WRINKLE-FREE CONVEYANCE IN NIPS

by

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ABSTRACT

Wrinkling in nips with ultra-thin webs is empirically studied. In web converting, nips are used for tension isolation drives, gravure coaters, prevention of air entrainment on rollers and winding rolls, calendaring, laminating, etc. A common concern is wrinkles/creases that can form in the nip. The effects of roller design (straight, concave, bow, expanding surface, and compliant spiral groove) immediately upstream of the nip, web tension, web speed, and nip load on wrinkles are tested. Over the range of process parameters tested, the bowed roller was the most robust at preventing wrinkles in the nip. It was also learned that under certain conditions, the nip, itself, helps to prevent wrinkles.

INTRODUCTION

In order to decrease product cost, the web handling industry is being asking to convey thinner and thinner materials. When web thickness is decreased much below 20 μm, the yield of "standard" web-converting machinery decreases drastically as a result of wrinkle waste. Cerda and Mahadevan [1] and Roisum [2] describe the physics of wrinkling. It is common knowledge that poor roller alignment, excessive roller deflection, poor roller geometry, and non-uniform nip loading can lead to wrinkling. When the aforementioned problems are remedied and wrinkles remain, web-spreading techniques are often required to prevent wrinkling. Web spreading is defined as a device that stretches the web in the cross-machine direction.

Common examples of web spreaders are: concave, bow, expanding surface, and compliant spiral groove rollers. Appendix A contains "cartoon-like" schematics of each roller type and a brief description of its spreading theory. Roisum [3] discusses in more detail the physics of why these rollers spread. Swanson [4] provides an empirical study of the effectiveness of web spreading rollers at preventing wrinkling with 20 μm web. Neither Roisum nor Swanson discusses the use of web spreading to prevent wrinkling in nips. Walker [5] and Rosium [6] give some basic rules-of-thumb on using web-spreading devices. Both authors mention the use of spreaders in front of nips, but guidance on the best type of spreader is not provided. The purpose of this article is to determine the optimal conveyance setup to prevent wrinkling of ultra-thin (less than 20 μm) web conveying through a nip.

EXPERIMENTAL DESIGN

Parameters like roller alignment, roller deflection and non-uniform side-to-side nip pressure are not studied. (They were optimized prior to the test in order to minimize their effect on test results.) The effects of roller design (straight, concave, bow, expanding surface, and compliant spiral groove) immediately upstream of the nip, web tension, web speed, and nip load on wrinkles are tested. Uncoated PET web with a thickness of 4.5 μm and a width of 1.4 m was used for all tests. Fig. 1 shows a schematic of the web path of interest. Fig. 2 is a photograph of the test setup.

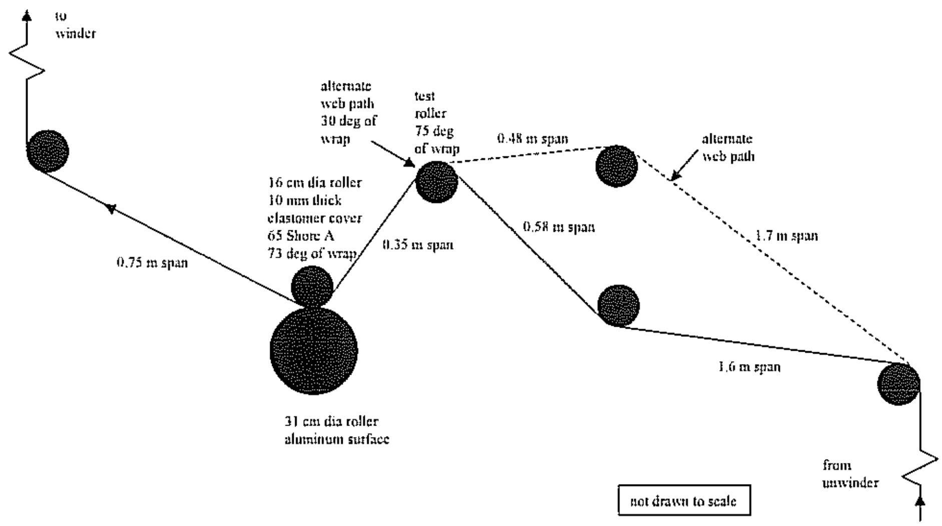

Figure 1 - Schematic of the Web Path

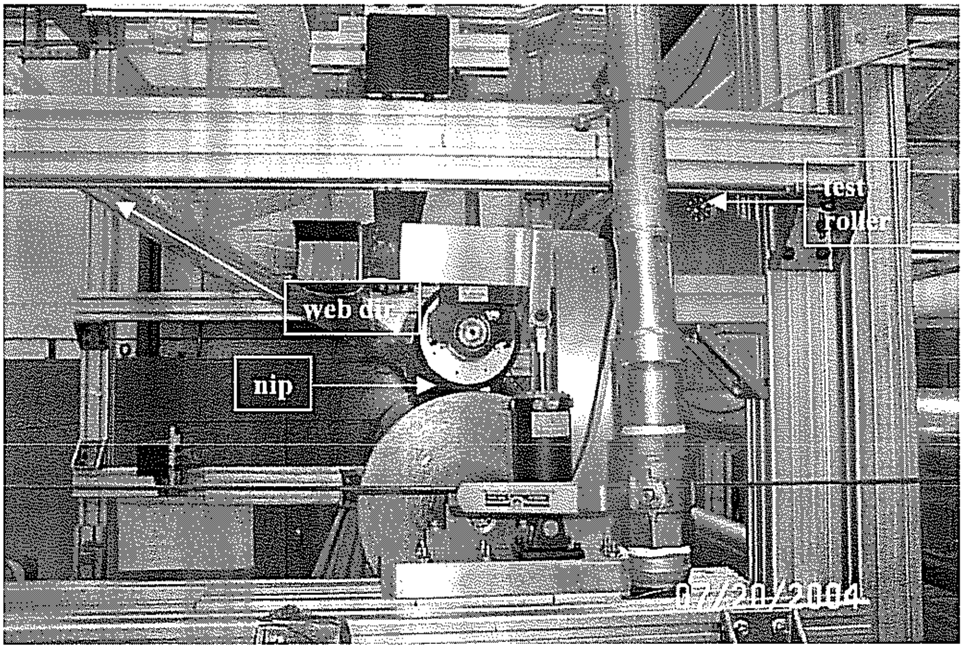

Figure 2 - Photograph of the Test Setup

Table 1 is a description of the various rollers tried immediately upstream of the nip. The bow roller and compliant spiral groove roller are shown in Fig. 3.

Test roller type	Description
Straight dia	10 cm dia, 80 grooves per meter, aluminum
Concave dia idler	13.4 cm dia in center, 13.42 cm dia on ends, 563 grooves per meter, aluminum
Bow	11.4 cm dia, 12 mm square groove pattern, elastomer cover, 3 mm of bow over 1.5 m face length
Expanding surface	14 cm dia, smooth elastomer cover, adjustable angle end plates titled 3 deg, 50 shore A
Compliant spiral groove	12.7 cm dia, 6 angled under-cut spiral groove starts per roller edge, elastomer cover, 26 shore A

Table 1. - Test Roller Descriptions

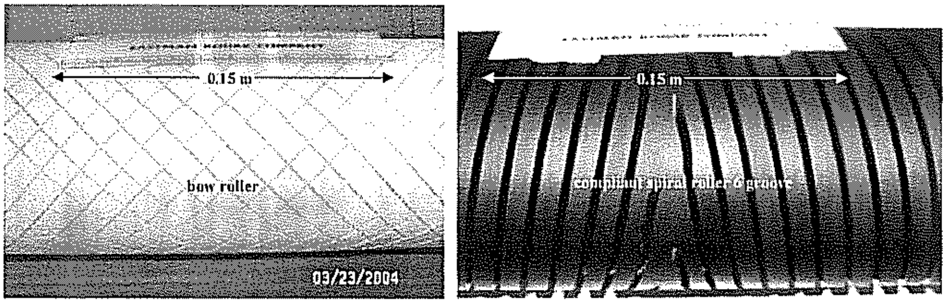

Figure 3 - Bow Roller and Compliant Spiral Roller 6 Groove

RESULTS

The effect of web tension, web speed, nip load, and upstream roller wrap angle on wrinkles in the nip were studied for various roller types used just upstream of the nip. In general, there are 16 (4 factors, 2 levels) experimental points for each roller type. For each roller type, the number of wrinkles entering the nip (wrinkles in), the number of wrinkles leaving the nip (wrinkles out), and the total number of wrinkles (wrinkles total) are listed for each experimental point in Table 2. (A wrinkle is defined as the web folding over onto itself, entering or leaving the nip. Counting wrinkles is a very inexact procedure, especially for ultra-thin web.)

		roller type=		straight			concave			bow			expander			spiral		
				wrinkles			wrinkles			wrinkles			wrinkles			wrinkles		
warp angle (deg)	nip load (N/m)	speed (m/min)	tension (N/m)	in	out	total	in	out	total	in	out	total	in	out	total	in	out	total
75	700	15	48	14	8	22	6	1	7	n/a	n/a	n/a	0	0	0	3	0	3
75	700	15	80	18	10	28	1	0	1	n/a	n/a	n/a	0	0	0	5	0	5
75	700	240	80	0	0	0	0	0	0	n/a	n/a	n/a	2	0	2	0	0	0
75	700	240	48	0	0	0	0	0	0	n/a	n/a	n/a	3	0	3	0	0	0
75	175	240	48	0	0	0	0	0	0	n/a	n/a	n/a	3	2	5	0	0	0
75	175	240	80	0	0	0	0	0	0	n/a	n/a	n/a	4	2	6	0	0	0
75	175	15	80	20	2	22	4	1	5	n/a	n/a	n/a	0	0	0	10	2	12
75	175	15	48	10	1	11	1	0	1	n/a	n/a	n/a	0	0	0	3	0	3
30	700	15	48	7	2	9	12	1	13	0	0	0	n/a	n/a	n/a	2	0	2
30	700	15	80	17	2	19	11	1	12	0	0	0	n/a	n/a	n/a	3	0	3
30	700	240	80	0	0	0	0	0	0	0	0	0	n/a	n/a	n/a	0	0	0
30	700	240	48	0	0	0	0	0	0	0	0	0	n/a	n/a	n/a	0	0	0
30	175	240	48	0	0	0	0	1	1	0	0	0	n/a	n/a	n/a	1	1	2
30	175	240	80	0	0	0	0	1	1	0	0	0	n/a	n/a	n/a	0	0	0
30	175	15	80	13	2	15	4	2	6	0	0	0	n/a	n/a	n/a	3	1	4
30	175	15	48	10	0	10	7	0	7	0	0	0	n/a	n/a	n/a	2	0	2

Table 2. - Summary of Test Results

Wrinkles for each of the rollers types is summarized below for each roller's "optimal" wrap angle. For the straight and concave rollers, the optimal wrap angle is defined as the wrap angle that produced the fewest wrinkles over the nip load, speed, and tension range tested for each roller. For the compliant spiral groove, the bow, and expanding surface rollers, the optimal angle was based on the manufacturers' recommendations. Fig. 4 is a column chart of the test data shown in Table 2 for each roller's optimal wrap angle. One important conclusion from the data: only the bow roller did not have wrinkles for any of the process conditions tested.

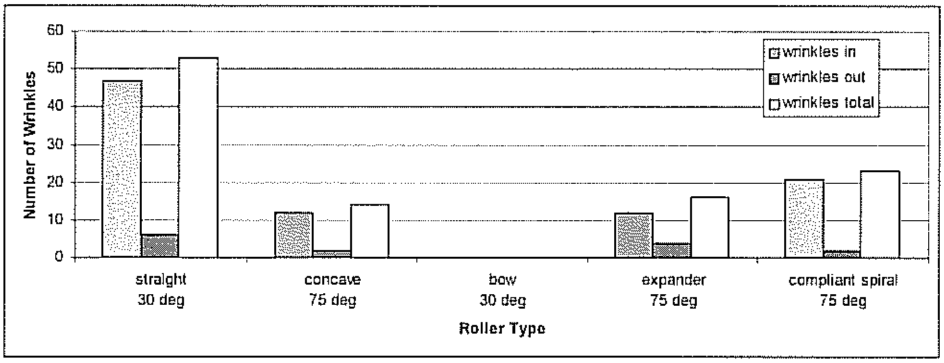

Figure 4 - Summary of Test Results for Each Roller's Optimal Angle

Looking at the data in Table 2, the most important process factor (besides roller type) affecting wrinkling is web speed. Fig. 5 is a column chart of the total number of wrinkles at the optimal wrap angle sorted by machine speed. The bow roller prevented wrinkling at 15 and 240 m/min. The straight, concave, and compliant spiral rollers prevented wrinkles at 240 m/min. The expanding surface roller prevented wrinkles at 15 m/min. Additional details on the wrinkling performance and design for each of the roller types will be discussed in the following five sections.

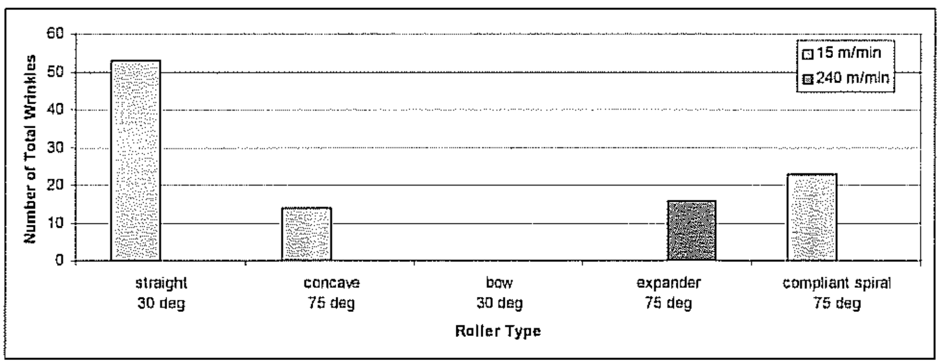

Figure 5 - Summary of Test Results for Each Roller's Optimal Angle, Sorted by Web Speed

Straight Diameter

The optimal angle to minimize wrinkling in the nip was 30 deg for this roller. *Why is that?* For a straight roller, the magnitude and number of drawlines and wrinkles near the roller increases with roller deflection and traction—30 deg minimizes both deflection and traction. Without using statistics, the results in Table 2 suggest that less wrinkling in the nip is present with: higher speed, lower wrap angle, and lower web tension. The effect of nip load was inconclusive.

Fig. 6 shows the entrance span for the straight diameter roller with a nip load of 700 N/m, a web tension of 48 N/m, and a wrap angle of 30 deg at 15 and 240 m/min. As previously mentioned, speed is an important factor in wrinkling in the nip. At 15 m/min, numerous drawlines are visible in the entrance span. Wrinkles are also present in the nip but not visible in the picture. (Note that the drawlines in the entrance span are not considered wrinkles unless they fold over onto the rubber nip roller.) At 240 m/min, all of these drawlines and wrinkles are gone. Based on the data in Table 2, at 240 m/min, the straight diameter roller was as good as or better than all of the spreading rollers at preventing wrinkles in the nip. *Why is that?* In general, with ultra-thin webs, the magnitude and number of drawlines and wrinkles near a straight diameter roller decreases with decreasing traction—air entrainment reduces traction of the poorly vented test roller. This is a second-order effect in preventing wrinkles with a nip. If the nip roller assembly was replaced with a standard straight diameter idler, the drawlines at 15 m/min would improve at 240 m/min, but it would not be as dramatic as shown in Fig. 6.

In Fig. 6, the web span entering the nip is actually being spread in the cross-machine direction. *What is causing the web to spread?* When straight diameter nip rollers are brought together, the nip width profile is smaller in the center than at the edges. This is a result of the deflection of the rollers' neutral axes. This hourglass nip profile results in a parabolic surface velocity profile [7], with the edges traveling faster than the center. Using carbon paper, the nip was 11 mm wide at the edges and 8 mm in the center at a nip load of 700 N/m. A theory explaining spreading is explained next. Like a concave diameter roller [8], this parabolic velocity profile produces a spreading action. The spreading force is present at low or high speeds. At high speeds, air entrainment reduces the traction of the rubber-covered nip roller prior to the nip. Once traction on the entrance of the rubber roller is lost, the nip spreading action is sufficient to pull the drawlines and wrinkles out of the web. At low speeds, the traction of the web against the rubber nip roller prevents the web from being spread. This would imply that a heavy nip in the center would cause wrinkling. While not studied, when the nip has an hourglass profile, not wrapping the rubber nip roller prior to the nip might actually be superior at preventing wrinkles.

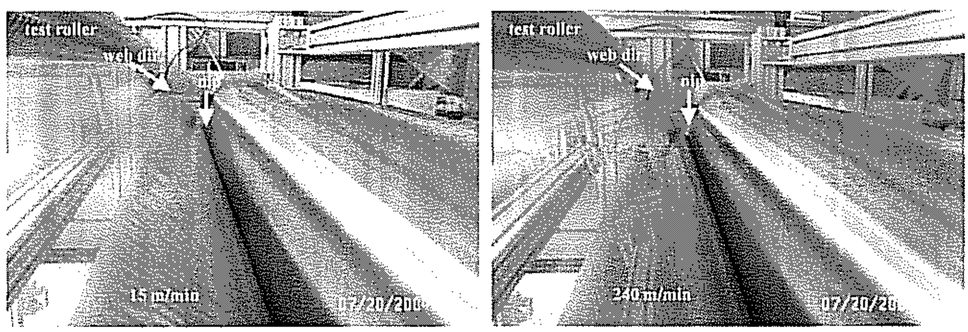

Figure 6 - Entrance Span for Straight Diameter Roller at 15 and 240 m/min

Concave Diameter

The optimal angle to minimize wrinkling in the nip was 75 deg for this roller. *Why is that?* For a concave roller, the magnitude and number of drawlines and wrinkles near the roller decrease with improved traction—75 deg has more traction than 30 deg. Without using statistics, the results in Table 2 suggest that less wrinkling in the nip is present with:

higher speed, higher wrap angle, and higher web tension. The effect of nip load is inconclusive. Based on the data in Table 2, at 30 deg of wrap the concave diameter roller was arguably worse than a straight diameter roller at preventing wrinkles in the nip.

Fig. 7 shows the entrance span for the concave diameter roller with a nip load of 700 N/m, a web tension of 48 N/m, and a wrap angle of 75 deg, at 15 and 240 m/min. At 15 m/min, drawlines are visible in the entrance span. Wrinkles are also present in the nip but not visible in the picture. At 240 m/min some drawlines remain, but the wrinkles are gone. As discussed in the straight diameter roller section, it is believed that the hourglass shape of the nip can spread the web at high speed.

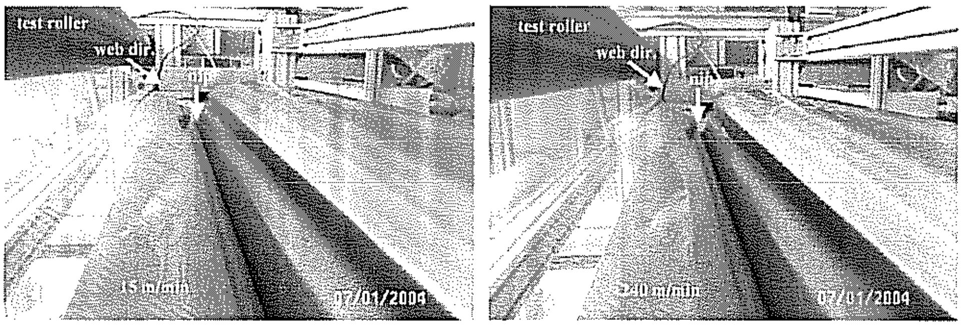

Figure 7 - Entrance Span for Concave Diameter Roller at 15 and 240 m/min

Owing to its low maintenance, a concave roller is arguably the best spreading roller to prevent wrinkles on the roller itself. The spreading action of a concave roller does not extend far enough downstream to make it an effective spreader prior to a nip. This is shown in Fig. 7, at 15 m/min, where drawlines have reformed downstream of the concave roller.

Bow

Only one wrap angle, 30 deg, was tested for this roller. (Based on the manufacturer's literature, it was expected that this roller would perform equally well at 75 deg of wrap.) This roller showed no drawlines or wrinkles for all conditions tested. Fig. 8 shows the entrance span for the bow roller with a nip load of 700 N/m, a web tension of 48 N/m, and a wrap angle of 75 deg at 15 and 240 m/min. Unlike previous rollers, web speed has no effect on the appearance of the web. This bow roller has grooves, as shown in Fig. 3. It is expected that the spreading effectiveness of an ungrooved bow roller would not be as effective at high speed under these process conditions.

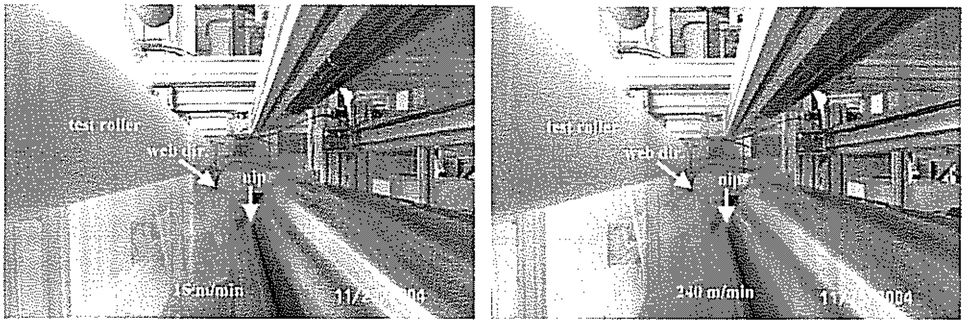

Figure 8 - Entrance Span for Bow Roller at 15 and 240 m/min

The bow roller is relatively free spinning. It takes 2.6 N of web tension to initially rotate the bow roller and 1.8 N to keep it rotating at slows speeds. At 240 m/min and 48 N/m of web tension, the bow roller was rotating at line speed. The roller was bowed 3.2 mm over its 1.6 m face length. The direction of bow was set up as shown in Fig. 9. The plane of the bow is perpendicular to the wrap angle bisector with the center high point pointing in the direction of web travel—as recommended by the manufacturer.

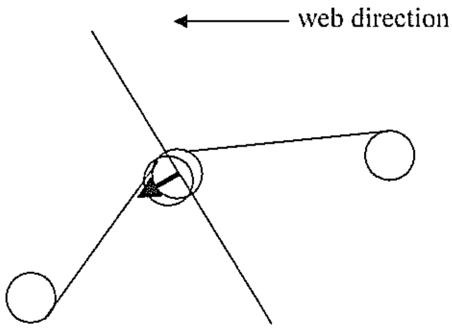

Figure 9 - Setup of Bow Roller

Expanding Surface

Only one wrap angle, 75 deg, was tested for this roller. (Based on the manufacturer's literature it was expected that this roller would perform worse at 30 deg of wrap.) This roller showed no drawlines or wrinkles at 15 m/min for all conditions tested. Fig. 10 shows the entrance span for the expanding surface roller with a nip load of 700 N/m, a web tension of 48 N/m, and a wrap angle of 75 deg at 15 and 240 m/min. Unlike the straight and concave diameter rollers, this roller performed better at lower web speeds. Unlike the straight, concave, and bow rollers, wrinkling was present in the nip at 240 m/min. The expanding surface roller required good traction to spread the web, the smooth roller at high speeds had insufficient traction to spread the web, and wrinkles in the nip resulted.

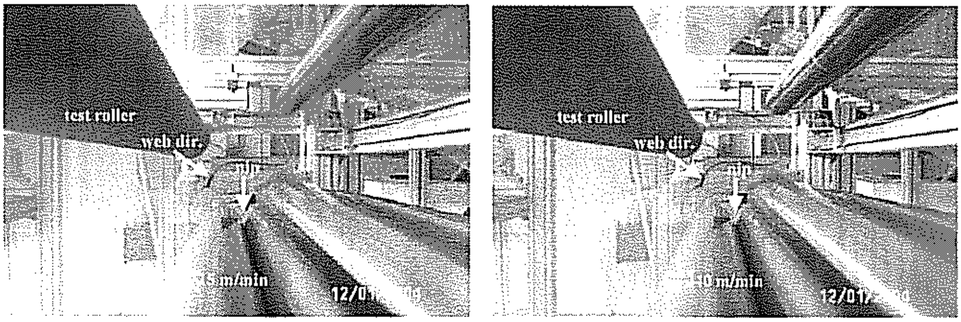

Figure 10 - Entrance Span for Expanding Surface Roller at 15 and 240 m/min

The expanding surface roller has significant drag. It takes 8.4 N of web tension to initially rotate the bow roller and 5.7 N to keep it rotating at slows speeds. At 15 m/min and 48 N/m of web tension, the expanding surface roller was rotating at line speed. At 240 m/min and 48 N/m of web tension, the expanding roller was not rotating at all. The end caps were tilted 3 deg. The web enters the roller where the sleeve expansion begins.

Compliant Spiral Groove

The optimal angle to minimize wrinkling in the nip was 75 deg for this roller. (Based on the manufacturer's literature, it was expected that this roller would perform worse at 30 deg of wrap. The results from these tests are inconclusive in terms of what wrap angle performs better.) Based on the data in Table 2, at 30 deg of wrap, the compliant spiral grooved roller was worse than a straight diameter roller at preventing wrinkles in the nip at 240 m/min. Without using statistics, the results in Table 2 suggest that less wrinkling in the nip is present with higher speeds. The effects of wrap angle, nip load, and tensions are inconclusive. The fact that the effect of tension on wrinkling was inconclusive was surprising, given that the rollers should operate better with greater rubber deflection. Sometimes increasing tension helps; while other times, it made the situation worse. This was observed when counting wrinkles and observing the overall flatness of the web entering the nip.

Fig. 11 shows the entrance span for the compliant spiral grooved roller with a nip load of 700 N/m, a web tension of 48 N/m, and a wrap angle of 75 deg at 15 and 240 m/min. At 15 m/min, drawlines are visible in the entrance span. Wrinkles are also present in the nip but not visible in the picture. At 240 m/min, some drawlines remain, but the wrinkles are gone. As discussed in the straight diameter roller section, it is believed that the hourglass shape of the nip can spread the web at high speed.

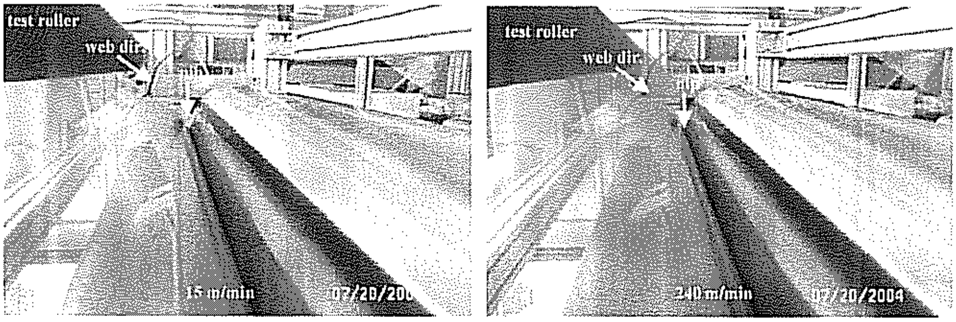

Figure 11 - Entrance Span for Compliant Spiral Grooved Roller at 15 and 240 m/min

One- and 4-groove-compliant spiral rollers were briefly evaluated. In general the 1-groove roller made wrinkling worse than the standard straight idler. The 1-groove design was not flexible enough for the low tensions that are used with ultra-thin webs. The 4-groove design was more flexible and resulted in better performance than 1-groove, but it was not nearly as effective as the 6-groove design.

CONCLUSIONS

Wrinkling in nips with ultra-thin webs was empirically studied. The effects of roller design (straight, concave, bow, expanding surface, and compliant spiral groove) immediately upstream of the nip, web tension, web speed, and nip load on wrinkles were tested. Over the range of process parameters tested, the bowed roller was the most robust at preventing wrinkles in the nip. The bow roller prevented creases over the entire range of process conditions tested. The expanding surface roller worked well at low speed; but as a result of its low traction and high drag, it performed poorly at high speed. With a straight diameter roller at 240 m/min, all of the drawlines and wrinkles going into the nip were gone. It was also learned that under certain conditions, the hourglass shape of the nip profile provided a spreading effect that could prevent wrinkles. This surprising result explained why the straight diameter roller performed so well at 240 m/min. In certain cases, the concave diameter roller, the expanding surface roller, and the compliant spiral grooved roller were less robust at preventing wrinkles than just a straight diameter roller.

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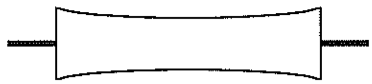
APPENDIX A

Straight diameter

Deflection of the roller's neutral axis as a result of web tension causes the web to contract

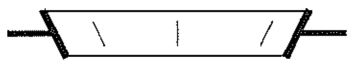


Concave diameter

The end result of the roller's parabolic surface velocity causes the web to spread

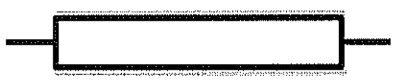
Bow

Deflection of the roller's neutral axis as a result of moments applied to the roller in combination with the rubber surface stretching causes the web to spread



Expanding surface

Stretching of the roller's rubber surface as a result of tilting its end-plates causes the web to spread



Compliant spiral grooved

Deflection of the roller's complaint rubber surface as a result of web tension causes the web to spread

Name & Affiliation	**Question**
Keith Good Oklahoma State University	I agree with your comments about not wrapping the rubber nip roller. That would have been interesting as part of the tests. Also now you are illustrating that we need to look at a dichotomy in nip design – is that right? Previously we have been trying to keep nip force constant across the width and thus even out the velocity across the web width. Now you are telling us that we ought to design some flexibility into the nip rollers and make them spreaders.
Name & Affiliation	**Answer**
Brian Rice Eastman Kodak Company	Yes. It depends upon what your nip is supposed to do. For a lot of cases, you have to have a flat profile for coating and other processes. I have actually seen some equipment where they have nip rollers in front of winders. I think this was done to help spread the web prior to winding.
Name & Affiliation	**Question**
David Pfeiffer JDP Innovations	Have you considered the effect of web air flotation on the straight roll, because you probably have a very small air film? Supporting the web on an air film over a curved surface is a good spreading method as there is some ability for the film to move edgewise. A wrinkle traveling around a roll is a multiply curved surface, whereas a straight roll is a singly curved surface. The web wants to be singly curved. Do you have a comment on that?
Name & Affiliation	**Answer**
Brian Rice Eastman Kodak Company	I agree with what you say 100 percent. The straight roller was poorly vented and had very little traction. Without friction, you can't have creasing. The thing I found interesting, though, was the nip area. It appeared that loss of traction on the entrance at the nip roller was the reason why we had such good performance in the nip.
Name & Affiliation	**Comment**
J. D. Pfeiffer JDP Innovations	With a rubber covered nip roller, you have an enforced speed difference because the surface of a rubber roll is actually going slow outside the nip, speeding up in the nip. With that enforced speed difference, you are causing some flotation of the web at that point.
Name & Affiliation	**Answer**
Brian Rice Eastman Kodak Company	The loss of traction on the entrance of the rubber nip roller can be explained by air entrainment.