FILM SURFACE CONSIDERATIONS FOR ENHANCED WINDING OF THIN FILMS

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ABSTRACT

The primary defect for thin films (< 25μm) consists of sinusoidal ridges that run around the wound roll of film. Previous work has shown that these defects are buckles caused by compressive stresses in the transverse direction and that their formation can be minimized by adjusting winding conditions. The work presented here shows that the film surface also has a critical role in controlling this defect. The effort includes (1) measurements of properties for films with differing surfaces, (2) calculations to determine whether buckles will occur, and (3) winding experiments to verify the conclusions. Recommendations are included to design surfaces that are resistant to internal buckles and their related defects.

NOMENCLATURE

E	Elastic modulus of film layer
E_r	Elastic modulus of film in the stack or radial direction
K_1	First stack compression coefficient
K_2	Second stack compression coefficient
P	Pressure for stack compression measurement
r	Radial dimension in a wound roll of film
R_a	Mean of the departures of the profile from the mean line
R_z	Average height difference between the 5 largest peaks and valleys
R_t	Maximum peak-to-valley height found
z	Transverse direction in wound roll of film
ε	Strain in film
μ	Poisson's ratio of film
σ	Stress in wound roll of film
θ	Circumferential direction in wound roll of film

Subscripts:

r	Radial or stack direction
z	Transverse direction
θ	Circumferential direction

INTRODUCTION

The surface characteristics of films have a substantial effect on the quality of wound rolls. Earlier studies in this area addressed problems related to the film adhering to itself during winding. Additives were included in polymers which generated surface texture that reduced the friction between film layers by lowering the contact area. Slide angle tests and other means of measuring friction were used to establish levels and types of additives needed in film production. If the additive parameters were not adequate, humps or pimples would form in the roll. In the worst case, the film would block together and the rolls could not be unwound. The amount, size, shape, and chemical composition of these additives have been investigated by numerous people over the years. This has resulted in many patents [1-4].

Films are designed to meet both the needs of the film application and to maximize yields during manufacturing. One way to classify films is based on thickness. Thick films (>100 μm) exhibit different types of defects during winding than thin films (<25μm). We have found that different additive approaches are required in these two regimes. The thin films tend to form buckles in wound rolls which are called MD ridges (see Figure 1 and reference [5]). These are caused by transverse direction compression and are the dominant defect in this thickness range. Recently, a patent [6] has been granted in this area that makes use of the understanding of the formation of these buckles. This paper will discuss the theory behind these new surfaces and will present test results for films made using the enhanced film surface.

THE EFFECT OF SURFACE ON THE PROPERTIES IN WOUND ROLLS OF FILM

Additives in films affect the material properties in the radial or stack direction [7] and influence the amount of air that is entrained during winding [8]. PET and a number of other films are first cast into a sheet and then stretched biaxially. Cast films have a very smooth surface even with the presents of surface additives. During stretching the additive particles form asperities on the surface of the film that can approach approximately 40% of the particle diameter. In a stack each of these asperities is a potential contact point with its neighboring film layer. The more points of contact between layers of film, the stiffer the film will be in the stack direction. Previous work [7] has shown that the key parameters that affect the stack stiffness are film thickness, the asperity count per unit area and the slope of the asperity size distribution.

The stack or radial stiffness in the wound roll will be the key variable considered for the evaluation in this study. It can be controlled by both the additive concentration and particle size distribution. Stack compression tests were conducted for all of the test films to document the results and confirm the relationship between stack stiffness and additive concentration. The stack compression data were taken in a vacuum using a multiple compression approach. Here, the film stack is inserted into the test chamber and it is evacuated. The film is compressed several times until the compression results are consistent. This eliminates problems with the initial compression of the film. All of the films considered in the comparison are included in Table 1. This includes both the new (HDS) and commercially available (UC) films.

The value of K_2 is the simplest measure of the relative stack stiffness of films. This value comes from fitting the stack compression data using

$$P = K_1 \exp(K_2 \varepsilon) - K_1 \quad (1)$$

as suggested by Pieffer [9]. Figure 2 shows a plot of a typical stack compression curve and illustrates that K_2 is an exponential slope factor for stacks of film. According to reference [7], films with higher concentrations of additive (a steeper asperity distribution) will have a higher K_2.

Figure 3 shows a plot of asperity size distributions for films with two concentrations of the new additive (HDS) and one for an old product (UC). Here, we have a plot of the sum of all asperities larger than a given height plotted against the asperity height. The count at an asperity height of zero is the total count. The value at any other height is the total number of asperities that height and taller. This gives a good picture of the increase in the number of contact points as layers of film are brought together.

The UC film employs a milled additive and the asperity distribution exhibits typical characteristics of this type of product. The slope of the distribution is inversely proportional to the asperity height. This is caused by a large number of very small particles and fewer over-sized ones that were either not milled properly or were formed by an agglomeration of several particles. The characteristic shape of this curve has the effect of reducing the slope of the asperity distribution in the range that influences the stack stiffness. This can be seen by comparing the slopes of the distribution curves and the resulting stiffnesses on Figure 3.

Additives composed of a "single particle size" are now available (see Figure 4). These produce the asperity size distributions included as HDS films on Figure 3. This additive is a cubic form of calcium carbonate at a selected particle size of 1.25μm (other sizes are available). This type of additive produces film with a maximum asperity height slightly below 1 micron (see Table 1). The two concentrations included for HDS show the effect of increasing concentration for a given additive system. Here, both the slope of the asperity distribution and the stiffness factor K_2 are directly proportional to additive concentration.

The surface friction results (film-to-film) on Table 1 show that the HDS films are "tackier" (higher slide angle) than the UC product. Traditionally, this would mean that the UC surface should perform better in winding test and result in higher production yields. This difference in slip probably is related to the number of extremely small (< 0.2 micron) asperities produced by the UC additive. These very small asperities do not have a dominant effect on winding as will be shown later.

STRESS AND BUCKLING ANALYSIS OF WOUND ROLLS

The stress analysis used for this work follows the approach outlined in reference [5]. It uses an approach similar to most of the codes for stresses in wound rolls with two important additions. Most of the calculations available are for the plain stress case and yield results with no stresses in the transverse direction. These calculations are deficient for use in many cases because they approximate narrow rolls where the width to radius ratio is well below one. Most rolls of film fall in the range where the width of the roll is much greater than the radius. In this work the plane strain approach is used because it assumes the roll is very wide or the width to radius ratio is much greater than one. This is the better assumption for most primary and secondary production rolls. This type of calculation results in estimates of the transverse direction compression that occurs due to Poisson's ratio effects introduced by the reduction in film tension (circumferential stress) and the build up of radial stress.

There has been discussion of the magnitude of Poisson's ratio effects due to the build up of radial load. We used the relationship

$$\mu_r = \mu \; E_r / E \tag{2}$$

which is discussed in the Appendix and in references [10] and [11]. This is the same approach used in reference [10]. Since E_r is much less than E, the value of μ_r will be much smaller than μ and investigators have rightly found that it is near zero. We elected to replace μ_r / E_r with μ / E in the derivation of all equations. This eliminates the need to measure μ_r and includes any transverse direction stress that is introduced by squeezing the film layers in the radial direction in wound rolls.

Transverse direction stresses also are introduced by changes in the film tension through Poisson's ratio effects. When the film tension is reduced, the film will try to grow in the transverse direction . For the plane strain case, this growth is prohibited and a resulting stress change occurs. The total stress in the transverse direction is the sum of that produced by radial and circumferential effects and it is obtained from

$$\sigma_z = \mu \; (\sigma_r + \sigma_\theta) \tag{3}$$

where details of the derivation are included in the Appendix and reference [5].

Table 2 includes the information used in the stress calculations for the 2.5μm films under consideration. Figures 5 to 7 include stress information for typical winding conditions for these films. Results for the four test values of K_2 are included ranging from the standard product where K_2 is 20.8 to the high concentration condition of HDS where $K_2 = 41.6$. Figure 5 shows the radial pressure in the wound roll plotted against the roll radius. Note that the radial pressure level is directly proportional to the film stiffness or K_2. The higher stresses are by themselves neither good nor bad. The film is not damaged by squeezing it in the thickness direction at these stresses. Higher radial stresses do, however, act to support each layer of film radially which may in turn make it more resistant to buckling. It's the combined stress pattern that determines whether or not the film will buckle.

Figures 6 and 7 includes the circumferential and transverse direction stresses, respectively, plotted against the roll radius. The films with stiffer surfaces have higher values of circumferential stress and lower values of transverse direction stress. This is the expected combination. The stiffer film is compressed to a smaller extent in the radial direction. The circumferential stress in each wrap of film is 20.7 MPa as it is wound. Succeeding wraps of film squeeze the roll radially and reduce the radius of each wrap below it. For films with higher stack stiffness, the reduction of both the radius of each wrap and the film tension inside the roll is smaller. Therefore, the residual circumferential stress is higher. Compressive stress in the transverse direction is introduced to a large degree by this reduction in film tension inside the wound roll. This makes the transverse direction compression inversely proportional to stack stiffness as shown. This is the desired direction, since any compression is undesirable in the plane of the film.

The key results are shown on Figure 8 which includes a plot of the buckling number for MD ridge formation plotted against the roll radius for the same range of film stiffnesses. The derivation of the buckling parameter is described in reference [5]. If it exceeds 1, the film can buckle. Note that the magnitude of the buckling number and the potential to buckle decreases dramatically as the film stiffness is increased by the addition of higher levels of additive and the "single size" additive particle. This is the key finding of the analytical effort. Now we need to see if winding results supports this hypothesis.

WINDING EXPERIMENTS

Films were produced using three concentrations of the HDS additive and were compared with the standard product (UC). The HDS films were comparatively "tacky" (higher slide angle measure of friction). This was apparent when handling laboratory samples of film, which appeared to block together. This had no negative effect on the roll formation and production yields, however. The initial response in production was good. The HDS films produced defect free mill rolls. Roll formation improved with added concentration for the HDS films and detailed work continued with only the highest additive loading (5200ppm).

The following criteria was used to produce data on roll quality:

Outstanding (O): Surface was substantially free of wrinkles, ridges and creases. Rolls have a mirror-like finish and the single sheet is not damaged.

Good (G): Surface was almost free of wrinkles, ridges and creases. Rolls looked good and sheet quality was acceptable.

Poor (P): Surface had wrinkles, ridges and creases. Roll defects were very visible and sheet quality was unacceptable.

Mill rolls produced on our manufacturing line, primary slit rolls 315mm wide and capacitor rolls 63.5mm wide were used in the comparison. The results are included on Table 3 for the high concentration HDS and UC films. All of the rolls of HDS films produce were outstanding while the UC rolls were only rated good.

The results from the narrow roll slitting test included additional information that could be used to show a difference in winding and processing. The UC film was difficult to process and broke during slitting. Table 4 includes a summary of the results of this test. Again, the HDS film performed much better than the standard product.

HDS film at a 5200ppm loading was produced in an extended production run to obtain comparative yields. The results were dramatic. Yields increased by 43% and the resulting slit rolls of HDS film had a very smooth surface with a mirror-like appearance with no MD ridges.

CONCLUSIONS

The value of the stack compression coefficient, K_2, has a dramatic effect on the internal stresses of wound rolls. Figures 5 through 7 show this effect for 2.5µm film. In general the radial pressures are directly proportional to K_2 while the level of compression in both the circumferential and transverse directions are inversely related to K_2. The preferred magnitude for K_2 is not obvious from the stress results.

The buckling number results provide a means of determining which surfaces should perform better. This result for the 2.5µm film considered here is included on Figure 8. It clearly shows that buckling can be eliminated by increasing the stack compression coefficient for the film. This can be achieved by increasing the slope in the asperity distribution for the film surface by controlling the additive type and concentration.

Films with relatively high concentrations of a "single sized" additive particle produced films with higher measured values of K_2. The slope of the asperity distributions above a 0.2 µm asperity height was much higher for these films than for a typical film with a milled additive. Within a given additive system, the stack stiffness was directly proportional to additive concentration (see Figure 3).

Winding test results showed a substantial improvement for the films with higher values of K_2. Roll appearance was superior for the high K_2 film and yields improved by 43% when compared with a product with a much lower stack stiffness.

The slide angle (friction coefficient for the film surface) result is not an adequate predictive tool by itself for the winding performance of a thin film. The milled additive system produced film with a lower friction coefficient and traditional wisdom states that these films should wind better. This is not correct. The test results show that the tackier HDS film wound better. Adequate control of the surface friction is required to avoid defects caused by bonding of adjacent surface layers. MD ridges must be controlled by other means.

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APPENDIX: Plane Strain Derivation from Reference [5]

Starting with the geometry shown on Figure A-1, two basic relationships needed for the derivation of the required differential equation can be determined. The geometrical relationship between strains can be obtained by assuming a small displacement in the radial direction. The key force balance equation is obtained by summing forces in the radial direction. The resulting equations are

$$r\, d\varepsilon_\theta / dr = \varepsilon_r - \varepsilon_\theta \quad \text{(A-1)} \qquad \text{and} \qquad r\, d\sigma_r / dr = \sigma_\theta - \sigma_r \quad \text{(A-2)}$$

The stress-strain relationships include replacing μ_r with $\mu\ (E_r / E)$ which comes from looking at the film as both a stack and as single sheets (see reference [10 & 11]). For this approach the three relationships are

$$\varepsilon_r = \sigma_r / E_r - \mu\ \sigma_\theta / E - \mu\ \sigma_z / E \quad \text{(A-3)}$$
$$\varepsilon_\theta = \sigma_\theta / E - \mu\ \sigma_r / E - \mu\ \sigma_z / E \quad \text{(A-4)}$$
$$\varepsilon_z = \sigma_z / E - \mu\ \sigma_r / E - \mu\ \sigma_\theta / E \quad \text{(A-5)}$$

Now, the plane strain and stress relationships can be derived by assuming either ε_z or σ_z is zero, respectively. For plane stress the resulting differential equation is

$$d^2\sigma_r / dr^2 + (3/r)\, d\sigma_r / dr + (1/r^2)\,(1 - E/E_r)\,\sigma_r = 0 \quad \text{(A-6)}$$

which is identical to the equation in reference [10]. The plane strain equation used here and in reference [5] is

$$d^2\sigma_r / dr^2 + (3/r)\, d\sigma_r / dr + (1 - E/E_r)\,\sigma_r / \{r^2 (1 - \mu^2)\} = 0 \quad \text{(A-7)}$$

where an additional term enters into the derivation. For the plane strain case, the incremental stress added by a wrap of film is determined by solving equation (A-7). The stresses in the θ and z directions are obtained from that result using equations (A-2) and (3). The total stress is found by summing the calculated incremental stresses due to successive wraps of film as the roll builds. Of course, the circumferential stress must include the winding tension as an initial stress state.

This derivation has been included to explain the source of the transverse compression included in the roll stress calculated results. References [5] and [10] should be consulted for more details.

Table 1 Film Property Comparison

Sample	Examples with $CaCO_3$ HDS Films			Example with Ca_3PO_4 UC
	#1	#2	#3	#4
Film Thickness μm	2.5	2.5	2.5	2.5
Equivalent OD of μm Additive Particle	1.25	1.25	1.25	1.46
Additive Loading ppm	2730	3447	5285	6518
Surface Roughness Tallysurf				
R_a - μm	0.063	0.086	0.100	0.060
R_z - μm	0.740	0.890	0.800	0.830
R_t - μm	0.950	1.000	0.950	1.140
Slip - Degree	37	38	35	27
K_1 - KPa	4.54	5.30	5.35	4.70
K_2	28.1	35.1	41.6	20.8

Table 2 Values Used for Stress Analysis

Elastic Modulus of PET Films	3.79 GPa (550Kpsi)
Poisson's Ratio (Measured)	0.13
Thickness of film	2.5μm
Core Outer Radius	100mm
Core Inner Radius	90mm
Outer Radius of the Roll	350mm
Elastic Modulus of Core	6.14 GPa
Tension	0.525 N/cm (0.3pli)
Entrained Air Pressure	94.5 KPa (13.7psi)
K_1 and K_2	See Table 1

Table 3 Film Windability and Processability

Film Type	2.5 micron HDS	2.5 micron UC
Additive	$CaCO_3$	Ca_3PO_4
Additive Concentration ppm	5200	6500
Mill Roll Formation	O	G
63.5mm Wide Capacitor Rolls	O	G
Slit Rolls 315mm	O	G

Table 4 Narrow Roll Slitting Test

	2.5 micron UC 6500ppm		2.5 micron HDS 5200ppm	
	Operator #1	Operator #2	Operator #1	Operator #2
Ease of Running	Very Difficult	Very Difficult	Excellent	Excellent
Number of Web Breaks	3	2	0	0
Output				
Number of Rolls (5000m long)	0	0	55	55
% of Reels to Length	0	0	100	100
1st Quality Reels Number	0	0	36	36
% of Total	0	0	65	65
Length Before Breaking meters	425 425 520	1493 2195	5000 5000	5000 5000

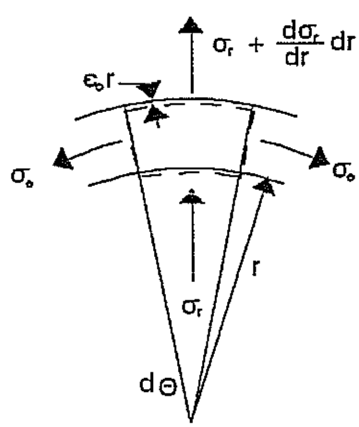

Fig. A-1 Element Sketch for Derivation

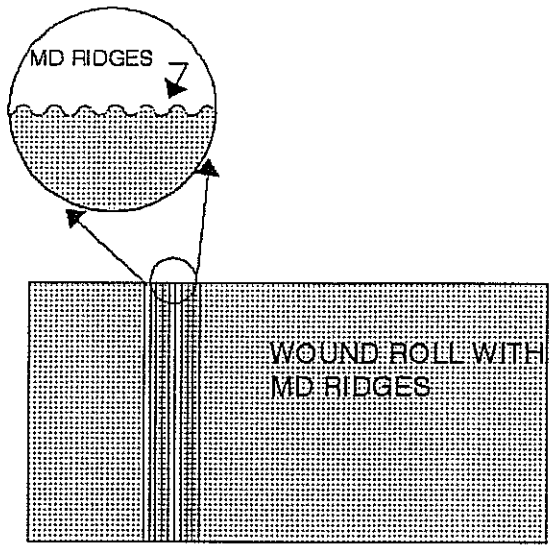

Fig. 1 Sketch Showing the Shape of MD Ridges in Thin Films

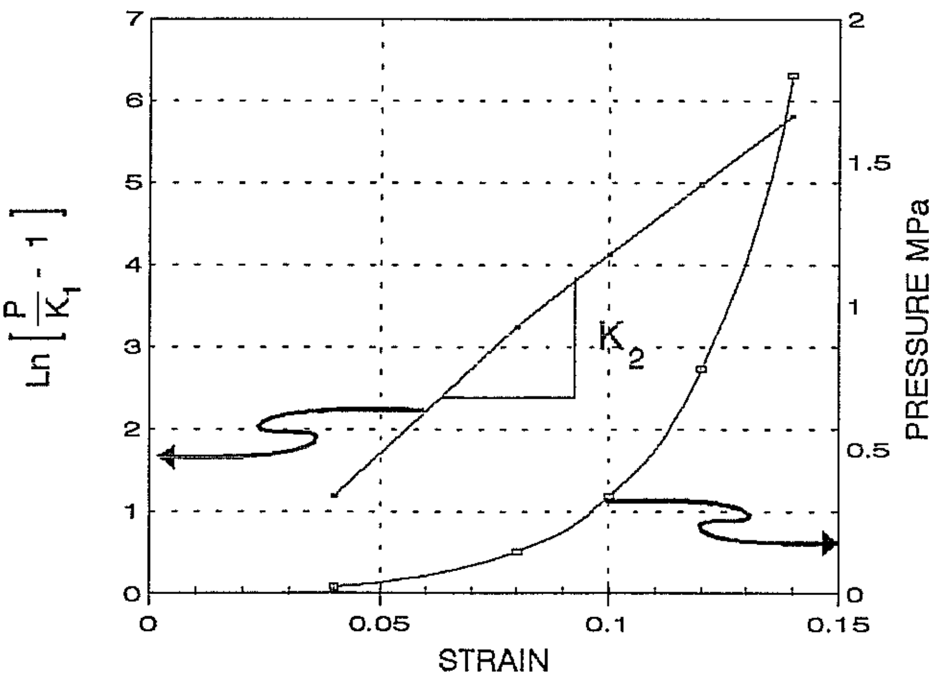

Fig. 2 Typical Stack Compression Results Showing K_2 as the Stiffness Factor

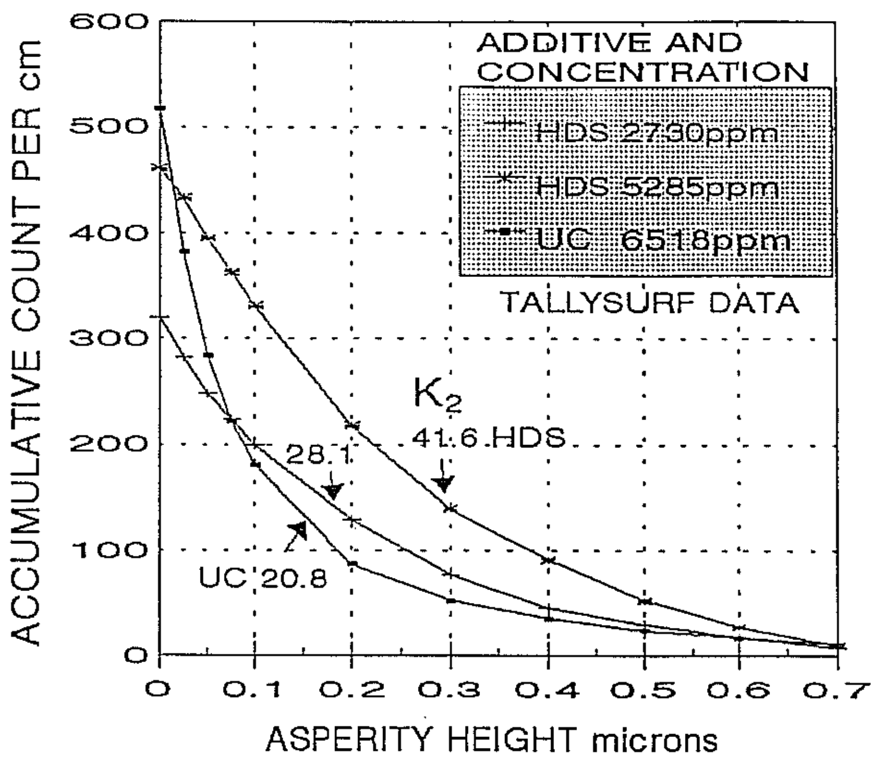

Fig. 3 Asperity Sized Distribution for HDS and UC Films

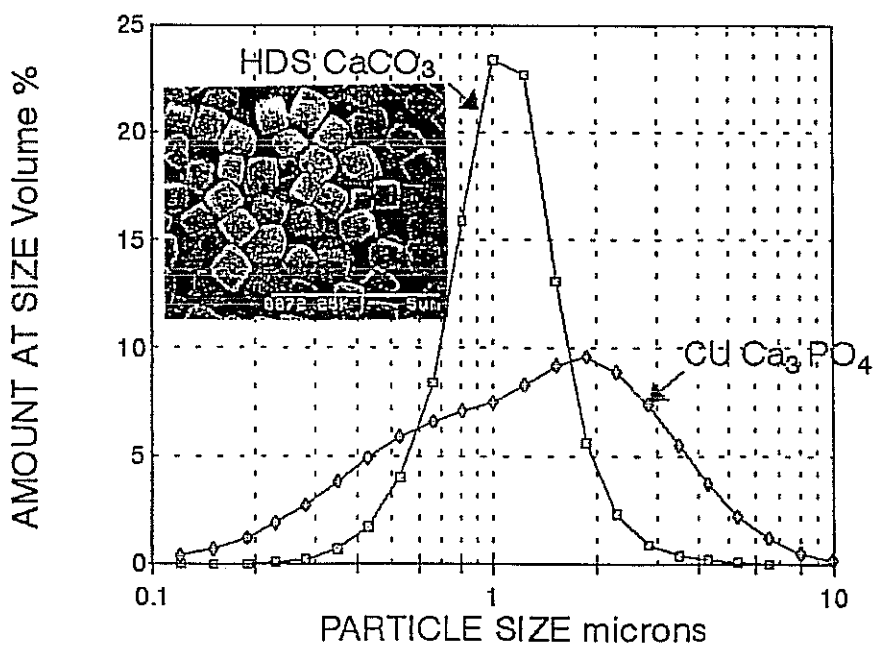

Fig. 4 Particle Size Distribution for HDS and UC Additive

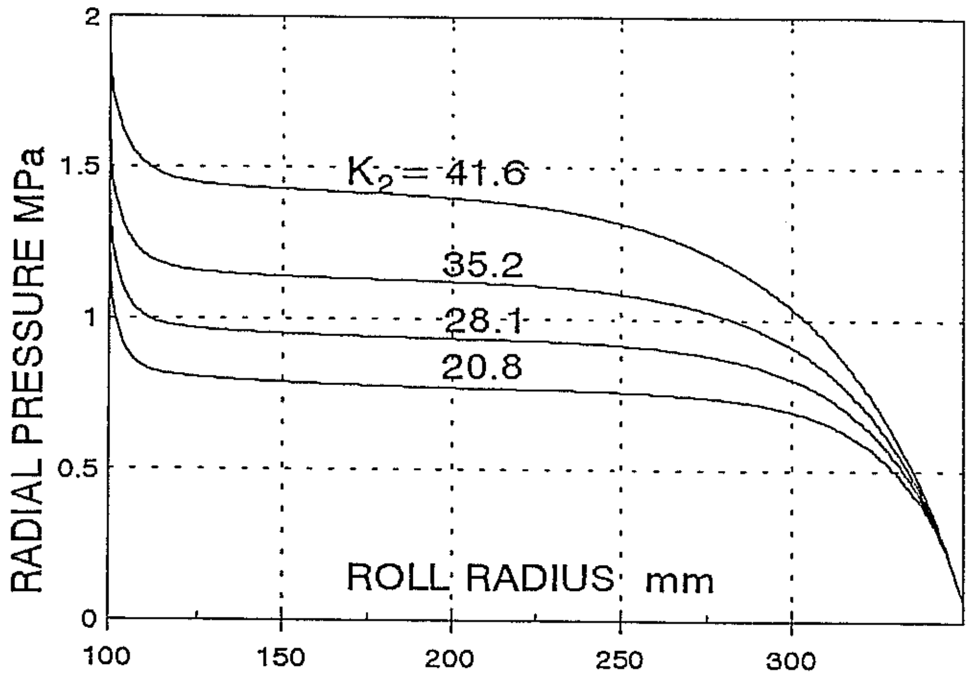

Fig. 5 Radial Pressure Distribution for Films with Differing Stack Compression Coefficients

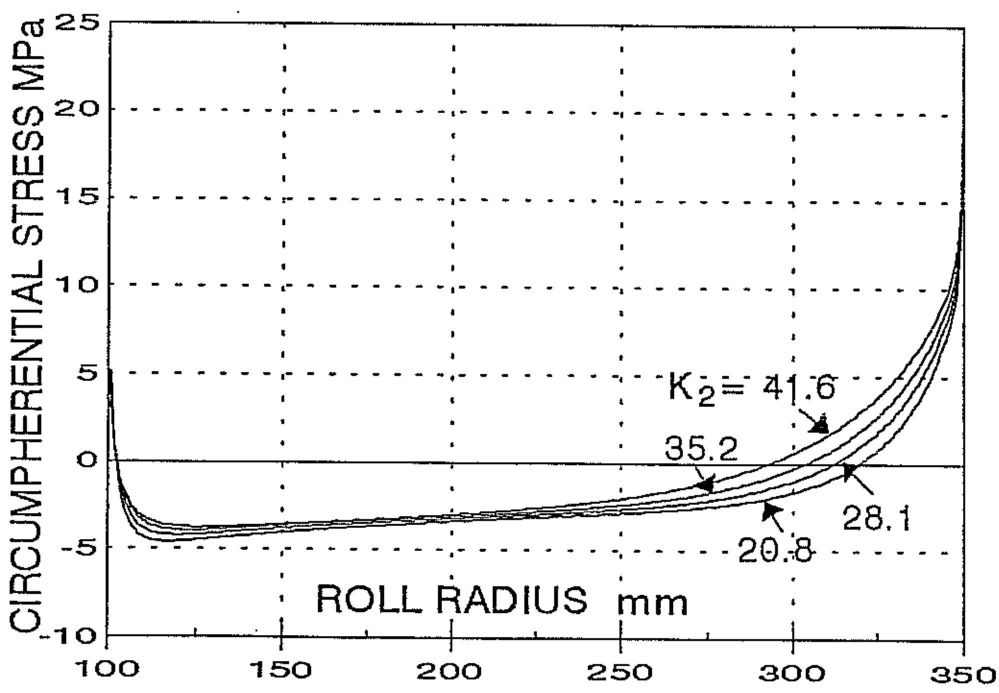

Fig. 6 Circumferential Stress for Films with Differing Stack Compression Coefficients

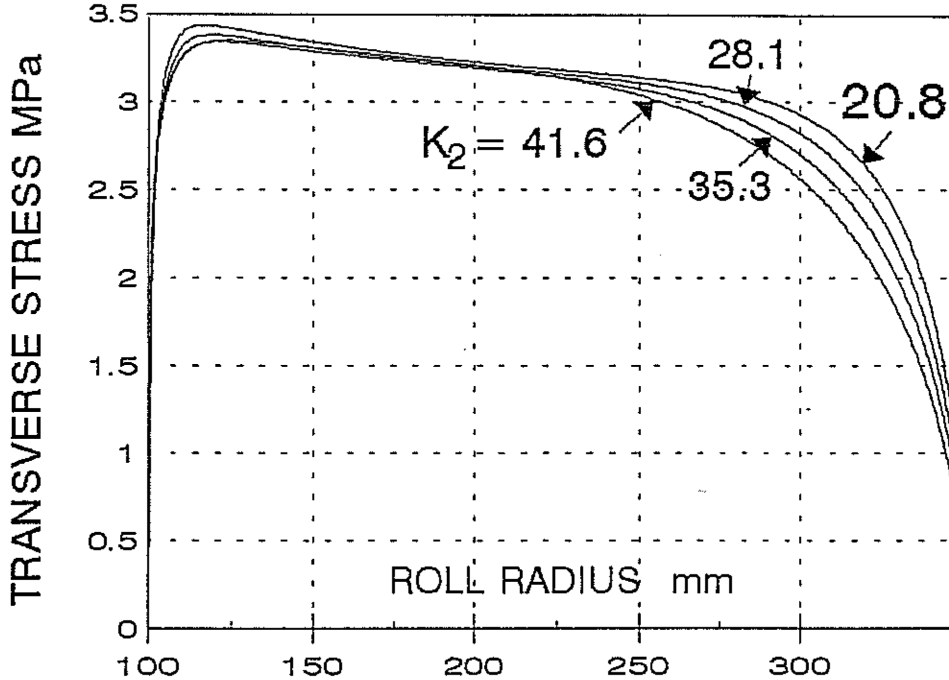

Fig. 7 Transverse Stress for Films with Differing Stack Compression Coefficients

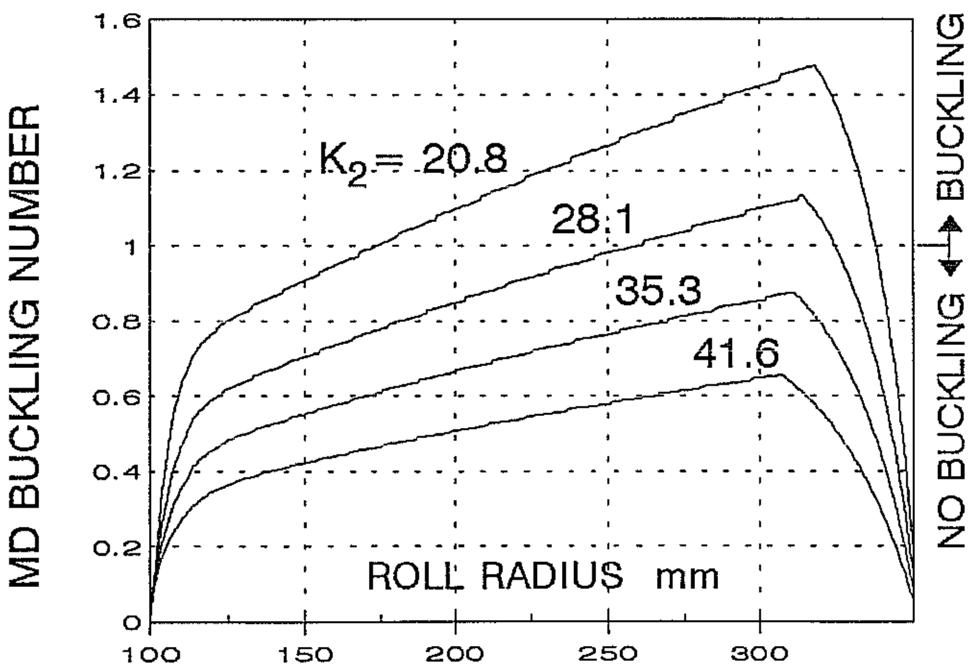

Fig. 8 MD Ridge Buckling Number for Films with Differing Stack Compression Coefficients

Question - Could you talk about the other side of the picture where you have no additives? Because, I would think that with no additives the K2 would become extremely high.

Answer - What happens when you have no additives and the slip angle goes from 45 degrees to higher. In other words, the film blocks to itself. You get Vander-walls bonding between the film layers and we wind up with what we call square rolls and then you can't unwind the rolls and the film gets distorted dramatically. When you get down to almost no additive K2 does get high.

Question - If you change the winding tension to bring that roll pressure down to the same level as the lower K2 films, would you still have seen the same beneficial effect on MD wrinkles?

Answer - We certainly try winding at all levels of tension, and everything moves up and down as you change the tension. In fact if you get too low of tension the roll gets so soft that it's ridging is worse. So the increase in the value K2 benefit is independent of tension level.

Question - I missed what the substrate film was, what was the film you referred to?

Answer - This is PET (Mylar). And we'll sell you some if you would like some.