MEASUREMENT OF WEB CURL

By

Ronald P. Swanson
3M Company
USA

ABSTRACT

Generally it is desirable for web based products to have a flat planar shape. Unfortunately coated and laminated products often assume a curved shape. This is a defect commonly called “Curl”. The first step in solving most defect problems is an accurate, repeatable and quantifiable measurement system. This paper discusses current curl measurement standards and describes a new measurement method. This method, the Kappa Gauge, which is fast, accurate, inexpensive and eliminates many of the problems of the current measurement standards. The resultant curvature measurement (Kappa) is linear with the moment causing the curl and therefore makes solving curl problems much easier.

CURL IN WEB BASED PRODUCTS

Curl is a common problem in coated and laminated products. The root cause of curl can have many sources including: strain mismatch in laminated products, curing or drying stresses in coated products, core set in thicker products and a mismatch in thermal or hygroscopic expansion coefficients. Although the source of the curl problem may be quite variable, all will result in a product that does not lay flat.

CURRENT MEASUREMENT STANDARDS

There are three basic curl measurement techniques used as currently accepted standards. The first technique will be referred to as “corner lift”, where samples are cut, conditioned and placed on a flat surface. Height measurements are made from the surface to various points along the edge of the sample.

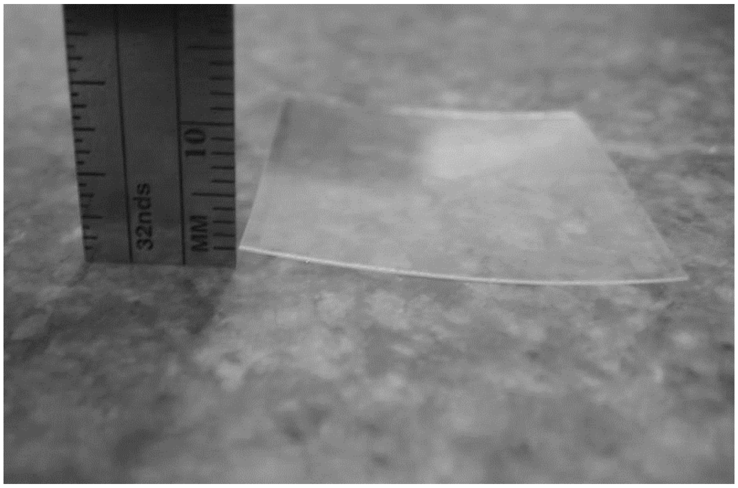


Figure 1 – Corner Lift Curl Measurement

Curl measurement values are reported as the maximum or average of the measurements. Examples of this type measurement technique include: ASTM F415-87(2005) Standard Test Method for Curl in Carbon Paper, ASTM F556-88(2001) Standard Test Method for Curl of Carbonless Copy Papers, TAPPI T 520 cm-96 “Curl of gummed flat paper”, ANSI/ISO 4330-1994 (ANSI/NAPM IT9.10-1996) “Photographic Film and Paper – Determination of Curl” Methods B and C.

The second curl measurement technique consists of hanging a specific length sample so as the end of a non-curled sample would just touch a horizontal surface and measuring the height of the lifted end. This technique will be referred to as the “hanging strip test”. Curl measurement values are reported as the height of the lifted edge. An example of the measurement technique is ASTM D3813/D3813M-98(2003) Standard Test Method for Curling and Twisting on Unwinding of Pressure-Sensitive Tapes.

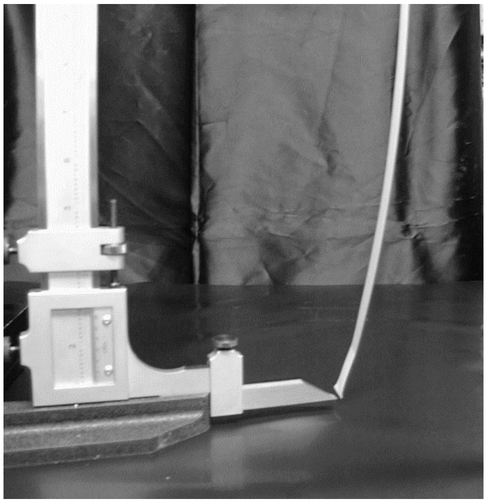


Figure 2 Hanging Strip – Test

The third curl measurement technique consists of holding the sample so that the curl axis is vertical and compares the shape to a template of various curves. This technique will be referred to as the “vertical axis test”. Curl measurement values are reported as curl radius or chord height. Examples of this type of measurement technique are ASTM D4825-97(2002) Standard Test Method for Measurement of Curl in Cut-Sized Office Paper and ANSI ANSI/ISO 4330-1994 (ANSI/NAPM IT9.10-1996) “Photographic Film and Paper – Determination of Curl” Method A.

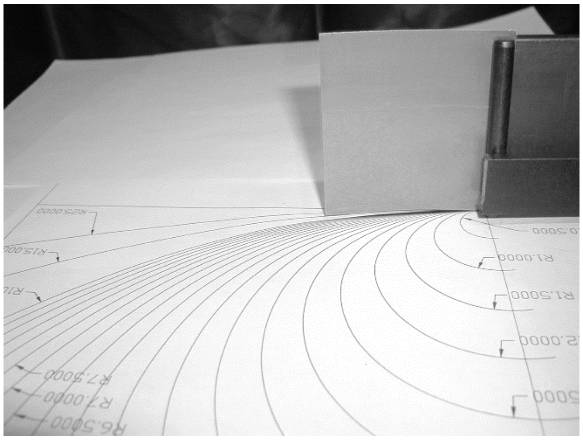


Figure 3 – Vertical Axis Test

PROBLEMS WITH CURRENT CURL MEASUREMENT STANDARDS

Lack of Useful Units

Measurements that report edge height or curl classification, may be quantifiable and comparable, but are not useful for purposes such as first principles modeling of curl problems.

Static Electricity

Many web based products are non-conductive and can easily be statically charged through normal handling. Completely removing this charge from both side of the web can be difficult and time consuming. Edge or corner lift tests are very sensitive to the effects of static charge, because of the significant forces developed when surfaces are in close proximity. The hanging strip test is also sensitive to the effects of static charge because of the low resistance to motion of the long hanging strip.

Gravity

Gravity can have a significant effect on all three types of measurement techniques. The vertical axis test is the least effected of the four techniques, because the gravity is acting against a wide strip with a high bending moment of inertia. Wide strips have more coupling between the MD and TD directions due to cupping and anticlastic bending. Narrower samples produce more accurate radius of curvature data, but can twist under the load of gravity, as shown in Figure 4 for the vertical axis test.

An accurate test should also yield the same measurement value independent of the sample orientation. This is generally not the case with the edge lift tests because gravity has different effects on concave and convex samples. Although in both cases, gravity tends to flatten the sample and the test will under predict the actual radius of curvature.

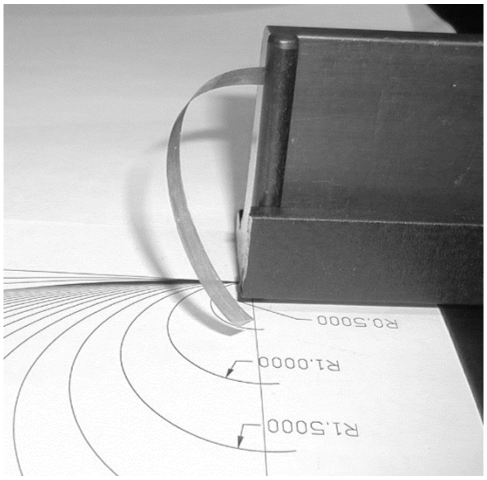


Figure 4 – Gravity Effect

Sample Stiffness and Weight

Current curl measurement techniques are affected by the relationship between sample stiffness and weight. Different sample constructions with similar radius of curvatures can have significantly different measurement values between samples with high weight/low stiffness and sample with low weight/high stiffness. A stiff/low weight samples will retain most of its natural curvature in these tests, but low stiffness/ heavy samples will tend to flatten out due to external forces from gravity and static electricity.

Twisting

Web based products often have properties strongly aligned with the machine direction (MD) or traverse direction (TD). Occasionally the axis of the maximum curl does not align with the MD or TD. If strip samples are cut in the MD or TD direction, a twisted sample will result. Samples cut along the major and minor curl axis will exhibit pure curvature without twist. Twist is common in samples where curvature is similar in all directions and also in asymmetric laminates.

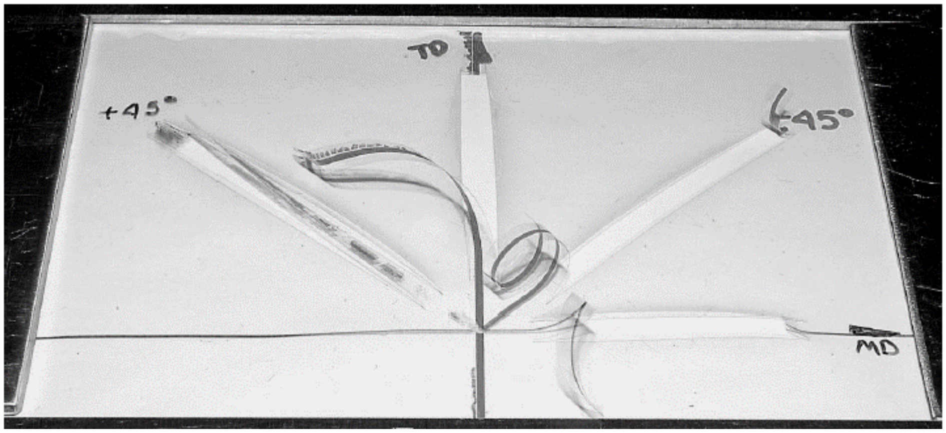


Figure 5 – Off Axis Curl

THE “CURL GAUGE”

A measurement method called the “Curl Gauge” was presented at the Applied Web Handling (AWEB) Conference in 2006. The method consisted of placing a strip sample on two strategically spaced pins and reading the curl radius on the background circular arc template.

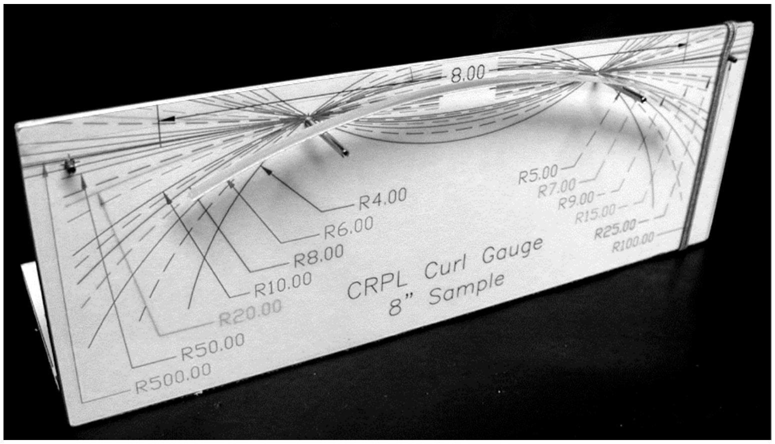


Figure 6 – “Curl Gauge”

A simple calculation was done, by modeling the sample as a uniformly loaded, simply supported beam with cantilevers at both ends. Minimization of the beam deflection, based on pin spacing, showed that the optimal pin spacing is 22.3% of the beam length in from both ends. This slightly deviates from a balance of moments calculation which would yield 25%. In practice, the difference between 22.3% and 25% is probably insignificant.

The curl gauge was a step forward in our ability to quantify curl problems, but still lacked an ability to solve curl problems that is illustrated in the following example.

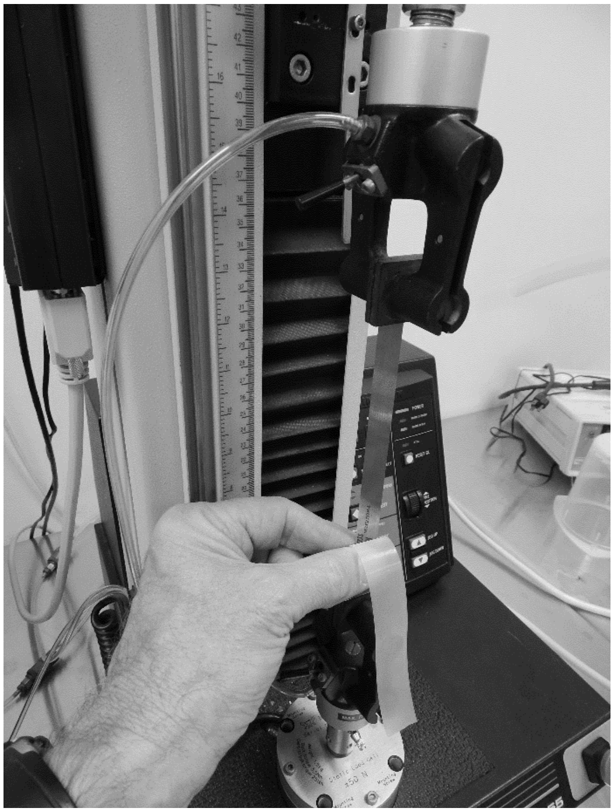


Figure 7 – Simple Lamination Experiment

An experiment was performed to illustrate how the Curl Gauge can be improved. A simple lamination experiment used an Instron® material testing system to tension a 25 μm (0.001") thick steel feeler gauge. After the feeler gauge was tensioned, a length of untensioned Magic Tape® was hand laminated to the feeler gauge at approximately zero stress and strain. The experiment was repeated at several different feeler gauge tensions. The resulting curl radius was measured using the Curl Gauge. The resulting curl radius was plotted against feeler gauge tension as shown in Figure 8. This plot would not be very useful if your goal was to find process conditions that will produce a flat product.

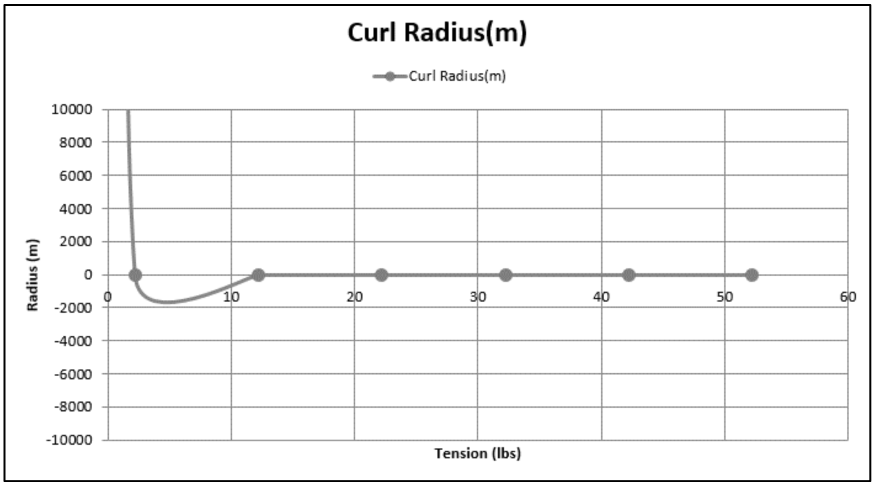


Figure 8 – Lamination Experiment Curl Radius Vs. Tension Plot

If we examine the equation for curvature, Equation {1}, and realize that web profiles have small slopes (dw/dx) and therefore $(dw/dx)^2$ can be assumed to be zero. The curvature equation can be simplified as shown in Equation {2}. Equation {3} is the Euler–Bernoulli Beam Equation. Combining Equation {2} and Equation {3} shows that curvature, often represented by the Greek symbol Kappa (K), is proportional to the driving force for curl moment (M).

$$K = \frac{\frac{d^2w}{dx^2}}{\left(1+\left(\frac{dw}{dx}\right)^2\right)^{3/2}} \quad \text{Full Curvature Equation} \qquad \{1\}$$

$$K \cong \frac{d^2w}{dx^2} \quad \text{Simplified Curvature Equation} \qquad \{2\}$$

$$\frac{-M}{EI} = \frac{d^2w}{dx^2} \quad \text{Euler–Bernoulli Beam Equation} \qquad \{3\}$$

$$K \propto M \quad \text{Curvature is Proportional to Moment} \qquad \{4\}$$

If we reexamine the lamination data and plot the sample curvature instead of curl radius, as shown in Figure 9, curvature is indeed proportional to feeler gauge lamination tension. This plot is much more useful to help find process conditions that will produce a flat product. The line of proportionality can be extended to find the tension in which the curvature is zero.

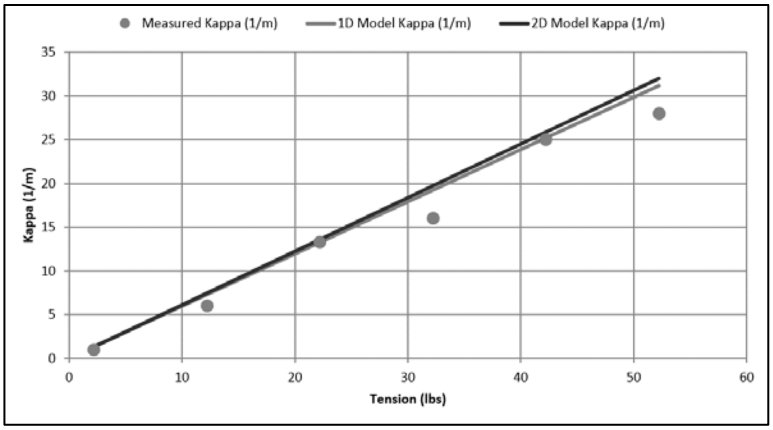


Figure 9 – Curvature Vs. Tension Plot

THE “KAPPA GAUGE”

The old Curl Gauge can be reconfigured to read in curvature (Kappa) as shown in Figure 10 and Figure 11. The Kappa Gauge has 6 different sample lengths ranging from 50-250 mm. Figure 12 shows cutting the sample to length. For the best resolution, cut the sample as long as possible. The sample is too long if it does not read the same magnitude of curvature when turned over, as shown in Figure 13.

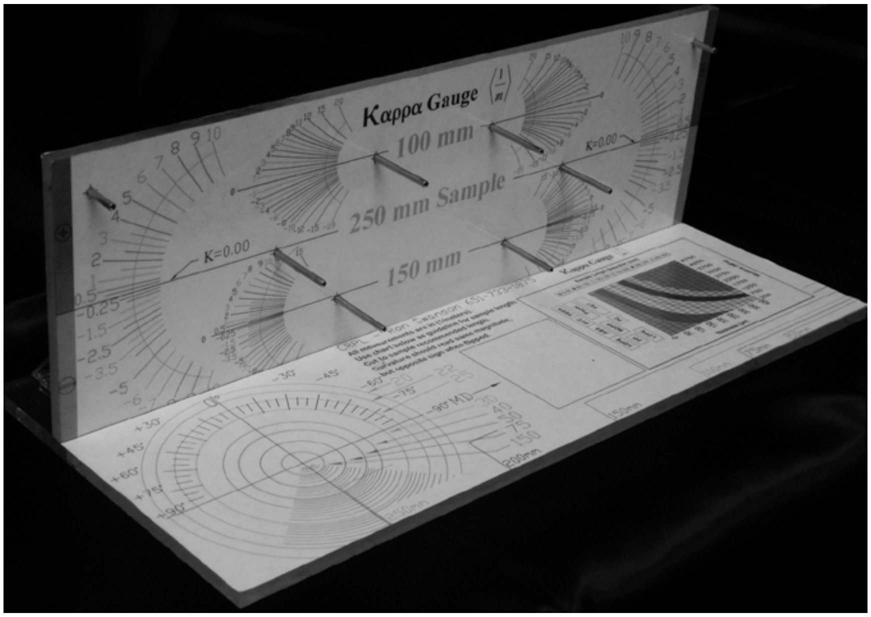


Figure 10 – Kappa Gauge (Front)

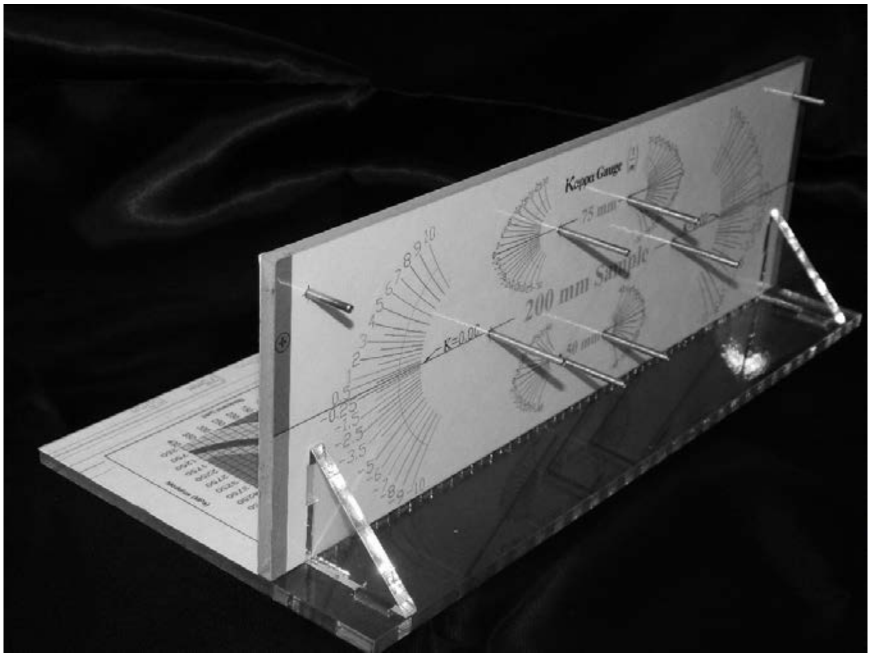


Figure 11 – Kappa Gauge (Back)

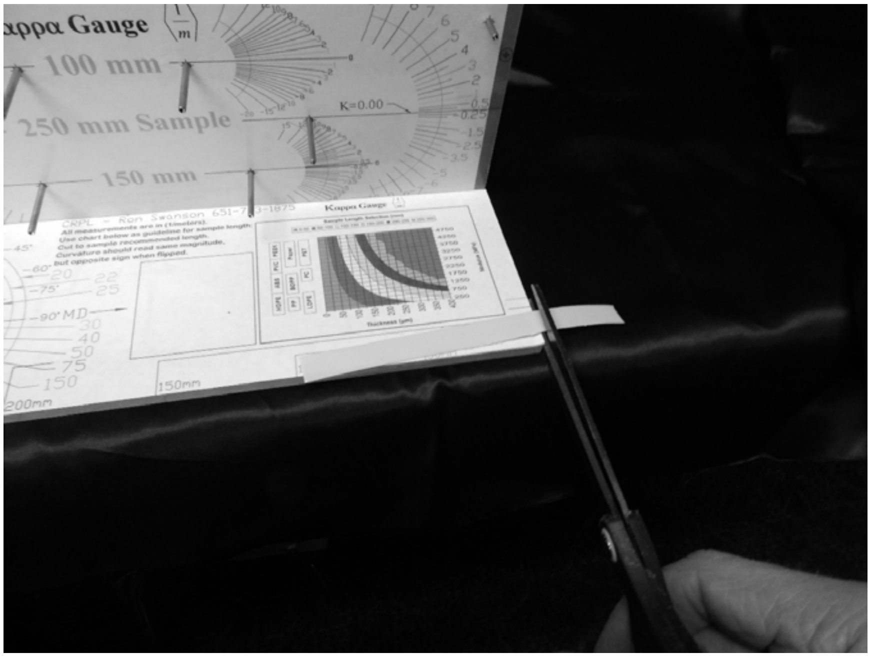


Figure 12 – Cutting Sample to Length

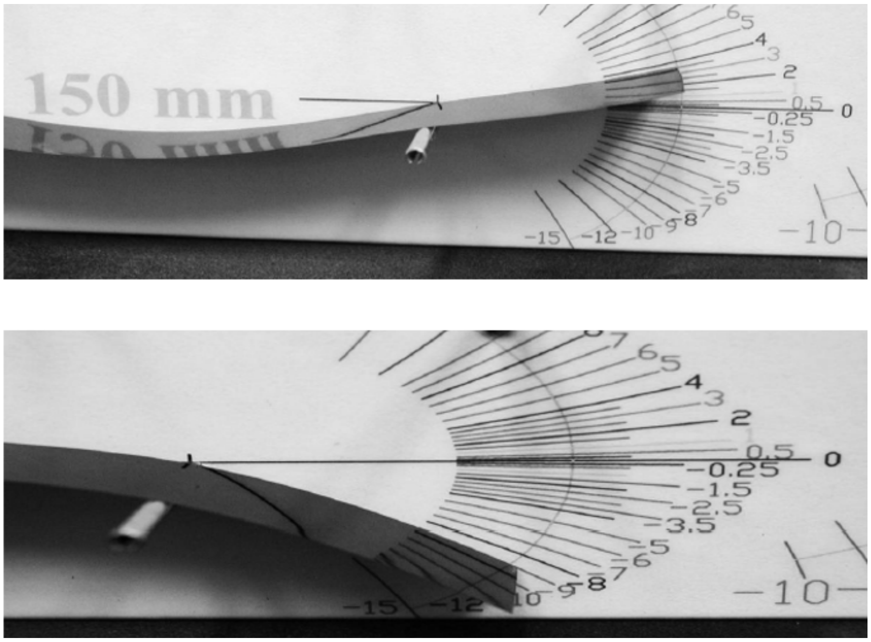


Figure 13 – An Excessively Long Sample

“Tube” samples that have too much curvature to use the 50mm sample length gauge can be measured on the front protractor gauge, as shown in Figure 14.

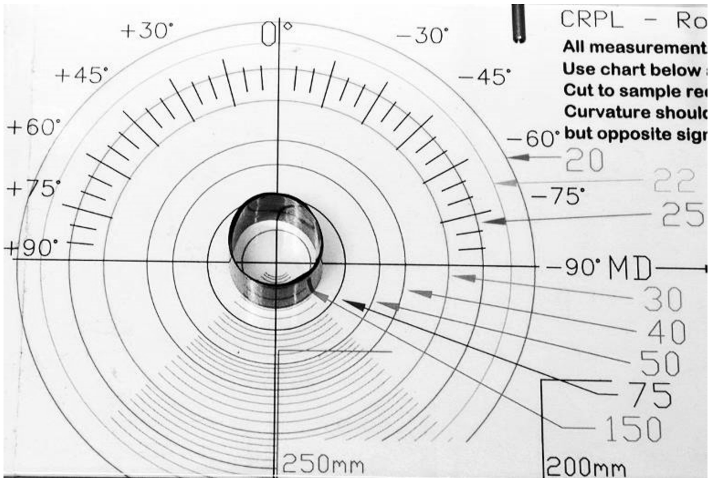


Figure 14 Measurement of Large Curvatures

Some curl samples twist and will not lay flat on the Kappa Gauge pins, as shown in Figure 15.

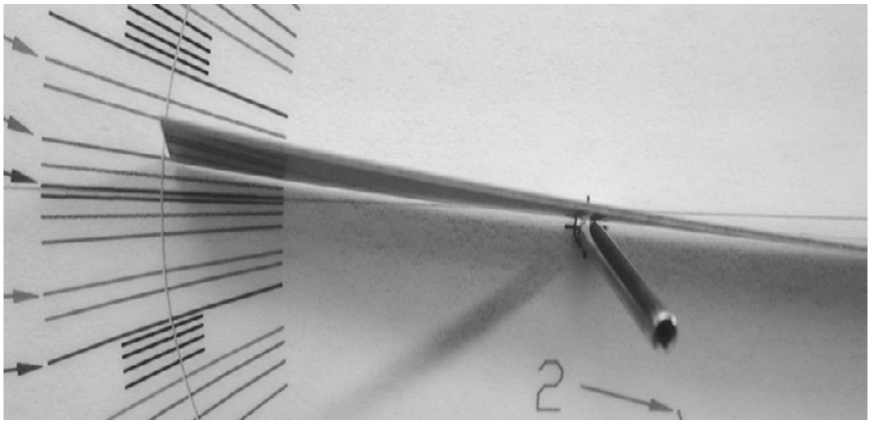


Figure 15 – Sample Exhibiting Twist Curl

Knowledge of the root cause of twist can not only lead to effective curl measurements, but can be insightful into the nature of the product curl. Twist results when a narrow sample is cut that is not aligned with, or orthogonal to, the major curl axis. Figure 16 shows a product that has a major curl axis at about +35 degrees.

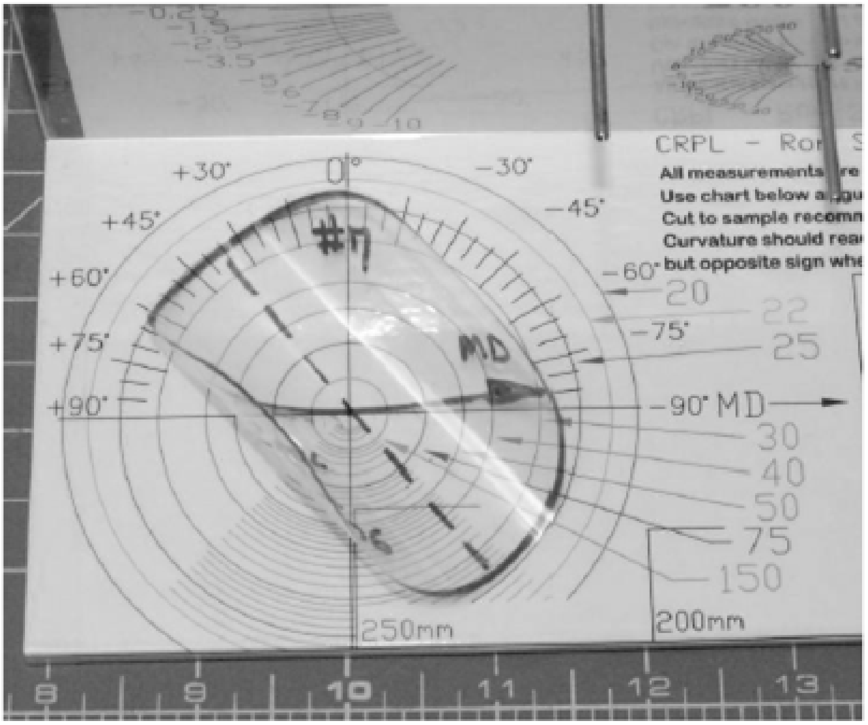


Figure 16 – Measuring Twist Curl Angle

The angle of the major curl axis can be determined by marking the MD direction of the web and cutting a circular disk for the product. The disk is then placed on the protractor of the Kappa Gauge, as pictured in Figure 16. The round disk will naturally curl around the axis of the major curl. After the major axis angle has been measured and noted, samples can be cut along and orthogonal to the major axis. Samples cut along major and orthogonal to the curl axis will not twist and will have the maximum (K_{max}) and minimum (K_{min}) curvatures respectively. Twist in MD or TD samples indicate off-axis curvature, as shown in Figure 17.

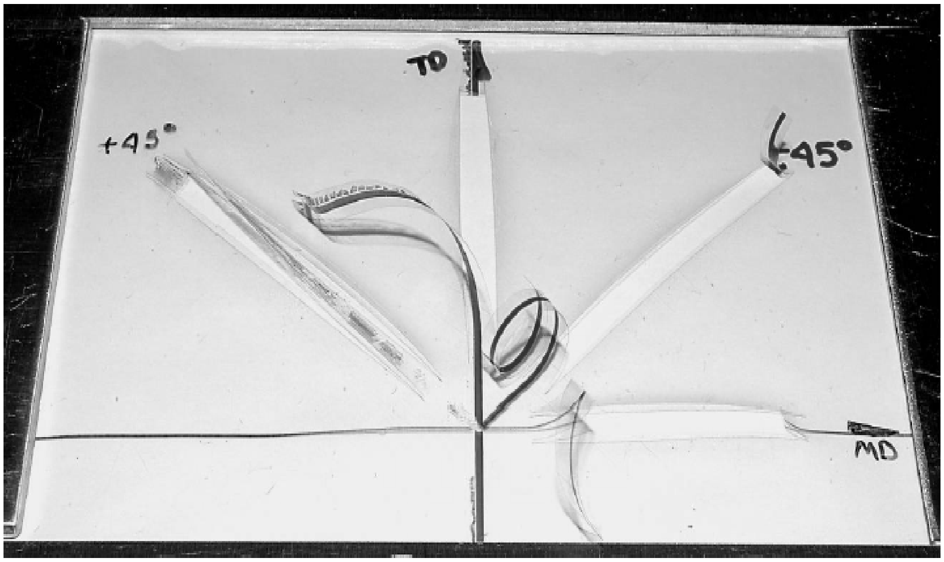


Figure 17 – Off-Axis Curvature

Knowledge of K_{max}, K_{min}, Twist Angle (θ) fully describes the state of curvature of a web sample. Although the MD and TD curl cannot be directly measured because the samples will not lay flat on the pins, the MD and TD curvatures can be calculated using Equation {3} and Equation {4}.

$$K_{MD}= K_{max}\cos^2(\theta) + K_{min}\sin^2(\theta) \qquad \{1\}$$

$$K_{CD}= K_{max}\sin^2(\theta)+K_{min}\cos^2(\theta) \qquad \{2\}$$

SOURCES OF WEB CURL

The Kappa gauge can be used to quantify, explain and hopefully eliminate curvature in web based products. Several examples will be given here.

Core Set Curl

Figure 18 is an example of a web exhibiting what is commonly called core set curl. Plastic materials creep over time and start to take on the shape in which they are held for a period of time.

Figure 18 – Core Set Curl

An excellent paper on core set curl is “The Bending Recovery of Polymer Films”. Greener introduces a quantity called Bending Recovery (BR) shown in Equation {5}.

$$\mathrm{BR} = \frac{\mathrm{R}_{\mathrm{Applied}}}{\rho_{\mathrm{Measured}}} \quad \text{Bending Recovery} \qquad \{5\}$$

This author slightly changes the equation in light of the curvature measured with the Kappa gauge and calls it Bending Ratio. The two terms are numerically equal.

$$\mathrm{BR} = \frac{\kappa_{\mathrm{Measured}}}{\kappa_{\mathrm{Applied}}} \quad \text{Bending Ratio} \qquad \{6\}$$

Sample can be cut to an appropriate length for the Kappa Gauge and measured for initial curvature. The sample is then wrapped around the cylinder. The sample is periodically unwrapped and its curvature measured. The data can be plotted as Bending Ratio (BR) vs. the log of time, as shown in Figure 20.

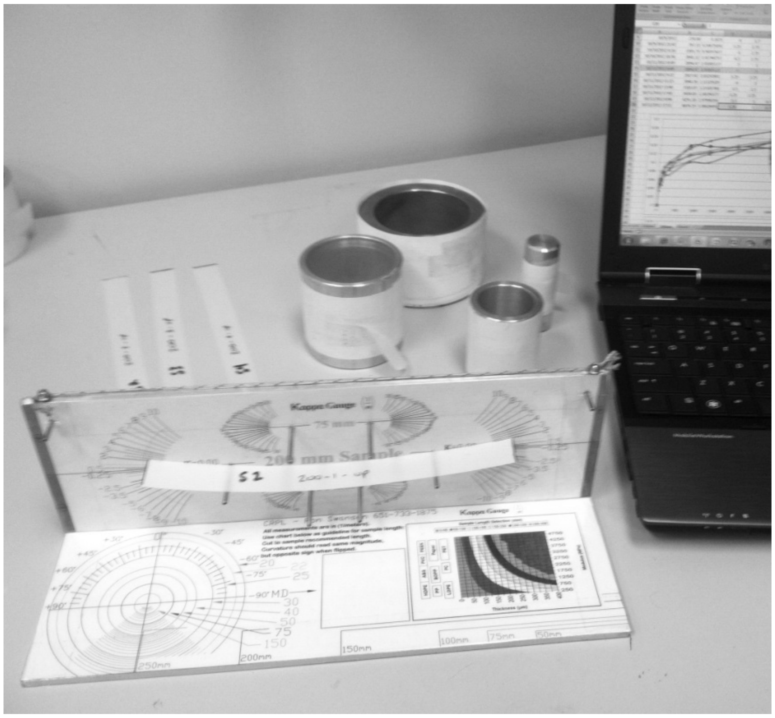


Figure 19 – Bending Ratio Testing

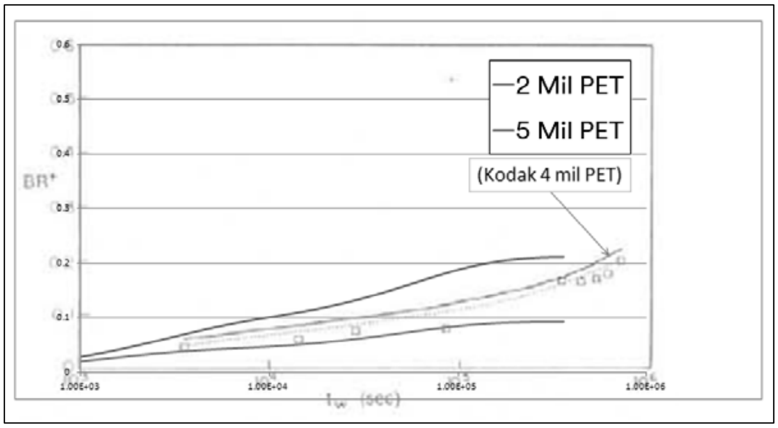
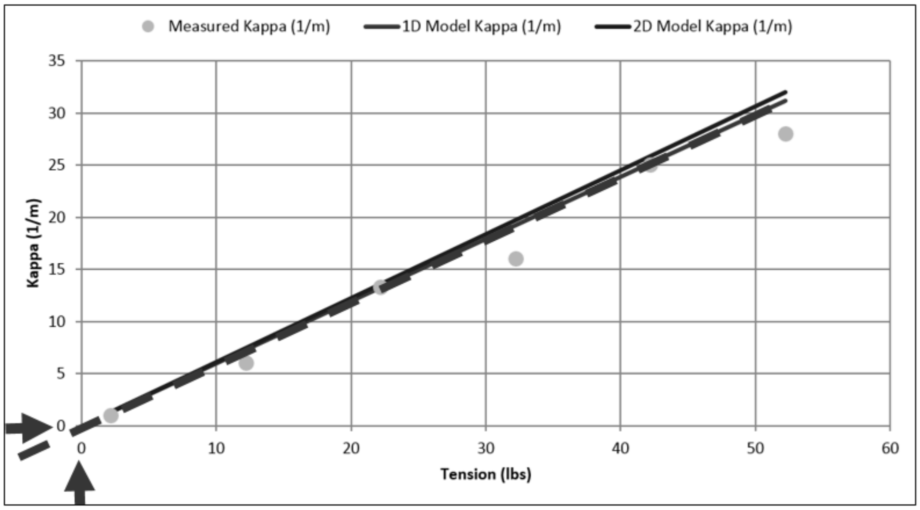


Figure 20 – Bending Ratio Results Plot

Lamination Curl

Webs are commonly laminated to build composite structures. This process also commonly produces curl in the laminate structure. The common solution to this curl problem is to match the strains in both laminates, as described by T.J. Walker [9]. Another simple and effective method is to use the linear nature of the Kappa Gauge curvature measurement. Measure the web curvature (K) under the present process conditions. Adjust the tension of one of the laminate webs and remeasure the web curvature (K). Plot these two points on a Kappa vs. tension graph. Draw a line through the two points and extending to zero Kappa. The tension needed on that web, to produce a flat laminate, can be read out on the "x" axis of the plot, as shown in Figure 21.



0 Lbs. Feeler
Gauge Tension

Figure 21 – Predicting Tension to Obtain Zero Curvature

<u>Thermally Induced Curl</u>

The Kappa Gauge can be used to measure curvature as a function of temperature. Polymer webs can have very high Coefficients of Thermal Expansion (CTE, α). A mismatch in the coefficients of thermal expansion about the neutral axis of the web can cause the web to act like a bimetallic spring, and have a curvature that is a function of temperature as shown in Figure 23.

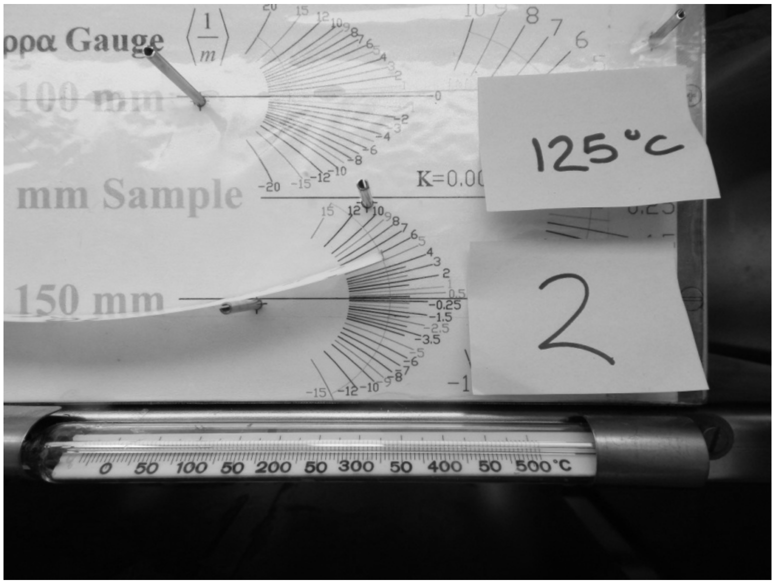
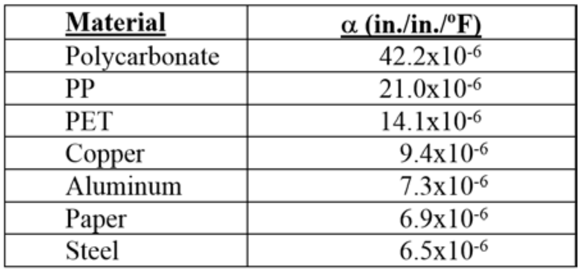


Figure 22 – Measuring Curl at Elevated Temperature



Material	**α (in./in./ºF)**
Polycarbonate	42.2×10^{-6}
PP	21.0×10^{-6}
PET	14.1×10^{-6}
Copper	9.4×10^{-6}
Aluminum	7.3×10^{-6}
Paper	6.9×10^{-6}
Steel	6.5×10^{-6}

Table 1 – Coefficients of Thermal Expansion

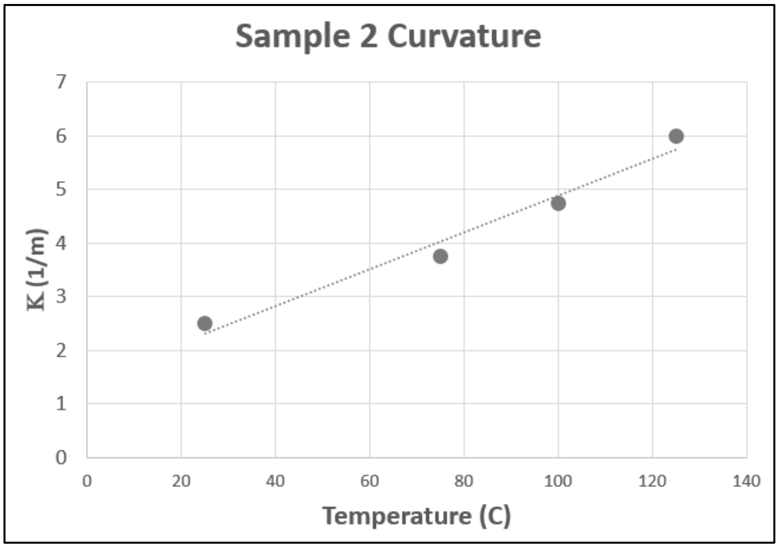


Figure 23 – Curvature vs. Temperature Plot

Lamination Curl at Elevated Temperatures

Webs are often laminated at elevated temperatures. The modulus of polymer webs can be significantly lower at elevated temperatures as compared to room temperature. The traditional strain matching as shown by Walker [9] would need to be modified to account for this change in modulus, but how?

An experiment, similar to the “Simple Lamination Experiment” discussed above, was done with polymer webs strips in a heated Instron® material testing system. The hot bonding state ($_1$) modulus was measured as well as the final room temperature state ($_2$) modulus. The results are shown plotted in Figure 25 against three possible theories; conservation of strain, conservation of energy, and conservation of tension. Probably not surprising to most engineers and scientists, the conservation of energy Equation {8} was the best predictor of the strain that should be used for stain matching webs in hot lamination processes. In practice the method illustrated in Figure 21of using a linear line projected to zero Kappa to determine process conditions that result in a flat laminate would be much simpler.

$$\varepsilon_2 = \left(\frac{E_1}{E_2}\right)^0 \varepsilon_1 = \frac{1}{E_1}\sigma_1 \quad \text{Conservation of Strain} \qquad \{7\}$$

$$\varepsilon_2 = \left(\frac{E_1}{E_2}\right)^{0.5} \varepsilon_1 = \sqrt{\left(\frac{1}{E_1}\right)}\sqrt{\left(\frac{1}{E_2}\right)}\sigma_1 \quad \text{Conservation of Energy} \qquad \{8\}$$

$$\varepsilon_2 = \left(\frac{E_1}{E_2}\right)^1 \varepsilon_1 = \frac{1}{E_2}\sigma_1 \quad \text{Conservation of Tension} \qquad \{9\}$$

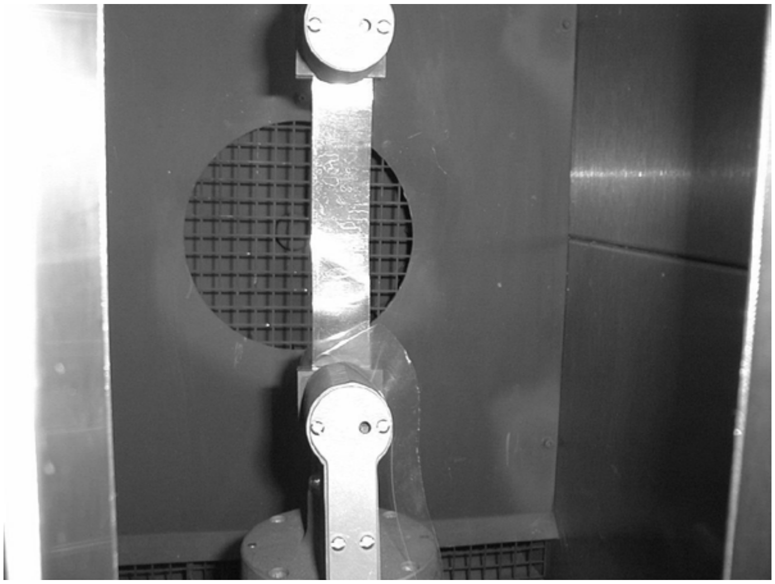


Figure 24 – Heated Instron® Lamination Experiment

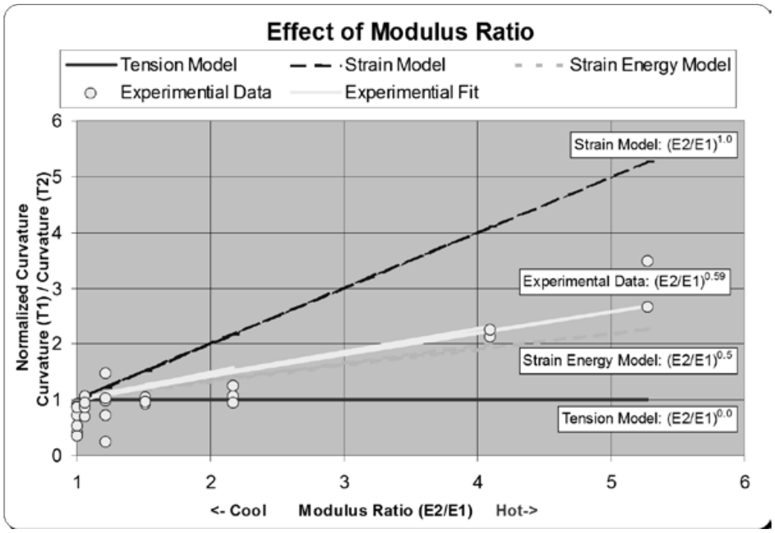


Figure 25 – Effective Modulus Ratio

Curl Due to Humidity

Changes in relative humidity (%RH) can cause significant curl, especially in paper backed products as shown in Figure 26. Web Based products are often dried and cured in thermal ovens before being wound into large rolls. This insures that the paper backings are almost completely devoid of moisture. Moisture defuses into large rolls very slowly, often requiring years to come to equilibrium. When single sheets of the paper backed products, are later exposed to moisture, it can quickly diffuse through the thickness of one sheet. Uncoated paper alone would be balanced about the neutral axis and would uniformly expand in all directions and not become curled. Paper coated with material of lower coefficient of hygroscopic expansion will curl significantly at elevated humidity levels. The curvature of these web based products will be linearly related to relative humidity as shown in Figure 26.

Figure 26 – Curl Due to Humidity

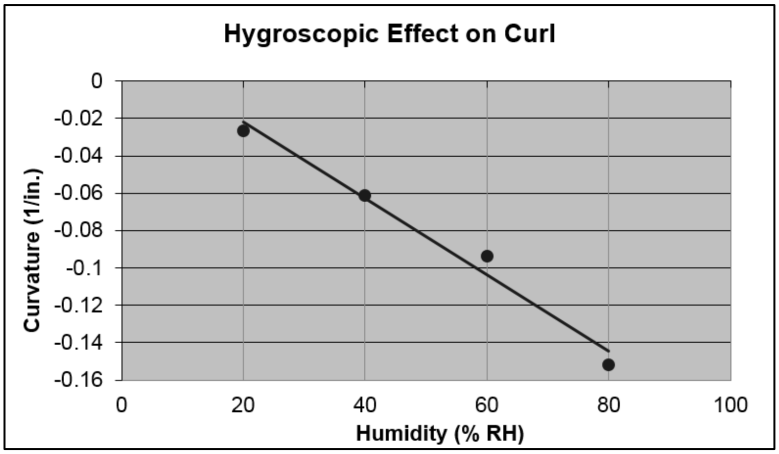


Figure 27 – Sample Curvature vs. Relative Humidity

Material	β (in./in./%RH)
Paper	$130.0\text{x}10^{-6}$
Acetate	$70.0\text{x}10^{-6}$
PET	$6.1\text{x}10^{-6}$
PE	$0.0\text{x}10^{-6}$

Figure 28 – Coefficients of Hygroscopic Expansion (CHE)

Curl Due to Drying and Curing Stress

E. M. Corcoran [10] of Bell Labs wrote a very interesting paper in which he studied why paint cracks when telephones are repainted. He used the measurement of the lifting of the end of a cantilever mounted steel feeler gauge, coated on top with paint, to measure the stress the paint exerted on the steel feeler gauge during drying and curing. This technique has been used in many more recent technical papers.

Accurately measuring the lift of a cantilever mounted steel feeler gauge generally requires an expensive instrument such as a laser micrometer. A simple inexpensive alternative is to use a Kappa Gauge to measure the change in curvature of a coated steel feeler gauge.

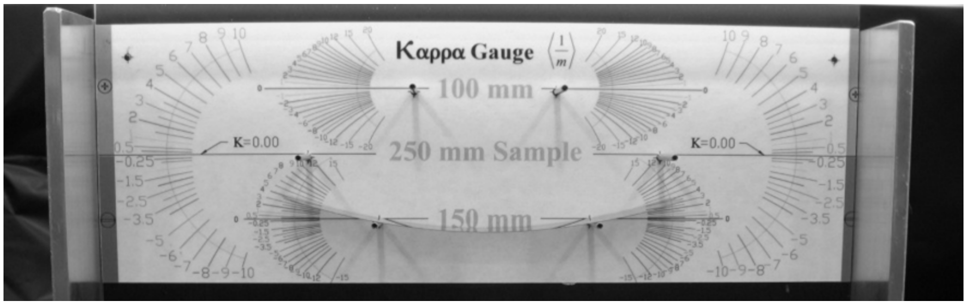


Figure 29 – Kappa Gauge Stress Measurement

Assuming that EI stiffness of the steel gauge is much larger than the EI of the coating, the stress exerted on the steel feeler gauge by the coating can be calculated using Equation {12}. Equation {12} can be derived starting with Equation {10}, the definition of strain in pure bending. Substituting the thickness divided by two (t/2) for y, the distance from the neutral axis to the top surface and combining Equations {2}, {10} and {11}will result in the simple Equation {12} the curing stress that a coating imparts on the surface of the steel feeler gauge.

$$\varepsilon = \frac{y}{\rho} \quad \text{Strain in Pure Bending [11]} \qquad \{10\}$$

$$\sigma = \epsilon E \quad \text{Definition of Stress [11]} \qquad \{11\}$$

$$\sigma_{\text{Curing}} = \frac{1}{2} E_s t_s K \quad \text{Curing Stress} \qquad \{12\}$$

σ_{Curing} = Curing Stress
E_s = Modulus of Steel Gauge
t_s = Thickness of Steel Gauge
K = Curvature of Steel Gauge

CONCLUSIONS

1. The current web curl measurement standards were summarized.
2. Measurement difficulties associated with these standards were identified.
3. A new curl measurement system, the “Kappa Gauge”, has been presented which is fast, simple, inexpensive and accurate.
4. Sample twist has been identified as off-axis curl. Measure major axis angle, then the major and minor curl radius.
5. Several common curl problems and how the Kappa Gauge can be used to minimize curl problems was discussed.

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