LAYER-TO-LAYER SLIPPAGE WITHIN PAPER ROLLS DURING WINDING

by

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ABSTRACT

Crepe wrinkles are created during reeling and winding of paper rolls against a rolling drum. These defects are associated with interlayer movement of paper within the body of the roll. To study this movement, rolls made from five different papers were loaded against a rotating drum under controlled conditions and the layer-to-layer movement quantified by means of "J"-lines marked on their face. The interlayer movement of paper is directly related to frictional stress; the coefficient of friction multiplied by the radial compressive stress in the paper roll, and the shear stress created by rolling friction of the paper roll.

The amount of interlayer movement can be reduced by lowering the nip load, increasing the drum diameter, or covering the drum with a soft material. Interlayer movement increases sharply when the coefficient of friction falls below a critical value, which explains why crepe wrinkles can appear after a seemingly imperceptible change in coefficient of friction.

NOMENCLATURE

ϵ	=	strain
σ_r	=	radial compressive stress, kPa
σ_s	=	shear stress, kPa
σ_t	=	tangential stress, kPa
μ	=	static paper to paper coefficient of friction
C	=	distance moved by "J"-line tip, cm
E_r	=	radial compressive modulus of paper, kPa
E_t	=	in-plane elastic modulus of paper, GPa
F	=	frictional force, N
K_1	=	proportionality factor, kPa

K_2	=	compressibility factor
N	=	sled weight, N
R	=	depth at which "J"-line movement begins, cm
t	=	paper caliper, μm

INTRODUCTION

A crepe wrinkle consists of one or more folds of the paper in the machine direction, from several centimetres across, to the full width of the machine. The shape of the wrinkle is often erratic, following a path in the cross-direction that looks like a lightning bolt, as shown in Figure 1. Crepe wrinkles are created during reeling and winding of paper rolls, and appear to be a consequence of out-of-plane buckling under in-plane compressive forces. They tend to form in large diameter paper rolls made from paper that is dense, thin, and slippery. Paper grades susceptible to this problem include lightweight coated papers, highly filled supercalendered groundwood grades, and newsprint containing a high proportion of flotation deinked fibre.

High speed reeling and winding of paper is done against a rotating drum to remove the boundary layer of air that follows the paper surface. The forces generated in the nip increase the tension wound into the roll beyond that of the tension of the web before the winder nip. However, below the immediate surface layers, the drum rolling against the conformable paper roll generates shear forces that cause the paper layers to slip.

This effect was demonstrated by Pfeiffer by rolling a cylinder over a stack of paper layers laid on a flat metal plate (Figure 2) [1]. This experiment simulates a drum in contact with a paper roll of infinite diameter viewed from the reference frame of the paper roll. By measuring the change in tension in each layer of paper as the drum rolled over the stack, he found that the greatest tension was imparted to the top layer. The nip-induced tension diminished to zero several layers below the surface and at a greater depth, the tension became negative, indicating that the paper is subjected to a compressive stress in the plane. In subsequent experiments, Pfeiffer constructed a curved backing plate with fifteen overlying paper layers [2] in which he detected negative tensions to this depth. In a paper roll, this could cause interlayer slippage which would increase the in-plane compressive stress. Slippage is one of several contributions that lead to the formation of crepe wrinkles.

The "J"-line is one method of demonstrating that slippage takes place between paper layers within the body of the paper roll during winding [3]. A "J"-line begins as a straight, radial line marked on the roll face, during a splice when the roll is stationary or on the run with a chalked "bow string". After subsequent winding, the line takes the so-called "J" shape with the tip of the "J" pointing in the direction of roll rotation. This indicates that the paper below the surface of the roll has moved. On commercial winders, the size of the "J"-line can be correlated with the probability of crepe wrinkles appearing within paper rolls [3]. This correlation is specific to a given winder.

In this report, the paper properties and nip mechanisms which influence the degree of slippage are identified. We propose that the rolling nip generates a shear stress within the paper roll which is opposed by frictional stress, the product of the coefficient of friction (μ) and the radial compressive stress (σ_r) within the roll. The balance between the shear stress and the frictional stress will determine the amount of slippage and the magnitude of the "J"-line. These stresses will depend on operating parameters such as drum nip load as well as paper properties such as coefficient of friction (μ), radial compressive modulus (E_r) and in-plane modulus (E_t).

EXPERIMENTAL

Rolling Nip Experiments

To understand how nip conditions and paper properties contribute to paper slippage, we observed the movement of paper layers within small rolls of newsprint loaded against a moving metal drum. These rolls (356 mm in diameter and 76 mm wide) were wound from commercial papers with a range of mechanical properties (Table I) using a centre-winder without a nipping roll. The paper roll size was chosen to give a large number (~100) of rolls of similar paper properties from a single commercial roll and to provide a narrow zone of contact with the winder drum to avoid problems with uneven profiles. Several in-going web tension levels were selected by adjusting the backstand brake of the centre-winder. The selection of the newsprint and specialty grade papers for this study was based on their relative propensity to create crepe wrinkles which ranged from high for a newsprint containing 50% flotation de-inked pulp, to moderate for newsprint from the southern United States, to low for directory and newsprint from Ontario and Quebec. This choice of paper also gave a broad range of mechanical properties (Table I). The measurement procedures for coefficient of friction (μ), in-plane modulus (E_t), and compressive modulus (E_r) are described in Appendix A.

The action of the winder nip was simulated by loading the small rolls against a single 610 mm diameter drum and driving the roll for a pre-determined number of revolutions. Two rolls were mounted on a shaft to give stability (Figure 3). This simulates precisely the conditions after a paper break on the winder, and gives accelerated conditions for normal winder operation where paper is continually accumulating. The movement was monitored by marking radial lines on the roll and measuring the depth below the surface at which the movement stopped (R) and the distance moved by the tip of the "J"-line (C), as shown in Figure 4.

In a typical experiment, two rolls from the same set are mounted on the winder shaft. At a pre-determined load, the rolls are driven for a number of revolutions. After winding, the drive is stopped and the "J"-lines are photographed against a template. The experiment is then continued for another set of revolutions and this procedure is repeated until the final count is reached.

Measurements of "J"-lines from Rolling Nip Experiments

On careful examination of the "J"-line marking, we found that several outer layers show an extremely large movement in a direction counter to the rotation of the roll (Figure 5). The tension in these layers is high. Below these layers, the movement is in the opposite direction, giving the characteristic "J" shape. These observations are qualitatively in accord with Pfeiffer's [1,2], but paper slippage occurred at greater depths below the surface and consequently for a greater number of paper layers than those reported in his experiments.

At a fixed winder nip load, the distance "C" which the "J"-line tip moves increases linearly with the number of roll revolutions (Figure 6), but the depth at which the movement starts (R) remains constant (Figure 7). This observation suggests that the rolling nip creates a shear stress below the roll surface that pushes the paper layers in the direction of the roll's rotation. The differences in "J"-line movement between the assorted rolls shown in Figure 6 are the combined effect of different paper mechanical properties (Table I) and wound-in tension.

Effect of Drum Diameter and Cover Material

The effect of three drum diameters on the "C" parameter is shown in Figure 8. The infinite drum diameter measurement was made by placing two rolls on a weighted shaft and, by means of a handle, rolling them on the floor in the same manner as a lawn roller. After 25 revolutions there is a significant advantage in using a larger diameter drum. The difference in slippage between drums of different diameter decreases with a greater number of rotations.

The penetration of the winder drum into the paper roll can be reduced by covering the winder drum with a compressible material. Two materials, a neoprene rubber and softer blue foam (often used as a pad under sleeping bags), were glued to the surface of the winder drum. Using a conformable drum surface reduces the deformation of the paper roll and the size of the "J"-line in relation to the compressibility of the cover material (Figure 9).

Effect of Frictional Stress ($\mu\sigma_r$)

The amount of slippage within the roll body will be a determined by the difference between the shear stress created by the rolling nip and the frictional stress that holds the layers in place (Figure 10). The frictional stress between adjacent paper layers has two components: the paper to paper coefficient of friction (μ) which is a material property, and the compressive stress (σ_r) which is related to the roll structure. We measured the compressive stress (σ_r) of each roll by inserting thin (76 μm) metal strips into the finished rolls and measuring the force required to withdraw the strips with an Instron tensile tester as described in Appendix B.

The magnitude of the "J"-line parameter, "C", is reduced as the frictional stress is increased (Figure 10). The shape of the hand-fitted line to the data points suggests that there is a critical frictional stress below which the slippage increases sharply. Although conditions would be different for rolls of commercial size, this relationship suggests why crepe wrinkles can appear after seemingly imperceptible changes in coefficient of friction.

Effect of Radial Compressive Stress (σ_r)

The compressive stress (σ_r) within a roll of paper depends, not only on the tangential stresses (σ_t) induced during winding, but the response of the paper as determined by the in-plane (E_t) and compressive (E_r) elastic moduli. The effect of E_t and E_r on σ_r could be determined by direct measurement if σ_t was known. However, σ_t was not measured in our experiments. To estimate the effect of the in-plane (E_t) and compressive elastic modulus (E_r) on the radial compressive stress (σ_r), we have used a mathematical model.

We chose Hakiel's approach [4] because it considers anisotropic elastic properties (different radial and in-plane moduli) and allows for a non-linear radial elastic modulus. Both these conditions are necessary for paper because the modulus in the machine direction (E_t) is approximately three orders of magnitude greater than the radial modulus (E_r) and the radial modulus depends on compressive stress (Table I and Appendix A). We measured the radial stress profiles of our centre-wound rolls, using the method described in Appendix B. The in-plane modulus, measured with an ultra-sonic tester, and radial elastic modulus, determined by measuring the compression of stacks of paper, were used as inputs in Hakiel's model. Using trial and error, we found a unique level of wound-in stress (σ_t) that gave a good fit to the measured radial compressive stresses (σ_r) as shown in Figure 11. To determine the effect of different elastic moduli on the radial stress profile, the parameters for each paper were inserted into Hakiel's model for a selected level of wound-in stress. The differences in E_t/E_r for the papers in Table I cause a 20% change in radial compressive stress (σ_r), as shown in Figure 12.

Effect of Nip Load

The rolling nip generates forces which unwind the paper below the roll surface. The amount of unwinding increases as a power of nip load as shown in Figure 13 and is greater for rolls with lower wound-in tension. At low to moderate nip loads, the unwinding is balanced by nip-induced wound-in tension but, at very high loads, the unwinding forces will dominate. This finding demonstrates why the size of the "J"-line and the probability of the occurrence of crepe wrinkles increases as the weight of the roll increases.

Discussion

The amount of unwinding below the surface of the roll is determined by the balance between the shear stress generated by the nip and the frictional stress between paper layers. The frictional stress is the coefficient of friction multiplied by the radial compressive stress in the roll. The magnitude of the "J"-line increases as frictional stress is reduced and increases sharply at a critical value. This suggests why crepe wrinkles can appear after a seemingly imperceptible change in coefficient of friction. This is important for paper containing flotation deinked pulp because this component lowers coefficient of friction [5].

Radial compressive stress is primarily determined by winding conditions such as nip load and ingoing web tension. Increasing the radial compressive modulus (E_r) or decreasing the in-plane modulus (E_t) will increase the radial compressive stress (σ_r) tending to stabilize the roll. On some paper machines, there may be opportunities to increase the radial compressive stress (σ_r) by lowering the machine-direction modulus (E_t) by means of fibre orientation, fibre properties, draws on the paper machines, or controlling the strains built into the web during drying. The factors affecting radial compressive modulus (E_r) are not known, but should be studied to determine if this parameter can be independently controlled in papermaking.

Interlayer movement of paper within the roll can be reduced by increasing the diameter of the winder drum or covering the drum with a compressible material.

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APPENDIX A

Measurement of Paper Mechanical Properties

The paper material properties that affect interlayer slippage are: coefficient of friction (μ), in-plane elastic modulus (E_t), radial compressive modulus (E_r), and caliper (t). The measurement procedures for these properties are described in this appendix. The measured values are shown in Table I.

Coefficient of Friction

The coefficient of friction was measured using a model 36-20 TMI horizontal friction tester. The test procedure was based on TAPPI STD T549 pm-90, but replacing the 200 g sled with one of 1360 g to give a more distinct value for static coefficient of friction. All tests were performed at a speed of 400 mm/min. In each test, one sheet is placed on the base of the tester (15 cm x 40 cm) and another on the sled (6.5 cm x 9 cm) with the machine direction parallel to the longer dimension and the top side of one sheet against the bottom side of the other as it would be within the roll. After each test, the sheets were discarded and replaced with fresh sheets. The static coefficient of friction was calculated as the force to move the sled divided by the weight of the sled:

$$\mu = \frac{F}{N} \tag{1}$$

Each determination is the average of ten measurements on the first pass. Throughout the testing, care was taken to avoid handling the paper which would contaminate the surface with natural oils.

Radial Compressive Modulus

The radial compressive modulus (E_r) was determined by compressing circular pads of paper 5.08 cm in diameter by 1 cm thick with a model 810 MTS tensile-compression material tester. The diameter of the pads were less than the platens of the tester, to avoid aberrations caused by bending of paper outside the compressed zone. The pressure (P), and strain (ϵ) measurements from the unloading cycle were fitted to Pfeiffer's equation [2,6,7].

$$P = K_1(e^{K_2 \epsilon} - 1) \tag{2}$$

to obtain the coefficients K_1 and K_2 that characterize the compressibility of the paper in the radial direction. Equation (2) gave an excellent fit to our compression data, and additional coefficients, as discussed by others [4,8], were not required. The derivative of equation (2) is the radial compressive modulus:

$$E_r = \frac{dP}{d\epsilon} = K_1 K_2 + K_2 P \tag{3}$$

In-plane modulus

The in-plane elastic modulus (E_t) was determined using a custom laboratory system to measure the speed of ultrasonic pulses in the paper [9].

APPENDIX B

Measurement Of The Mechanical Properties Of Paper Rolls

Radial Compressive Stress

The radial stress (σ_r) within the paper rolls was measured using a technique based on the pull-tab test [10,11]. Thin stainless steel strips (76 μm thick by 5 mm wide), sanded with 800 grit paper and washed in acetone, were inserted through the rolls with a custom tool. This technique is suited to the narrow rolls (76.2 mm) used in our experiments because the small insertion force does not buckle the strip. The force required to remove the strips was measured with an Instron tensile tester. The calibration between radial stress (σ_r) and the force required to remove the strip was determined with the TMI 36-20 coefficient of friction tester for each type of paper by measuring the force required to move the strip for different dead weights, as shown in Figure 14.

Table I
Material Properties Of Paper Used In Winding Experiments

Paper	*Caliper (μm)*	*In-plane Elastic Modulus*	*Coefficients for Radial Compressive Modulus E_r^+*		*Coefficient of Friction*
		E_t (GPa)	*K_1 (kPa)*	*K_2*	*μ*
United States	*85.6*	*3.96*	*76.0*	*32.9*	*0.324*
Ontario	*84.8*	*4.21*	*106*	*26.2*	*0.389*
Quebec	*74.7*	*5.53*	*95.2*	*34.3*	*0.625*
Directory	*61.2*	*5.16*	*83.2*	*37.0*	*0.649*
Recycled	*77.2*	*4.54*	*108*	*43.9*	*0.243*

(+) The radial compressive modulus is given by: $E_r = K_1K_2+K_2P$ where P is the interlayer pressure in kPa, as described in Appendix A.

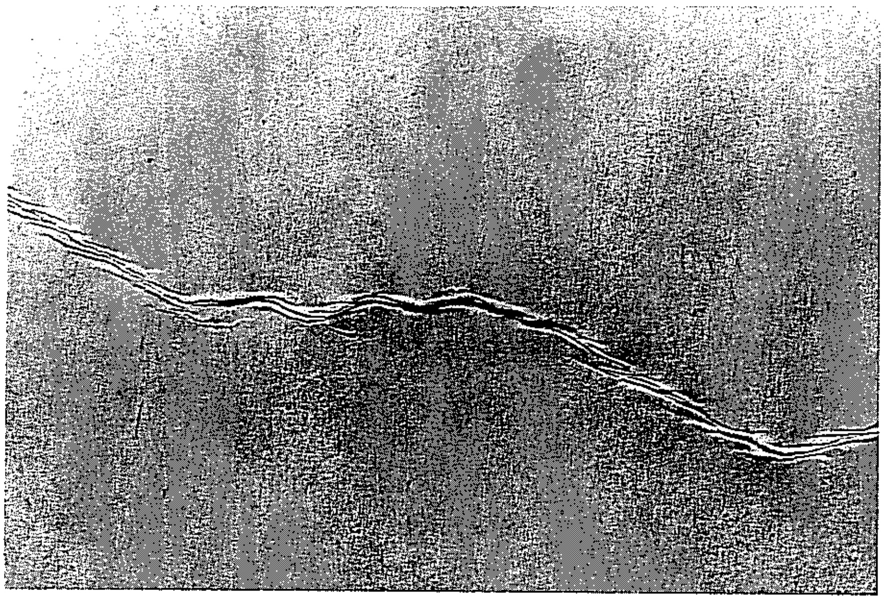

Figure 1. Example of a crepe wrinkle.

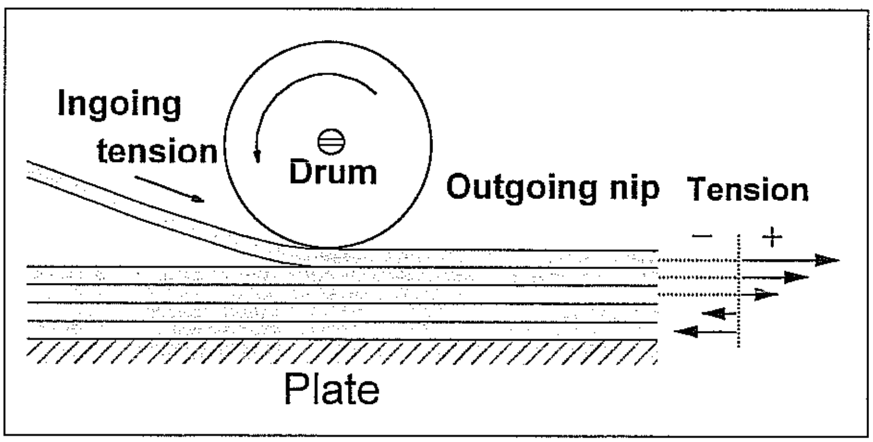

Figure 2. Pfeiffer's experiment to demonstrate the forces on paper layers in a rolling nip. The drawing simulates winding from the frame of reference of an infinite paper roll as a winder drum rolls on a pad of paper.

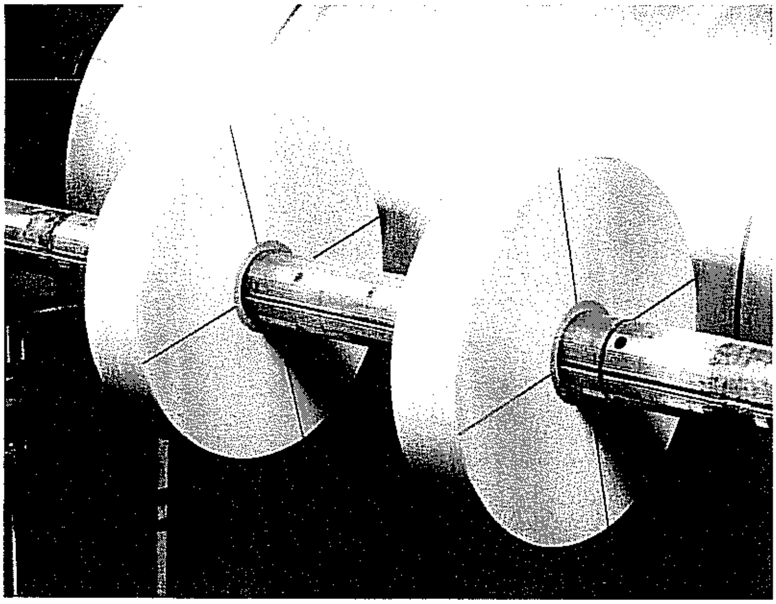

Figure 3. Experimental set-up showing two paper rolls mounted on a single shaft, loaded against a rotating drum.

J - Line Parameters

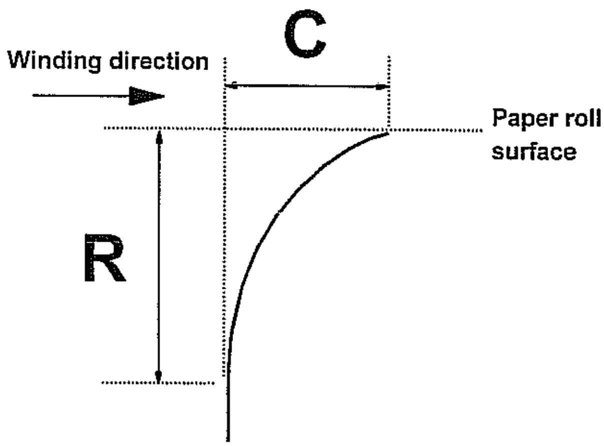

Figure 4. The "J" line is characterized by two distances: the distance moved by the tip "C" and the depth at which the movement starts, "R".

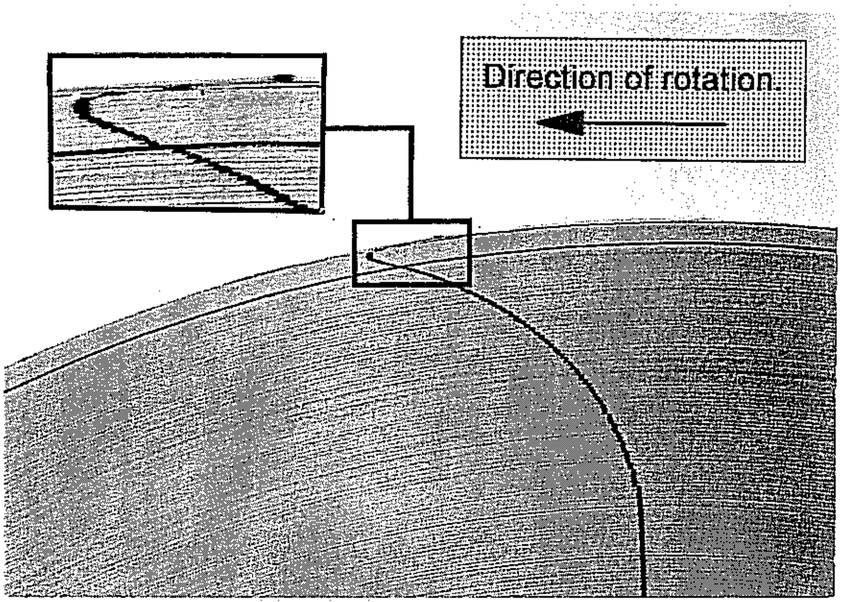

Figure 5. In the nip, the outer paper layers move counter to the drum rotation which increases their wound-in tension.

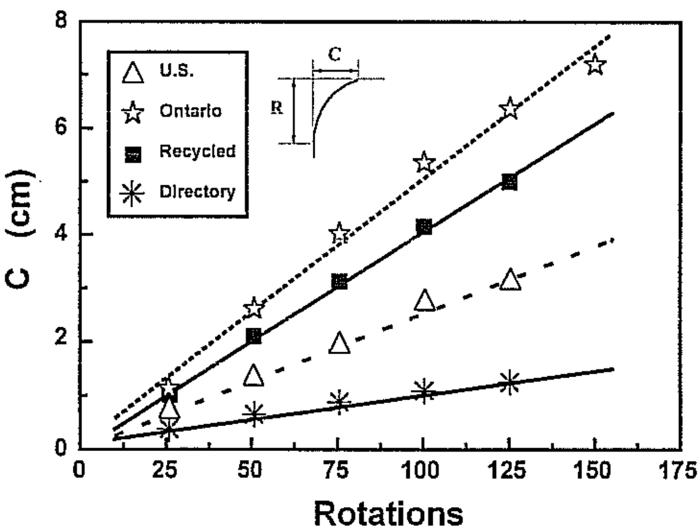

Figure 6. Movement of "J"-line tip as a function of the number of roll revolutions.

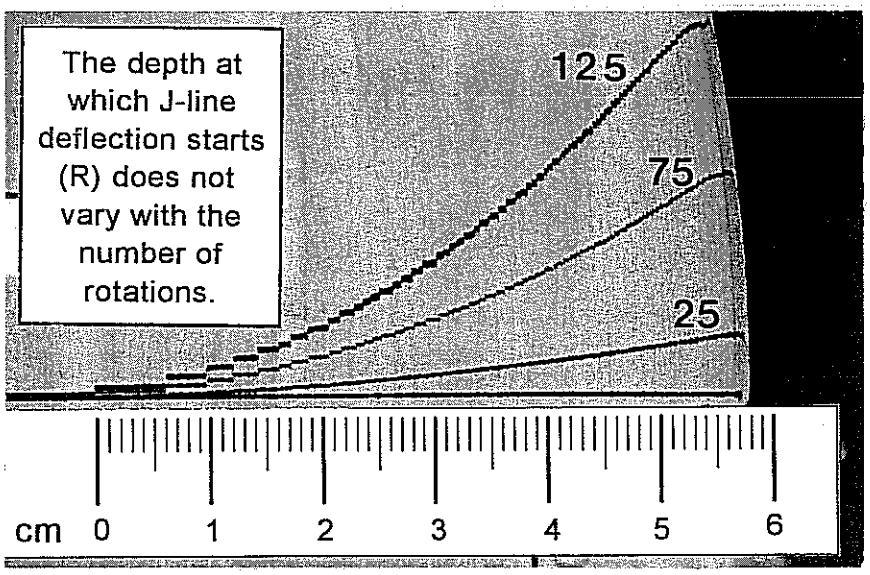

Figure 7. As the number of revolutions increases, the "J"-line distance increases but the depth remains constant.

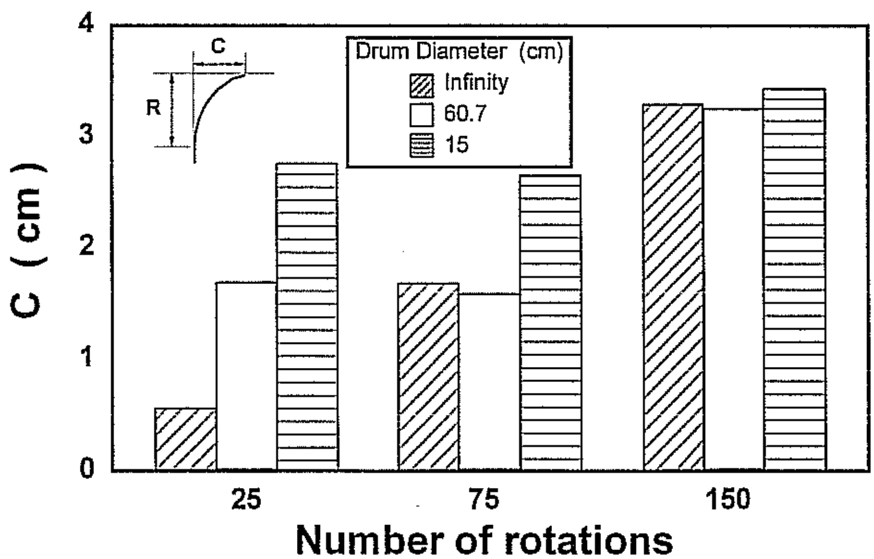

Figure 8. The effect of drum diameter on movement of paper layers where "C" is the distance moved by the tip of the "J"-line

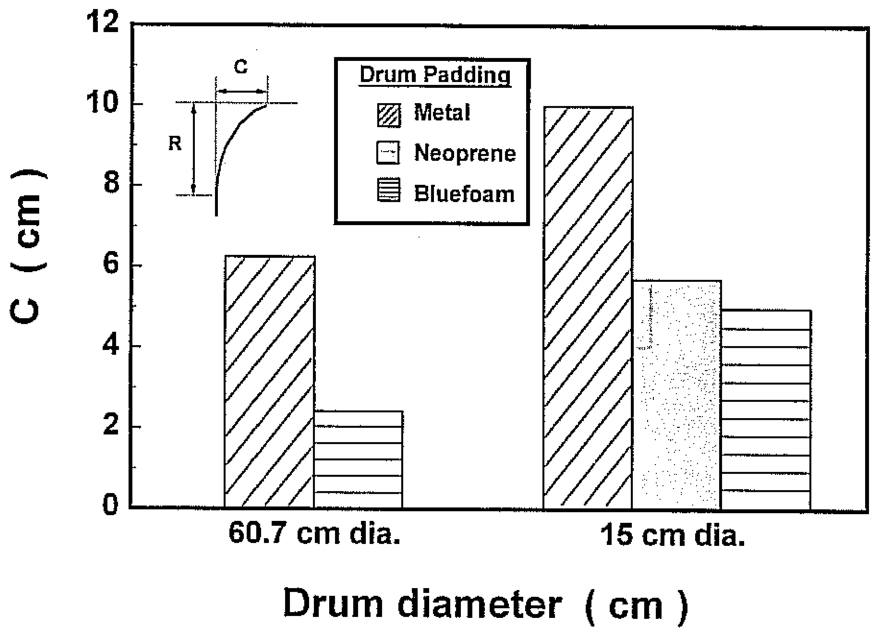

Figure 9. A conformable drum surface reduces deformation of the paper roll.

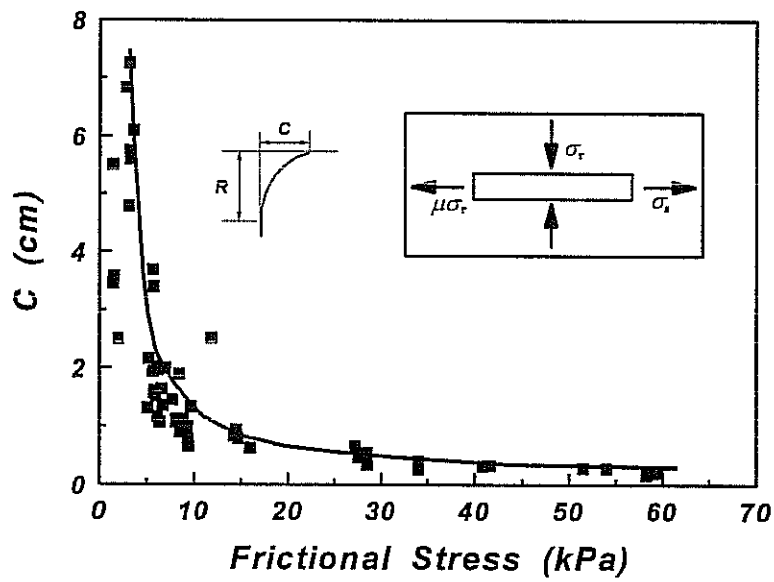

Figure 10. Interlayer movement of paper as a function of frictional stress. The frictional stress is the coefficient of friction multiplied by the radial compressive stress ($\mu\sigma_r$).

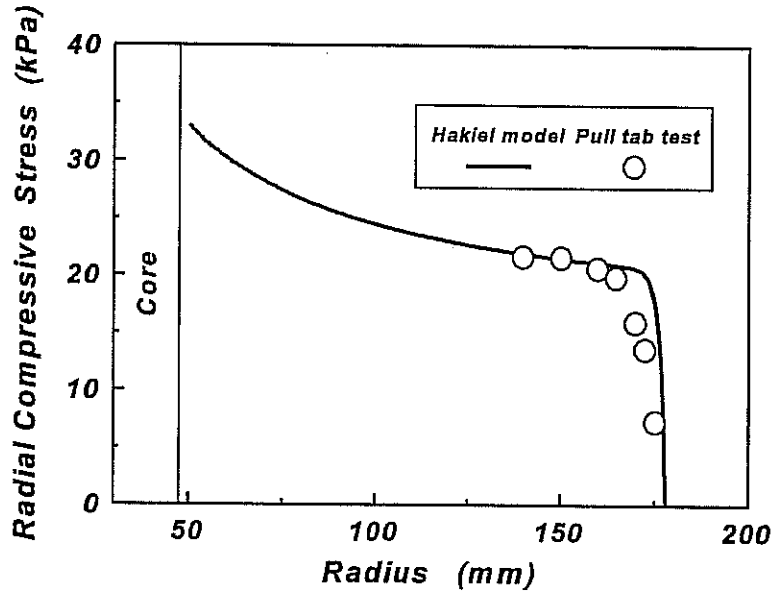

Figure 11. Fit of Hakiel's non-linear, aniostropic model to the measured radial stress profile.

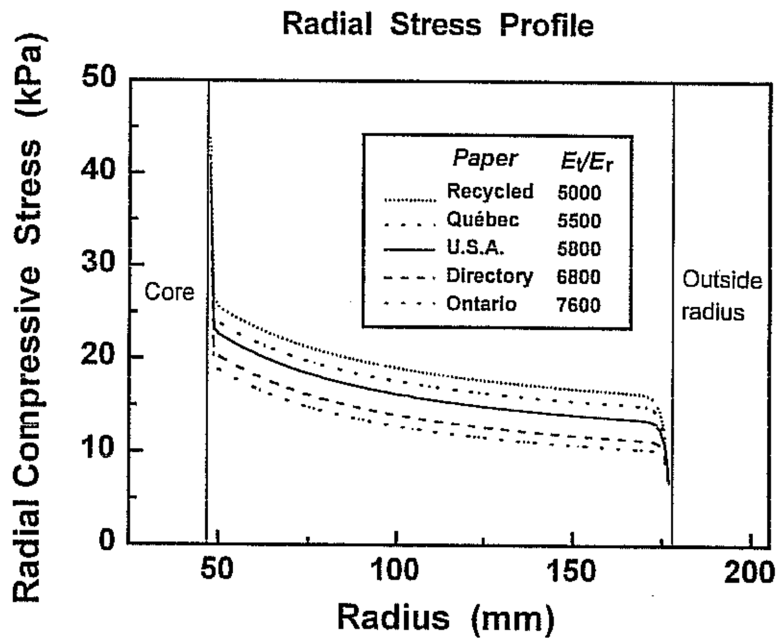

Figure 12. Radial stress profile for different moduli (E_t/E_r) at the same wound-in stress.

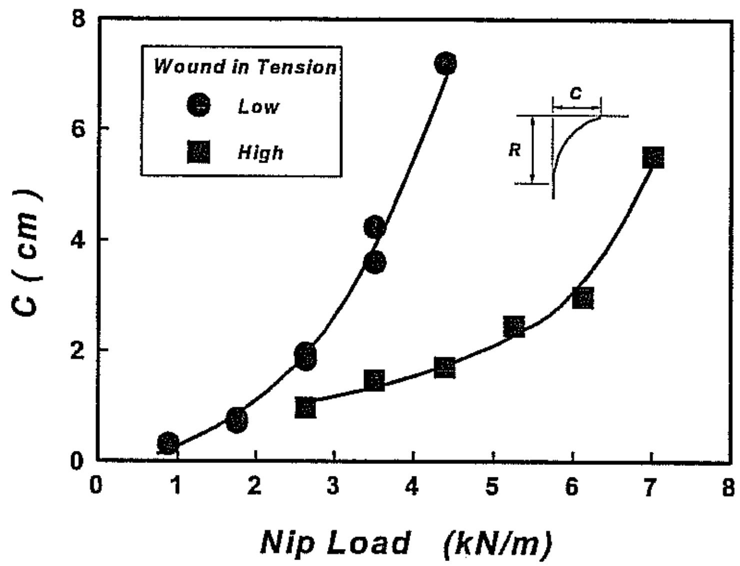

Figure 13. The size of the "J"-line increases with nip load. Interlayer movement is greater for a roll with low wound-in tension than for one with a higher wound-in tension.

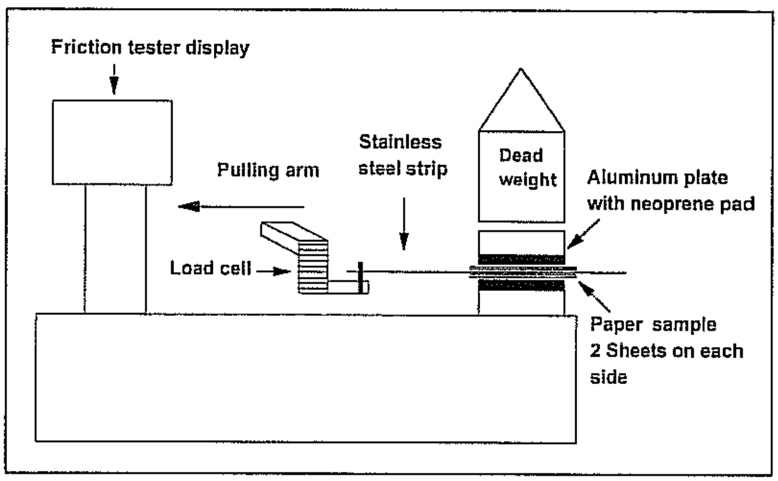

Figure 14. Apparatus for calibration of steel strips used to measure radial stress, σ_r.

Question - How was the outer layer of the paper roll fixed?

Answer - The outer layer was taped in place.

Question - When you taped the outer most layer to the reel body, don't you loosen the tension? Because if tension is lost, doesn't this affect the measurements of "C"?

Answer - When we tape that layer, there is some tension loss, but this is restored when we start winding. There is an enormous movement in the top layers and the tension increases significantly. But we're measuring the slippage below the top surface. What happens in the outer layers is less important than what happens 1/4 to 1/2 inch below the surface.

Question – The R dimension of the J-line that you are showing, is for rolling without paper added to the roll. In the real world with paper being added to the roll, wouldn't you find a substational difference in the R dimension and the "C" dimension?

Answer - Our experiments simulate what happens after a snap-off or break. Yes, the shape of the J-line would be different if paper was accumulating on the roll.

Question – You indicate that defects are associated with a change in motion rather than overall smooth motion. Will smooth motion generate a crepe wrinkle?

Answer - You can generate crepe wrinkles with smooth motion. We can generate crepe wrinkles in these rolls and larger commercial rolls loaded against a rotating drum.

Question - Did you do any work near the core which is the cause of the telescoping defections that we see?

Answer - We were looking at the outside of the roll rather than near the core.

Question - Did your R value correlate to Pfeiffer's instant center?

Answer - We found in our experiments that the movement was much deeper than in J.D. Pfeiffer's experiments. He was using an incompressible plate beneath 15 layers. With a compressible paper roll the stresses go deeper.

Question - The papers in your experiments were uncoated. Would you expect a J-line to be different with coated paper, and how would you measure the coefficient of friction of paper that was coated on one side?

Answer - The J-line lines would be similar. The coefficient of friction would be measured with coated side against the uncoated side as it would be within the paper roll.

Question - The instant center is near the surface only a few layers below the drum contact. The reason the line goes so deep is the disturbing force falls away from the instant center.

Answer - I agree and this is apparent on the video clip.

Question - Did any of these experiments produce wrinkling?

Answer - Yes.

Question - In your "C" versus friction stress curve, is there an average above "C" where you would get wrinkling?

Answer – It is not that easy.

Question - You have measured the friction between paper layers, did you also measure the friction between the paper and the drum?

Answer - We only measured friction between the paper layers because we were looking at layer to layer movement within the paper roll body.

Question - The force applied by the drum depends on the friction between the paper and drum.

Answer - I agree, the outer layer. But for this problem, the stress induced is by the defamation of the paper roll.