An investigation of heat curl in newsprint

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ABSTRACT

Curl in paper sheets affects performance in printing and converting processes. Here we present a series of experiments designed to identify the cause of curl in newsprint produced from nominally the same furnish on two different paper machines. The tendency of the sheet to curl is shown to be dependent on the z-directional distribution of in-plane elastic modulus. Moreover, distribution of the MD:CD ratio of in-plane elastic modulus appears to have a greater effect on the tendency of a sheet to curl than the distribution of elastic modulus in either the CD (cross-machine direction) or the MD (machine direction) independently.

Application:

A laboratory investigation of curl in newsprint produced from the same furnish on two different paper machines.

THE CURL OF PAPER STRIPS IS TYPICALLY attributed to either the two-sidedness of hydro- and hygroexpansivity, resulting in relaxation of residual strains upon rewetting of the sheet, or to the inherent chirality of the cellulose structure within the fiber itself. Here, we are concerned primarily with identifying contributors to curling tendency that can be affected by manufacturing conditions. Hence we do not consider chiral curl, which, although somewhat dependent on the degree of fiber orientation anisotropy in the sheet, is predominantly affected by the fiber itself. *(1–4)*

A model for the bending stiffness of multi-ply structures is given by Carlsson and Fellers *(5, 6)*, and this was extended to include terms for hygroexpansivity and applied to the curl of two-sided sheets *(7)*. In a subsequent study, Pijselman and Poustis *(8)* investigated curl in three-ply structures. They concluded that the elastic modulus and thickness of the individual plies do not considerably affect curling tendency, though the distribution of hygroexpansional strain in the *z*-direction should be symmetrical.

The papers investigated in this study were 45 g/m^2 newsprint formed from nominally the same furnish on two paper machines:

1. Hybrid former with a short fourdrinier section followed by a twin-wire section
2. Roll-blade gap former.

The approach taken was to apply the theory of curl and bending stiffness in multi-ply structures to the delamination of single-ply structures.

EXPERIMENTAL

The difference in curling tendency was quantified by measuring the height of curl of 10 cm diam. circles placed on a ceramic tile. Samples were exposed for 15 s to heat from a 250 W infrared lamp at a distance of 18 cm. The height rise was measured for both sides of the sheet. The angle of curl to the machine direction was measured using a protractor. While more sophisticated measures of curl are available *(9)*, the tests carried out here were sufficient to identify the different curling tendencies of the two samples.

Tensile strips were cut in the machine direction (MD) and cross-machine direction (CD) and split between one and five times in the *z*-direction using adhesive tape. The thickness and grammage of each strip were recorded. For each strip, bending stiffness was measured using the resonance length method *(10)*. To account for the variation in the amount of material split from the sample along the strip length, the mass and grammage of the resonating length were recorded. In addition, strips were coded such that all recorded measures were associated with a particular sample. Measurements were also carried out on unsplit samples, and ten repeats were made for each level of splitting in each direction.

The effect of two-sidedness was investigated by splitting the samples in two using the Beloit sheet splitter. Samples were dried under restraint in a heated drum dryer to reduce the effect of dimensional stability on the moduli.

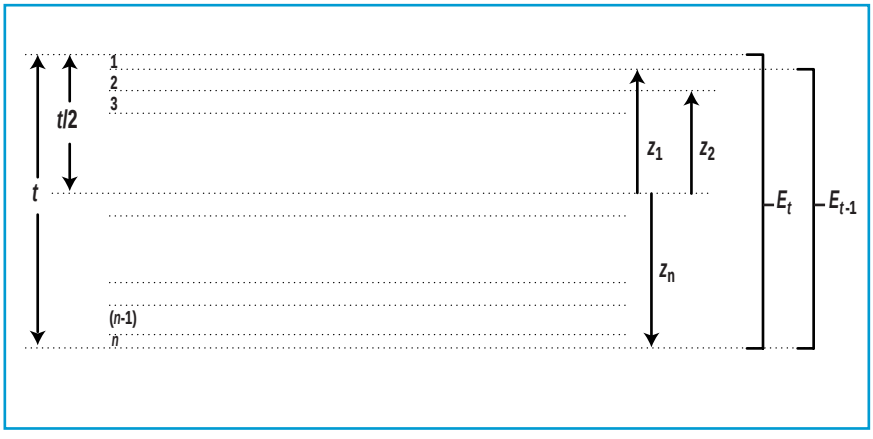
INTERPRETATION OF DATA

The experimental procedure provided information on the properties of the material remaining after stripping with adhesive tape. Some data processing was required to determine the modulus at a given position in the *z*-direction. For multi-ply structures, the bending stiffness can be expressed in terms of the thickness and the in-plane elastic moduli of the individual plies *(5, 6)*, such that:

$$S = D - \frac{B^2}{A} \qquad (1)$$

where

$$A = \sum_{k=1}^{n} E_k (z_k - z_{k-1}) \qquad (2)$$



1. Schema for determination of parameters used to calculate in-plane moduli. The in-plane modulus of individual laminae can be determined knowing the stiffness and thickness of the whole sheet and that of split samples.

	HYBRID FORMER		ROLL-BLADE GAP FORMER	
	Top	Bottom	Top	Bottom
Height rise, mm				
Left				
Mean	33.6	3.7	27.5	4.2
Std. dev.	3.2	2.6	7.0	1.4
Right				
Mean	33.2	2.8	26.7	3.5
Std. dev.	3.9	1.8	5.5	0.9
Angle to MD, degrees				
Mean	3.5	1.5	3.0	3.3
Std. dev.	3.2	1.3	3.0	2.9

I. Results of curl tests after exposure to heat from IR lamp

$$B = \frac{1}{2}\sum_{k=1}^{n} E_k\,(z_k^2 - z_{k-1}^2) \qquad (3)$$

$$D = \frac{1}{3}\sum_{k=1}^{n} E_k\,(z_k^3 - z_{k-1}^3) \qquad (4)$$

and where

S = bending stiffness, N·m

E_k = in-plane elastic modulus of the kth layer, N/m^2

z_k = distance from the bottom of the ply to the midpoint of the multi-ply structure, m.

The testing of samples delaminated using adhesive tape provided data for the stiffness, modulus, and thickness of the remaining sample. Thus, by manipulating Eqs. 1–4, the distribution of in-plane moduli through the sheet was calculated. Calculation of E_k was made on the basis of measured stiffnesses and thicknesses using the relationship in Eq. 5.

$$S = \frac{Et^3}{12} \qquad (5)$$

where

E = Young's modulus, N/m^2

t = sheet thickness, m.

The experimental data for stiffness, thickness, and grammage for each condition were entered into a spreadsheet and sorted by decreasing thickness. The values taken for the unsplit samples were the mean of 10 repeats, and each sample was subjected to 10 repeats of 1 to 5 splits in the MD and CD, yielding data for 51 locations in the z-direction. The moduli of the tested samples were calculated using Eq. 5 from the known values for bending stiffness and thickness.

Following the schema in **Fig. 1** and using Eqs. 1–4, the modulus of each layer could be calculated. The modulus of lamina 1 was calculated using the thickness and modulus of the whole sheet and that of the sheet remaining after removal of lamina 1 with adhesive tape. Similarly, that of lamina 2 was calculated using the thickness and modulus of the sheet after removal of lamina 1 and after removal of lamina 2, etc., until a modulus distribution through the z-direction had been obtained. The modulus of lamina n was known directly from its bending stiffness.

RESULTS

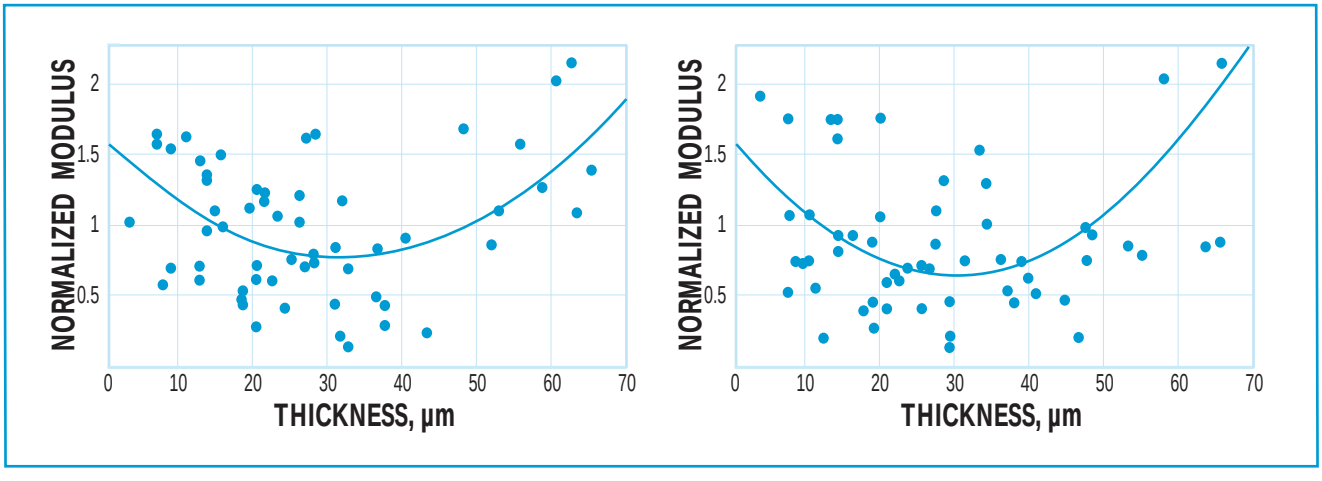
The results of exposure to the infrared lamp are given in **Table I**. While both samples exhibit a tendency to curl toward one direction, the tendency is greater for the sheet formed on the hybrid former. The sheet formed in the gap former exhibits no two-sidedness in the angle of the curl to the MD, whereas there is a small effect in the sheet formed on the hybrid former.

Elastic moduli calculated from stiffness testing of whole samples and those split once in the Beloit sheet splitter are summarized in **Table II**. Note that the split sheets typically exhibit lower moduli than the whole sheets. This is presumably the result of relaxation of dried-in strains during the wetting of sheets prior to splitting. Independent ultrasonic testing of similar samples using the TSO ultrasonic stiffness tester showed that the MD:CD ratio of in-plane moduli for the unsplit sheet was about 15 *(11)*. This was confirmed by tensile testing of the un-

	ELASTIC MODULUS (*E*), GPa								
	MD			CD			MD:CD ratio		
		Split*			Split*			Split*	
	Whole	top	bottom	Whole	top	bottom	Whole	top	bottom
Gap former									
Mean	4.94	1.93	1.97	0.85	0.45	0.44	5.81	4.29	4.48
Std. dev.	0.22	0.27	0.11	0.16	0.08	0.08	…	…	…
Hybrid former									
Mean	5.25	2.20	1.94	0.68	0.79	0.71	7.72	2.78	2.73
Std. dev.	0.09	0.32	0.19	0.11	0.15	0.24	…	…	…

*Samples were split using the Beloit sheet splitter.

II. Sheet elastic properties



2. Distributions of z-directional modulus for gap former. (Modulus values normalized to the mean.) Left: MD, $\bar{E}_{MD}$ = 2.38 GPa; right: CD, $\bar{E}_{CD}$ = 156 MPa.

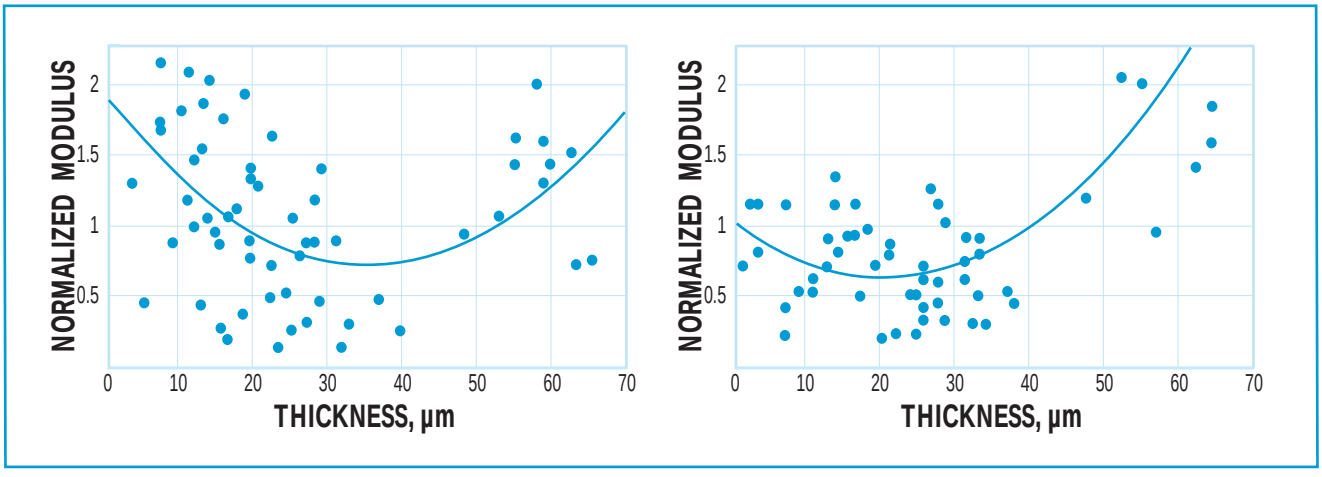
split sheets, which showed similar results for the MD:CD ratio. Because each strip had a different thickness, measurements were made on single strips using an electronic caliper. It is probable, therefore, that the discrepancy arises from the calculation of moduli from Eq. 5, where the stiffness is proportional to the cube of the thickness.

Figures 2 and 3 show the *z*-directional MD and CD modulus distributions—calculated from the adhesive-tape stripping experiments and normalized to the mean—for the gap former and hybrid former, respectively. The solid line through each set of points represents a quadratic fit to the points and is intended only as an illustrative guide to the shape of the distribution. The decreasing density of points toward the right-hand side of each curve is a result of the testing procedure, where samples were split from one side only. In each case, it is clear that there is a distribution of in-plane moduli through the *z*-direction of the sheet, though this is least pronounced in the CD for the sheet formed in the gap former. The distributions for the hybrid former exhibit the greatest skew of modulus distribution, and this is toward the nominal top side in the MD and toward the nominal bottom side in the CD.

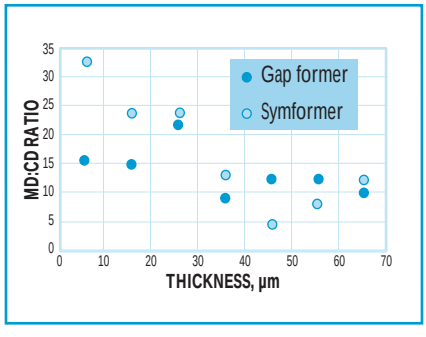
The data presented in Figs. 2 and 3 confirm the presence of a *z*-directional distribution of in-plane elastic moduli. Further, the data show that this distribution exhibits a greater skew for the sheet formed in the hybrid former. The cause of the different curling tendency of the two sheets is made apparent by processing the same data to yield a plot of the *z*-directional MD:CD ratio of in-plane moduli. This is shown in **Fig. 4**, where the MD:CD ratio has been obtained for 10 µm increments through the thickness of the sheet. It is apparent from the figure that the sheet formed in the gap former exhibits a reasonably flat MD:CD profile through the thickness of the sheet, while the profile for the sheet formed in the hybrid former has a steep distribution toward the nominal topside.

CONCLUSIONS

Curl in paper is usually caused by two-sidedness of elastic properties and, hence, by hydro- and hygroexpansivity. Two papers made from nominally the same furnish on different machines were tested. The re-



3. Distributions of z-directional modulus for hybrid former. (Modulus values normalized to the mean.) Left: MD, $\bar{E}_{MD}$ = 2.05 GPa; right: CD, $\bar{E}_{CD}$ = 99 MPa.



4. Distribution of z-directional MD:CD modulus ratio for gap former and hybrid former

sults showed that both papers exhibited minimal two-sidedness of elastic properties. However, when the sheets were split through the thickness and tested, the results showed a higher degree of curl for the sample with a distribution of MD:CD ratio of in-plane elastic moduli in the thickness direction. This characteristic was found for the sheet formed on a hybrid former and was negligible in the sheet formed on a roll-blade gap former. Further work is required to characterize the contribution of fiber orientation distribution through the thickness of the sheet, as observed by Bando *et al. (12)*, and the effect of fiber orientation distribution on shrinkage, and hence residual strain, distributions through the thickness of the sheet. TJ

KEYWORDS

Cross direction, curl, elastic stregnth, infared heating, machine direction, newsprint, paper sheets, stiffness, thickness, two sidedness, twin wire machines, z direction

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