Basic understanding of paper curl and its troubleshooting strategy

종이 컬의 이해와 문제 해결 전략

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BASIC UNDERSTANDING OF PAPER CURL AND TROUBLESHOOTING STRATEGY

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INTRODUCTION

Paper curl can be described as an out-of-plane deformation so that a sheet is curved. Curl is intimately related to the dimensional properties within the layered structure of a sheet of paper. If the dimensional changes between tow or more layers are reversible, then the resultant curl will be reversible. Likewise, to the extent dimensional changes are permanent, curl will be irreversible. Relatively small changes in the dimensions of one layer with respect to another cause rather severe curls.

The basic causes of curl are uneven expansions and contractions of the paper sheet resulting from moisture variations. Paper will also exhibit changes in dimension in response to temperature changes. However, in most practical situations, the hygroexpansion behavior will almost always dominate. Uneven contraction and/or expansion produces a bending moment that results from uneven shear forces. The simplest situation is that a sheet is made up of two layers of equal thickness. In the example in Fig.1, layer A contracts at the rate of 0.12% for each percent of moisture loss that takes place with a lowering of relatively humidity to 10%. Layer B contracts at the rate of 0.1% for each percent moisture loss. In going a condition of 50% RH to 10%, 4% moisture is lost and layer A contracts 0.48%, while layer B contracts 0.4%. In order to remain flat, a bending moment would have to be applied toward layer B. Without the bending moment, the sheet will curl toward layer A. In this case the curl radius formed is 3.3 inches. For an increase in moisture, curl would be toward layer B.

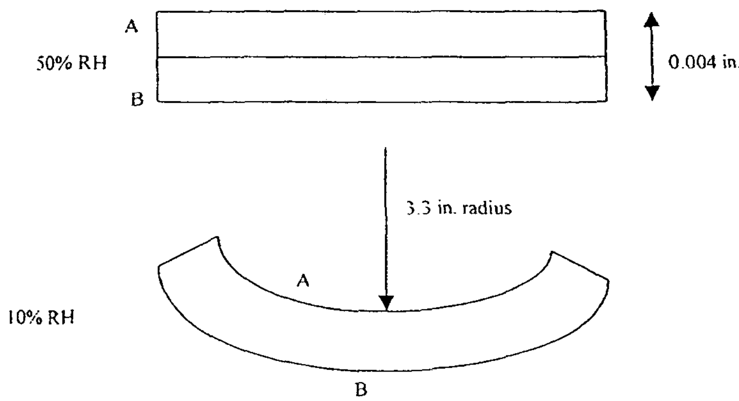

Fig. 1. Curl caused by the humidity changes.

CAUSES OF DIMENSIONAL CHANGE

We need to know what causes dimensional changes in paper to understand why the differences take place in dimensional changes of layers within a sheet. The following is a list of some of the reasons why the dimensional changes take place and why they may vary in magnitude.

- Addition of moisture will normally increase dimensions and losing moisture will decrease them.
- Dimensional changes are higher perpendicular to the predominant fiber orientation.
- Dimensional changes will vary from materials, compositions and process treatments.
  - Type of fiber(Species, pulping process, etc.)
  - Filler content
  - Starches and glues
  - Amount of refining
  - Shrinkage during drying
  - Applying sufficient tension to stretch a sheet irreversibly

- Exposing paper to high RH(usually above 80%) will release internal strain and/or internal stress. On redrying without restraint of shrinkage, paper will shrink to shorter dimensions than the original. Internal strain(or internal stress) are produced when there is drying with restraint of shrinkage.
- Exposing paper to temperatures higher than ambient can results in net shrinkages when returned to ambient temperature.
- Applying tension(with/without the simultaneous application of temperature and/or moisture change) or applying compression(by shear within a sheet), shear can be developed by one layer expanding relative to another from thermal or moisture expansion.

WHAT HAPPENS BETWEEN LAYERS

By using the reasons for dimensional change and dimensional change differences, we can qualitatively explain various ways curl is formed. We also can divide curl further into reversible and irreversible reactions. Reversible curl can be defined as one which reverts to the original curl conditions of the sheet after the RH or other condition applied is removed. Let us say a sheet that curls to an 8 inch radius when exposed to low RH, lowering its moisture to 2%, was flat at 5% moisture. If the sheet becomes flat again when it is returned to 5% moisture, this would be an example of reversible curl. On the other hand, if a curl radius of 12 inches remained, part of the curl formed would be considered irreversible curl, i.e. the difference between flat and a 12 inch radius. The remainder of the curl, the difference between 12 and 8 inch radius would be reversible curl.

Paper in a stack exposed to low RH

The moisture in the top sheet begins to diffuse to the surrounding atmosphere. The top layer of the sheet contracts relative to the bottom layer. Differential contraction takes place because it takes a finite time for moisture to diffuse out of and through the sheet. The top surface is at a lower moisture content because it has given up some to the surrounding atmosphere. The top sheet(s) curl toward the top of the stack(Fig. 2). Exposure to high RH would produce curl toward the stack. Paper loaded in copiers will react in this way. If curl is excessive, a jam can be caused. This type of curl is highest during the first few minutes of exposure. This can be shown experimentally by taking a ream of paper and exposing the stack to an adverse RH for various length of times from one to thirty minutes. The top sheet is measured for curl and compared. Best results are obtained by using a newly exposed sheet for each measurement.

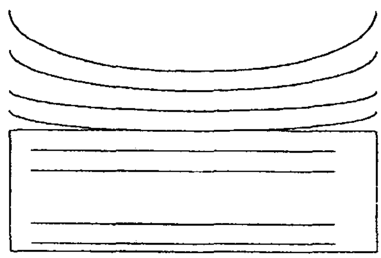

Fig. 2. Low humidity curl in a stack.

Two layers with different composition or treatment in manufacture

If we were to make handsheets which have a different fiber or a different degree of refining in each layer, exposure to low RH would produce curl toward the surface which changes dimensions more for a given moisture change. Curl would be away from that surface at higher RH. The same thing would happen if we laminated the two handsheet layers after they were dried separately.

In xerographic copying, this element of curl could either enhance or detract from the amount of curl formed in a top sheet of an exposed ream. This suggests that the higher expansive surface should face toward the bottom of the stack in low RH conditions and toward the top in high RH to reduce jam causing curl conditions.

Two layers with differing fiber orientation

Paper with two layers with different fiber orientation will also have a difference in moisture expansion and contraction properties. The situation is more complicated to analyze than simple difference in expansion properties due to composition. The surface with more fibers oriented in the machine direction will tend to exhibit a machine direction axis curl when curl is to that surface(Fig. 3).

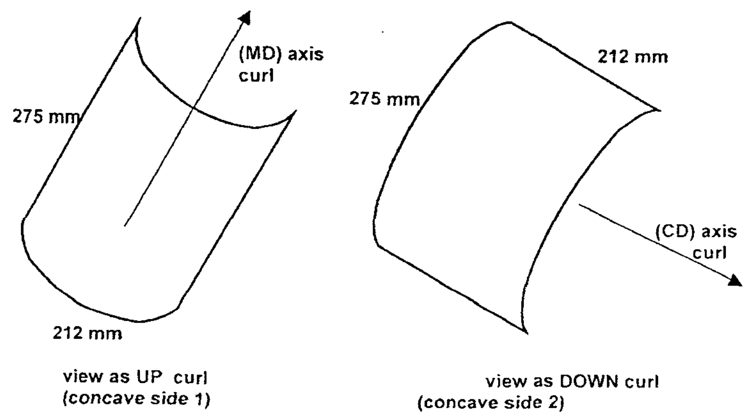

Fig. 3. Bimodal curl diagram.

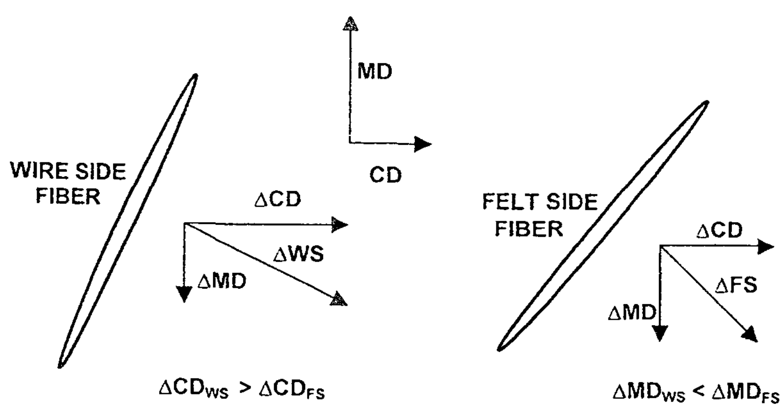

Fig. 4. Fiber orientation in the paper sheet.

Curl that forms to the side opposite of the more oriented fibers will tend to have a cross direction axis. This means that the curl tendency of a sheet with differential fiber orientation can be to either surface, depending on circumstances, but with a curl axis that differs by 90 degrees. With the illustrated wire side fiber having more alignment in the machine direction than the felt side fiber(Fig. 4), the following occurs. In the cross direction, the wire side has higher changes in dimension with moisture content. MD axis curl is obtained with higher contraction of the wire side in the CD, Conversely, there is higher dimensional changes in the machine direction on the felt side, then a CD axis curl with higher contraction of the felt side or higher expansion of the wire side is obtained.

Release of internal strain(internal stress)

With two layers of differing composition, treatment or fiber orientation and the finished sheet is nearly flat, the internal strains built in the sheet will be different in these layers(Fig. 5). If a two layered sheet with different shrinkage properties (Fig. 5a) illustrated by partial lengths in layers x and y is allowed on free drying, form a curvature toward layer x(Fig. 5b). However, in normal drying there are flattening constraints during drying which cause the sheet to dry flat or nearly so(Fig. 5c). The drawing(Fig 5c) depicts the difference in internal strains that have developed in the structure and each length($\Delta x1$ and $\Delta y1$) represents a potential shrinkage that can take place if the internal strains are released. If they are released equally, curvatures formed will tend toward the free dried shape(Fig. 5b). Without differences between the layers in a sheet, equal exposure of each layer to higher than ambient RH or temperature would only cause shrinkage but not curl. There may be cockling.

There are two ways curl that can be resulted form releasing internal strain. One, by modifying, wetting or heating one surface of a sheet more than the second, with internal strains present. Second, the sheet structure has different amounts of internal strain available in each layer, and the layers are treated equally with moisture or heat.

One side treated

A simple way to demonstrate this type of curl is to wet one surface of a sheet. Initially the sheet will curl away from the wetted surface. After drying sufficiently the sheet will curl toward the wetted surface. For papers with uneven internal strains, the degree of curl toward the moistened surface will vary and depend on the direction in which a strip is cut from a sheet. A difference in fiber orientation between the wire side and felt side will produce results like those shown in Table 1.

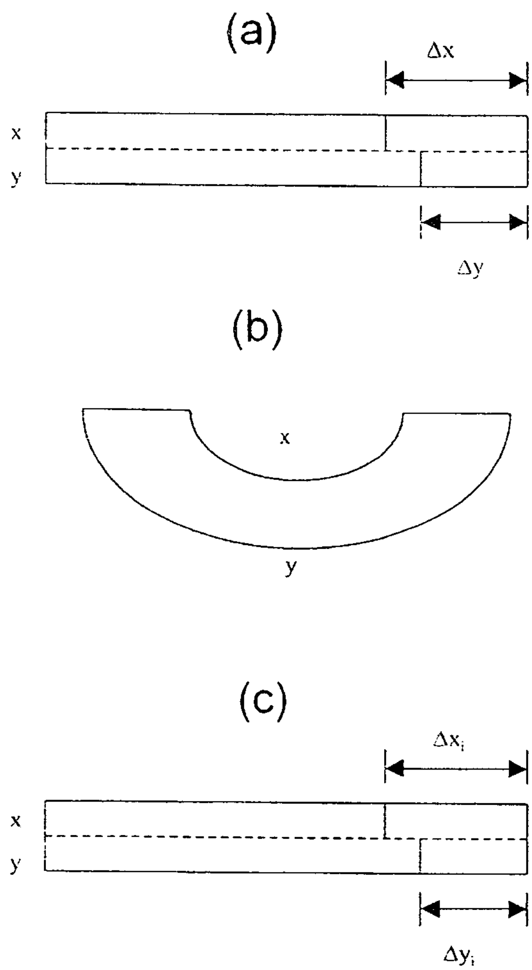

Fig. 5. Formation of differential internal strains.

Table 1. Differential wetting and fiber orientation

Paper	MD strip		CD strip	
	Side moistened		Side moistened	
	Wire	Felt	Wire	Felt
A	12	2	34	27
B	32	0	3	38

Curl after drying : curl in mm, toward moistened side

Paper A has fibers more oriented on the wire side, but does not exhibit what would be expected but instead tends to show slightly more curl toward the wire side in both directions. On the other hand, paper B shows what could be expected in that it is a sheet that has fibers more oriented on the felt side. The behavior of these papers when exposed to high humidity or complete wetting is more like what is expected. Evidently one side wetting has to be carefully controlled to obtain results consistent with what paper structure would predict.

Both surfaces treated equally with moisture or heat

This type of reaction can be illustrated by describing an experiment. A pulp was beaten for differing times and some of it were made into standard handsheets. The shrinkage on treatment of these sheets with 100% RH and subsequent redrying without constraint are given in Table 2.

Table 2. Beating time and shrinkage

Beating time (min.)	Shrinkage (%)
10	0.66
60	0.82
120	1.1

Handsheets were also made by laminating combinations of the 10 min. beaten pulp with each of the other beating time. The dried laminated sheets were then exposed to 100% RH so that curl could from without the effect of gravity on redrying. In each case, curl after redrying was toward the layer with the higher tested shrinkage in Table 2. The 10/120 combination had a curl radius about 1/3 that of the 10/60 combination. The differential shrinkage value of the 10/60 combination will be 0.16%, while 0.44% or about three times the differential shrinkage for the 10/120 combination. When the differential shrinkage of the laminated sheets is calculated from the curl results, 0.15% and 0.4% are obtained for the 10/60 and 10/120 combinations respectively.

Similar results can be obtained by mechanical treatment of paper before gluing or laminating them together. For example, a 60 g/m^2 cross direction strip is stretched 2.5%, on release the sample has 1.5% stretch remaining. This strip was glued to an unstretched strip. Two unstretched strips were also glued together in the same manner. The samples were exposed to a nichrome wire heating lamp for several seconds and allowed to recondition to room ambient humidity. The control sample did not curl, while the sample with the stretched strip formed a curl radius of three inches toward the stretched layer. Samples of stretched and unstretched paper were exposed to the same heat source with the following results after reconditioning.

Control strip : 0.05% shrinkage
Stretch strip : 0.18% shrinkage

The differential shrinkage was 0.13%(The differential shrinkage on exposure to 100% RH was 0.67% in the same relative way). One significance of the preceding experiment is that stretching irreversibly introduces additional internal strain. This is potentially recoverable by treatment with heat and moisture.

Bending moments

The idea that mechanical strains produce permanent dimensional changes can also be seen in bending. You may be familiar with core curl, that develops in the windings at the core of a roll. This is curl produced in paper that is held in a curved position for a sufficient time. In the bent position, the outside of the curvature is in tension, while the inner is in compression in the plane of the sheet. If a sheet of paper is put into a six, or even a three inch diameter tube shape for a few seconds, little if any permanent curl is produced. At these levels of bending strain and time complete elasticity seems to exist. If the time is extended to several hours, then permanent curl deformation develops. The data in Table 3 illustrates the effect of time.

Rate of bending deformation is increased by the flow of moisture into or out of a sheet. In an experiment to compare to the data in Table 3, a sheet was bent to a 1.5" radius at the same temperature and humidity, then placed outdoors in the sun for 2 minutes, then allowed to condition indoors again for 5 minutes, formed a curl radius of 2.5", double the effect of maintaining the same bending strain at nominally constant ambient conditions for 18 hours.

Table 3. Effect of time on bending curl

Time (hr.)	Curl radius (in.)
2	12
18	5

Thickness : 4 mil

Combined internal strain(internal stress) release, bending moments, and reversible dimensional changes

Xerographic curl

The process of xerographic machine is quite complicated because most likely *differential heating, strain release* or *differential strain release, bending,* and *reversible dimensional changes* take place. A differential moisture within the structure produced the layered dimensional changes. Because of the complicated interactions taking place, curl of 75 g/m^2 paper will differ substantially at low(less than 5%) and high(more than 6%) sheet moistures. At low moisture, curl will be toward the printed side, while at high moisture curl will be away from the printed side.

Other paper variables that affect xerographic curl are *wire to felt fiber orientation, wire to felt side moisture* and *thermal diffusivity, average internal strain* and *basis weight*. For 75 g/m^2 paper, moisture content is the most significant variable. If paper moisture content is controlled to a consistent low level of 4-4.8%, we probably will not encounter any away from print curl for most papers. *Controlling moisture in this range will allow the manufacturer to concentrate on the other variables that affect fuser curl.*

The other factors become the important ones to control. Wire to felt side fiber orientation should be balanced so they are nearly equal, as in a twin wire paper. The optimum balance will depend on which xerographic machine the paper is used in. In order to prevent CD axis curl to the wire side, when the wire side is printed first, the wire side should be slightly more oriented, which tends to produce MD axis curl to the wire side. MD axis curl is easier to stack than CD axis curl, an important consideration in automatic duplexing.

Lower internal strain levels should reduce the amount of strain release induced curl. Paper made with high drying tensions and high felt tensions would have more internal strain and the paper surface touching the hot fuser roll will tend to shrink more compared to the unheated side, causing curl to the heated side. Experimentally, rewetting paper and redrying with free shrinkage reduced fuser curl 50% at low moisture. A suggested level of internal strain is 0.6 - 0.7% for optimizing performance without producing cockling.

> The internal strain of a sheet will produce additional shrinkage when subjected to high moisture and temperature if the sample is not under any appreciable tensile load(i.e. less than 10 g/inch width). Experimentally, this can be shown by exposing paper to relative humidity above 83% and then comparing sample dimensions at a standardized moisture content such as 6%. The shrinkage tendency of MD vs. CD is dependent on the paper. Exposure to high relative humidity involves changes in moisture content and a transient or dynamic movement through the sample thickness.
>
> The amount of shrinkage at a given relative humidity appears to be a fraction of the total shrinkage obtained by wetting a paper and measuring its net shrinkage after drying without restraint. The shrinkage obtainable at a given relative humidity as a fraction of rewet shrinkage is a linear function of relative humidity exposure. The shrinkage obtainable at 100% RH is about 70% of that produced by water wetting of the sheet.

Internal strain also can produce shrinkage through heating. If paper is treated with heated rollers, a net shrinkage takes place, when dimensions are compared at a common moisture content. The extent of shrinkage depends on paper moisture content, heating time, and temperature. From the same experiments, moisture loss seems to predict the shrinkage reasonably well. The effect of high humidity treatment (or heating) is to reduce the amount of internal strain available for further shrinkage.

Table 4. Effect of treatment on shrinkage

RH treatment	Shrinkage(%)	Heated roller shrinkage(%)*	Total shrinkage(%)
None	–	0.24	0.24
85%	0.15	0.19	0.34
95%	0.46	0.06	0.52

* Shrinkage after RH pretreatment
Heated roller treatment : 160℃ for 0.1 sec.
Conditioned to 6% moisture after each treatment to measure net shrinkage

If the amount of moisture lost from the unprinted side is increased, curl toward the printed side is greater. If the rate of moisture diffusion from the unprinted side is increased by making it more porous to moisture flow, that sheet will tend to have more printed side curl. This effect can be seen when higher basis weight sheets are run through a xerographic fuser. If the basis weight is high enough(around 135 g/m^2), the moisture driven from the printed side apparently ends up somewhere in the center of the sheet, making the back side essentially nonporous to water. Therefore, curl is observed only on the printed side, which does not materially change as moisture content is increased.

TESTING METHODS FOR PAPER CURL

The propensity of paper to curl is an important aspect affecting the runnability for both producers and converters, and final product quality. In particular, curl which manifests itself after printing is of particular importance to newsprint manufacturers. A measurement of the propensity of curl is needed before control strategies can be evaluated and implemented.

Measurement of paper curl using Structured light

For this application, the simple definition of curl as being the inverse radius of curvature was used(Fig. 6). The method used to identify the sample curvature was to project structured light on the surface, image the resulting shapes and so derive measure of the surface geometry. The structured light chosen was a simple line, projected horizontally onto the sample. With the sample positioned so that it was inclined at a small angle(10 degrees) to the line, and curled in the direction of the line, this produced a symmetrical curve when viewed from above. The set-up of the equipment is illustrated in Fig. 7. It is expected that a lower-cost laser diode would have performed as adequately as the laser actually used.

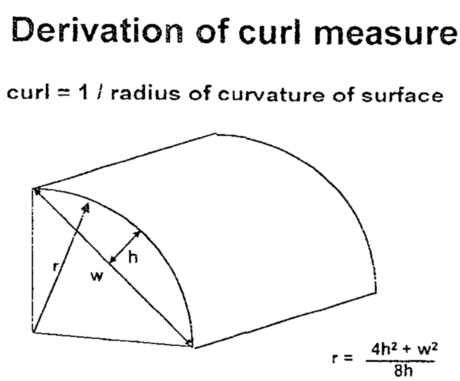

Fig. 6. A definition of curl.

In deriving the measure of curl, two important assumptions were made :

- the direction of curl of the sample was aligned with the structured light
- the nature of the curl was cylindrical

Taking these as given, some simple geometry could be applied to the resulting curved line to transform the line to an arc of a circle, and so drive the curl radius.

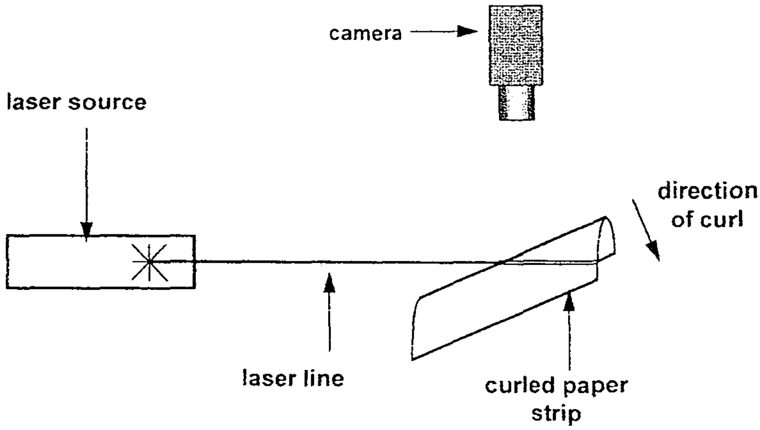

Fig. 7. Equipment set-up.

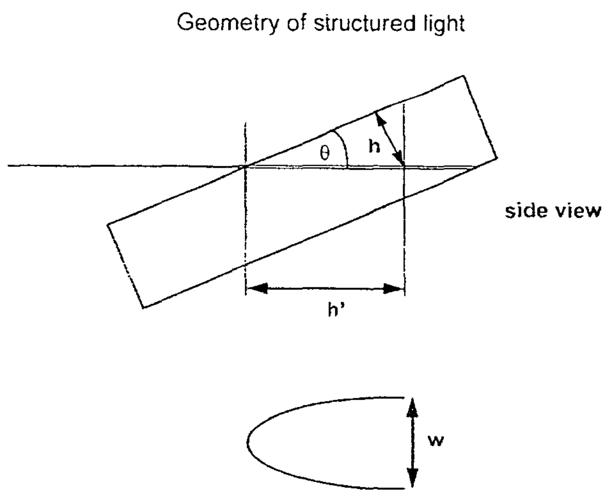

Fig. 8. Geometry of structured light.

$$h = h' \times \sin(\Theta)$$

Radius of curvature,

$$r = \frac{4h^2 + W^2}{8h}$$

where

θ : angle sample is inclined to the horizontal

w : distance between two points on a horizontal section through the curved line

h' : measured perpendicular distance from the top of the curved line to that section

h : actual distance in direction of curl

To test the basic procedure, some trials were carried out using paper cylinders of known diameter. These were imaged as described above, and the dimensions of the curve were taken manually. That is, the user used a mouse to draw a rectangle on the screen which framed the curve. The derived radii of curvatures compared well with the actual values.

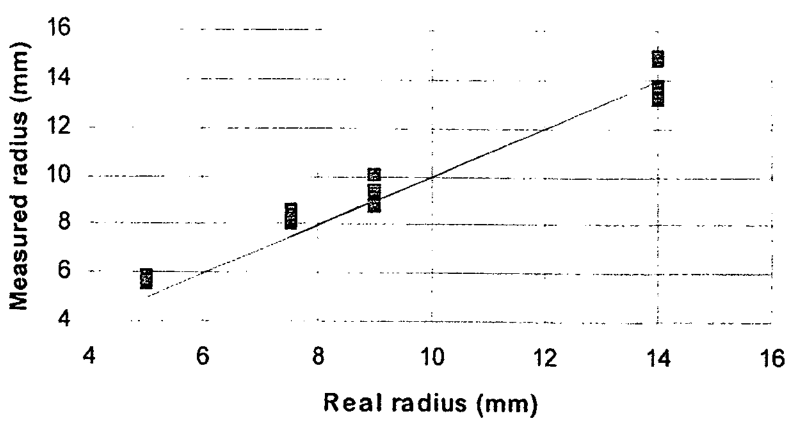

Fig. 9. Real radius vs. measured.

The measurement has proved to be a quick, useful application of image analysis and structured light to the measurement of curl radius of narrow strips of paper. The image is simple and can readily be automated. The measure does rely on an assumption about the nature of the curl, and depends on accurate location of the sample relative to the structured light.

FIBRO dimensional stability and curl tester

A speckle pattern is applied on the test specimen, which is then positioned under a pixel-synchronous CCD video camera capturing an image. The specimen is then exposed to a different level of humidity, temperature or tension. After the requested conditioning time, a second image is captured and the two images are compared to calculate the dynamic in-plane displacements across the specimen surface. A full test involves the comparison of a sequence of two or more captured images at different conditions.

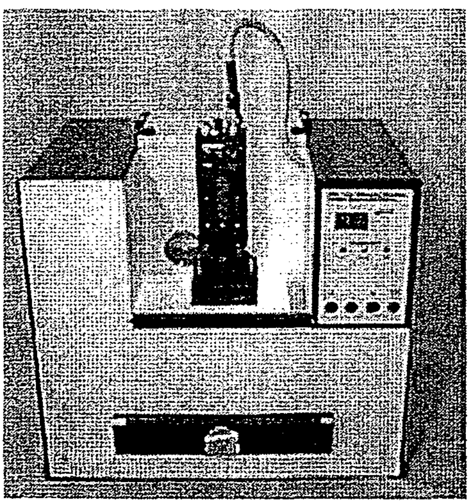

Fig. 10. Dimensional stability tester.

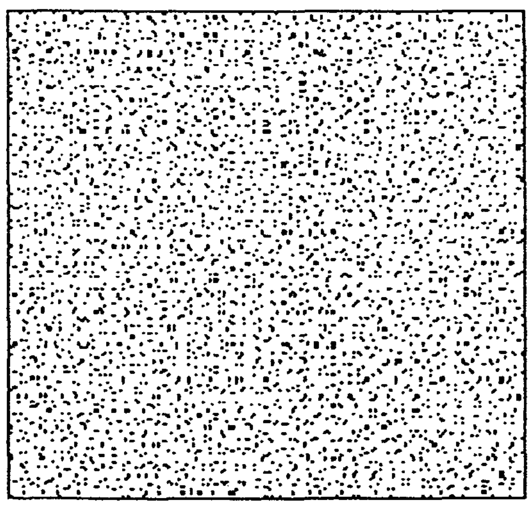

Fig. 11. An example of speckle.

For evaluation of out-of-plane displacements, two pixel-synchronous CCD cameras are used to view the same specimen area from a perpendicular angle which eliminates distortion of an angled camera. The 3-D approach can be used to describe the static shape of a cockled or curled surface as well as the dynamic deformation caused by moisture, temperature or tension.

With Electronic Speckle Photography(ESP), white light is used to capture a video image of a surface with a speckle pattern. The speckles can be applied in different ways as long as there is a sufficient amount of speckles, the speckle pattern is random and the speckle size can be detected by the system. Normally speckles are applied as dry copying toner randomly sprinkled over the specimen surface. When specimens must be handled between image capturing, the speckles must be fixed to the surface. For static shape measurements such as cockling and curl when only the out-of-plane observation is of interest, the speckles can be projected on the specimen surface.

In conventional image analysis applications, light conditions are extremely critical because of the light intensity thresholding. With ESP, however, the differences in light intensity have no significant influence as long as there is enough of gray scale information in the captured image. The reason is that ESP is using a **finger print** of the speckle pattern instead of looking at individual speckles. Each image is normally divided into 256(16 by 16) sub-images for analysis. Consecutive images are compared on the sub-image level and the displacement in microns are calculated across the specimen surface. The comparison of sub-images using Fast Fourier Transformation(FTT) and cross correlation offers an accuracy of 1/100 of a pixel. This corresponds to displacements as small as one micron across a specimen view of 50 x 50 mm. Other field of view can be used depending on lens system and viewing distance.

The irreversible shrinkage traditionally interpreted as the release of **dried-in strain** or **frozen strain** is a function of the highest moisture content reached in the cyclic humidity treatments and the previous moisture history that the paper has experienced before the current test. In this example, the displacement of each sub-image is represented by a vector across the surface. When the relative humidity is increased from 50 to 80% RH, the specimen expands from the fixed point in the lower lefthand corner. When the process is reversed from 80% to 50% RH, the specimen contracts towards the fixed point. The contraction across the specimen area is less than the expansion because of hysteresis phenomena.

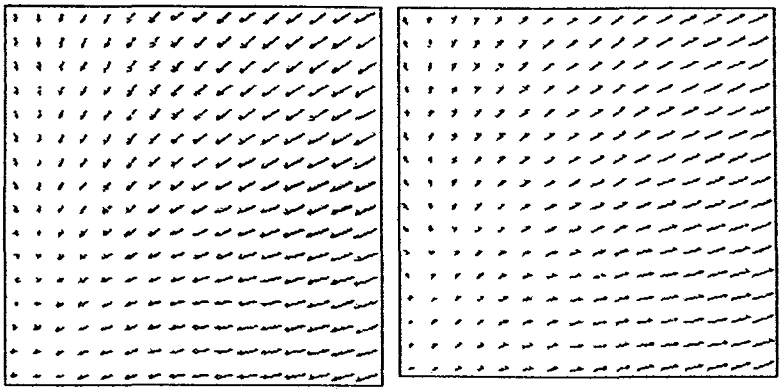

Fig. 12. Images for speckles before and after contraction.

X test

An X cut is made in the sheet diagonal to the CD and MD, without heat application, and the amount that the cut corners raise up is measured. It has been used on some specialty paper grades.

TSO measurement

TSO is tensile stiffness orientation angle in degrees. A maximum angles are 2-3 degrees from MD for copy paper and boxboard and 3-5 degrees for many other grades including, offset and other roll printed paper, liner and medium(5 degrees). Although a differential angle between WS and FS is need to produce curl, the reason testing a manufactured sheet works is that the TSO of one half of the paper(wire side) may be nearly constant.

L&W curl and twist tester

4" x 4" samples placed flat inside a chamber are conditioned(usually to three standard RH values of 30, 50 and 65) for 6 minutes. The height of the paper at 81 points measured by an optical light diode with vertical beam of 0.3 mm. A camera, angled against the beam records the light beam measuring point. The viewing angle is a function of the distance to the illuminated point on the sheet.

Split sheet zero span tensile ratio

Sheets are split and zero span tensile is measured WS and FS, MD and CD. The ratio of MDWS/MDFS divided by CDWS/CDFS is calculated. Similar tests could be performed by measuring tensile stiffness. Likewise, moisture contraction from 80% to 20% RH has been measured. In this case, the ratio CDWS/CDFS divided by MDWS/MDFS is used. In general, if the result is higher than 1.0, the wire side of the paper has more fibers oriented in the MD than the FS.

Multiple sheet splitting

Erkillä et al developed a technique that splits a sheet into 5-10 g/m^2 layers using a combination of single and double sided adhesive tape. Each layer is stuck to an area of adhesive tape. By wetting the remaining paper sheet after each sheet is removed, the position of each layer within the sheet can be determined. Each layer is imaged by a video camera, and then the edges of the fiber segments in the image are detected by imaging processing software. The fiber edges are then used to determine both the mean and distribution of alignments of the fibers in each layer. Erkillä et al were then able to relate the distribution of fiber orientations through the cross-section of paper samples to their forming conditions in a logical way.

Humidity cycling

1" x 3" strips are cut MD and CD and mounted on edge and cycled through high RH to look for reactive and nor-reactive curl components. One would look for the reversible and irreversible curl components. The irreversible component would be the change in curl at the original RH after cycling through high RH. The reversible component would be the change in curl from high RH to the original RH. It is recommended to do test for two MD strips and two CD strips. With each pair start a slight WS curl on one and a FS curl on the other. It is important that the beam effect of the starting curvature be taken into account.

Oven curl test

Paper is placed in an oven and heated, measuring the deflection from flat. It is suggested to use an oven with a window so the maximum deflection observed can be measured when it occurs. A sample will usually go to a maximum, then recede, unless it is a board sample. Another suggestion is to perform the test with the WS and FS up and to impart a small MD and CD axis curl, making a total of four samples tested. This is to account for the beam effect.

Hot plate curl

2" squares of paper are put on a hot plate heated to 350 °F and measuring the maximum height of the corners from the surface of the hot plate. One has to be careful to measure the maximum as samples will recede. Test seems to be used for copy paper.

Copy machine curl test

Paper is cut to copy machine size from large rolls. Sheets are run in a copier simple/duplex WS and FS printed first more than 20 copies and a hanging curl measurement is made. Machine adjustments are made to obtain satisfactory curl. It is recommended to do test with paper at the proper low moisture specification or guideline, a high moisture will produce away from print curl. The paper tested very soon after manufacture tends to show more curl than after storage.

Heat lamp cure test

Take paper from the paper machine windup and cut into 1" x 6" strips MD and CD. Place WSMD and FSMD strips up(slight up curl in each would be preferable) side by side under a heating device and heat until curl is a maximum, record curl to the nearest 0.10"(Hanging curl can be measured as an alternative). Repeat for WSCD and FSCD strips. The heating device could be two infrared heat lamps or nichrome wire heat lamp. The greater the heat input, the faster maximum curl can be reached. A ruler graduated in tenths of an inch can be fastened to the base to make reading the curl height more convenient.

Hot strip(bend) curl test

This method involves contacting strips of paper with a heated surface(300°F ± 10) that has a radius of curvature of 8 inches. The curvature provides good contact with the sample. The method has been used to evaluate copy paper curl.

When doing the test, strips should be held in a curved shape of approximately 8" radius so that the whole strip can contact the block at the same time. Samples 3/4-1" width and 8-11" long can be used(two CD strips can be cut from the 8.5" edge, then two CD strips can be cut from the remainder of the 11" edge). A contact time of 1-3 seconds is used and the curl is immediately measured with a curl test templates as hanging curl(cord height of 8.5" arc). Strip also should be held against the block with a pressure that will nearly move the block. Curl tendencies can be interpreted in terms of the curl obtained from WS/FS MD and CD test pairs strips(CD strips indicate MD axis curl and MD strips indicate CD axis curl).

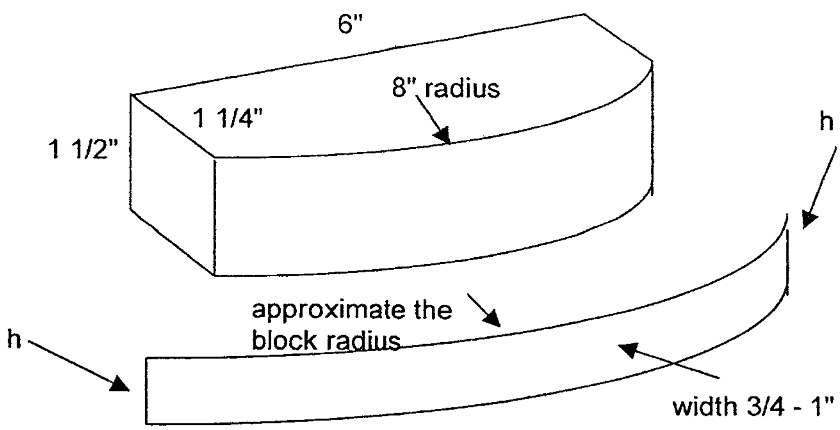

Fig. 13. Hot bend curl testing block.

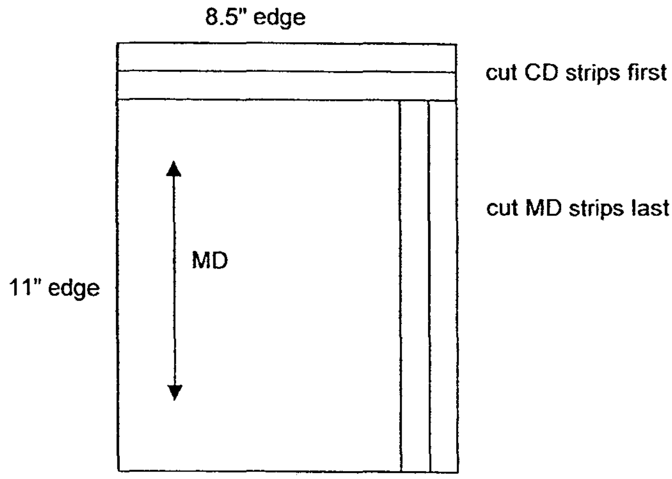

Fig. 14. Strip cutting diagram.

Interpretations for xerographic or laser curl

If the CD strip pair shows more curl to the wire side(MD axis curl), while the MD strip pair shows more curl to the felt side or no significant curl preference, then low moisture curl tendency WS printed is an MD axis toward print curl. If the MD strip pair shows more curl to the wire side(CD axis curl), while the CD strip pair shows more curl to the wire side or no significant curl preference, then low moisture curl tendency WS printed is a CD axis toward print curl. Of the two cases, the first is more preferable, since it would tend to avoid CD axis curl into a duplex tray and thereby reduce jams due to poor stacking. On the other hand, we should avoid excessive MD axis curl also.

Interpretations for moisture curl

If CD strips curl more to wire side(MD axis curl) and MD strips curl more to felt side(CD axis curl), then the fibers on the wire side are more MD oriented than on the felt side. For the opposite configuration(CD strips with more curl to the felt side and MD strips more curl to the wire side), the fibers on the felt side are more MD oriented. If only CD strips curl more to the wire side or only MD strips curl more to the felt side, the wire side fibers are probably more MD oriented than the felt side. If only CD strips curl more to the felt side or if only MD strips cure more to the wire side, the fibers on the felt side are probably more MD oriented.

1) Example of good Hot bend test result

The following test results are good because the WS heated sample curl to the WS is equal and opposite of the FS heated sample curl to the FS. The results can be called balanced. If the results are within about 10 mm, they are probably balanced. Both MD and CD samples should have results like this.

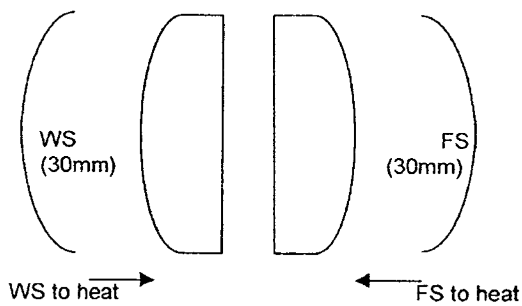

Fig. 15. Good hot bend test result.

2) Example of poor hot bend test result

In this situation, the WS to heat sample has WS curl but the FS to heat sample have less curl to the FS. Sample b result is more severe than sample a but both are different enough to indicate a problem. If either(or both) MD or CD samples show this behavior, it should be corrected. It should be noted that MD and CD samples may have differing results. For example, the CD sample would react as illustrated, but the CD sample would be such that the FS to the heat would have curl to the FS, while the WS sample would show less WS curl, be flat, or to the FS. This behavior is indicative of a difference in fiber orientation between WS and FS, which is potentially correctable by adjusting stock speed relative to the wire speed.

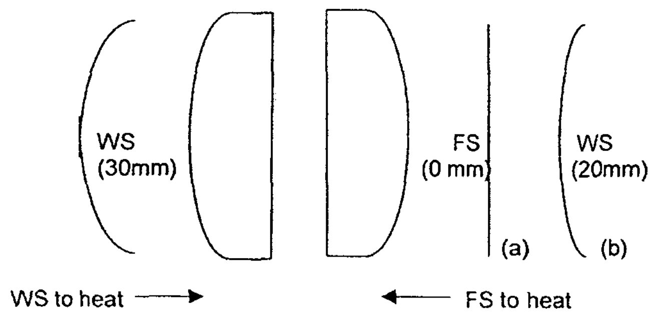

Fig. 16. Poor hot bend test result.

STRATEGIES FOR CURL CONTROL

By examining the reasons for curl we can take steps to improve it. It is need to minimize furnish coefficient of moisture expansion(CME). Even more important is the adjustment of wire versus felt side structure and composition to be more alike. For laminates and board, this means making the structure of individual layers more alike. Sheet shrinkage, top to bottom drying and moisture content affect curl observed in end uses. There needs to be a balance of wire and felt side coating or surface sizing. It is useful and even necessary to continually test products in end uses machines for which they are intended.

The basic statement of sheet deviation from the flat is

$$w(x,y) = 0.5\ (K_x x^2 + K_y y^2 + K_{xy} xy)$$

x and y are the MD and CD coordinates on the sheets and K_x, K_y, and K_{xy} are the MD, CD and diagonal curl components(curvatures as inverse radius).

$$K_x = \frac{2(\delta e_{MD})_{BOTTOM-TOP}}{Z} \qquad \text{(MD)}$$

$$K_y = \frac{2(\delta e_{CD})_{BOTTOM-TOP}}{Z} \qquad \text{(CD)}$$

z : thickness

e : strain

For diagonal curl,

$$K_{xy} = \frac{2(\delta \phi_{TOP-BOTTOM})(\delta e_{CD} + \delta e_{MD})}{Z}$$

ϕ : fiber orientation angle

Curl is the effect of differential change in two halves of the sheet for MD and CD curl, while diagonal curl is an effect of differential fiver orientation angle between WS and FS. If we take δe in percent and sheet thickness in mils as z to obtain a hanging curl(cord height of 8.5" length), h, in mm.

h = 1935(δe)/Z ≅ 2000(δe)/Z

It is extremely important to recognize the fact that curl is a result of the way the sheet of paper is put together. Process variables which control curl include furnish, sheet structure, and drying. Furnish variables include inherent CME from fibers, refining, and additives. Sheet structure effects include the development of differences in top versus bottom CME from fiber orientation and material stratification.

Furnish and stock preparation

The adjustments which can be made include pulp, refining, and additives(filler, sizing, starch, etc.). The objective is to reduce the inherent moisture expansivity as much as possible. In doing this the maximum internal strain that can be produced in drying is reduced when the same amount of shrinkage during drying is allowed. Although a reduction in inherent expansivity appears not to substantially change expansivity for the same shrinkage(Table), results from an experimental paper machine showed CD expansivity was reduced by 27% when freeness increased from 325 to 500 ml CSF(0.136 to 0.107% per 10% RH).

Table 5. Effect of pulp and refining on % wet expansion(30% RH)

Pulp	Free drying		Restraint drying	
	Unrefined	Refined*	Unrefined	Refined
A	2.4	3.6	1.0	1.2
B	3.9	6.3	1.1	1.1

* 300 ml CSF

Based on the results from an experimental paper machine, the addition of 17% filler reduced CD moisture expansivity of a machine dried sheet by 10%(from 0.127 to 0.115% per 10% RH). The addition of 2% cationic starch increased it 10%. We would expect an addition of 17% filler would also change other sheet properties significantly (such as a 30% reduction in stiffness), so it is probably not a practical way to reduce expansivity. In terms of curl that takes place by exposure to a different RH, assuming the sheet structure and manufacturing is the same otherwise, a reduction in 10% moisture expansivity should be reflected in a 10% reduction in curl(when stated in terms of 1/R or 100/R).

To measure the effect of pulp and furnish changes by means of moisture expansivity with any reasonable degree of precision with handsheets, it is necessary to dry them without restraining shrinkage. After handsheets are removed from the mould with blotters, the sheets are removed from the blotters and dried between other dry blotters. After they have been dried, strips cut from the handsheets can be measured for expansivity characteristics.

- Measure free-dried CME or tensile stiffness index
- Reduce or change refining and/or choose fibers with lower CME. Brushing type refining results in increased CME, while cutting type refining results in less reactive

fibers. Hardwoods typically have lower CME than softwoods, but this is not always the case.

Wet end

Most curl adjustments available on the wet end are involved with sheet forming. However, significant changes in curl can be seen if the press section is rebuilt in a different configuration. Curl control on a fourdrinier machine involves adjusting the velocity of stock to that of the wire, as well as other variables. These variables include the following : stock consistency, forming board position, foil adjustment, dandy roll to wire speed, wet felt conditions.

This is a matter of trial and error on each machine to obtain a jet to wire speed which will adjust fiber orientation between wire and felt sides so as to minimize curl. In one curl problem, if the jet to wire theoretical speed ratio was between 0.954 and 1.046, no curl or slight curl was measured using a heat lamp test. Beyond these ratios, curl became moderate to severe. For xerographic paper, the jet to wire control requirements are probably more stringent, where a change in ratio of 0.03 could be enough to change curl by 10(100/R units). Machine speed itself may be a factor in the importance of a change in ratio. Regardless, once an optimum operating jet to wire speed has been attained, its control to that value should allow good curl results over a period of time.

Both forming board position relative to the point of jet impingement and foil angles apparently have a significant impact on curl also. Forming board positioning and table rolls which produced turbulence in the stock seems to reduce curl. The use of varying degrees of foil angles also has changed curl. A condition which could change felt side fiber orientation is a dandy roll which has a speed different from the wire, especially if the stock is fluid at that point. Quantification of this has not been reported at this point in time. As mentioned earlier, changes in wet felt configuration can change curl characteristics. It is also possible that variations in condition of the felt itself could change sheet characteristics. One such condition is for a felt to become filled or loaded, changing its porosity.

Effect of fiber orientation

- *Reduce WS to FS difference in CME(or TSI) both MD and CD*
- *Measure CME of split sheets*
- *Measure tensile stiffness orientation(TSO) of the sheet in the full CMD*
- *Minimize TSO's by balancing the manifold, adjusting headbox edge control valves, and adjusting jet-to-wire ratios*
- *Adjust jet-to-wire speed to reduce CME differential. Generally, a jet-to-wire ratio near 1.0 produces the best curl, but trials need to be made to confirm this for each paper machine(when anisotropy two sideness is eliminated curl may not by minimized but may become unstable(diagonal) at the transition point between the two stable curl modes.*
- *When available, laser arc polarization measurement should be useful*
- *Alternately use curl tests and balance WS and FS heated measurements*

Drying

Drying can affect sheet curl of a sheet as it comes off a machine. Experiments on a small laboratory dryer have shown some interesting results. Sheets of previously made papers A and B were rewetted and were held against the dryer by means of a felt as shown Fig. 17. The output curl at lower temperatures was toward the drier surface and at higher temperatures away from the drier surface.

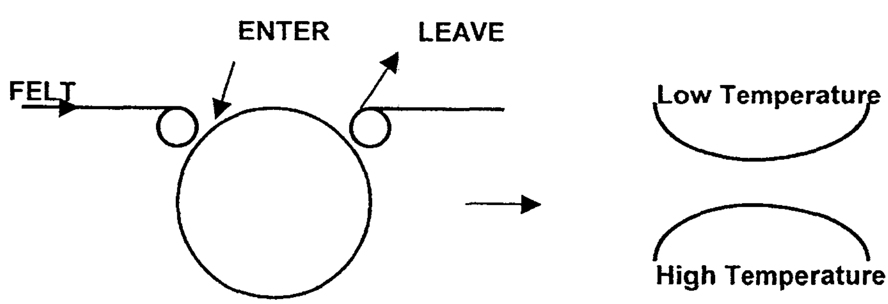

Fig. 17. Drying experiment schematic.

Experimental results have been previously reported. If the results are graphed in terms of toward and away from drier curl versus surface temperature for either paper, we see that curl become toward the drier surface as temperature increases. At about 270°F, there is curl both toward and away from the drier surface. On the test samples where this condition existed there was a bimodal curl. You could flip the curl from one surface to the other mechanically.

The observed results are probably the result of where moisture resides last in the structure. Previous work indicates that curl is formed forward the surface from which moisture is removed last. If that is the case, then lower temperatures should favor moisture being removed last at the dryer surface. Likewise, higher temperatures place remaining moisture at the felt surface.

With the FS toward the dryer we find curl toward that side at lower temperatures. But also note the CD axis curl toward the FS(paper A). At higher temperature curl moves to the WS away from the dryer, but the curl axis becomes MD. Note with WS toward the dryer the axis of curl also is dependent on which paper surface the curl is toward(paper A).

Concave to WS : MD axis curl
Concave to FS : CD axis curl

These are the more natural curl tendencies of a sheet with fibers more oriented on the wire side. Likewise, with paper B we find the opposite reactions since it has the characteristics of a felt side oriented sheet.

Curl of paper in xerographic and offset printing can be influenced by drying conditions. Moisture content is critical to xerographic curl. Most manufacturers control moisture to relatively low levels of 4.5–5% so that curl is a repeatable property. If moisture is maintained in this range, toward print curl is the norm. At moisture above 5.5–6%, away from print curl is often encountered in many xerographic machines. Of course, the extent of curl change away from print with increase in moisture content is also a function of copy machine variables such as fuser temperature, dwell time and roll diameters.

A drying condition important to xerographic and offset processes is the restraint of shrinkage. The less a sheet shrinks, the more internal strain is developed. Lower internal strain will tend to reduce toward print xerographic curl at low moisture and away from print curl at high moisture. In addition, low internal strain will reduce the effect of one side release of internal strain in offset printing. This would reduce curl toward the printed side after the paper has been dried.

Size press or coater

The basic idea behind improving curl by sizing or coating is to balance the amount of hydrophilic binder between the two surfaces. With surface sizing it would be a matter of balancing the amount of pickup on each surface. Adjustment in pickup between surfaces may require the equipment that would allow a different the percent solids application to each side of the sheet. Such an arrangement could be useful in experiments on curl reduction. Adjustment of the sheet's ability to absorb sizing could be another approach to adjusting curl.

With one side coated stock, the problem may be attacked by applying a coating of binder on the opposite surface in an amount that equals binder coat weight on the other surface. For two side coated papers, the adjustment in hydrophilic binder applied to each surface is a key factor. From coating weights and binder percentage, we can calculate the amount of binder being applied to each surface. Curl we observe at low humidity should be toward the surface with the higher binder content. To reduce this type of curl, either reduce the binder weight applied to the side with the concave curl, or increase the binder weight on the opposite side.

Converting

Problems from curl being treated here are those in which two or more layers of material are laminated or sandwiched to make a product. It is critical to match as closely as possible moisture expansion properties at least the outer layers. Mismatches are very easy to produce in such things as labels, where the backing is a glassine product, while the labels are a more ordinary paper. I believe we should include both the measurements of reversible expansivity at low moisture and internal strain release at high moisture. Both are potential problems in both parts of the label sandwich.

CURL EVALUATION AND IMPROVEMENT

A reasonable and practical approach to curl problems to be to look at the structural properties of paper and board as they relate to observe curl. This requires that we assess the properties of the manufactured sheet such as

- Curl coming off the manufacturing equipment(papermachine, winder, etc.)
- Curl in an end uses application, including tests

Curl in an end uses application can often contain more than moisture change curl, ie. effects of internal strain, and may be moisture dependent, as well, like xerographic curl.

Assessment of the structure(Effect of manufacture)

If the sheet structure is truly from a single furnish going to the former, we need to determine the formed properties within the structure by taking apart that structure. If the former makes separate layers(as in a multi-cylinder machine), it may be possible to get samples of the separate layers. Otherwise, sheet splitting into at least two layers can be done, and is probably the more desirable as it provides properties as manufactured.

For single furnish paper, the simplest way to assess sheet structure(bypass sheet splitting and related work) may to use the **warm oven** and/or **hot bend** curl test procedure or perhaps some others. Although these test methods do not specifically measure dimensional changes, the curl obtained can be used to evaluate sheet structure.

For more than one furnish and multiply structures, the best assessment is probably analyzing the individual plies using moisture expansion measurements.

Basic approach

The paper structure chosen here is a two layered structure as a simplification to develop the idea. The layer with the higher free dried CME will also have the higher internal strain. If there is diagonal curl, the major axis of the CME could deviate from MD and CD.

The curl will occur when the moisture content is increased or decreased and there is difference in the CME and internal strain between two layers. The actual change in curl will depend on the difference and the extent and range of the moisture change. Curl can also occur when internal strain is altered such as by exposure to an RH above 80%. Fig. 18 is a basic outline of variables that can affect the CME and internal strain of each layer.

Curl improvement

The information available for improving curl can be applied in one of two ways. The first, we can use a model(e.g. Figure 18 and Fig. 19) and apply it to a particular curl problem. The second, we can begin a process study to determining what variables affect the curl structure formed on the wire and with subsequent drying. The first step in this process would be to measure the present state of curl, its variability when we try to keep all expected effects constant, keeping a record of all current conditions, including furnish, wet end, pressing, surface applications and drying.

The next step is to make adjustments on the wet end in small increments to determine how curl moves as we make the adjustment. Adjustments of jet to wire speed, impingement angle and consistency are likely to produce changes. Also, condition and changes in foils and forming board may be factors. If a dandy roll is used, its speed relative to the wire may be a factor, if the slurry is still wet. There may be a need to determine wire versus felt side pickup of surface size, as it is now, and how it could change with furnish and wet end changes.

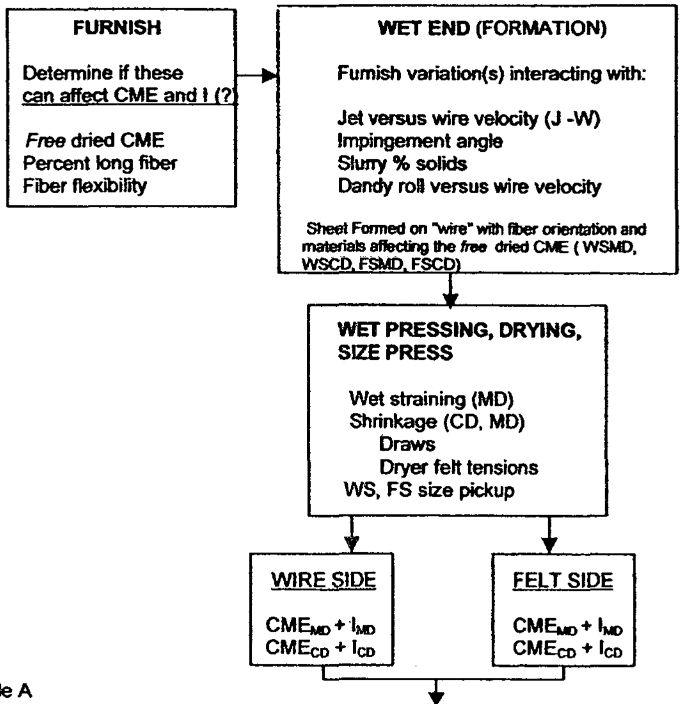

Table A

[1] MDWS < MDFS	[2] MDWS >MDFS	[3] CDWS < CDFS	[4] CDWS > CDFS	
FSMD hot bend to felt side (CD axis curl)	FSMD hot bend to wire side (CD axis curl)	FSCD hot bend to felt side (MD axis curl)	WSCD hot bend to wire side (MD axis curl)	(strip lengthwise direction)
FSCD warm oven to FS	WSCD warm oven to WS	FSMD warm oven to FS	WSMD warm oven to WS	(vertical axis of of sample)
FS print copy curl FSMD curl	WS print copy curl WSMD curl	FS print copy curl FSCD curl	WS print copy curl WSCD copy curl	(4.5-4.8% moisture)

Fig. 18. Basic curl flow diagram.

Table A lists the more likely for possible curl outcomes of curl tests. CME and internal strain [1] and [4] will often occur together because of fibers on the wire side being more MD oriented than the felt side, producing MD axis curl to the wire side and/or CD axis curl to the felt side. CME and internal strain [2] and [3] has also observed together.

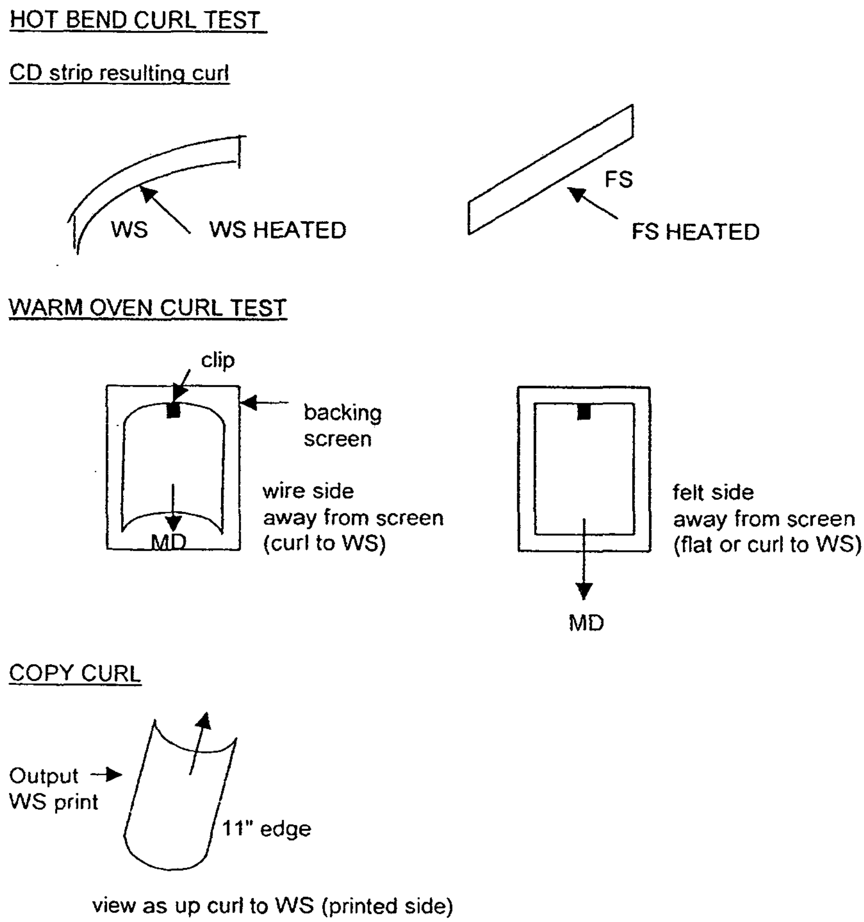

Fig. 19. Diagrams of curl test results.

Curl in end uses

Adjusting paper curl for end used may be more complicated. The first adjustment is to make the layers as equal as possible, but in some cases, as equal a possible may not be ideal. A slight curl to a particular side may be better. Lower internal strain(copy paper) is probably almost always preferred, when it does not produce other defects such as cockles.

Besides sheet structure, we may need to consider moisture content, as with xerographic or copy paper. For these papers moisture has a strong affect on which surface the paper will curl toward. At low moisture, it is toward the print side and at higher moistures away from the print side. In offset printing, the degree of curl could be affected by the amount of moisture uptake and internal strain. With aqueous inks, the amount of ink applied would determine the amount of moisture uptake.

MULTI-LAYERED BOARD CURL

The fibrous arrangements within the board structure and the inherent moisture expansion and contraction properties of the furnish can play a role in making the board prone to curl. The printing process may also have an effect on making the board curl, especially if it puts water or moisture into the board.

To understand curl in a way that will allow us to reduce it, several things have to be taken into consideration.

- The relative CME of each layer's furnish
- The effects of forming each layer(fiber orientation)
- Each layer has its own curl characteristics(differential fiber orientation/fines)
- The effects of the coating and printing process
- The use of drying control to make a flat board coming off the machine will not necessarily produce a flat sheet in end uses

Methods of studying board curl

Inherent curl of the board

The evaluations which follow ought to be compared to the inherent curl of the board itself. In this way it may be possible to assess what is affecting curl. Curl can be measured using a **warm curl** measurement, and/or perhaps a **hot bend curl** if the board is not too stiff.

Furnish

If different types of fiber furnish is used in each layers, it is very likely that these have differing expansion(or contraction) properties when their moisture content changes. A CME measurement has to be made using free dried handsheets that are made from these furnishes. It also would be useful to measure CME variations over time and compare them to curl. Because board is dried with shrinkage constraint, much of the difference between the furnishes become a difference of internal strain within the sheet structure. These differences could show up when the board is subject to wetting and drying. When one furnish is found to have a higher CME than another, it is need to find ways to reduce the one that is high or increase the one that is low. This could be done by changing refining or changing the furnish.

The individual layers can be analyzed using sonic modulus or CME techniques such as the Quick Skan measurement or other sheet dimensioning device. Free dried handsheets of the furnish of each layer are analyzed. For good curl characteristics, board layers should have CME properties that are very similar, especially the outer layers.

Table 6. CME of handsheets

Furnish layer 1 free dried CME	
Furnish layer 2 free dried CME	
Furnish layer 3 free dried CME	

Fiber orientation

When the board is formed each layer is made with a different degree of fiber orientation in each forming unit. The more fibers are oriented in the machine direction the higher the free shrinkage in the cross direction, because fibers themselves have very high shrinkage in the width of the fiber. The way this can be studied by taking the finished sheet and split it into its layers, at least into the outer two layers. The split sheet can be analyzed using CME or sonic modulus(tensile stiffness index). If possible, CME measurements should be done simultaneously so the samples will receive exactly the same treatment. Thereby can be compared without additional interpretation. The measurements made can be divide into two categories.

- Split layers of manufactured paper(MD, CD, geometric mean as made and rewet-free dried CME or TSI)
- Sample of each layer from the wet end that are free dried, measuring MD and CD and calculating the geometric mean CME or TSI

If one wishes to use TSI in place of CME, MD/CD ratios should be used. Care has to be taken initially to determine that tensile stiffness index results are comparable on furnishes that are different. WS/FS ratio calculated by expansion and stiffness should be comparable to moisture expansion results.

Table 7. CME on as made layers(split sheets)

	Layer 1	Layer 2	Layer 3
MD			
CD			
CD/MD			

$$Curl\ propensity = \frac{(\frac{CD}{MD})_{layer\ 1}}{(\frac{CD}{MD})_{layer\ 2}}$$

Generally all these measurements(MD/CD ratio for TSI) should be as close as possible, especially the outer layers. For TSI measurements, the moisture content should be the same. Additional measurements(MD/CD ratio for TSI) on wet end samples should be done if sheets cannot be split into its layer components.

Table 8. CME of wet end samples

	Layer 1	Layer 2	Layer 3
MD			
CD			
CD/MD			

Generally all these measurements should be as close as possible for the compared layers, especially the outer layers. For TSI measurements, the moisture content should be the same.

Curl characteristics of each layer

Another potential problem is that each layer probably has a different fiber orientation within the thickness of that layer. This difference will cause that layer to have its own curl characteristics. These may affect curl of the board. The effect would be most prominent in the outer layers. Also, the differential orientation of each layer could be in the same direction, making them additive. Measurements of hot bend can be made.

Table 9. Measurements of hot bend curl

Heated surface	Layer 1	Layer 2	Layer 3
MD top			
MD bottom			
CD top			
CD bottom			

Top and bottom refer to where the surface of the layer faces. At least the two outer layers should have this test run on them. If both layers 1 and 3 have significant curl to the top, for example, this could significantly increase curl to the top. The best scenario is to have hot bend curls that are nearly equal to the top and bottom MD and CD. The next best would be for the outer layers to have equal but opposing curl. This line of testing should allow additional insight into the causes of multi-layered board curl.

Coatings

Curl may be caused applying coating, especially if it is on one surface. If they are hydrophilic such as those which contain a starch binder, then this will contribute to the moisture expansion potential to the surface that is coated. If the binder used is insensitive to moisture, then this will contribute to curl by tending to prevent the surface to which it is applied from changing dimensions while the remainder of the sheet contracts or expands. These problems may be minimal if the coating weight is very small, but the potential effect should be investigated until it is ruled out. Possible ways to deal with curl caused by coating are 1) apply a similar coating to the opposite surface and 2) adjust curl of the board to counteract coating curl effect. *A suggested way of evaluating curl from coating is to measure a warm oven curl. The hot bend curl test may also work if the board is not too stiff.*

Table 10. Curl with and without coating

Curl without coating	
Curl with coating	

Printing process

These also may be a problem from the printing process itself. If it is offset, water is being applied to the board surface. Initially the surface expands, but as the paper dries that surface now contracts beyond the original dimensions because some of the internal strains are released.

Drying

The use of drying will only enable the production, within some limits, of a flat sheet, or nearly so, off the end of the machine. In doing so, the inherent structural curl components like the difference in the amount of internal strain in each layer, the amount being in proportion the potential free shrinkage of each layer, will only be built into the sheet. They will be available for curl production if the sheet is put in high humidity or moistened in some way. The sheet will also have a difference in moisture expansion between the layers.