# WRINKLING OF FOILS

By

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## ABSTRACT

Aluminum and copper metal webs less than 150 microns (6-mils) are considered foils. Demand for aluminum and copper foils are growing, driven by growing markets for flexible electronics, flat panel displays, lithium batteries, and solar products. In many of these products, thinner foils have cost or weight advantages, but as with nearly any web, thinner means an increased sensitivity to wrinkling in web handling processes.

Nearly all of published web handling research and development work have been based on polymer films and paper webs. Since the web wrinkling theories are based on first principles, they should apply to the foil webs. However, applying models confirmed with paper or foil on narrow widths (less than 0.3m or 12-in wide) to the uncharted territories of foils with 20x elastic modulus and 4x width increases will likely lead to interesting discoveries.

This paper will present a comparison of empirical wrinkling results from trials of handling thin and wide aluminum and copper foils (less 25 micron thick by greater than 0.6m wide (less than 0.001-in thick by 24-in. wide). The experimental results will be compared to wrinkling theory, with conclusion about how wrinkling in foils differs from film and paper webs.

## NOMENCLATURE

| | |
|---|---|
| $E$ | Young's modulus of elasticity, Pa |
| $h$ | Web thickness, m |
| $K$ | Shelton web span stiffness parameter, $m^{-1}$ |
| $L$ | Span length, m |
| $L_0$ | Span length after misaligned roller (exit span), m |
| $L_1$ | Span length before misaligned roller (entry span), m |
| $L_2$ | Span length before roller upstream of misaligned roller (pre-entry span), m |
| $R$ | Roller radius, m |
| $w$ | Web width, m |

| | |
|---|---|
| $\varepsilon$ | Strain in web in machine direction, -- |
| $\theta_{tram}$ | Slope of web and roller relative to aligned upstream roller, radians |
| $\theta_{wrap}$ | Wrap angle of roller between two spans, radians |
| $\theta_{cr}$ | Roller misalignment angle required to induce troughing, radians |
| $\mu$ | Coefficient of friction, -- |
| $\sigma_{ycr,I}$ | Lateral stress required to buckle web in span, Pa |
| $\sigma_{ycr,II}$ | Lateral stress required to buckle web on roller, Pa |
| $\sigma_x$ | Stress in machine direction (positive induces tension), Pa |
| $\tau_{cr}$ | Shear stress in web, Pa |
| $\nu$ | Poisson's ratio, -- |

## PROBLEM DEFINITION

*Will copper and aluminum foil webs run wrinkle-free on equipment designed for paper and film handling? What is the recommended roller alignment specification for aluminum and copper foil web handling?*

Roller alignment specifications drive equipment cost. If roller alignment is non-critical, then machining tolerance can be relaxed and machine alignment procedures will take less time. If roller alignment tolerances are tight, equipment design, fabrication, assembly, and maintenance will all cost more. Misaligned rollers can create lateral shifting in processes, but mostly, roller alignment tolerance is driven by wrinkling, specifically, shear wrinkles.

*What roller misalignment will create shear wrinkles in wide aluminum and copper foil based on shear wrinkle models? Can the shear wrinkling models that successfully predict shear wrinkles in narrow film and paper experiments be applied to predict wrinkling in wide metal foils?*

In predicting when shear wrinkles will form from roller misalignment, the most significant difference between foils and papers or films is their much greater modulus of elasticity. The machine direction Young's modulus of many papers and polyesters (PET) will range from 3-7 GPa (450kpsi to 1Mpsi). The Young's modulus of aluminum is approximately 70 GPa (10Mpsi). The modulus of copper is usually listed as 105 GPa (15Mpsi), but in foils, may be closer to aluminum foil or below (55-70 GPa or 8-10 Mpsi). High modulus creates greater stiffness. Foils will have much higher critical buckling stresses.

## PREDICTIONS FROM ISOLATED-SPAN SHEAR WRINKLING MODELS

When the isolated span shear wrinkle model [3] is run using the parameters of thin, wide copper or aluminum foil it predicts that their high modulus and low strain will make wide foils extremely sensitive to roller misalignment. The isolated span model predicts a buckling zone as a function of web tension (or web strain) and roller misalignment angle as a function of many product and process variables, including span length, web width, web thickness, web elastic modulus, web Poisson's ratio, and web to roller traction forces.

In a typical shear wrinkle plot, there are two transitions from buckle-free and buckling conditions. The first transition, commonly called Regime I, predicts the buckling of the span, what is commonly called troughing [3]. In Regime I the critical angle to form troughing increases with tension or strain due to a tension stiffening effect. The equations below (X, Y, Z) govern the buckling of an isolated span. It is not clear from a review of these equations, but the net result is that Regime I buckling is a direct function of average strain. The high modulus of foils does not provide a stiffness advantage in Regime I buckling sensitivity. For a given tension, the strains and the critical troughing angle will be lower. However, at equal strains, the web geometry (thickness, width, span length) will be the critical factors on when troughs form.

$$\theta_{cr} = \frac{6\tau_{cr}L^2}{Ew^2} \quad \{1\}$$

$$\tau_{crit} = \sqrt{\sigma_{y_{cr}}^2 - \sigma_x\sigma_{y_{cr}}} \quad \{2\}$$

$$\sigma_{ycr,I} = -\frac{\pi h}{L}\sqrt{\frac{E\sigma_x}{3(1-\nu^2)}} \quad \{3\}$$

The second transition, Regime II, is a traction limited effect where decreasing tension reduces web-to-roller traction to a point where the roller-applied forces will no longer be able to exceed the web critical buckling stress [3]. Regime II wrinkle-free conditions will expand with thicker webs and lower traction forces. The traction forces between a web and roller are a function of tension (in units of force per width), web width, wrap angle, and coefficient of traction. [Coefficient of traction is a function of coefficient of friction, and lubrication variables of roller diameter, web speed, roller and web roughness, and viscosity of the environmental lubricant whether air or liquid.]

In the isolated-span shear wrinkle model, width will be a strong factor in the Regime II transition. Narrow aluminum or copper will not wrinkle due to insufficient web-roller friction to create the buckling load. However, wide aluminum and copper foils can have sufficient friction to shift Regime II tension, predicting the formation of troughs at small tram angles for typical handling tensions.

$$\sigma_{ycr,II} = \frac{E}{\sqrt{3(1-\nu^2)}}\frac{h}{R} \quad \{4\}$$

Beyond the clear cut theoretical lines of Regime I and II, experimental results often show a rounding or 'knee point' in the tension (or strain) vs misalignment plots. The shape of this transition zone is not predicted by the Regime I and II models, but can create a significant wrinkle-free zone not predicted by the isolated span model.

What is the relationship between product width and thickness in isolated-span shear wrinkles for polyester films? Is the relationship different for foils?

One of the great advantages of process models is the 'what-if' analysis, where combinations of product and process variables can be explored for their significance. This is especially useful when first principle models become increasing complex and difficult to grasp from equations alone.

Figure 1 shows the Regime I and II model outputs for 12 micron (0.5-mil) thick polyester film at widths ranging from 300 to 1500 mm (12 to 60-in.). From this, it is clear that width is an important variable in Regime I wrinkle sensitivity, but has a small effect on Regime II behavior, largely because 12 micron film has a low buckling stress that is easily reached even with 300mm (12-in.) widths.

In a strict following of Regime I and II theoretical curves, polyester films become sensitive to roller misalignment in the common roller alignment specification angle of 0.2 mradians. However, two factors make the 0.2 mradian specification acceptable for thin polyester. First, the roller angle where wrinkles form has been shown to be two times [6] the Regime I troughing criteria. Second, the transition zone from Regime I and II opens the wrinkle-free process window above the model lowest critical angle.

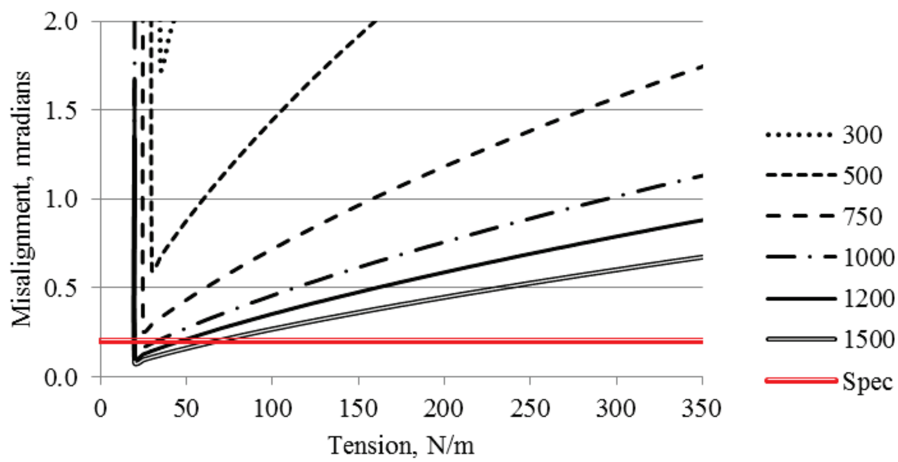


Figure 1 – Shear Wrinkles vs. Polyester Film Width

Figure 2 shows a comparison of isolated-span shear wrinkle modeling of polyester and aluminum. In all cases, the width is fixed at 1200mm (48-in.) and the theory is plotted for decreasing thicknesses of 35, 20, and 8 micron (1.4, 0.8, and 0.3 mils) thicknesses.

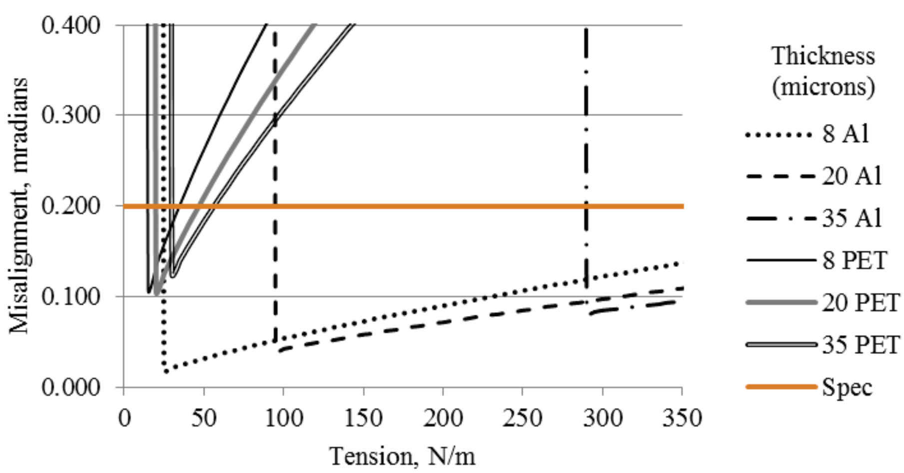


Figure 2 – Shear Wrinkles – Aluminum vs. Polyester as a Function of Tension

In shear wrinkling theory plots of tension (in force per width) vs. misalignment angle, if you choose a tension along the Regime I zone and move vertically to greater roller misalignment, you will find that thicker webs will wrinkle at small angles than thinner webs. This is quite surprising at first when many converters would believe that wrinkles sensitivity decreases with thickness cubed.

From this plot, you could also conclude that thickness will be a much more important factor in foils than in polyester over the same tension range. Thicker foils (>35 micron) will be completely in Regime II and impossible to shear wrinkle over a tension range of 50 to 250 N/m. Thinner foils, 20 micron and below, will prove difficult to run on equipment designed to a 0.2 mradian tramming specification, unless the transition zone from Regime I to II will create a process window.

The polyester vs. aluminum comparison is more interesting and instinctive when tension is converted into strain (Figure 3). On a strain-tram angle plot, if you choose a tension along the Regime I zone and move vertically to greater roller misalignment, you will find the expected trend of thinner webs wrinkling at small angles than thicker webs. However, the difference is still far less than the cubic effect believed by some converters. The change from 8 to 35 microns, a greater than 4x thickness change would provide a 64x wrinkle sensitivity change in a cubic effect, but the model shows a modest 2x benefit for thickness.

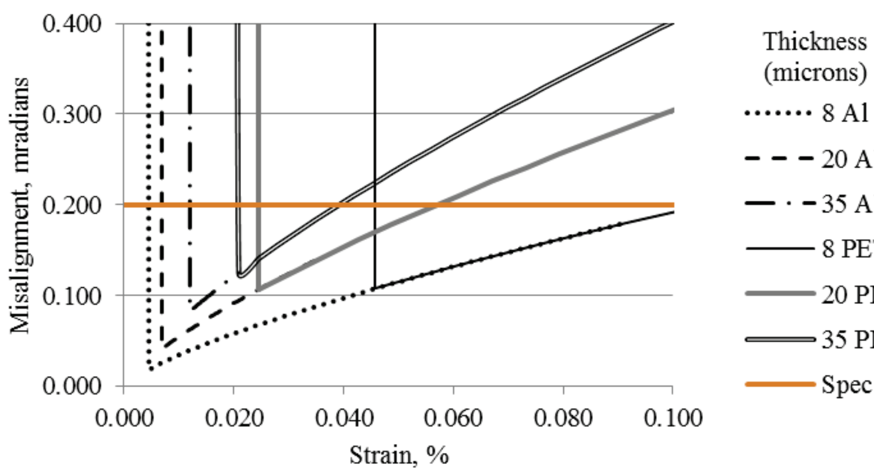


Figure 3 – Shear Wrinkles – Aluminum vs. Polyester as a Function of Strain

One more surprising conclusion from the strain-tram angle plots is that modulus is a non-factor in Regime I behavior. Both the aluminum and polyester webs have Regime I curves that lie atop each other for a given product thickness. Only the Regime II asymptote is shifted by modulus. Multiplying this Regime II strain difference by the higher foil modulus predicts a large wrinkle-free foil handling process window.

Figure 4 shows the effect of foil width on Regime I and II theory curves (20 micron or 0.8 mil thickness). As with polyester, increasing width greatly increases Regime I shear wrinkle sensitivity. If the theoretical curves are strictly followed, foils would be extremely difficult to run wrinkle free on equipment aligned to a 0.2 mradian specification at width above 1m (40-in.).

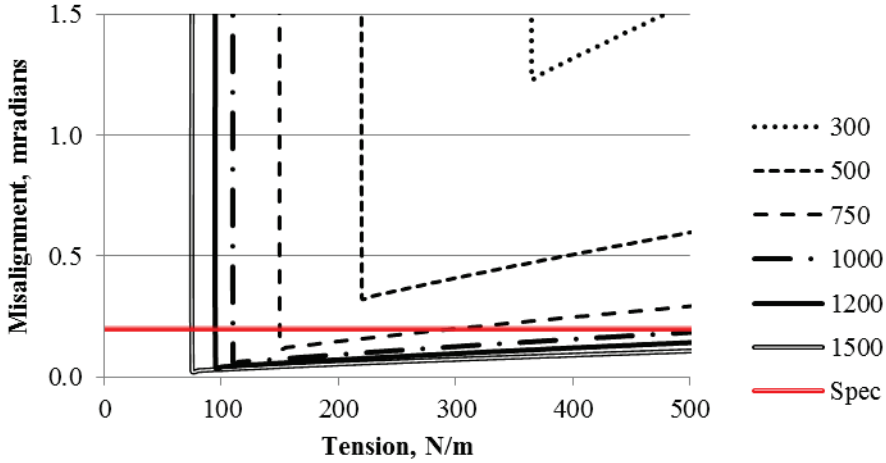


Figure 4 – Shear Wrinkles vs. Foil Width

After reviewing what isolated-span shear wrinkles models would predict, the next step is to complete experiments to confirm whether these models will predict actual troughing and wrinkling.

## RESULTS OF FOIL WRINKLING EXPERIMENTS

Our experimental set up was a wide version of the classic shear wrinkle experiments, similar to the experimental equipment used at web handling labs at 3M Company and Oklahoma State University [3].

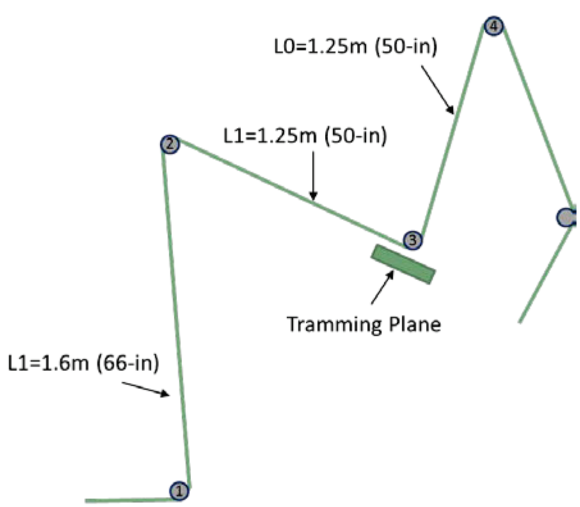


Figure 5 – Elevation Diagram of Shear Wrinkle Experimental Setup

The shear wrinkle experimental system includes four rollers (see Figure 5 and 6). The first and second rollers control the pre-entry (L2) span length. The second and third rollers control the shearing entry span length (L1). The third and fourth roller control the exit span (L0). The second, third, and fourth rollers are positioned to create a 90-degree wrap on the third roller. The third roller is mounted on a pivot frame able to change the rollers alignment by pivoting about the roller's center, creating web bending in the entry span (L1) and twisting in the exit span (L0). Dial indicators measure the shift of one end of the roller. The misalignment angle is found by dividing the end error by the measured distance from the central pivot point.

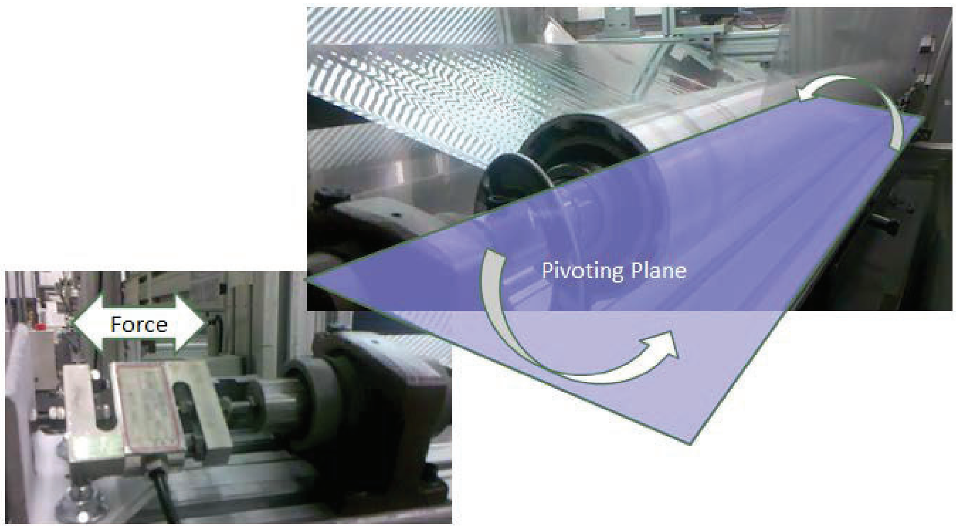


Figure 6 – Images of Shear Wrinkle Experimental Setup

In all experiments, a target roller is installed in a pivoting frame. The web tension and speed are fixed. The web is transported through the system with the target roller initially aligned. The target roller is slowly misaligned and the web behavior is observed, looking initially for the transition to troughing (which can be difficult to detect in baggy webs under low tension conditions) and wrinkling (when the buckled web passes over the roller, usually forming a crease). Besides entry span troughing and wrinkling, other behavior was also observed, including troughing in the pre-entry spans and wrinkling on other rollers, either upstream on roller #2 (commonly called a back-side wrinkle) or downstream (possibly from twisting).

**Narrow Foil Wrinkling**

Initial shear wrinkle trials were completed with 10 micron (0.4-mil) thick by 0.4m (15.7-in) wide copper foil. The results are shown below and plotted vs. Regime I and II predictions.

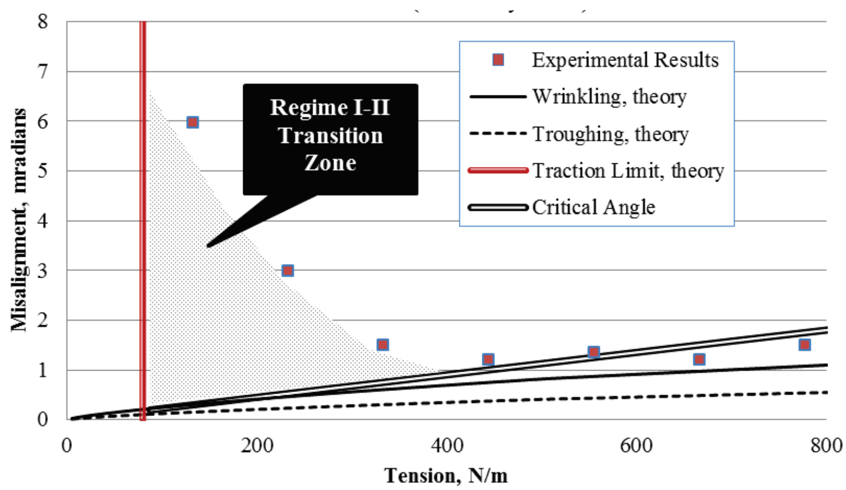


Figure 7 – Shear Wrinkling in Copper Foil - Results vs. Theory

In Figure 7, the critical tram angle is plotted alongside the wrinkling theory curve. Where the critical tram angle is above the wrinkling theory curve, the experimental results have good agreement with Regime I predictions; however, in low tension, low strain conditions, the critical tram angle and the wrinkle theory curve are much further apart and the likelihood of moment transfer is high.

This plot of the experimental wrinkling results against the isolated-span shear wrinkle model are in good agreement for the higher tension, higher strain conditions. As the tension drops towards the traction limit, the experimental results show a transition zone seen in other shear wrinkle published work [3]. The misalignment required to create wrinkles will deviate from the Regime I theoretical curve and asymptotically approach the vertical Regime II theoretical line.

Where Regime I and II theoretical curves are poor predictors of shear wrinkling is in the transition zone. In the case of some films and foils, this transition zone is small enough to be overlooked, at least based on narrow web results. However, for this case of copper foil, in the transition zone wrinkles form at misalignments 10 to 30 times higher than Regime I would predict. This is a significant process window, especially since this occurs in the 80-250 N/m (0.5 to 2 lbs/in) tension range common to much of paper and film converting equipment. If Regime I results were used to specify equipment, the typical specification of roller alignment better than 0.2 mradians (less that 0.2 mm/m or 0.2 mils/in) would not be good enough to avoid shear wrinkles or at least provide an adequate safety factor, but from the experimental results, the 0.2 mradian alignment specification is acceptable.

**<u>Wide Foil Wrinkling</u>**

*Can wide foil (greater than 1m or 40-in.) shear wrinkling be predicted by isolated-span models?*

Again, using the shear wrinkle experimental system, we attempted to create shear wrinkles in aluminum and copper foils at wide widths (> 1m). Our system was tension force limited, so we were not able to assess wrinkling over the same higher tensions and strains as the narrower copper foil.

At lower tensions (40-80 N/m or 0.25-0.5 lbs/in), we could not create shear wrinkles in the aluminum foil, even at extreme misalignment angles. Figure 8 shows images of shear wrinkles generated in wide copper foil from roller misalignment.

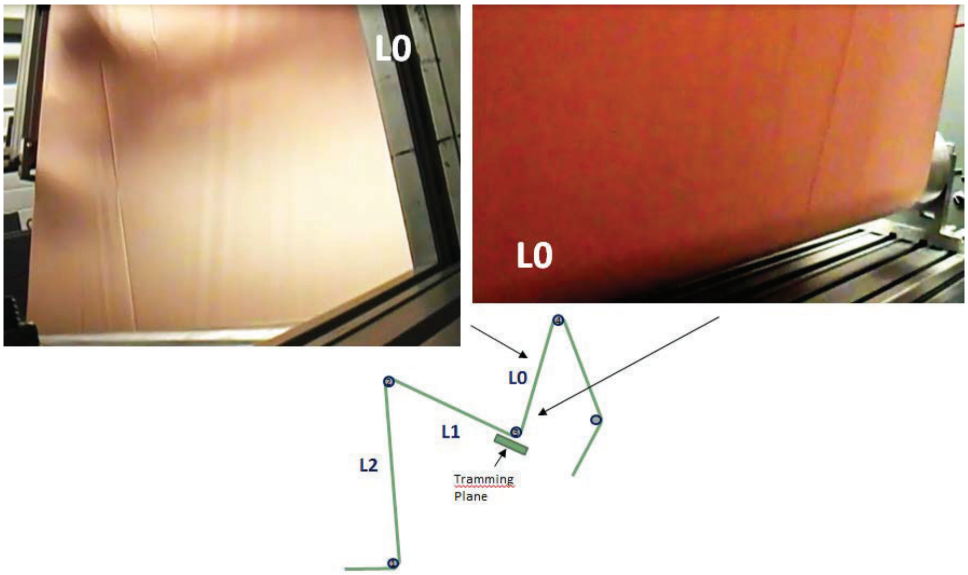


Figure 8 – Images of Shear Wrinkles in Wide Copper Foil

Figure 9 shows our experimental results for troughing and wrinkling plotted vs. tension (in force per width) and roller misalignment angle (in mradians) compared to the isolated-span shear wrinkle troughing theory. Where the theory suggests that 0.2 mradians misalignment would create shear wrinkles, the experimental results show wrinkling occurring at angles 7 to 10 times greater in copper and at angles 15x larger in aluminum.

Unfortunately, a more complex model, likely one that includes moment transfer will be required to predict shear wrinkles in wide foils. Fortunately, wide aluminum and copper foils can run on equipment designed to a 0.2 mradian specification commonly found in paper and film converting equipment.

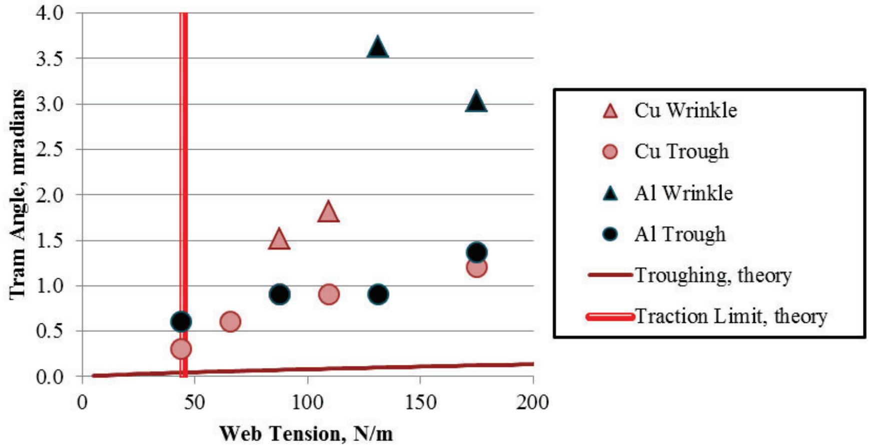


Figure 9 – Shear Wrinkling in Wide Aluminum and Copper Foils - Results vs. Theory

**Discussion of Results**

*Why are wide aluminum and copper foils less sensitive to roller misalignment than isolated-span models predict?*

The variance of the narrow copper experiment results from Regime I and II theory is most likely due to exceeding one of the critical isolated span assumptions – that the web exits perpendicular from the upstream roller. For low strain conditions (low tensile stress relative to elastic modulus) and low length to width span ratios, roller misalignment angles can quickly approach the critical tram angle where the upstream end of the entry span become slack on the short side. Even before reaching the critical tram angle, the low tension on the short side of the entry span can slip over the upstream roller, creating the condition known as moment transfer.

Wide, low strain webs have extremely small critical angles where the short side of the web in the entry span of a misaligned roller will quickly move to slackness. The upstream end of the entry span with slackness on one side and high tension on the other can quickly exceed the belt equation traction limits of the pre-entry roller. As moment transfer occurs, the web may twist or slip on the pre-entry roller and no longer satisfy the isolated-span shear wrinkle criteria of exiting perpendicular to the pre-entry roller.

Shelton [2] published an equation to predict multi-span interactions based on web span parameters, roller wrap angle, and roller tram angle.

$$\theta_{tram} < \mu\theta_{wrap}\left[\frac{\sqrt{3}\varepsilon}{2}\frac{(\cosh KL_2 - 1)}{\sinh KL_2}\right] \quad \{5\}$$

With the small KL values of foil web handling (<0.05 in many cases), this tram angle where span interaction begins can be three times lower than the common roller alignment specification of 0.2 mradians. In cases of web steering systems, span interaction is viewed as a detrimental to stable web guide performance. However, in preventing the wrinkling of high modulus, wide foil from roller misalignment, span interaction and moment transfer are a benefit, opening up the wrinkle-free process window beyond what isolated-span shear wrinkling models would predict.

*Why does bending past the critical tram angle change shear wrinkle sensitivity?*

For beams, lateral force is required to bend. Increasing bending should require increasing applied load; however, when the span goes into buckling (troughing) the force to bend the web essentially plateaus. Without increasing applied force, traction forces can never reach the critical buckling stress of the shape stiffened web. Handling beyond the critical slack edge angle and moment transfer reduce the maximum shear stress created in any but extremely long spans, reducing the forces available to induce shear wrinkles from misaligned rollers.

## Foil Lateral Bending Force Measurement

In an effort to understand the lateral forces of bending wide foil webs, we installed a lateral force measuring system on the target roller. When the roller was aligned and not bending in the entry span, the lateral force on the roller is zero. With increasing misalignment and bending, the lateral bending force increases and can be measured by the reactive force to hold the roller from shifting laterally (see Figure 6).

The force increases according to beam bending models up to the critical tram angle then plateaus as the bending of the buckled beam is much easier than the pre-buckled beam. In foils, the critical angle can be quite small, less than the common paper and film equipment alignment specification of 0.2 mradians.

Figure 10 shows the lateral force to shift the web left and right as a function of tramming angle. To make the plot dimensionless, the lateral force is divided by the web tension force and the tramming angle is divided by the critical tramming angle (as per equation {6} below) [3].

$$\theta_{crit} = \varepsilon \left(\frac{L_1}{w}\right) \quad \{6\}$$

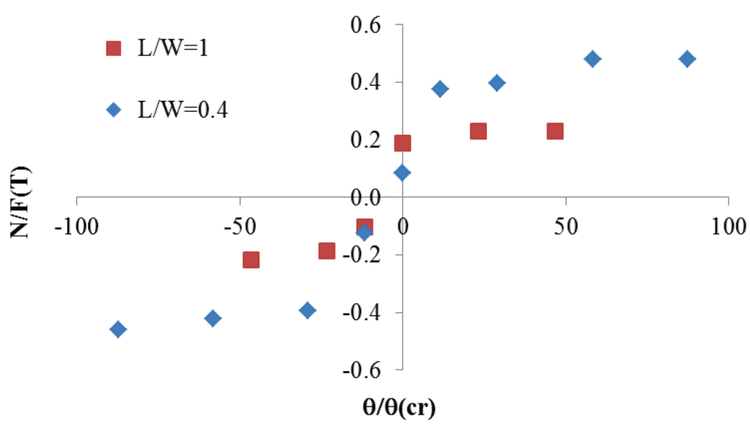


Figure 10 – Lateral Force vs. Roller Tram Error – Wide Aluminum Foil

Conditions for our lateral force trial are in Table 1. Cases 1 and 2 are from the actual lateral shifting trials. Case 3 is for the narrow copper foil shear wrinkle experiments.

| WEB INFO | | Case 1 | Case 2 | Case 3 | | Case 1 | Case 2 | Case 3 | |
|---|---|---|---|---|---|---|---|---|---|
| T | Tension | 214 | 214 | 214 | N | 48.00 | 48.00 | 48.00 | lbs |
| t | Thickness | 20 | 20 | 10 | μm | 0.0008 | 0.0008 | 0.0004 | in. |
| w | Width | 1.2 | 1.2 | 0.4 | m | 48 | 48 | 15.7 | in. |
| E | Modulus | 68.9 | 68.9 | 68.9 | GPa | 1.00E+07 | 1.00E+07 | 1.00E+07 | psi |
| μ | Web-Roller COF | 0.3 | 0.3 | 0.3 | -- | 0.3 | 0.3 | 0.3 | -- |
| L1 | Roller Span Length | 1.3 | 0.5 | 1.0 | m | 50 | 20 | 40 | in. |
| L2 | Roller Span Length | 1.7 | 1.7 | 1.0 | m | 66 | 66 | 40 | in. |
| θ(roller) | Roller Wrap | 1.6 | 1.6 | 1.6 | radians | 1.6 | 1.6 | 1.6 | radians |
| **Calculated Values** | | | | | | | | | |
| L1/w | Length to Width | 1.0 | 0.4 | 2.5 | -- | 1.0 | 0.4 | 2.5 | -- |
| ε | Average Strain | 0.013% | 0.013% | 0.077% | -- | 0.013% | 0.013% | 0.076% | -- |
| σ | Average Stress | 8618 | 8618 | 52693 | kPa | 1250 | 1250 | 7643 | psi |
| I | Bending Inertia | 0.031 | 0.031 | 0.001 | in^4 | 7.4 | 7.4 | 0.1 | in^4 |
| KL | Shelton Span Parameter | 0.040 | 0.016 | 0.241 | -- | 0.040 | 0.016 | 0.244 | -- |
| θ(crit) | Slack Edge Tram Angle | 0.13 | 0.05 | 1.91 | mrad | 0.13 | 0.05 | 1.94 | mrad |
| θ(spec)/θ(crit) | Spec to Critiacl Angle Ratio | 1.54 | 3.83 | 0.10 | -- | 1.54 | 3.84 | 0.10 | -- |
| θ(cr, int) | Span Interaction Angle | 0.13 | 0.13 | 1.40 | mrad | 0.13 | 0.13 | 1.41 | mrad |
| δ(cr, int) | Span Interaction Offset | 0.15 | 0.15 | 0.56 | mm | 6.02 | 6.02 | 22.21 | mils |

Table 1 – Given and Calculated Values from Lateral Force Cases

Shelton has published this relationship of lateral bending forces for tram angles greater than the critical tram angle. [1] In Figure 11, the positive angle and force values are plotted on Shelton's log-log nomagraph of lateral force vs. tramming angle as a function of L/W ratios. Our measurements are close to Shelton's predictions, but lie approximately on a length to width value 2x our actual ratios.

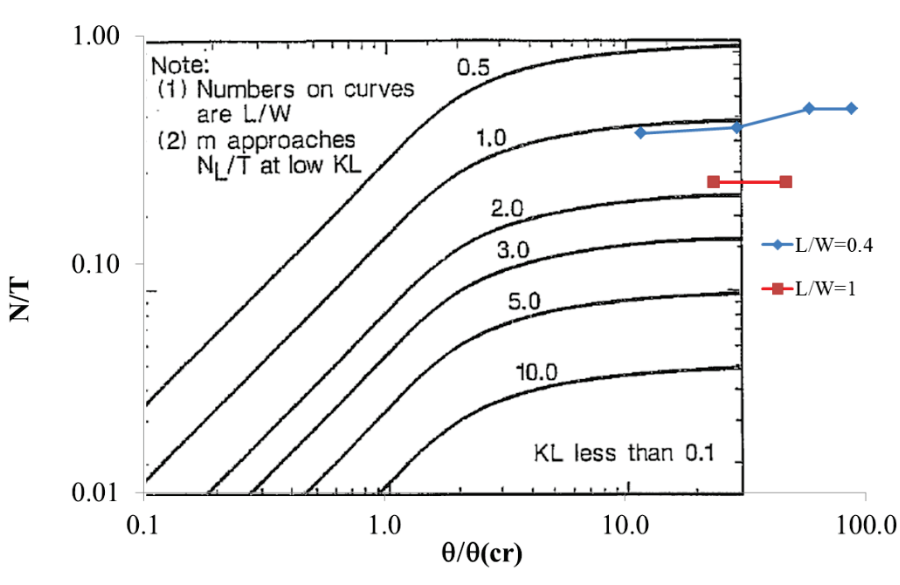


Figure 11 – Normalized Lateral Force vs. Roller Tram Error vs. L/w Ratio

## CONCLUSIONS

Isolated-span shear wrinkling models are not a good predictor of shear wrinkling in wide foils.

Low strains of foils quickly lead to handling at roller misalignment angles beyond the critical slack edge conditions and moment transfer between spans, even in well-aligned equipment.

Handling beyond the critical slack edge angle and moment transfer reduce the maximum shear stress created in any but extremely long spans, reducing the forces available to induce shear wrinkles from misaligned rollers.

## ACKNOWLEDGMENTS

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*Wrinkling of Foils*

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| **Name & Affiliation** | **Comment** |
|---|---|
| Keith Good, Oklahoma State University | The plots of misalignment versus strain showing how you can normalize the effects of modulus and thickness was nicely done. That is something that is not commonly known. |