Anatomy of a Wrinkle

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April 17, 2008

Introduction:

Figure 1 illustrates one of the most common defects in web handling - wrinkling. Wrinkles start as troughs in free spans. But, not all troughs become wrinkles. Troughs are caused by compressive CD stress. If the trough extends to the point of entry onto a roller, it may become a wrinkle. It seems that a trough has to deepen until it reaches a critical point where it propagates onto a roller surface. Once formed, the wrinkle may then grow and collapse on itself to become a permanent crease.

Experienced researchers have understood the basic physics of this process for some time. It was documented in a paper presented at an IWEB conference in 1997 titled "Shear Wrinkles in an Isolated Span" by Good, Kedl and Shelton. Elastic instability plays a role. At some level of compressive stress, the web almost has to pop up off the roller surface. The trough geometry is also a factor. At the point of contact with a roller the 3D geometry of the trough interacts with the roller in a way that encourages it to advance onto the roller. The coefficient of friction between the web and roller is obviously a major factor. It is a well-known fact that making a roller more slippery can often eliminate wrinkles.

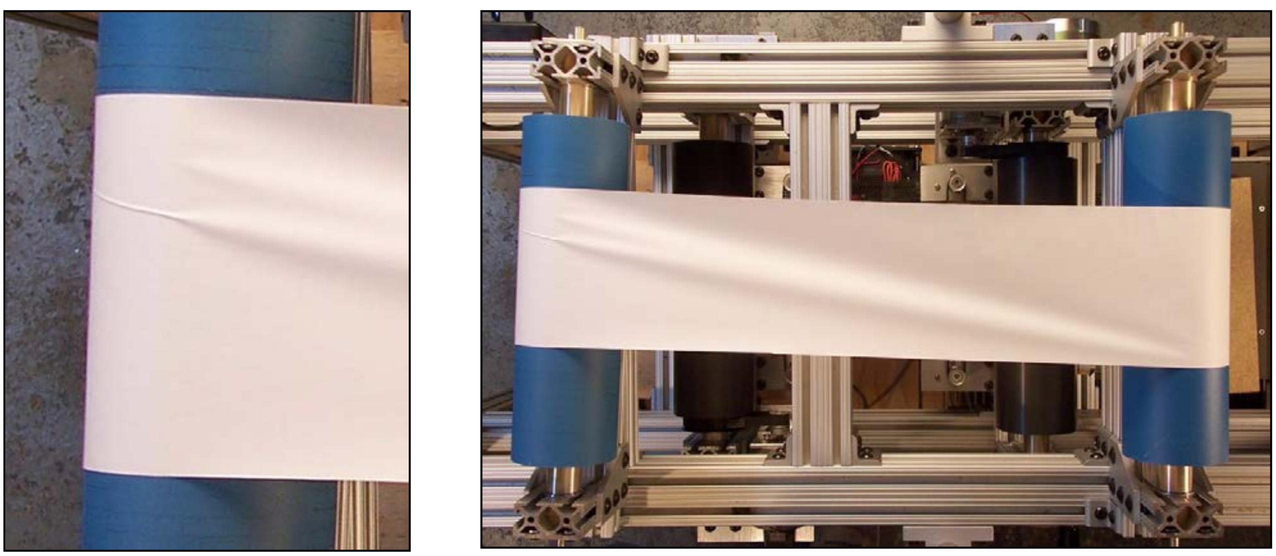


Figure 1
Wrinkling in a paper web

In this paper, each step of wrinkle formation is studied using stop-motion photography so that the interaction of these factors can be observed. This is done on a lab machine specially constructed for this type of study. It can handle a latex web operating at large strains so that the web deformation may be directly observed. It can also be run at very slow speed for observation and then stopped gently for photos.

The machine:

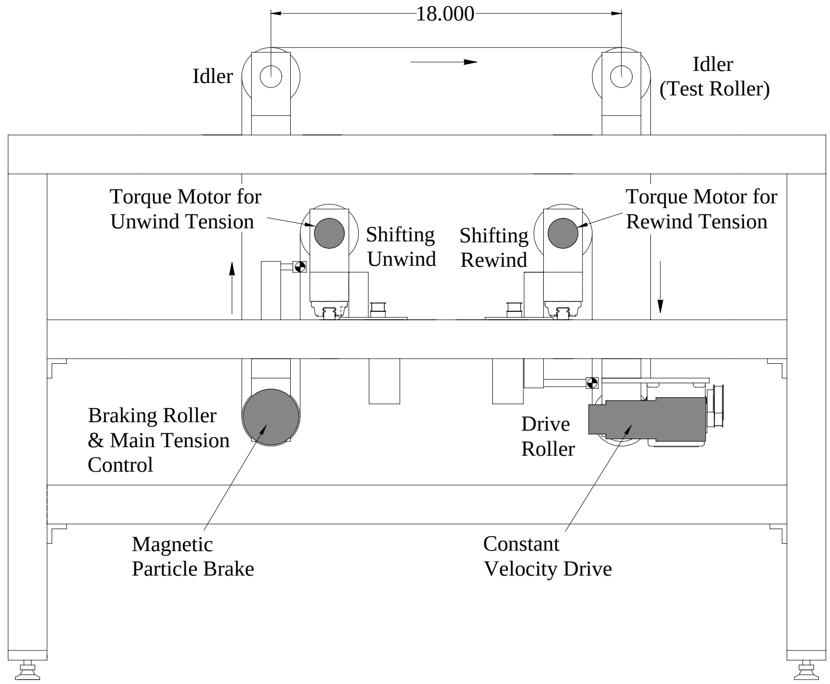


Figure 2

Lab machine designed to run extremely slow with frequent stopping

Rollers: 10 inch face length, 3 inch diameter, coated with polyurethane. Coefficient of friction between rollers and latex approximately 1.0.

Drive: Closed-loop velocity control with tachometer feedback - 0 to 20 Ft/min

Tension control: Magnetic hysteresis brake, no feedback - 0.5 to 6 Lb

Lateral position control: Closed loop control at unwind with edge sensor. Currently the rewind is open loop. However it is on a THK rail with a drive arrangement identical to the unwind so lateral control can be easily added.

Rewind and unwind tension: Constant torque to insure rolls don't overrun and to provide input tension to the capstan drive and brake. No feedback. Torque is minimum possible.

During test runs, the working tension is isolated from the unwind and rewind to minimize winding issues. Winding tension is on the order of 1/10 the running tension and a complete roll has less than 25 layers.

If 10 spans of web pass through the 18 inch test span it will have reached 99.995 % of its steady state position. In most experiments, 5 to 6 Ft of web is adequate. The web is then rewound by hand at low tension by threading it directly from the rewind to the unwind.

The machine can handle all common materials. But, special attention was given to enabling operation with latex

The latex used in the experiments described here was 26 mils thick, 240 psi modulus, 5.5 inches wide, and 20 feet long.

Latex can be stretched several hundred percent without damage. It does exhibit some bad characteristics such as viscoelasticity and nonlinearity. But, so do most of the plastics used for film production. By running at elongations of ten percent (0.1 inch per inch) it is possible to make deformations visible without provoking much more nonlinear behavior than is seen in ordinary webs. Printing a rectangular grid on the web enhances visibility of the deformation.

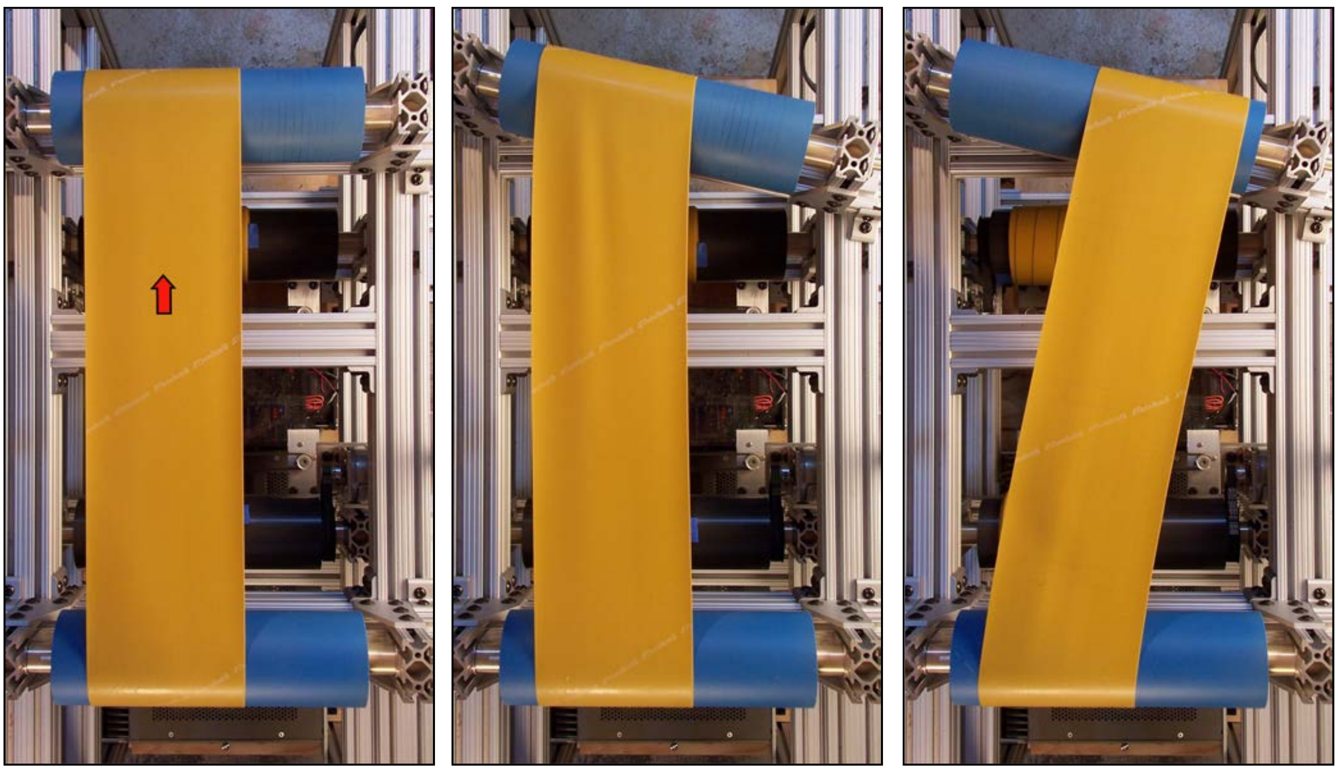
Another advantage of using a latex web is that it has a high Poisson ratio, which amplifies the MD and CD interaction.

Two fundamental principles:

Two fundamental principles play an important role in the explanations that follow. One is the normal entry rule. It says:

> *A web entering onto a roller will align its direction of travel perpendicular (normal) to the roller axis. If the web is not initially perpendicular, it will travel laterally on the roller at a rate proportional to the tangent of the angle between the web and the roller until it reaches the perpendicular condition.*

An extreme example is illustrated with a latex web at a misaligned roller in Figure 3 .



(a) **(b)** **(c)**

Figure 3

(a) **Web traveling between aligned rollers**
(b) **Downstream roller misaligned by 12 degrees**
(c) **Final position of web after running long enough to reach its steady position**

The other principle is the normal strain rule. It says:

> *In a steady state, the ratio of the stretched lengths of an infinitesimal patch of the web at the entries of two successive rollers is proportional to the respective ratios of the web velocities at the two rollers (provided the strains and velocities are measured normal to the roller axes). In other words, if the web speeds up by 1% relative to the previous roller, it will have to elongate by 1% to insure that the mass flow is the same at the two locations.*

An extreme example of this rule in action is illustrated in Figure 4, once again with a latex web.

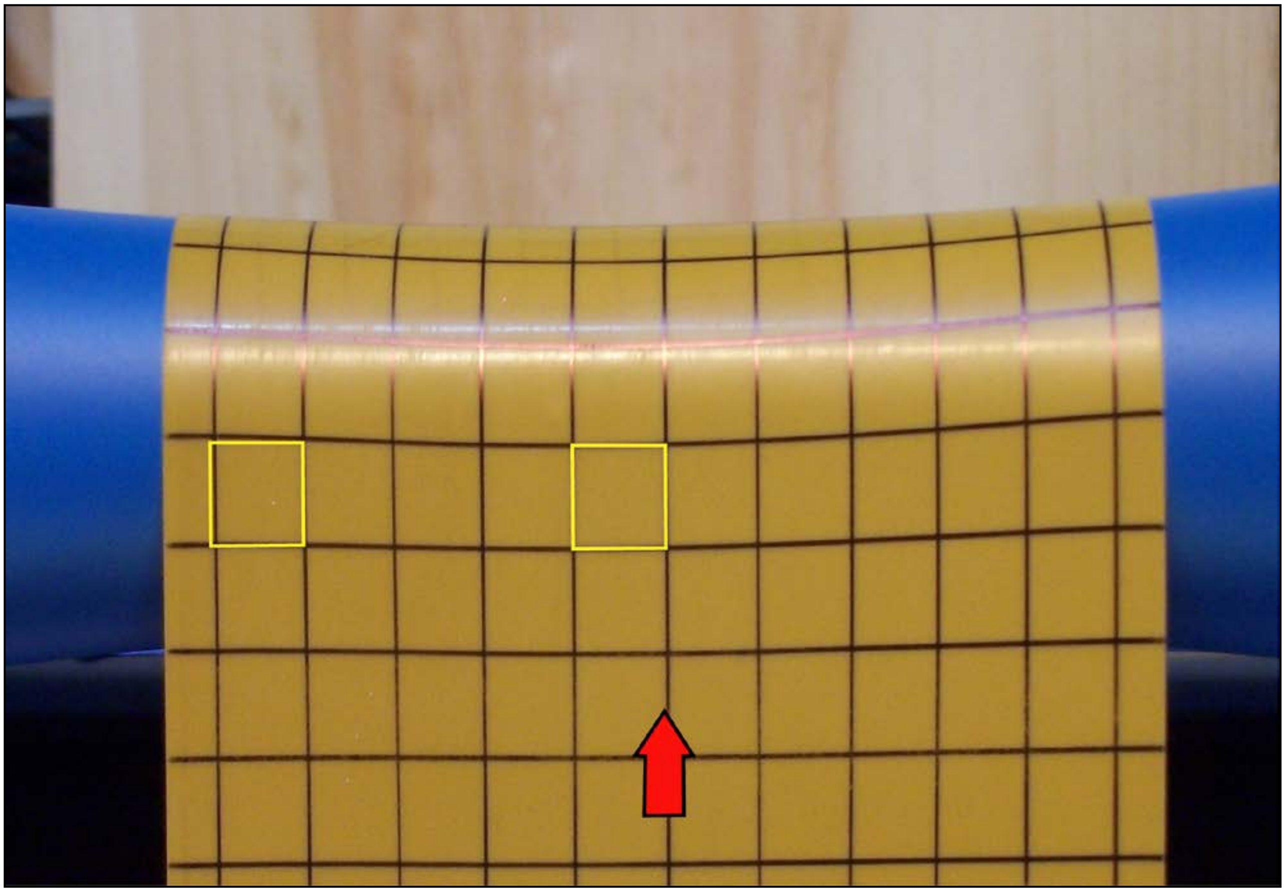


Figure 4
Latex web on an extremely concave roller

In this case the web is passing over a concave roller with a very deep profile. Because of the increased roller circumference at the web edges, it must move with higher MD velocity there. This produces higher tension at the edges relative to the middle. This can be seen if you examine the relationship of the two identical yellow boxes to the black grid. The yellow boxes were drawn on the photo, using photo-editing tools. The black grid was drawn directly onto the web before photographing it. The box near the center fits the black grid perfectly. Near the left edge, the black grid has stretched in the MD direction so that it is a little longer than at the middle. There is also a small amount of CD contraction of the black grid due to Poisson's ratio. The overall effect, therefore, of the concave roller profile is to cause each of the black horizontal lines to take the shape of a "smile" at the roller. If it were not for the normal entry rule, the vertical lines of the grid would remain perpendicular to the curved horizontal line, causing them to "toe" in towards the center of the web. This doesn't happen because normal entry rule causes them to spread outward to meet the roller perpendicular to its axis. The net result is lateral spreading.

Convex rollers have the reverse effect and generally produce wrinkles.

The setup for studying wrinkles:

There are many causes for wrinkles.

- Roller misalignment
- Roller deflection (reverse bow)
- Tension drop across a driven roller
- Expansion of a web due to temperature or moisture
- Twist

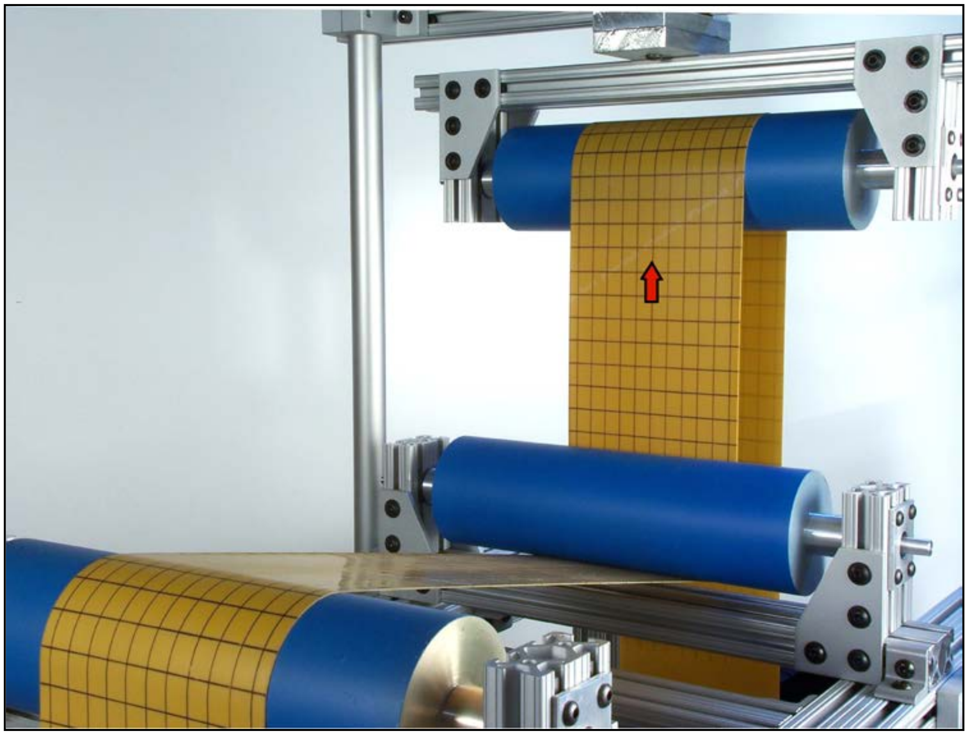


Figure 5
Twisted web setup

Twist is an ideal case to study because,

- It produces a single wrinkle in the center of the web.
- The wrinkle is aligned with the machine direction and, therefore, doesn't move laterally.
- Wrinkle formation is easily controlled by adjusting the twist angle.

This arrangement is based on an experiment described by Dr. Good and one his students, P. Straughan at the 1999 IWEB conference. The top roller pivots about a point in the span that has the red arrow on it. The pivot bracket is visible at the very top of the photo.

Operating tension was 6 Lbf. The twisted span is 8.5 inches long. Wrinkles form at a twist angle of 45 degrees. Figure 6 shows the web in its twisted position before it begins moving in the machine direction.

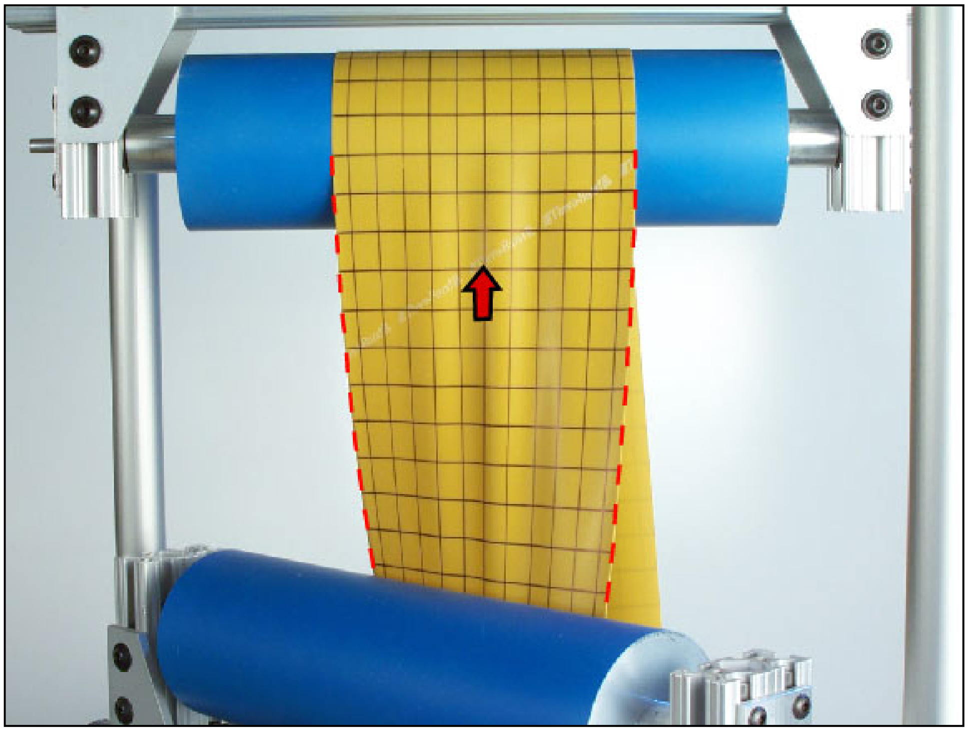


Figure 6
Web twisted 45 degrees

This view is perpendicular to the axis of the twisted roller at the top. The dashed red lines trace out the web edges. The web appears to taper from full width at the top to a narrower value at the bottom. At the very bottom and top of the span, the web width hasn't changed, because the web is not moving yet. So, most of the taper is an illusion due to the angle of view. However, the taper near the top, where the web is viewed head-on, is real. This is because the edges have come closer together midway down the span. That is why the web has buckled. This is easy to understand if you imagine the web is gone and the dashed red lines are strings. Then, if the roller kept twisting, the strings would keep getting closer until they would overlap and make contact at 180 degrees of twist. Thus, the geometry of the twist creates compressive CD stress. The MD lines that were perpendicular to the roller axis before twisting have become slightly inclined toward the edges. This will bring the normal entry rule into play.

Development of a wrinkle:

In Figure 7 the web has been allowed to advance in the machine direction. The troughs now begin to concentrate near the midline of the web. As a reference, a horizontal yellow line has been superimposed on the photo just beyond the point of roller contact. Note that the horizontal black grid line is slightly curved in a “frown”. This indicates that the tapered web geometry has begun to advance onto the roller. Under the influence of the normal entry rule, the web on both sides of the midline will track toward the center bringing excess material into the center of the web, increasing the CD compression.

As the trough begins to advance onto the roller, the normal strain rule begins to augment the effect of the normal entry rule because the wrinkle is elevated above the roller surface and is therefore traveling at a higher velocity. This causes the wrinkled zone to behave like a crowned roller.

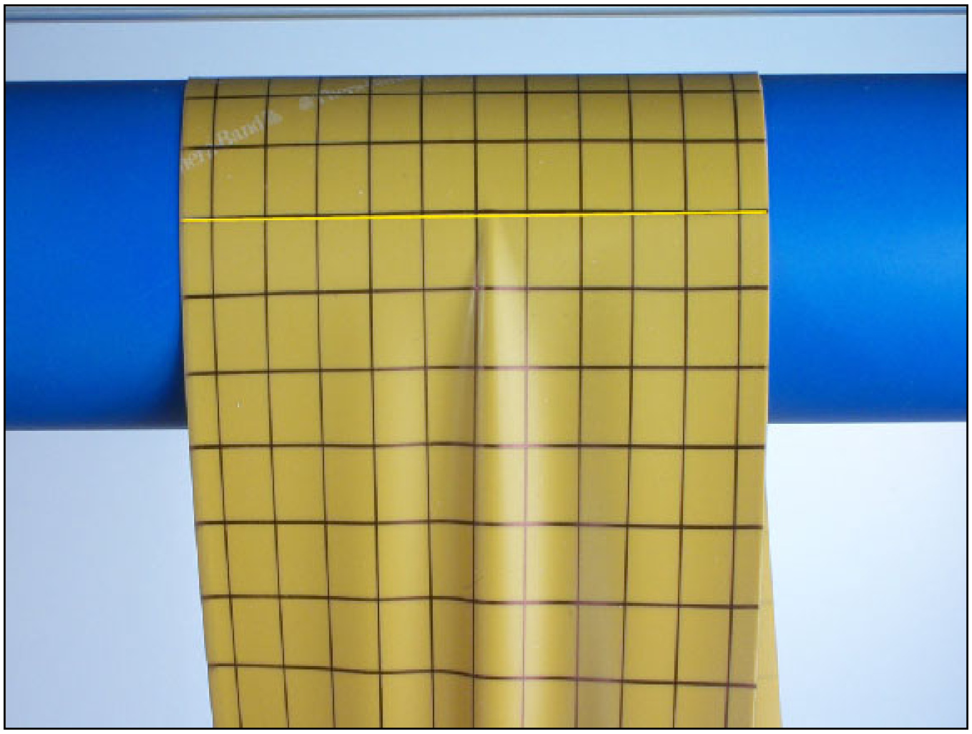


Figure 7
Web after advancing a few inches

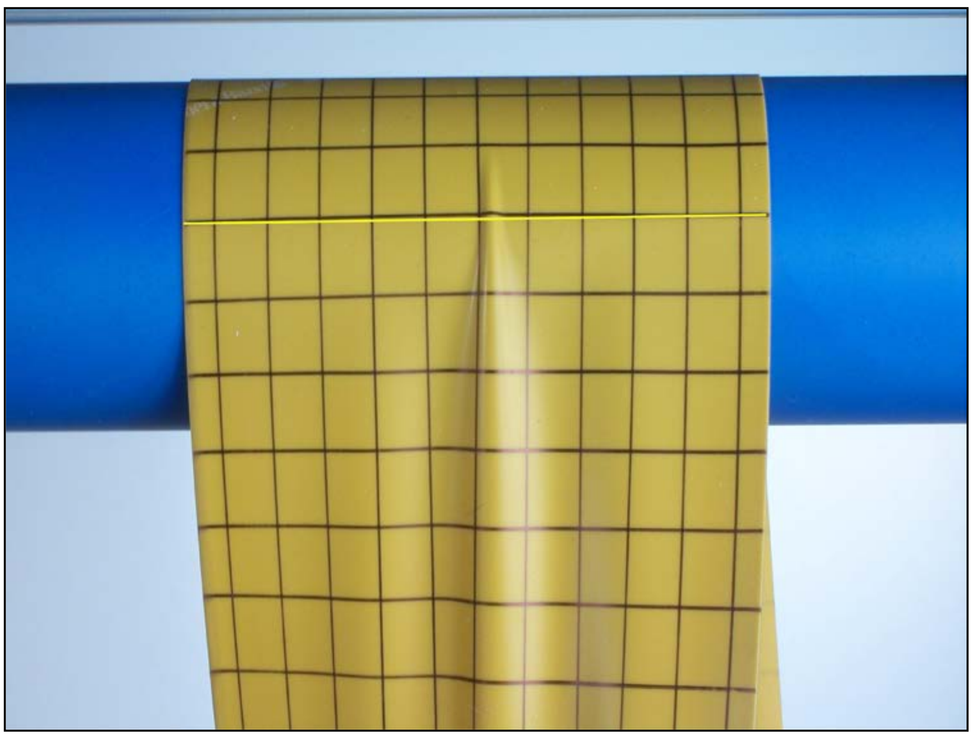


Figure 8
Wrinkle begins to form as the web advances further

In Figure 8 the web has advanced further and the wrinkle is forming. The “frown” is now more pronounced.

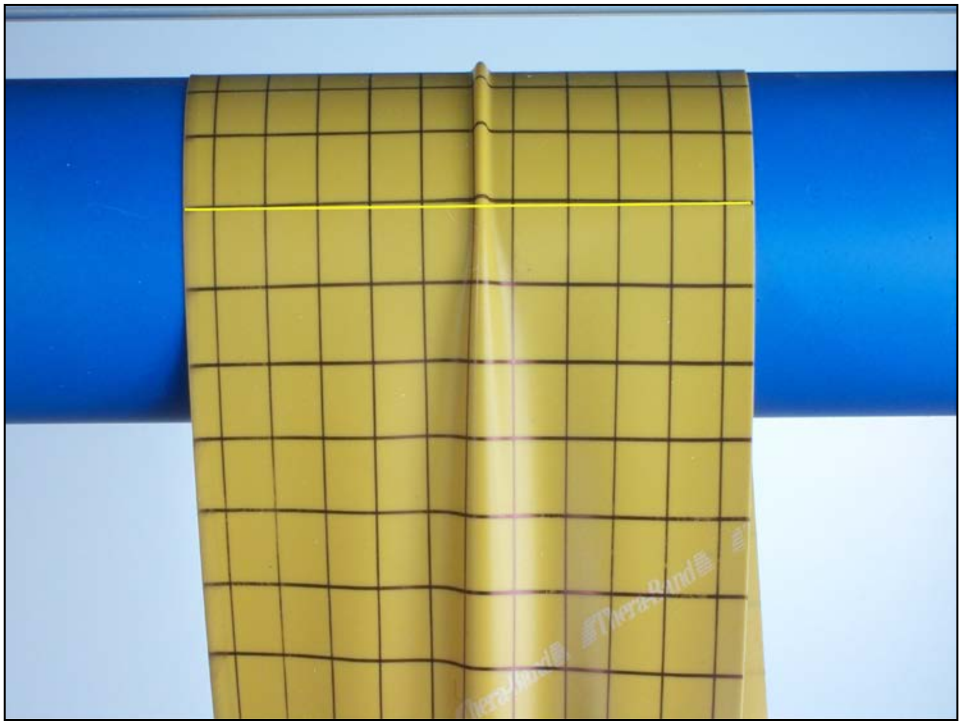


Figure 9

Material continues to collect in the center and the wrinkle grows in height

Figure 9 shows the wrinkle narrowing and growing in height as more material is brought to the center.

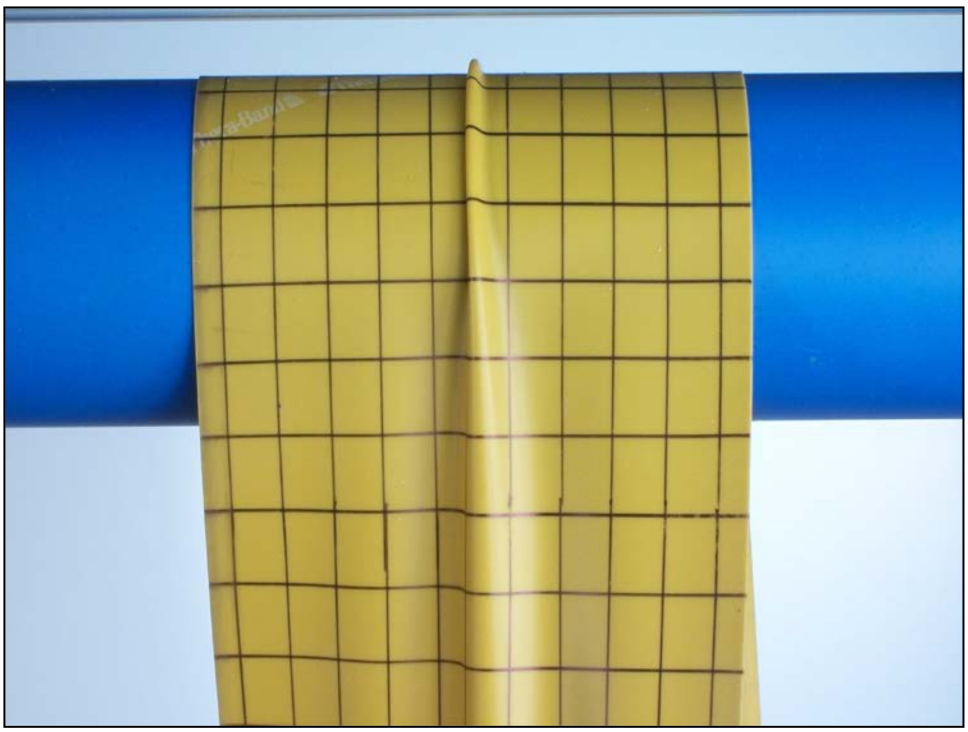


Figure 10

Wrinkle begins to fold over and form a crease

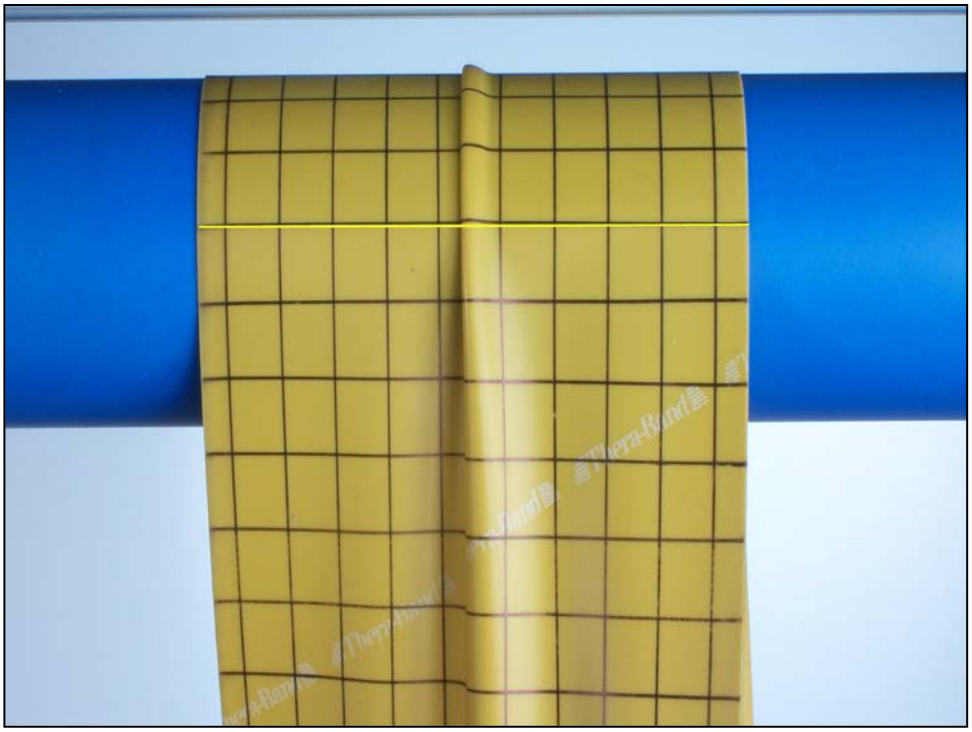


Figure 11
The crease continues to grow to absorb material coming in from the edges

Figure 10 shows the wrinkle beginning to fold over. Figure 11 shows the fold fully developed and growing. The overlap of the fold will continue to grow until the web narrows enough for the normal entry rule to reverse direction and begin balancing the effect of the normal strain rule.

The effect of realignment of the roller:

It's interesting to rotate the top roller back into alignment while leaving the web in its wrinkled state. Then, as the web is advanced, the wrinkling process reverses. Note also, that as this occurs, the horizontal grid lines become "smiles". In other words, the web geometry takes a spreading effect like that in Figure 4.

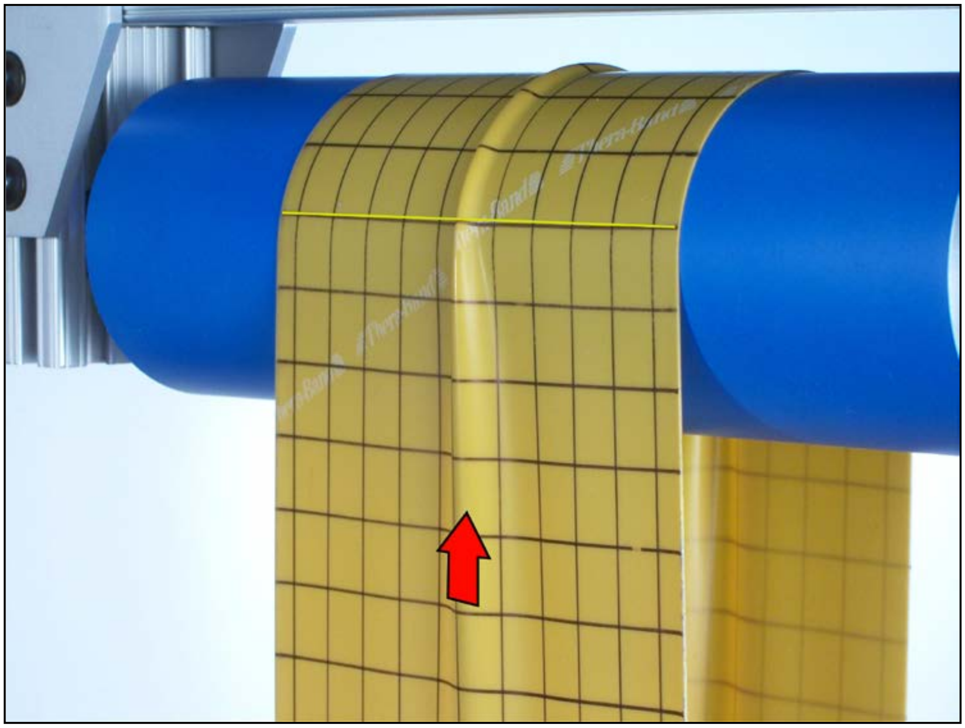


Figure 12
Wrinkle beginning to disappear as web moves onto realigned roller

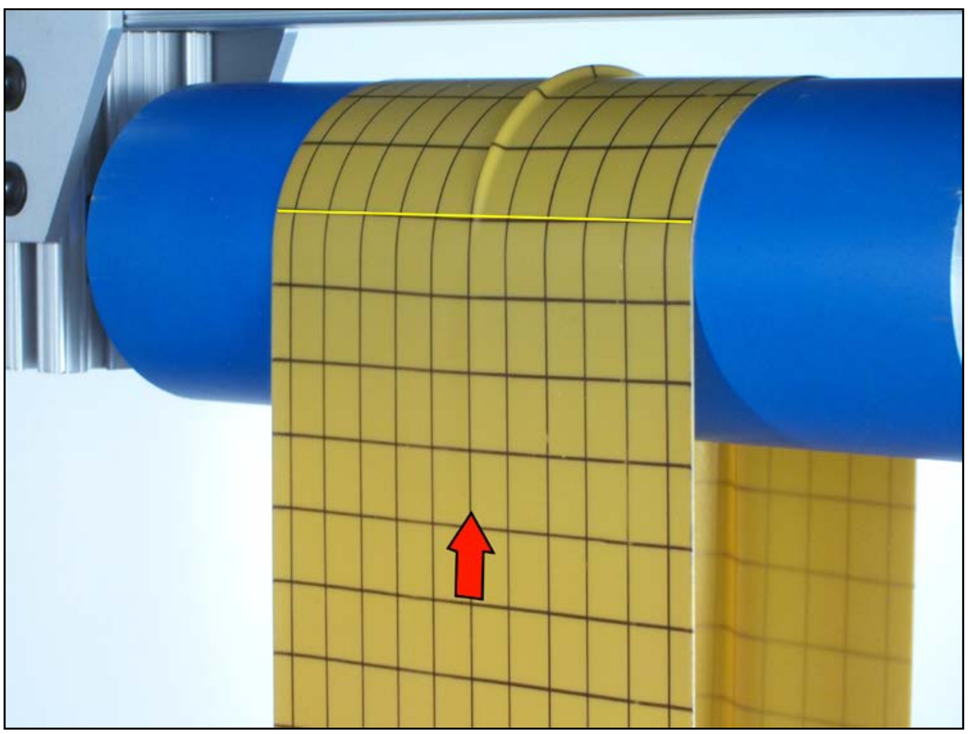


Figure 13
The wrinkle continues to diminish as the web moves

Forces involved in wrinkle formation:

Figure 14 illustrates the forces acting on a wrinkle. First there is the radial force, shown in red, which is produced by the interaction of roller curvature and web tension. These forces are shown only over the wrinkle. But, they exist all over the web surface where it is supported by the roller. This tends to keep the web flat against the roller surface. Then, there is the inward motion produced by the normal entry and normal strain rules, shown in violet. This creates a lateral force on the web at the center where the material accumulates. Friction between the web and the roller, shown in green, anchors the web on each side of the wrinkle to the roller surface. With nowhere to go but up, the web eventually buckles and the wrinkle forms.

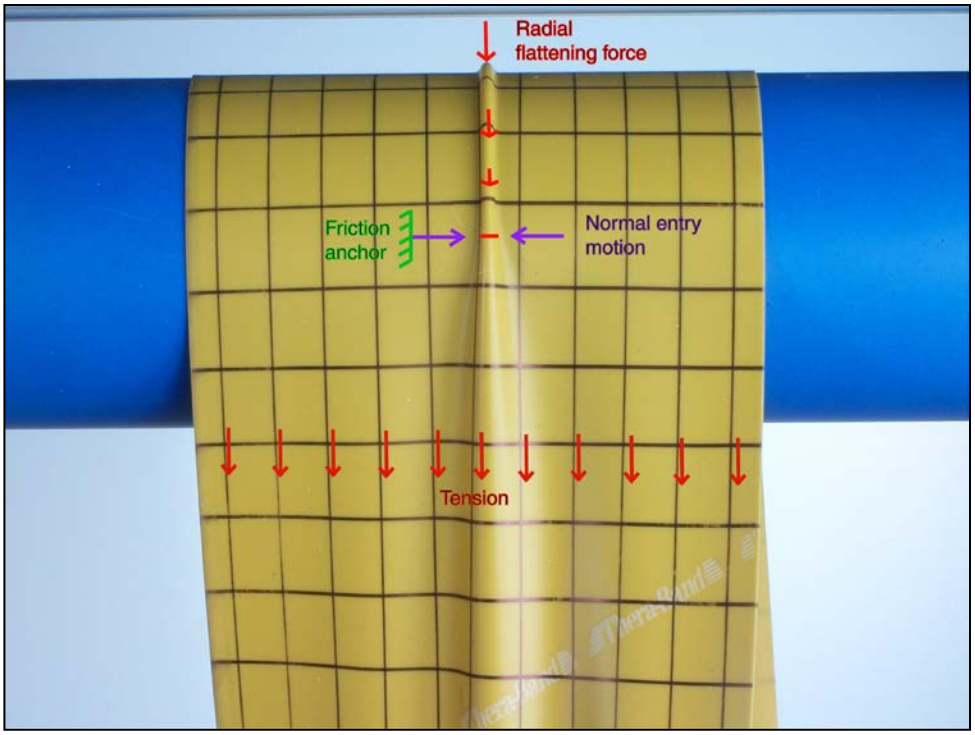


Figure 14
Forces acting on a wrinkle

Ways to reduce wrinkle formation:

Consideration of Figure 14 suggests several methods for eliminating wrinkles. One is to counteract the spreading effect of the web geometry with the roller shape - making it concave or bowed. Another method is to reduce the friction that anchors the web to the roller so that the forces generated by the normal entry and normal strain effects are limited. These techniques are illustrated in the accompanying PowerPoint presentation.

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