a geometric property of the web. It can be measured in a number of ways; however, we have found that the best method for measuring roughness is to use a noncontacting area measurement method. The benefit of such an approach is that it does not require any assumptions about the nature of the asperity distributions on the surface of the web to compute the roughness parameters. For predictive winding modeling, we find that we are primarily interested in peak roughness parameters such as R_{pm} and R_z, which are defined as the average of the five highest peaks with respect to the mean and the average of the five lowest valleys in the viewing area respectively [4].

We complete this section by briefly discussing how *stack modulus* is measured. Stack modulus is a critical product parameter and is well known to strongly influence the characteristics of a winding roll. Recalling that an ideal web is materially isotropic, we know that, in reality, webs are not ideal because the behavior in the thickness direction is generally characterized by a compressive modulus (e.g., stack modulus) that is a nonlinear function of pressure. The reasons for this nonlinear behavior are many and include the effects of roughness, thickness nonuniformity, web distortion, and air entrainment. Thus, it is critical to be able to characterize this important material property to be able to successfully develop predictive winding models.

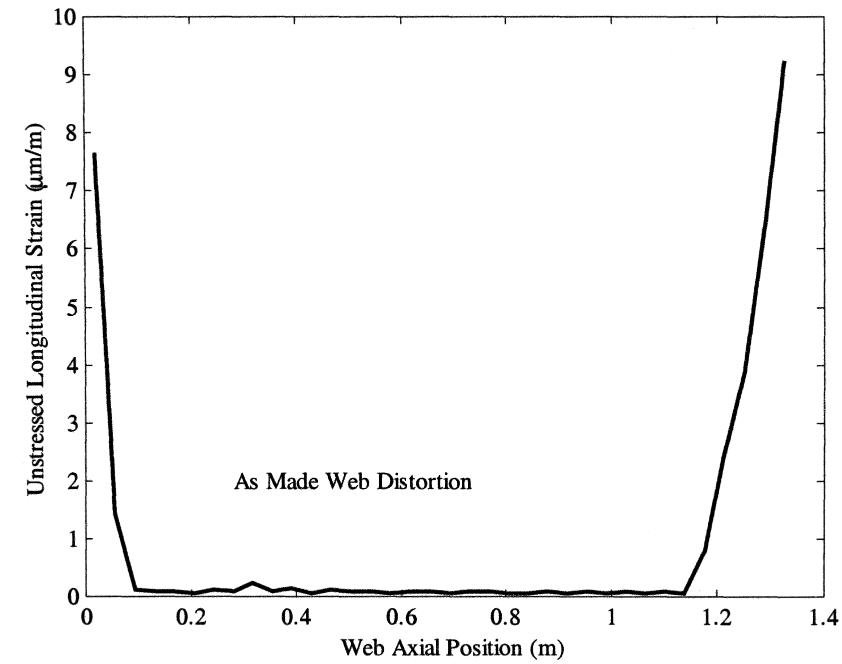


Figure 7 - Web distortion, typical PET web

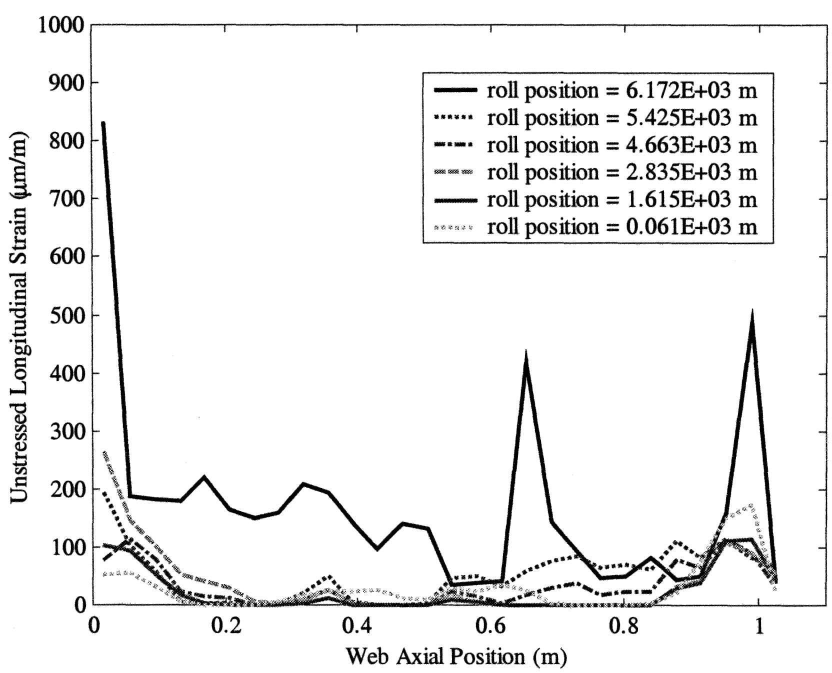


Figure 8 - Web distortion, typical paper web (same web as Figure 4)

Lei et. al. [4] describe in detail a method used to empirically determine the stack modulus. The method consists of first constructing three stacks of support from individual web plies, sequentially compressing each stack with a small preload, and measuring the resulting height of the stack by means of three LVDTs located at 120° increments around the perimeter of rigidly fixed, parallel upper and lower platens. The stack height measurement is divided by the number of plies, which yields the web thickness. Following this measurement, each stack is then compressed at a constant strain rate while simultaneously being measured displacement and load. The stack modulus, determined from the average of the results of the three stacks, is determined as a function of compressive stress by computing the tangent modulus from the empirical data. Figure 9 shows the stack modulus measurement apparatus.

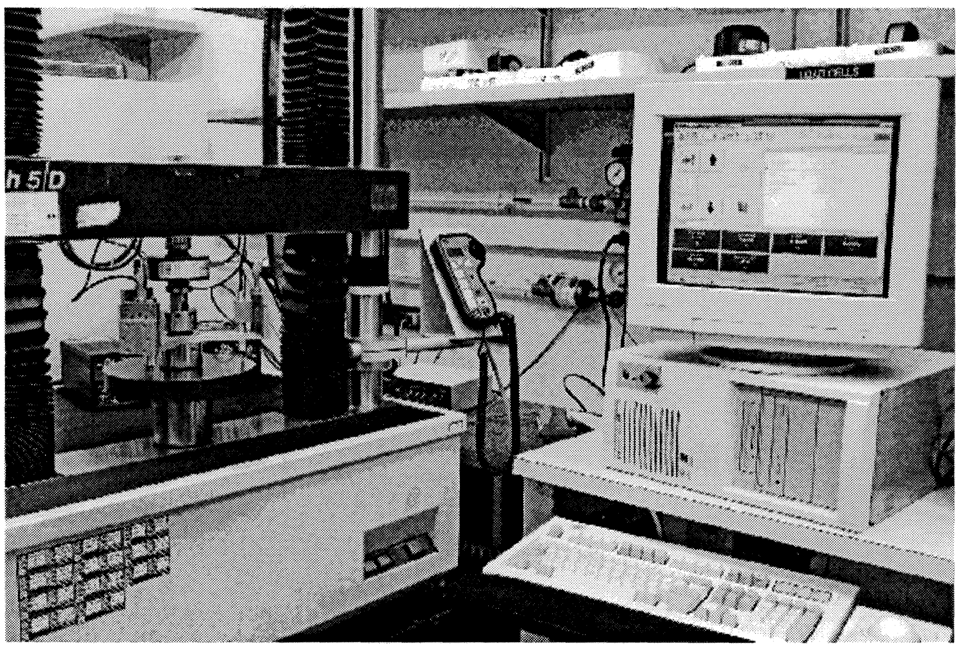


Figure 9 - Eastman Kodak stack measurement gauge

THE IMPACT OF IMPERFECTIONS ON WINDING MODELING

Having discussed a number of web imperfections and described methods to measure them, we now turn to the pragmatic aspects of the implications these imperfections have on winding. In particular, we wish to highlight the capabilities and shortcomings of existing predictive models, describe methods for incorporating into the models the impact of these imperfections and present some simple modeling examples where this has been done. In this section, we will focus on web thickness nonuniformity, web camber, web distortion, web roughness and stack modulus.

Any discussion of web imperfections leads to several fundamental questions. One of these is: how severe do web imperfections have to be before they exceed the limits specified by the end-use customer? Because the requirements depend on the application, this question does not have a unique answer. However, we can make progress if we ask and answer a more generic question; that is: how can we determine the impact of web imperfections on roll winding and the impact of roll winding on web imperfections? Ultimately, the resulting customer imperfections are dependent on the interaction between winding and wound roll interactions. Further, winding is a bit like "the chicken and the egg" paradox in that each affects the other, and it is not always clear which came first. However, if we accept that things can happen both ways (e.g. web imperfections exist, causing roll imperfections leading to further degradation of the web, or roll imperfections cause ideal webs to become nonideal) and make the further accommodation that the former is a more complicated scenario (and, probably, the most realistic); this allows us to frame our discussion as follows. How can the current winding models take into account web imperfections in a realistic way so that we have a capability to predict the subsequent impact on the web and roll?

As winding modeling has evolved over the years, one of the driving forces has been to develop predictive capability that faithfully takes into account the effect of web imperfections on roll and web quality. As in any undertaking, this evolution has progressed in the past from highly idealized beginnings to more recent efforts that seek to include real web imperfections. Citing only a few selected papers in the literature bears this out. One of the earliest works was that of Altmann [5] who treated the winding process as the addition of a sequence of stretched hoops shrunk fit onto the winding roll. This idealization has been employed ever since that time. He further assumed that the roll could be treated using a linear-orthotropic material constitutive law, thereby enabling an analytic solution to be developed. Hakiel [6] extended Altmann's work by treating the roll as a nonlinear-orthotropic material, specifically characterizing the radial compressive modulus as a nonlinear function of interlayer pressure. Solutions were obtained numerically using a quasilinearization procedure. Building from these early works, researchers continued to add complexity to the basically radial effects only models of Altmann and Hakiel (see Lei et. al [4] for a summary of these works). However, in the early 1990's, work began to appear where the scope was broadened to include both radial and axial effects. Papers by Hakiel [7], Kedl [8], Cole [9, 10] and Benson [11] presented various modifications to the earlier models to enable inclusion of axial effects.

For purposes of illustration of the theme of this paper, we focus on the model developed by Benson [10]. In that work, analysis was presented that allows for the calculation of deflection of an elastic web wrapped under tension onto a surface of revolution. The analysis is immediately applicable to the outer lap analysis on a winding roll and has the advantage of accounting for web bending in the axial direction. We will present a modified version of the analysis with a suitable extension that allows for inclusion of nonuniform web thickness, web camber, and web distortion into the formulation. We will demonstrate some typical results and discuss further extensions that should be considered in the future.

Figure 10 shows the geometry for the outer lap. A web of nonuniform thickness, $h(z)$, is pulled with tension, T, around a nonright-circular cylinder with an unloaded radius, $r(z)$. The nonright-circular cylinder represents a winding roll prior to the addition of the outer lap. As a consequence of the standard winding assumption that the outer lap can be treated as a circular hoop, the outer lap will have some characteristic radius, $S(z)$, where circumferential stresses are equal to zero. This reference radius is a function of axial position and incorporates the effect of web camber and web distortion. Further, since camber and web distortion are known a priori, the nonuniform reference radius will be known to within a single unknown parameter, R, defined as the average reference radius.

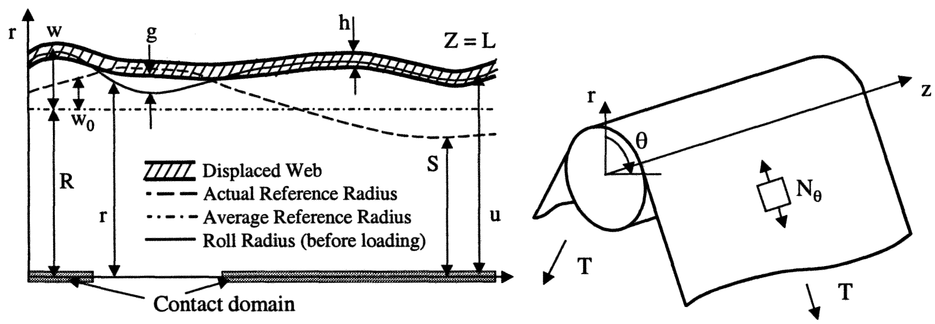


Figure 10 - Geometry of the outer lap

It will be determined from the consideration of radial equilibrium of the outer lap. The coordinates defining the axial and circumferential directions are z and θ. The radial deflection is defined as $u(z)$, measured from the centerline of the winding roll while $w(z)$ is the radial deflection measured from the average reference radius. w_o gives the deviation of the actual reference radius from the average reference radius. $g(z)$ is the gap between the roll before loading and the bottom of the web after loading. The radial length parameters are related through the following kinematic relation

$$u(z) = S(z) + w(z) - w_0(z) = r(z) + g(z) + \frac{1}{2}h(z) \qquad \{1\}$$

It is assumed that all the web physical properties are constant in the θ direction. The web has elastic modulus and Poisson's ratio from which the bending rigidity is

$$D(z) = \frac{Eh^3}{12\left(1-\nu^2\right)} \qquad \{2\}$$

From classical shell theory, the equilibrium of the web is governed by

$$\frac{d^2}{dz^2}\left(D\frac{d^2(w-w_o)}{dz^2}\right) + \frac{Eh}{S^2\left(1-\nu^2\right)}(w-w_0) = q(z) \qquad \{3\}$$

where $q(z)$ is external loading applied to the web in the positive radial direction.

Assuming that the stress resultant in the axial direction is zero, the membrane stress in the circumferential direction is

$$N_\theta = \frac{Eh}{S\left(1-\nu^2\right)}(w-w_0) \qquad \{4\}$$

Integrating across the total width will yield the applied tension

$$T = \int_0^L N_\theta dz \qquad \{5\}$$

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from which the average reference radius can be computed if we account for camber and web distortion in the following way

$$S = R + w_0 = R\left(1+\frac{w_0}{R}\right) = R(1+\varepsilon_0) \qquad \{6\}$$

where the initial unstressed longitudinal strain, ε_0, is determined based on whether we are considering camber or web distortion

$$\varepsilon_0 = \frac{w_0}{R} = \begin{cases} \dfrac{z-\frac{L}{2}}{R_c} & \rightarrow \quad \textit{web camber} \\ \dfrac{l(z)-l_0}{l_0} & \rightarrow \quad \textit{web distortion} \end{cases} \qquad \{7\}$$

where $l(z)$ is the width dependent web length measured by the offline web distortion measurement system. The average unstressed length, l_0, is arbitrary; in the case of the Kodak offline measurement system, it is selected to be approximately 3 m and is equal to the average length across the width

$$l_0 = \frac{1}{L}\int_0^L l(z)dz \qquad \{8\}$$

Substitution of equations {6-8} into equation {5} yields after simplification the average reference radius

$$R = \frac{\displaystyle\int_0^L \frac{hw}{1+\varepsilon_0}dz}{\dfrac{T\left(1-\nu^2\right)}{E} + \displaystyle\int_0^L \frac{h\varepsilon_0}{1+\varepsilon_0}dz} \qquad \{9\}$$

The bending moment on the axial face is

$$M_z = D(\kappa_z + \nu\kappa_\theta) \qquad \{10\}$$

where the axial and circumferential curvatures for small deflections are given by

$$\kappa_z = \frac{d^2(w-w_0)}{dz^2}, \quad \kappa_\theta = -\frac{1}{S} \qquad \{11\}$$

which yields

$$M_z = D\frac{d^2(w-w_0)}{dz^2} - \frac{\nu D}{S} \qquad \{12\}$$

A balance of moments of an axial face yields the following relationship between the transverse shear force, Q_z, and the bending moment

$$Q_z = \frac{dM_z}{dz} = \frac{d}{dz}\left(D\frac{d^2(w-w_0)}{dz^2} - \frac{\nu D}{S}\right) \qquad \{13\}$$

Boundary conditions for equation {3} are

$$\begin{aligned} &\textit{symmetric deflection} \rightarrow \frac{d(w-w_0)}{dz} = 0, Q_z = 0 \\ &\textit{free edge} \rightarrow M_z = 0, Q_z = 0 \end{aligned} \qquad \{14\}$$

The foundation stiffness, for simplification is modeled as an applied load. The simplest treatment, consistent with previous researchers [7 - 10], is to treat the stiffness as a Winkler foundation, whereby the foundation is modeled as a set of unconnected linear springs

$$q(z) = \begin{cases} 0 & if\ g(z) \geq 0 \\ -kg(z) & if\ g(z) < 0 \end{cases} \qquad \{15\}$$

This formulation allows *g(z)* to become negative which is achieved by compression of the roll surface due to belt wrap pressure from the web.

Using equations {1} and {6}, the equilibrium equation can be recast in terms of displacement with respect to the centerline of the roll, *u(z)*, as

$$\frac{d^2}{dz^2}\left(D\frac{d^2(u-R(1+\varepsilon_0))}{dz^2}\right) + \frac{Eh}{R^2(1-\nu^2)(1+\varepsilon_0)^2}(u-R(1+\varepsilon_0)) = q(z) \quad \{16\}$$

By a similar substitution and after simplification, the expression for the average reference radius becomes

$$R = \frac{\int_0^L \frac{hu}{1+\varepsilon_0}dz}{\frac{T(1-\nu^2)}{E} + \int_0^L hdz} \qquad \{17\}$$

The boundary conditions become

$$\begin{aligned} &\textit{symmetric deflection} \rightarrow \frac{d\left(u - R(1+\varepsilon_0)\right)}{dz} = 0,\, Q_z = 0 \\ &\textit{free edge} \rightarrow M_z = 0,\, Q_z = 0 \end{aligned} \qquad \{18\}$$

and the applied load is from equation {1}

$$q(z) = \begin{cases} 0 & \textit{if } \left(u - r - \frac{1}{2}h\right) \geq 0 \\ -k\left(u - r - \frac{1}{2}h\right) & \textit{if } \left(u - r - \frac{1}{2}h\right) < 0 \end{cases} \qquad \{19\}$$

Equations {16-19} form a closed set of equations that can be solved for the unknowns, *u(z)* and *R*.

The solution to the above set of equations was obtained numerically. The algorithm consisted of first writing each of the equations in finite difference form, creating the Jacobian matrix and then solving the resulting set of algebraic equations using Newton's method. The resulting program converges rapidly and was used to generate the results that are shown.

The use of the outer lap model will be demonstrated by considering two cases. In the first case, we consider the relative effects of web camber and thickness nonuniformity on contact pressure under the outer lap. Presented in Table 1 are conditions that were held constant during the simulation.

Variable	Units	Value	Variable	Units	Value
roll radius, r	m	0.254	modulus, E	GPa	4.69
web width, L	m	1.27	Poisson's ratio, ν	unitless	0.3
thickness, h_a	mm	0.254	tension, T	N	445

k = 1.0E+10 N/m^2/m

Table 1 - Simulation constants

Figure 11 shows results for several cases of camber. Camber is expressed in terms of camber curvature defined as R_C^{-1}. Observations of the results indicate that increasing camber curvature causes increasing nonuniformity in contact pressure across the width. The highest contact stress is seen at the left edge, which is the tight edge of the web. The camber values used in the figure are reasonably representative of conditions that might be expected in normal film manufacturing. It is interesting to note that the contact pressure tends to spike moving towards the edges: first up and then down. This behavior is well known and is the result of anticlastic curvature caused by the bending of the web over the roll. In winding where air entrainment is present, this effect will modify the air entrained and the rate of air escape during and after winding. Therefore, it is important that bending effects be considered in outerlap models; especially when air effects are included.

Figure 12 shows results for several cases of thickness nonuniformity. To run the model, width dependent thickness is defined as follows

$$h(z) = h_a\left\{1+\frac{\left(\frac{L}{2}-z\right)}{\frac{L}{2}}\eta\right\} \qquad \{20\}$$

where η is defined as the variation in thickness about the average thickness, h_a. Note that the web is thicker at z equal to zero and thinner at z equal to L. Observation of the results from Figures 11 and 12 indicate that a camber curvature of 0.000328 1/m^2 is approximately equivalent to thickness nonuniformity of ±25% on the contact stress distribution. Thus, it is expected that the magnitude of entrained air will be similar for these two effects when considering winding onto similar rolls. However, in terms of the impact on winding roll stresses, the effect of thickness nonuniformity will be much greater than camber as winding progresses. This is because the impact of sequential laps of nonuniform thickness wound, one on top of the next, has a much greater affect on the radial profile of the winding roll than sequential laps of cambered web.

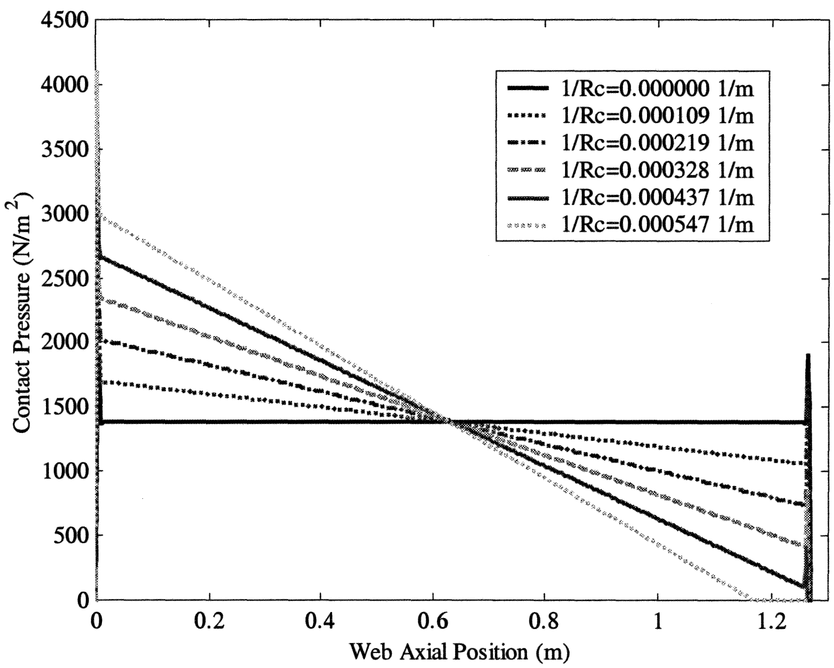

Figure 11 - The effect of camber on contact pressure under the outer lap for uniform thickness. Results are from the outer lap model. The camber radius is indicated in the figure.

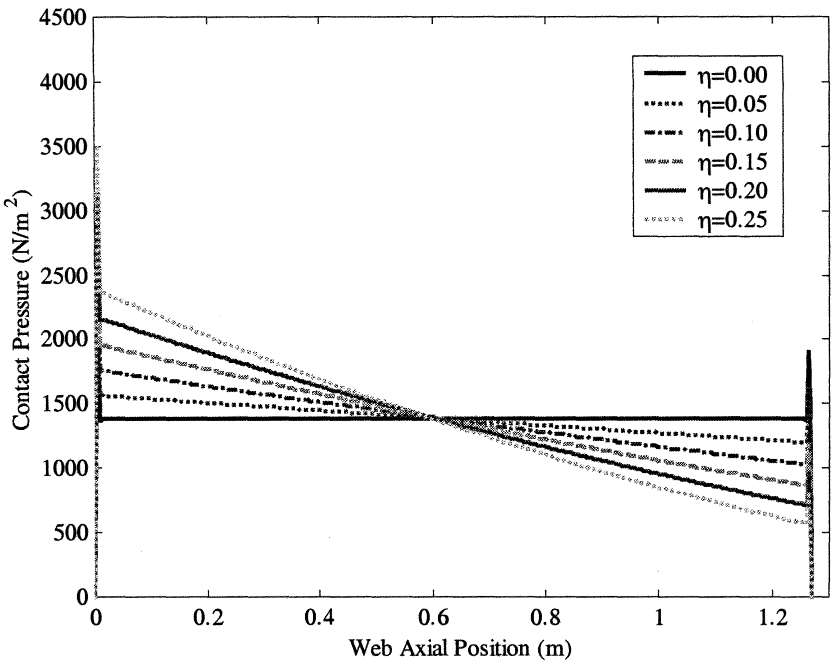

Figure 12 - The effect of thickness nonuniformity on contact pressure under the outer lap for noncambered web. Results are from the outer lap model. The thickness nonuniformity is indicated in the figure.

The second case considered to illustrate the use of the outer lap model considers the impact of web distortion on contact pressure. Two subcases were studied: tight-center baggy edge and tight-edge baggy center. The initial unstressed strain was assumed to be parabolic as a function of width in both cases and is described by the following

$$\varepsilon_0 = \begin{cases} \dfrac{2}{3}\varepsilon_{0c} - 4\varepsilon_{0c}\dfrac{z}{L}\left(1-\dfrac{z}{L}\right) & \rightarrow \textit{tight center} \\ -\dfrac{2}{3}\varepsilon_{0c} + 4\varepsilon_{0c}\dfrac{z}{L}\left(1-\dfrac{z}{L}\right) & \rightarrow \textit{tight edge} \end{cases} \qquad \{21\}$$

where ε_{oc} is the maximum unstressed strain in units of μm/m. Figures 13 and 14 present contact pressures for the tight-center, tight-edge cases respectively. The values chosen for simulation are again reasonably representative of normal film manufacturing. Again, we see that the affect of web distortion can have a rather significant effect on contact pressure and, correspondingly, it is expected that this effect can impact the magnitude of entrained air and the distribution of in-roll stresses developed during winding.

These examples serve to illustrate how camber, thickness nonuniformity and web distortion can be accommodated into outer lap models. In terms of the winding roll, similar formulation upgrades can and should be made. Work in the literature is frequently presented where the axial effects are decoupled in the in-roll problem. It is expected that two-dimensional effects will influence the nature of in-roll stresses, especially when air entrainment is incorporated into the model. A notable exception to this simplification is the recent work of Lee and Wickert [12]. Their roll was treated as an axisymmetric, two-dimensional accreting structure. The displacements in the roll and core were modeled using a finite element formulation. A detailed discussion was presented concerning the nature of the appropriate physical constitutive formulation, the nature of axial stress distribution, and the importance of stress concentration at the core/roll interface. The approach taken is commensurate with adding web imperfections.

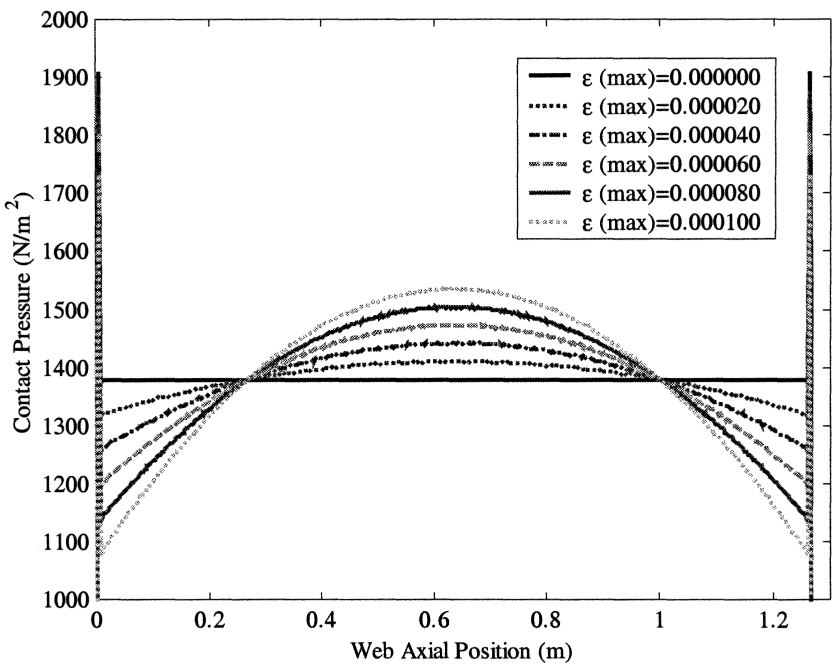

Figure 13 - The effect of web distortion (tight center) on contact pressure under the outer lap. Results are from the outer lap model. The maximum unstressed strain is indicated in the figure

An alternative to the finite element formulation for the in-roll problem is to treat the winding roll using a fully two dimensional formulation that is subsequently solved using a finite difference solution methodology. Use of this approach is likely to be viable and is demonstrated in the paper by Lei and Cole [13]. It should be pointed out that both methods would need to be assessed against the practicality of obtaining predictive results in a timely fashion. Fully coupled two dimensional models can easily become overwhelming in terms of compute time, and efforts must be made to ensure that this does not impair modeling progress.

We close this section by making additional observations. First, the imperfection model presented here can be easily modified to account for the development of axial stress (recall that we assumed this stress to be equal to zero). Knowledge of these stresses is important in determining the formation and severity of a defect known as a "hardstreak." A hardstreak is an area in the roll where the radial profile changes rapidly, usually, but not always, because of lengthwise-persistent, widthwise-thickness nonuniformity. Because of the rapid change in radial profile, high stresses are developed and these stresses may lead to permanent distortion in the web. The simplest way to compute axial stress is to assume that the outer lap is under conditions of plane strain. The resulting stresses can then be compared to the normal stresses and an assessment can be made if the plane strain assumption is valid. Alternatively, constraint equations for friction can be written and axial stresses solved for directly.

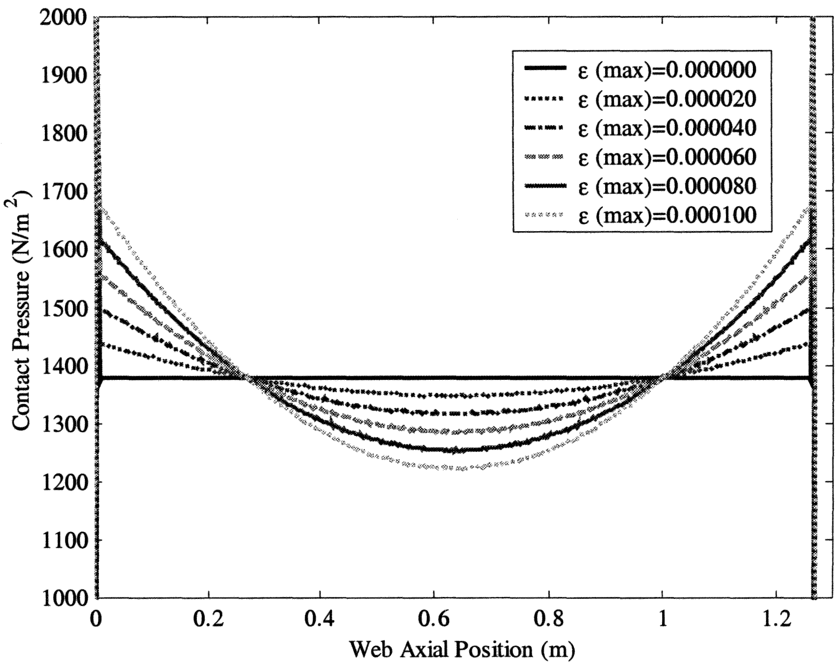

Figure 14 - The effect of web distortion (tight edge) on contact pressure under the outer lap. Results are from the outer lap model. The maximum unstressed strain is indicated in the figure

Second, to predict the formation of physical distortion in the web, a knowledge of the viscoelastic constitutive behavior of the web must be known. Much work has been performed in this area (see Qualls [14] for a summary) and this work can be exploited to extend the outer lap model as needed to enable prediction of web distortion.

Third, as discussed in the presentation of the outer lap model, we have made an assumption that treating the web as a nonright-circular cylinder of appropriate length is a valid means to model web camber and distortion. In reality, there is a major assumption inherent in this approximation and it is that the distortions are assumed to not be a function of measurement lengthwise position. For camber, this approximation is probably reasonable; however, for web distortion, the accuracy of the assumption will probably depend to a great extent on the nature of the distortion. For situations such as were presented in Figures 13 and 14, this approximation might be reasonable because these types of distortion may well arise from the nature of the manufacturing process, which will often tend to be length independent. For higher order web distortion; however, the frequency and phase of the width dependent distortion may be such that the axisymmetric assumption is no longer valid. In this case, winding models would either have to be extended to include circumferential effects or the two dimensional models modified to allow for a statistical treatment of the third dimension. Before moving in this direction, it would be prudent to further investigate the limitations of the axisymmetric assumption.

Finally, we have talked at length about air entrainment and the impact that web imperfections might have on predicting winding behavior for rolls comprised of nonideal webs. One point that was not mentioned is that there still exists a need to develop a better fundamental understanding of the nature of the web/air interface. Many of the air entrainment formulations have postulated idealized models for the interface. The key to the success of air entrainment system models is ultimately proven by the validity of the predictions. Often, what is seen is that the models are capable of making predictions over a limited process and product space. Perhaps one of the primary reasons for this has to do with the assumptions that are built into the system model via the submodels. For example, the model of Lei et. al. [4] assumes a simple parallel spring model where two length parameters characterize the relative sharing between contact and air pressure. We have found that this model tends to be somewhat simplistic and leads to difficulties in reliably determining values for the model inputs. We believe that this problem is probably due to lack of adequate treatment of the additional factors that influence the web/air interface. Such factors include web thickness nonuniformity, web distortion, and web roughness distribution. An analytical treatment of this subject was presented by Forrest [15] and an empirical study by Boutaous and Bourgin [16]; however, with the advent of more detailed efforts towards developing two dimensional models, more work is needed in this area as well.

THE IMPACT OF IMPERFECTIONS ON WINDING EQUIPMENT

A review of winding equipment indicates that many different designs are used depending on which part of the manufacturing flow is considered. For the sake of this discussion, we will delineate the manufacturing flow into three zones: base, coating and converting. In the base zone, the web is formed in a continuous process while winding takes place as a batch process at the end of the conveyance line. The coating zone typically consists of several processes including unwinding, conveyance, coating and winding. Converting is a generic term and includes all processes that convert the wide roll into end-use customer form. Examples of converting processes include slitting, perforating, and sheeting. In many converting processes, both unwinding and winding is required.

Depending on the location in the manufacturing flow and on the nature of the imperfection, web imperfections will have an impact on the design of winding equipment. As pointed out previously, a wide range of web imperfections can and do occur in practice. These imperfections can lead to winding problems. Some examples include thickness nonuniformity, typically generated when the web is formed, which can lead to wound roll hardstreaks. Hardstreaks are areas within the roll where the local radius is greater than surrounding areas. This defect can lead to substantial distortions in the web (Figure 8). Web distortions can also arise during the formation of the web in the base zone (Figure 7). Equipment layout and process settings are two examples of effects that give rise to distortions during this part of the manufacturing flow. For example, in the case of PET, temperature and stretching uniformity are critical to ensure that the web is as flat as possible. Web distortions are detrimental for several reasons. They can give rise to coating upsets, leading to customer waste; they can negatively impact winding, leading to winding failures; and they can exceed flatness requirements for sheet products.

Additionally, thickness nonuniformity can also impact wound roll stability, especially in converting operations where narrow rolls are manufactured [10].

Different designs are also used, depending on whether paper or film products are being wound. To illustrate, consider the winding design in base winding. In the case of paper, surface winders are typically used; while for film, center winders are more typical. Why are these the desired choices? First, paper winding tends to be done at a much higher speed than film and, second, roll lengths tend to be much longer for paper than for film. Therefore, a means must be available to mitigate the effect of air entrainment and to avoid the potential for torque transmission failure, e.g. in-roll circumferential slip, during winding. The problem of torque transmission failure is even worse for paper when the differences in physical properties are considered. The stack modulus for paper tends to be much lower than for film, and this leads to softer paper rolls. Surface winding meets the requirements for paper winding by providing a nip to reduce the amount of air entering into the roll and by eliminating the need to transmit torque through the roll during winding. For film winding, center winding is usually adequate because the speed and length requirements are not as extreme.

In wide roll coating processes, the most typical winding equipment used is center winding. Depending on the speed of the operation, an idling pressure roller is often used as well. This choice is driven by the flexibility that a center winder with idling pressure roller offers in terms of roll hardness. Center winding with an idling pressure roller is appropriate because typically, the speeds are not as great as in paper base and, further, the roll lengths are comparable to film-base winding. It should be noted that in both the base and coating zones, that the propensity for web imperfections to cause further wound-roll defects limits the magnitude of the imperfection that can be tolerated. This has the immediate effect of leading to web property requirements that must not be exceeded to ensure that manufacturing is robust. Thus, an important benefit of developing predictive models that accurately accommodate web imperfections is to be able to more effectively establish product requirements.

Turning to the converting zone, this is where winder design has the biggest impact on the ability of the process to tolerate web imperfections. In the previous two zones, apart from accommodating the differences between film and paper, e.g., materials with greatly different stack moduli, the primary approach to running reliably is to ensure that web imperfection requirements are not exceeded. In converting, there exist many different winder designs and the optimum choice is driven by which imperfection is most dominant. A few examples will be cited to illustrate this.

For the remainder of this section, consider the slitting process. In this case, both surface winders and center winders are routinely used. As in the base zone, paper is often wound using surface-winding equipment, while film is typically wound using a center winder with idling pressure roller. Unlike the base zone where the main drivers are speed and roll size differences, the primary reason in the converting zone is because of the difference in stack modulus between the two materials. In addition, choices are also dependent on the need for product size flexibility. For each type of winder, additional refinements are often driven by the reality that webs are not ideal and often have both thickness nonuniformity and distortion.

In surface winders, imperfections will often drive designs to have slit-independent core and surface winder-roller spindles. This is done to prevent slit-to-slit interactions from generating slit-to-slit tension variations that occur in a system with a common surface-winder roller. This would happen because of nonuniform web flow through the system due to axially varying web distortion. The impact of tension nonuniformity will be to primarily increase the risk of excessive lateral motion leading to a wavy or irregular sidewall. The simplest way to implement this type of design is to place the product rolls onto a common fixed mandrel while the surface-winder rollers are independently pivot or translation mounted. This achieves the decoupling required to insure that nonuniform tension does not develop during winding.

For center winders, common pressure rollers are not preferred, for the same reasons as stated above. Even though the pressure roller is not driven, a common pressure roller will still result in coupling between slits that will lead to slit-to-slit tension nonuniformity. Like surface winding, this will increase the risk of a wavy or irregular sidewall. In addition, tension nonuniformity will affect wound-on tension, which will impact roll hardness. Depending on customer requirements, this can lead to failed rolls due to telescoping.

In the case of both surface winding and center winding with an idling pressure roller, one might think that the best approach toward improving process latitude in the face of web distortion induced tension nonuniformity would be to use a flanged surface or idling pressure roller. However, this is not the case if thickness nonuniformity is present. When the web is nonuniform, this will tend to drive axial movement in the winding roll. If the surface winder roller or idling pressure roller is flanged, this will result in axial overconstraint which may lead to sudden axial shifting within the roll during winding [10]. A much better alternative is to use a flanged conveyance roller just upstream of the surface winder or idling pressure roller. This will eliminate the axial overcontraint that would otherwise develop and result in a process that is more robust. Figure 15 shows an example of a slitter where individual slits are center wound and use independent idling pressure rollers. The idling pressure rollers (shown retracted) are not flanged and the winding rolls are mounted on a common spindle. Drive torque is provided to each roll through independent magnetic clutches controlled through relative slip.

CONCLUSIONS

In this paper, we have attempted to provide insight into how to deal with nonideal, or imperfect, webs in winding processes. We have shown how web imperfections can be quantified. We have developed and illustrated a novel analytical technique that can be used to incorporate many of the quantified web imperfections into winding models. This is a requirement to be able to successfully establish specification limits for imperfections and to be able to more predictively impact winder design. We concluded by citing several examples of winding design configurations which are driven, to a large extent, by the reality that web imperfections are a very real part of the winding process. Without any intent to malign all the very successful work that has been done to date, it is hoped that this survey will spur further development in an area where there is still much work to be done.

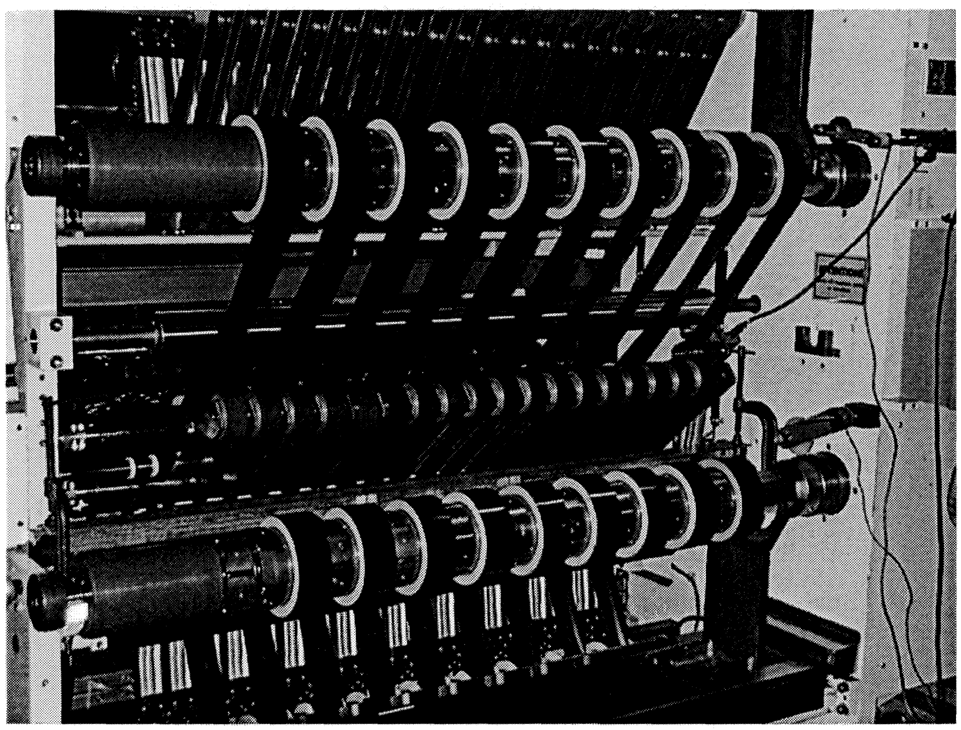

Figure 15 - Center wind pressure roller assisted winder with nonflanged layon rollers

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