TESTING AND ANALYSIS OF WEB SPREADING AND ANTI-WRINKLE DEVICES

by

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ABSTRACT

There are many web spreading and anti-wrinkle techniques and devices. A few have been analyzed, but most have not been tested with a uniform scientific method. Currently the decision of when and where to use such a device is based on personal experience, vendor advice or trial and error. This paper presents a test method, simple analysis and test results, for ten different techniques or devices.

NOMENCLATURE

E	Young's modulus of web, $3.5X10^9$ Pa (500,000 psi)
F	shear force at the free end of the cantilever beam, N (lb)
I	moment of inertia, mm^4 ($in.^4$)
K	Shelton's constant [6], 1/m (1/in.)
L	span length, 0.61m (24 in.)
M	moment at the free end of the cantilever beam N-m (in.-lb)
r	radius, m (in.)
T_H	tension, high side of roller, N (lb)
T_L	tension, low side of roller, N (lb)
V_s	surface velocity vector
W_{Face}	face width of roller, m (in.)
y	deflection at free end of cantilever beam, m (in.)
y	crossweb position, m (in.)
y_F	deflection at the free end of cantilever beam due to shear force, m (in.)
y_M	deflection at the free end of cantilever beam due to moment, m (in.)
α	end plate angle, 0.1 rad (6 Deg)

β	wrap angle, rad
β	angular position of roller, rad
Δr	change in roller radius, bumper height, m (in.)
ϕ	angle of the surface velocity vector, rad
μ	coefficient of friction, dimensionless
θ_F	slope at the free end of cantilever beam due to shear force, rad
θ_M	slope at the free end of cantilever beam due to moment, rad
σ	web stress, Pa (psi)

INTRODUCTION

Wrinkles are a common problem in the web handling industry. Two prevailing types of wrinkles are shear wrinkles [1] and machine direction (MD) wrinkles. Shear wrinkles are commonly caused by tram error, while machine direction wrinkles occur for many reasons [2]. A web spreading mechanism is usually required to eliminate the wrinkle.

Anti-Wrinkle rollers are defined as any roller that requires more tram error, to cause wrinkling, than a standard aluminum roller. Spreader rollers are defined as any roller that will cause two halves of a web, slit in the upstream span, to permanently separate.

TEST PROCEDURE

Three tests were done on each roller, starting with a simple rolling drag test. The second test was a wrinkle regime test, first used by Gehlbach, Good and Kedl [1] in 1987. This test resulted in a plot of tram error required for wrinkling versus web tension, which was compared with a standard aluminum roller to determine each roller's anti-wrinkle performance. The third test was to slit the web into parts and measure the amount of cross direction (CD) spreading.

Drag Test

A test stand was set up with two tension load cell rollers, one positioned upstream of the test roller and one downstream. The difference in tension between the upstream and downstream load cells was the drag of the test roller. The resolution of the system was about 0.05 kg (0.1 lb) The test speed was 15 m/min (50 fpm).

Wrinkle Regime Test

Figure (1) shows the test stand set up. A test roller was placed 610 cm (24 in.) downstream of a nipped roller. The test roller was mounted so that it could be moved out of tram, bending the incoming web span. The web wrapped the roller by 90 degrees, putting pure twist in the downstream span. The PET web was 25.4 cm (10 in.) wide by 0.02 mm (0.00079 in.) thick. Test speed was 15 m/min (50 fpm). The roller was slowly angled until a web span trough would go completely around the test roller. The test was repeated in the opposite direction to eliminate the effects of cambered web. A wide range of web stress levels were tested. A graph was generated with critical tram angles plotted against machine direction stress, referred to as a wrinkle regime plot.

Wrinkle Regime Plot

Figure 3. shows a wrinkle regime plot for a standard aluminum roller. Wrinkles occur in the area above the curve. Regime curves have two distinct regions or regimes [1]. Regime I is the high tension / high traction region, while regime II is the low tension / low traction region. There is usually a stress below which wrinkles will not form at all, call the regime II asymptote. The transition between the asymptote and the regime I curve is referred to as the knee.

Many of the anti-wrinkle rollers had a regime curve that was substantially above the standard curve. The regime I data was regressed to determine a regime I multiplication factor, which quantified how much additional tram error a given roller had before wrinkling occurred. The larger this regime I factor, the better this roller would be at resisting high tension / high traction wrinkles. The larger the regime II stress the better this roller would be at fighting low tension and/or low traction wrinkles.

Web Spreading Test

Web spread testing was done with the test roller in the tram position. The web was slit in half, just upstream of the nip roller. Measurement of the gap between the two halves of the web was done at the tangent point, as the web exited the test roller. The slit was then moved to 25.4mm (1 in.) from the right edge of the web, and finally to the left side.

DISCUSSION AND ANALYSIS

Table 1. lists the rollers tested and a brief description. Most of the anti-wrinkle and spreader rollers lend themselves to some type of analysis. Several of the rollers have been analyzed in the past and will be referenced here. This analysis was intended to be simple and insightful. Rigorous models would require more sophistication, including modeling of traction and slippage, which is beyond the scope of this paper.

Idler Roller

Table 1. describes this standard aluminum idler roller. The analysis of the regime I wrinkling has been described by J. J. Shelton [3]. The analysis of regime II wrinkling is beyond the scope of this paper.

Outward Spiral Tape

The standard idler roller was wrapped with strips of masking tape, with an outward spiraling pattern. Testing showed that this roller did not have anti-wrinkle or web spreading properties. Therefore, outward spiral tape does not lend itself to analysis.

Inward Spiral Tape

The standard idler roller was wrapped with strips of masking tape, with an inward spiraling pattern. Testing showed that this roller did not have anti-wrinkle or web spreading properties. Therefore, inward spiral tape does not lend itself to analysis.

PTFE Tape

The standard idler roller was covered with PTFE tape. The probable anti-wrinkle mechanism is lowering the friction coefficient. This would increase the regime II stress. The analysis of regime II wrinkling is beyond the scope of this paper.

Tape Bumpers

The standard idler roller was wrapped with one layer of masking tape, 25.4 mm (1 in.) wide by 0.18 mm (0.0072 in.) thick, at each edge of the web. Tape bumpers increase the diameter of the roller at the edge of the web. This will induce an added strain and hence stress on the edge of the web. The higher edge stress causes a moment that will tend to bend the web inward. The normal entry rule [4, 6] will induce a shear force that will cause the web to walk outward until normal entry is achieved. A simple analysis of web spreading from tape bumpers, would be to model half the web as a cantilever beam, as shown in figure 2. The magnitude of the bumper induced moment can be calculated by using (1) where Δr is the thickness of the tape bumper.

$$\sigma = \left(\frac{\Delta r}{r}\right)E \tag{1}$$

The belt equation (2) can be used to determine the maximum differential tension across the bumper. Using a coefficient of friction of 0.35, it was determined that the tension differential across the bumper was excessive and there must be slippage. The moment was calculated using the maximum differential tension across the bumper, and was found to be 0.21 N-m (1.83 in.-lb.).

$$\frac{T_H}{T_H} = e^{\mu\beta} \tag{2}$$

A simple, closed form, half web cantilever beam model was developed. A moment equal to that caused by the bumper will be applied at the free end of the beam. An unknown shear force, from the normal entry rule, can then be applied until the slope at the free end of the beam is zero. Equations (3-6) describe the deflection and slope at the end of force and moment loaded cantilever beams, respectively. The principle of superposition was used to develop (7,8). Equations (3-8) can be combined to form (9,10) which is the deflection (spreading) and induced shear force. Equation (9) predicts a half web deflection of 1.1 mm (0.043 in.). The separation of the slit web half should be twice this number or, 2.2 mm (0.086in.). The actual measured web separation was 2.4 mm (0.094 in.). This model predicted within 10% of the actual value. This is only a sample of one and does not constitute a validation of this model.

$$y_F = -\frac{FL^3}{3EI} \qquad \theta_F = -\frac{FL^2}{2EI} \tag{3,4}$$

$$y_M = -\frac{ML^2}{2EI} \qquad \theta_M = -\frac{FL}{EI} \tag{5,6}$$

$$\theta_F + \theta_M = 0 \qquad y_F + y_M = y_{F+M} \tag{7,8}$$

$$y_{F+M} = \frac{ML^2}{6EI} \qquad F = -\frac{2M}{L} \tag{9,10}$$

Linear finite element method was used to model the same situation. A rectangular plate element of order one was used with the nodal force at the free end of the beam calculated using (1). Unknown shear forces were added to each element at the free end of the beam. The magnitude of the forces were iterated to achieve normal entry at all free end nodes. As expected, the result were similar to equations (9,10).

A non-linear solution [5] was also used to model this situation. The solution accounts for non-linear tension stiffening effect, as well as bending. The resulting deflection was only 1% lower than equation (9). The difference between the linear and the non-linear model should diverge as the KL term for the web increases [6]. This is equivalent to the webs behavior going from a beam to a string. This particular test configuration, KL=0.83, the web should act like a beam.

Reverse Crown Roller

The roller was tapered, with a slope of 0.002, from the center outward. The analysis for the reverse crown roller is similar to tape bumpers. Modeling of reverse crown rollers has also been discussed by [2,7]. The magnitude of the reverse crown induced moment can be calculated to be 0.31 N-m (2.74 in.-lb.) using equation (1) where Δr is 0.13 mm (0.005 in.) Equation (9) predicts a half web deflection of 1.63 mm (0.064 in.). The separation of the slit web half should be twice this number or, 3.25 mm (0.128in.). The actual measured web separation was 0.38 mm (0.015 in.). This model over predicted the amount of spreading by a factor of eight, and under predicted the amount of edge spreading.

Curved Axis Roller

The curved axis roller has been analyzed by R. D. Delahoussaye [8].

Expanding Surface Roller

There are several types of expanding surface rollers. Some have polymer bands or slats that extend and contract as they rotate around the angled end plates. This design had a solid rubber sleeve. Common understanding of the operation of this type of roller is that the web enters the roller on the narrow side, expands as the roller rotates, leaving on the wide side. But this explanation did not account for two phenomena noted in the test. First, the measured web spreading was about two times the roller expansion. Secondly, the web spreads in the upstream span.

Rollers that spread in the upstream span, such as bumpers and curved axis rollers, are governed by the normal entry rule [4, 6]. This rule states that "A moving web, in traction, will move laterally to achieve entry normal to a roller's axis" Analysis of expanding surface rollers illustrate that a more general definition is needed. A corollary to the normal entry rule would be the parallel entry rule "A moving web, in traction, will move laterally to achieve entry at a point where the slope of the web is parallel to the roller's surface velocity vector."

Expanding surface rollers, like the curved axis roller, have two spreading mechanisms, parallel entry spreading and on-roller spreading. Figure 5. shows the geometry of the expanding surface roller. Equation (11) describes the lateral displacement of a point on the rollers surface. Equation (11) can be differentiated with respect to time to find the lateral velocity. The ratio of the lateral velocity to tangential velocity is the angle of the rollers surface velocity vector ϕ, as shown in equation (12). Equations (3,4) and the parallel entry rule can be combined to determine lateral spreading, Equation (13) and induced shear force, Equation (14).

$$U_y = \frac{y}{W_{Face}/2} \; r \sin(\alpha) \sin(\beta) \tag{11}$$

$$\phi = \frac{y}{W_{Face}/2} \; \sin(\alpha) \cos(\beta) \tag{12}$$

$$y_F = \frac{2}{3} L\phi \qquad\qquad F = \frac{2\,E\,I}{L^2}\phi \tag{13,14}$$

Figure 6 illustrates that maximum on-roller spreading would occur if you entered the roller at the narrowest point and exited at the widest point. Entry at the narrowest point would have zero parallel entry spreading in the upstream span. The maximum parallel entry spreading would occur when the web entered the roller 90 degrees after the narrowest point of the roller, however, entry at this point would only have half the on-roller spreading. Depending on the entry span geometry, parallel entry spreading could be large or small in relation to the on-roller spreading.

Equations (12) and (13) can be used to evaluate the parallel entry spreading of the expanding surface roller. The dependence of ϕ on lateral position indicates that spreading will increase toward the edge of the web. It also indicates that slippage must occur on high modulus webs and non-zero end plate angles (α). Friction and slippage must be used in any model to predict the behavior of expanding surface rollers.

Flexible Spiral Roller

Flexible spiral rollers are rubber rollers with angled, outward spiraling grooves cut in the surface, as shown in figure 6. Common understanding of the operation of this type of roller is that the web compresses the angular rubber lands. The land bending over, spreading the web. There is also concern that the spreading action is reversed as the web exits the roller. But this theory of operation does not explain why spreading is large in relation to land deflection, spreading does occur in the upstream span, or presents of permanent spreading. The flexible spiral roller, like the expanding surface roller, has a lateral velocity component at the web tangent point. The parallel entry rule can also be applied to this roller.

Equation (13) can be used to back calculate the angle of the rollers surface velocity vector ϕ. The measured center spreading of 0.36mm (0.014 in.) would require ϕ to be 0.0002 radians. If we assume the deflection was linear and occurred over an angle as large as 45 degrees, the lateral deflection of the land would only be 0.006mm (.0002 in.). Therefore substantial upstream spreading can occur with almost immeasurably small lateral deflection of the land.

Rigid Spiral Roller

Rigid spiral rollers are usually made of aluminum or steel, with outward spiraling grooves machined in the surface. The rigid spiral roller did not spread the web, but it did have anti-wrinkle properties. This phenomenon can best be described qualitatively. The definition of a wrinkle, used in these experiments, was when an upstream trough went completely around the test roller. A trough would start to go around the roller at about the same tram error as the standard idler. Before the trough could go completely around the roller, a spiral groove would push it off the edge of the web. This phenomenon did not occur when the roller was reversed.

RESULTS

Table 2. summarizes the results of the testing. The data confirmed many commonly held beliefs about these web spreading and anti-wrinkle rollers. Most of these devices do have anti-wrinkle properties, and some do spread the web. The effectiveness of the devices varied greatly. The result also disproved several commonly held beliefs, including: outward spiral tape spreads the web and removes wrinkles, flexible spiral rollers don't work because the web contracts at the roller exit, and that solid spiral rollers are not anti-wrinkle rollers.

Idler Roller

The aluminum roller was the standard by which the other rollers were judged. By definition the roller is not an anti-wrinkle roller. The idler roller wrinkle regime plot is shown in figure 7. This roller did not spread the web.

Outward Spiral Tape

Outward spiraling tape on rollers is sometimes thought to have spreading and anti-wrinkle properties. Figure 8. shows that the outward spiraling tapes anti-wrinkle performance was inferior to the standard roller. This test showed that this roller did not spread the web. Like a barber pole, the spreading effect of outward spiraling tape is an optical illusion.

Inward Spiral Tape

Figure 9. shows that the inward spiraling tape performed slightly better than outward spiraling tape, both of which were inferior to the standard idler.

PTFE Tape

Figure 10. shows that the smooth low friction surface moved the regime II asymptote to a much higher stress level. The regime I performance is slightly worse than the standard idler. This roller did not spread the web. A PTFE taped roller would be very insensitive to wrinkles at low and medium tensions.

Tape Bumpers

Figure 11. shows that tape bumpers lowered the regime II stress. The regime I performance was good. This roller did spread the web. A tape bumpered roller would be insensitive to wrinkles at medium and high tensions. This roller is a good, low drag, web spreading and anti-wrinkle device.

Reverse Crown Roller

Figure 12. shows that the reverse crown rollers increased the regime II stress. The regime I performance was good. This roller did spread the web. A reverse crown roller would be insensitive to wrinkles at low, medium and high tensions. This roller is a good, low drag, web spreading and anti-wrinkle device.

Curved Axis Roller

Figure 13. shows that the curved axis rollers increased the regime II stress. The regime I performance was excellent. This roller is an aggressive web spreading device.

A curved axis roller would be insensitive to wrinkles at low, medium and high tensions. This roller is a excellent, high drag, web spreading and anti-wrinkle device.

Expanding Surface Roller

Figure 14. shows that the expanding surface rollers did not wrinkle under any test conditions. The regime I performance was excellent. This roller is an aggressive web spreading device. A expanding surface roller would be insensitive to wrinkles at low, medium and high tensions. This roller is a excellent, high drag, web spreading and anti-wrinkle device.

Flexible Spiral Roller

Figure 15. shows that the flexible spiral rollers increased the regime II stress. The regime I performance was good. This roller did spread the web, and spreading increased with increasing tension. A flexible spiral roller would be insensitive to wrinkles at low, medium and high tensions. This roller is a good, low drag, web spreading and anti-wrinkle device.

Rigid Spiral Roller

Figure 16. shows that the rigid spiral rollers decreased the regime II stress. The regime I performance was good. This roller did not spread the web. A rigid spiral roller would be insensitive to wrinkles at medium and high tensions.

ACKNOWLEDGMENTS

I would like to thank 3M company for supporting this research. I would also like to thank Dr. James Dobbs and Roger Van Dien for helping with the experimentation.

REFERENCES

1. Gehlbach, L. S., Kedl, D. M., and Good, J. K., "Predicting Shear Wrinkles in Web Spans," Tappi Journal, Vol.72, No. 8, Aug. 1989, pp129-134.
2. Roisum, D. R., "The Mechanics of Web Spreading," Proceedings of the Second International Conference on Web Handling, Web Handling Research Center, Oklahoma State University, Stillwater, Oklahoma, June 6-9, 1993
3. Shelton J. J., "Buckling of webs from Lateral Compressive Forces," Proceedings of the Second International Conference on Web Handling, Web Handling Research Center, Oklahoma State University, Stillwater, Oklahoma, June, 1993
4. Pfeiffer, J. D., "Web Guidance Concepts and Applications," Tappi Journal, Vol. 60, No. 12, December 1977.
5. Swanson, R. P., "Air Support Conveyance of Uniform and Non-Uniform Webs," Proceedings of the Second International Conference on Web Handling, Web Handling Research Center, Oklahoma State University, Stillwater, Oklahoma, June, 1993
6. Shelton J. J., "Lateral Dynamics of a moving Web," Ph.D Thesis, Oklahoma State University, Stillwater, Oklahoma, July, 1968
7. Delahoussaye, R. D., Good, J. K., "Analysis of Web Spreading Induced by the Concave Roller," Proceedings of the Second International Conference on Web

Handling, Web Handling Research Center, Oklahoma State University, Stillwater, Oklahoma, June, 1993
8. Delahoussaye, R. D., Good, J. K., "Analysis of Web Spreading Induced by the Curved Axis Roller," Proceedings of the Second International Conference on Web Handling, Web Handling Research Center, Oklahoma State University, Stillwater, Oklahoma, June, 1993

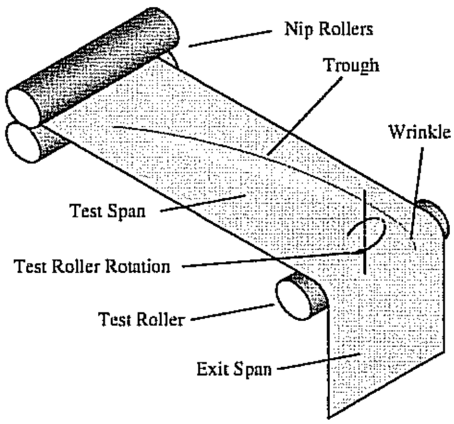

Figure (1) Test Setup

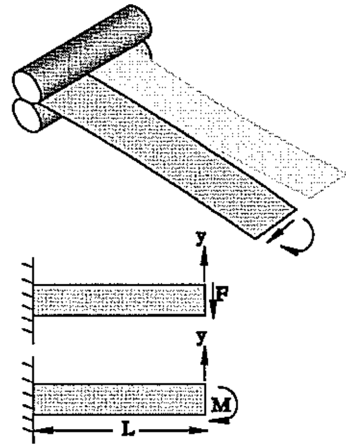

Figure (2) Cantilever Beam Model

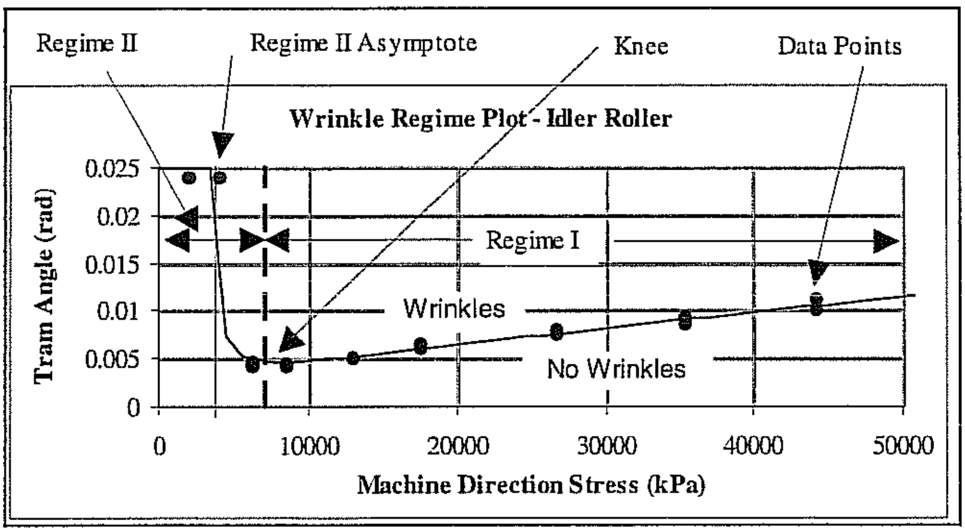

Figure 3. Wrinkle Regime Plot

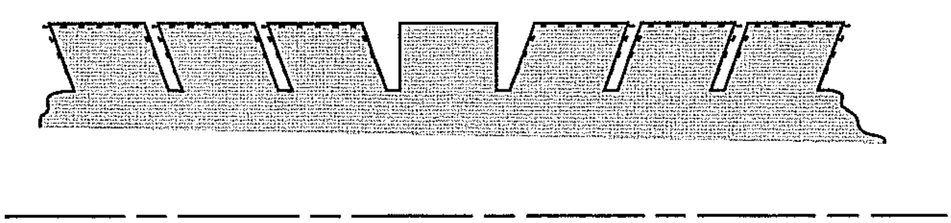

Figure 4. Flexible Spiral Roller

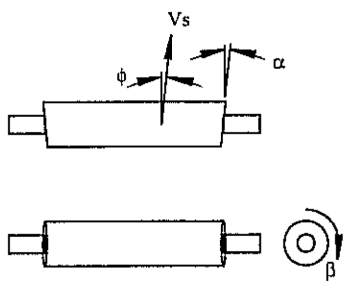

Figure 5 Expanding Roller Geometry

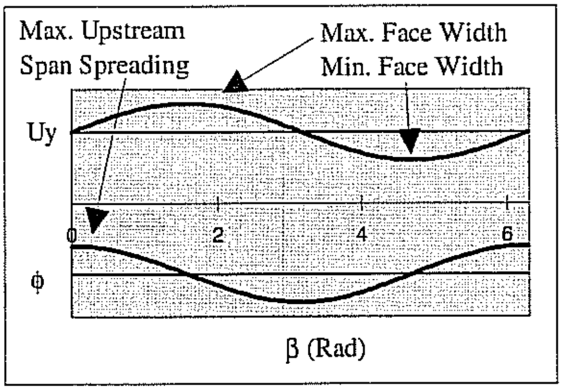

Figure 6 Expanding Roller Spreading

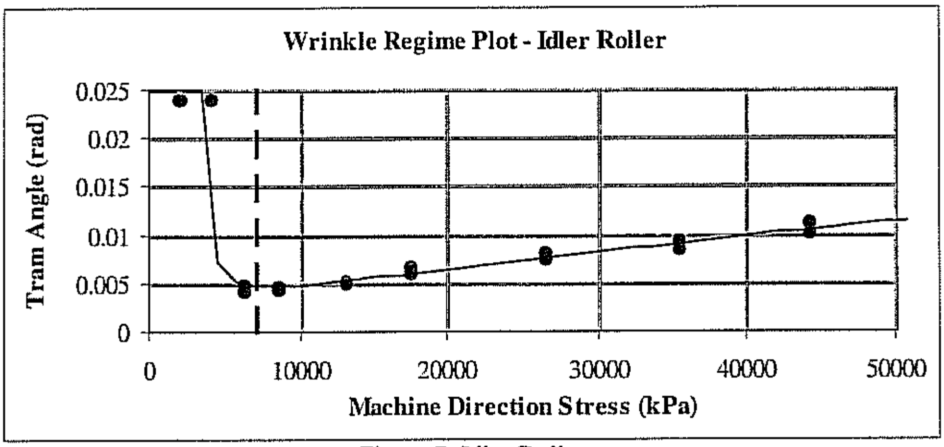

Figure 7. Idler Roller

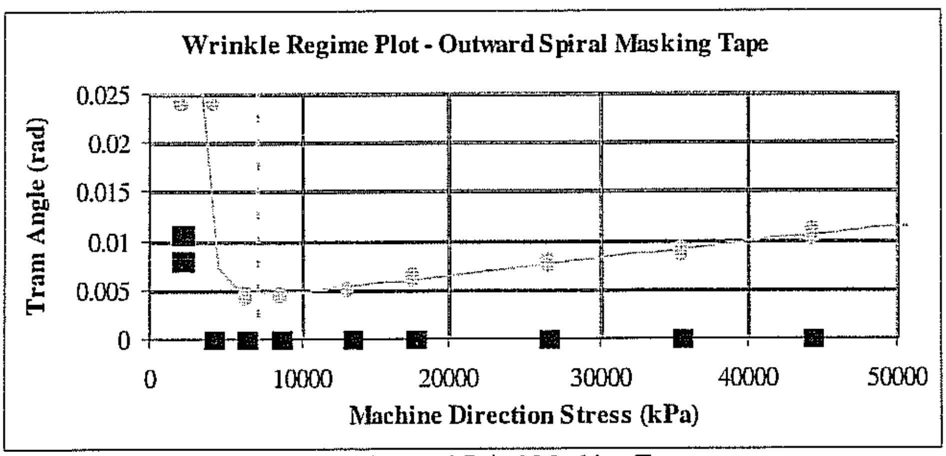

Figure 8. Outward Spiral Masking Tape

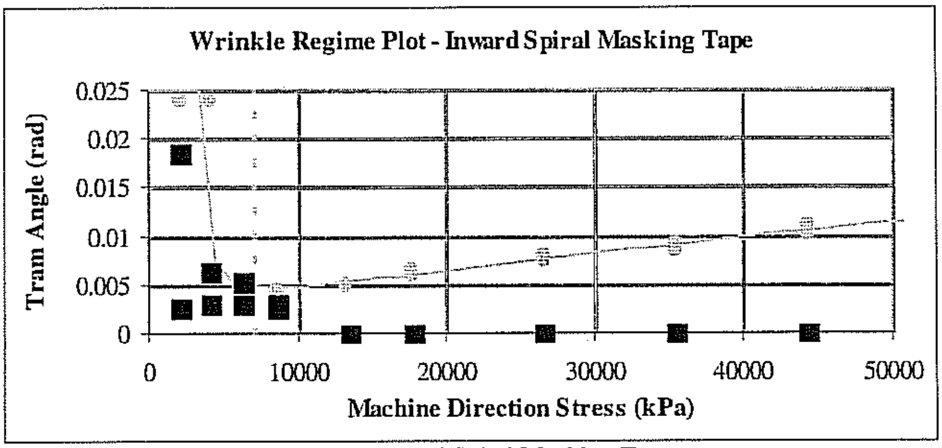

Figure 9. Inward Spiral Masking Tape

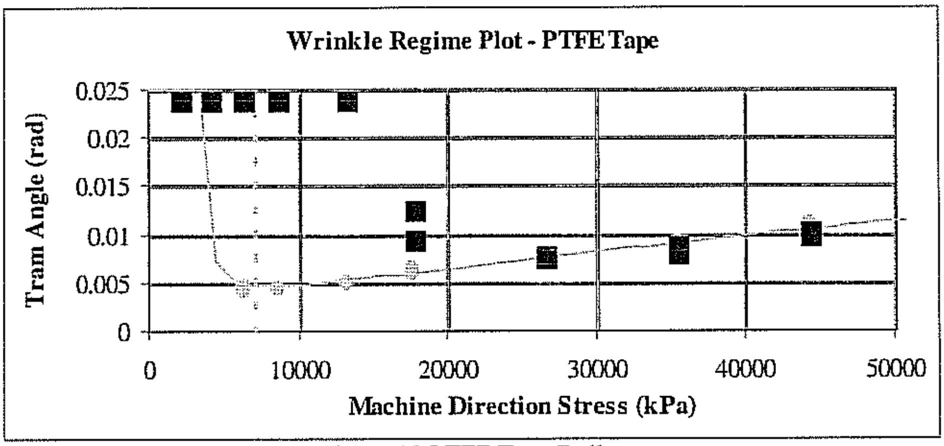

Figure 10.PTFE Tape Roller

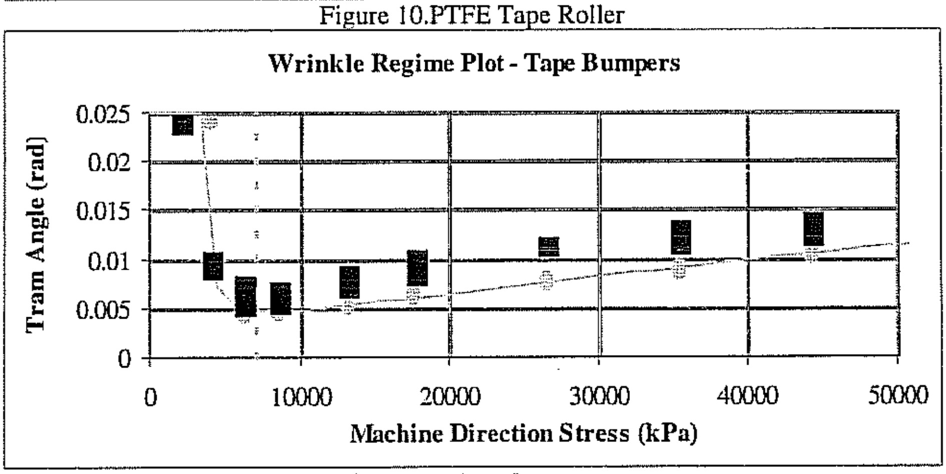

Figure 11. Tape Bumpers

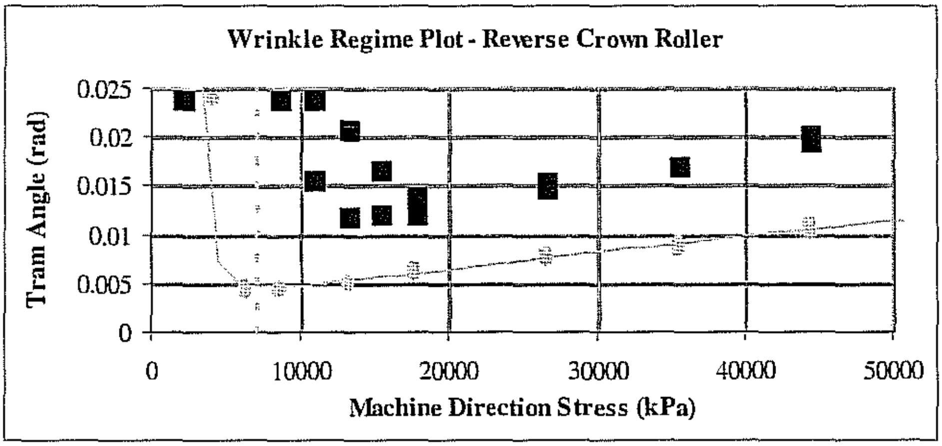

Figure 12. Reverse Crown Roller

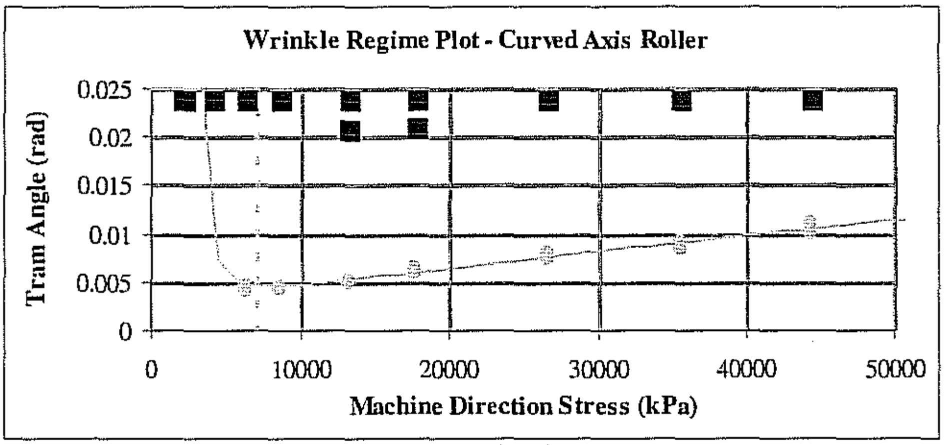

Figure 13. Curved Axis Roller

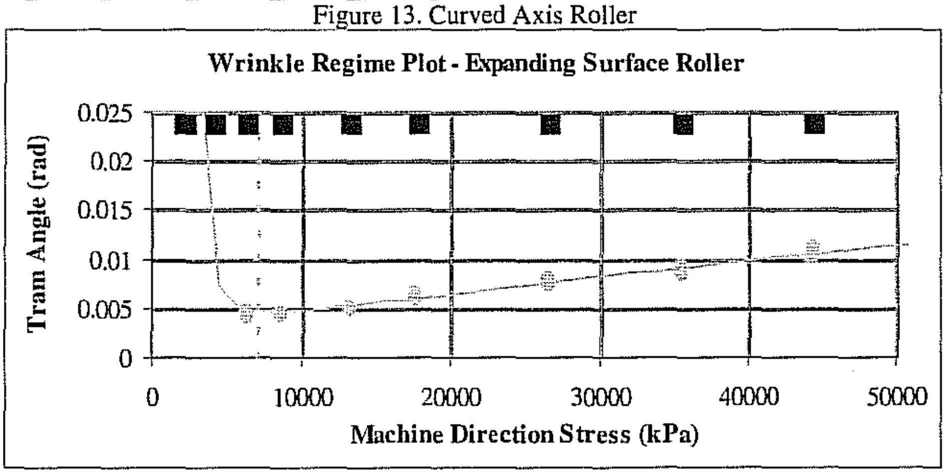

Figure 14. Expanding Surface Roller

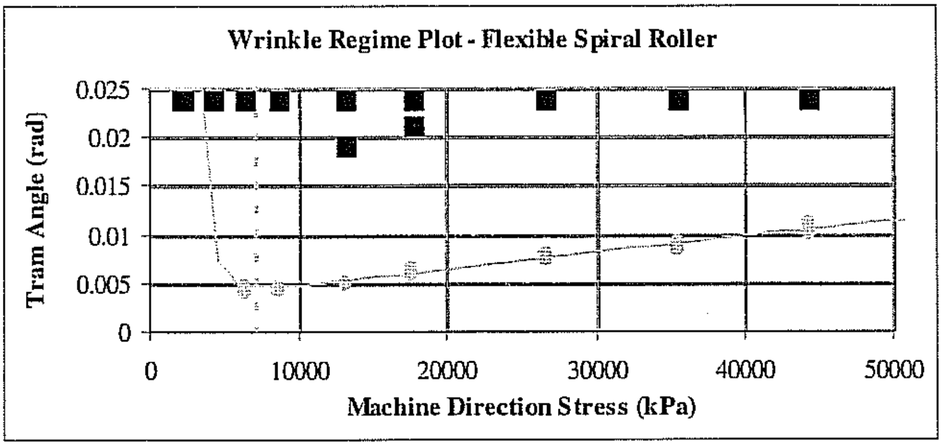

Figure 15. Flexible Spiral Roller

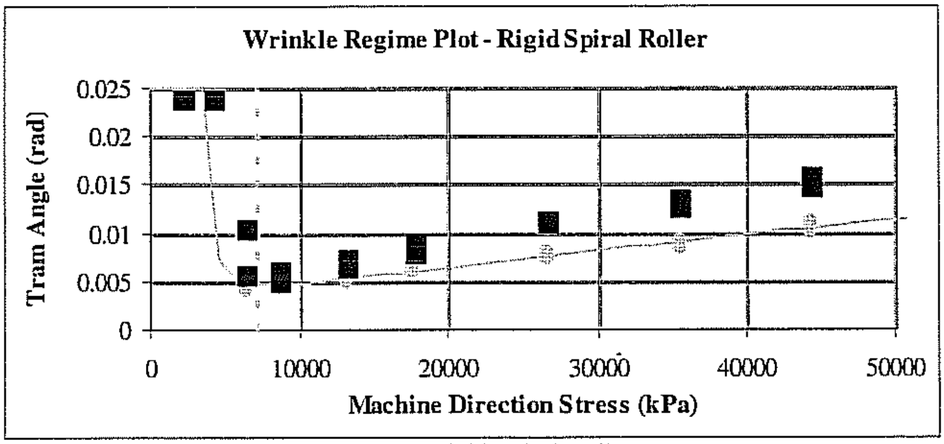

Figure 16. Rigid Spiral Roller

	Roller Name	Description	Size / Material
1	Idler Roller	Aluminum Idler	76 mm (3 in.) Nominal Diameter 306 mm (12 in.) Face Width Aluminum 0.0008mm 0.0008mm (32 micro in.) Ra
2	Outward Spiral Tape	Idler with 25mm (1 in.) 0.18 mm (.0072 in.) Masking tape	76 mm (3 in.) Nominal Diameter 306 mm (12 in.) Face Width Aluminum 0.0008mm 0.0008mm (32 micro in.) Ra
3	Inward Spiral Tape	Idler with 25mm (1 in.) 0.18 mm (.0072 in.) Masking tape	76 mm (3 in.) Nominal Diameter 306 mm (12 in.) Face Width Aluminum 0.0008mm 0.0008mm (32 micro in.) Ra
4	PTFE Tape	Idler with PTFE tape	76 mm (3 in.) Nominal Diameter 306 mm (12 in.) Face Width Aluminum 0.0008mm 0.0008mm (32 micro in.) Ra
5	Tape Bumpers	Idler with 25mm (1 in.) 0.18 mm (.0072 in.) Masking tape	76 mm (3 in.) Nominal Diameter 306 mm (12 in.) Face Width Aluminum 0.0008mm 0.0008mm (32 micro in.) Ra
6	Reverse Crown Roller	Reverse Crown 0.002 slope 153mm (6 in.)	76 mm (3 in.) Nominal Diameter 306 mm (12 in.) Face Width Aluminum 0.0008mm 0.0008mm (32 micro in.) Ra
7	Curved Axis Roller	Adjustable curve Adjustabe angle 15 Degree wrap	38 mm (1.5 in.) Diameter 306 mm (12 in.) Face Width Rubber
8	Expanding Surface Roller	Rubber Sleeve with Adjustable Angle End Plates	88 mm (3.25 in.) Diameter 330 mm (13 in.) Face Width Rubber
9	Flexible Spiral Roller	Angled Spiral Groove Cut in Rubber Surface	76 mm (3 in.) Nominal Diameter 306 mm (12 in.) Face Width Rubber
10	Rigid Spiral Roller	Aluminum Idler with Spiral Groove	76 mm (3 in.) Nominal Diameter 306 mm (12 in.) Face Width Aluminum 0.0008mm 0.0008mm (32 micro in.) Ra

Table 1. List of Roller Details

	Roller Name	Roller Drag Kg (lb)	Regime II Stress kPa (psi)	Regime I Factor	Center Spreading mm (in.)	Edge Spreading mm (in.)
1	Idler Roller	<.05 (<0.1)	7000 (1000)	1.00	0.00 (0.000)	0.00 (0.000)
2	Outward Spiral Tape	<.05 (<0.1)	2100 (300)	0.00	0.00 (0.000)	0.00 (0.000)
3	Inward Spiral Tape	<.05 (<0.1)	3500 (500)	0.00	0.00 (0.000)	0.00 (0.000)
4	PTFE Tape	<.05 (<0.1)	15400 (2200)	0.90	0.00 (0.000)	0.00 (0.000)
5	Tape Bumpers	<.05 (<0.1)	3150 (450)	1.39	1.19 (0.047)	@ 1.5" 2.59 (0.102)
6	Reverse Crown Roller	<.05 (<0.1)	11200 (1600)	1.89	0.20 (0.008)	4.70 (0.185)
7	Curved Axis Roller *	0.34 (0.75)	12950 (1850)	4.42	2.24 (0.088)	24.89 (0.980)
8	Expanding Surface Roller *	0.80 (1.75)	NA	>5.00	2.18 (0.086)	16.68 (0.657)
9	Flexible Spiral Roller	<.05 (<0.1)	11200 (1600)	4.43	0.36 (0.014)	0.94 (0.037)
10	Rigid Spiral Roller	<.05 (<0.1)	4900 (700)	1.47	0.00 (0.000)	0.00 (0.000)

* Depends on adjustable settings

Table 2. Results

Question - I think this is a good job of practical engineering work probably the best I have seen in years that we can take home and apply. Several years ago, there were a lot of questions on how spreaders acted and there was no evidence on how the spreaders worked.

Answer - Of these rollers only one came with an explanation how to use it. The rest came with packing peanuts.

Question - Explain in detail the difference in surface expanding roller in a curved axis roller.

Answer - The curved axis roller has a curved axis, expanded surface roller has a straight axis. If you would compare the surface velocity vectors, they would be similar. They produce similar results. They look similar to the web coming at the roller.

Question - With the spiral rollers mostly compliant soft cover and with the rigid, were the rolls driven, and if so were they driven faster or slower than the web?

Answer - The rollers were not driven in any case here, even the high drag rollers were not driven. I didn't actual measure if there were any micro-slip going on. It was going very close to the line speed if not exactly at line speed.