Curl Depending on Bending Moment and Drying Shrinkage

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Abstract: The curl is an issue during paper coating processes, such as the cast coating process. The curl can be reduced simultaneously in the machine and cross machine directions (MD and CD, respectively) by bending drying with rewetting of one side. The bending moment and drying shrinkage induced by the rewetting process dictates the curl in the MD and CD. Bending in one direction cannot change the curl in the other direction without rewetting. One-directional bending with rewetting of one side can change the amount of curl in the other direction. The pre-curl also has an effect on the final curl. For a given sheet structure, the combination of bending moment and drying shrinkage decides the final curl shape.

Keywords: curl, cast-coated paper, rewetting, bending, drying, pre-curl

Curl has been studied extensively by Glynn, Jones, and Gallay [1-3]. Our present study was based on parts of their results from one-sided rewetting experiments. The terms used within this study also follow the definitions provided by the aforementioned authors. TS denotes the top side curl or top side bending, and WS refers to the wire side curl or wire side bending. MD and CD denote the axes of curl or bending in the machine and cross machine directions, respectively [1-3]. Thus, CDWS refers to the CD axis wire side curl or wire side bending, and MDTS to the MD axis top side curl or top side bending. Our experiments were conducted to see how CD bending (CDWS or CDTS) with one side rewetting was related to the MD curl (MDWS or MDTS), because this feature was not discussed in depth in the works of Glynn, Jones, and Gallay [1-3].

The results were applied to the cast-coated paper (CCP) process in a mill to determine if they would really work to reduce the MD curl. Mineral-pigmented CCP can be produced by casting on a chrome-plated drum for high-gloss printing paper, inkjet glossy photo paper, and paperboard [4]. The general CCP process is illustrated in Figure 1. Rewetting, bending, and drying take place on the sheet during the cast coating process. The curl can be introduced at two places in Figure 1: at the cast drum drying after rewetting (process 1) and at the reel after the second rewetting (process 2). Process 1, at the cast drum, is CDTS bending under top side rewetting and top side drying conditions. As the first opportunity to control curl, back coating is possible, but the amount of back coating is limited by the drying speed. There is a small roll under the cast drum for back coating in process 1 (Figure 1). The small roll transfers water to the back side of the paper sheet to control the curl. The second opportunity to control the curl is during process 2 by choosing CDTS bending or CDWS bending at the reel under wire-sided rewetting conditions. The laboratory test results were applied to the reel area (process 2) to reduce the final MD curl.

In this study, the focus was on understanding the effect that bending drying in one direction with one side rewetting had on the final curl in the other direction. One purpose of our experiments was to show how the bending moment and drying shrinkage are related to the curl, and also to show that the laboratory test results can be applied to real mill production.

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Experimental

Method Used to Describe and Measure Curl
In this study, the curl shown in process 2 from Figure 1 was simulated. Rewetting was simulated by water spraying on the surface of paper samples. The spraying rate was 14–7 g of water on the 1 m² paper sheet. Drying and bending were simulated using a laboratory drum dryer and a flat dryer. The experiment was conducted under restricted drying conditions. The bending direction was one of the most important experimental factors. Sample sheets were bent in the machine direction around the drum dryer. Figure 2 illustrates one example of bending. Attempts were made at rapid drying with heating and slow drying without heating.

Because of anticlastic (saddle shape) behavior [5] on a paper sheet, the true curl direction is sometimes opposite to that in the saddle shape. Thus, the true curl can be measured by making a paper strip from the sample (Figure 3). Although there are many different methods for measuring curls [1-3,6-12], a curl template was chosen in terms of the curvature (Figure 4) for the sake of simplicity and numerical expression. The curl template was prepared using a CAD program, with curl radii (R) ranging from 5 to 400 cm. The curl of the paper strip was compared to the curvature on the curl template; the closest numbers were then recorded in terms of R and averaged. If the recorded curl radius R is positive the curl will be wire-sided, but, if negative, the curl will be top-sided.

Sample Preparation and Equipment
Uncoated bleached hardwood and softwood mixed papers were prepared. The uncoated paper was manufactured on a Fourdrinier former, with a basis weight of 170 g/m². Samples were obtained from the center area across the cross machine direction in the reel. Each sample sheet size was 20 cm (MD) by 16 cm (CD). A total of 100 samples were prepared. Each of 20 samples was used for the five different procedures described below. Because pre-curl can affect the final curl [1,2,13,14], samples exhibiting less curl, MDTS pre-curl, and MDWS pre-curl were prepared. All pre-curl samples were prepared by rubbing against a desk edge.

The following equipment was employed in the experiment; an Emerson speed flat dryer and a Victory drum dryer with a radius of 20 cm. The tensile stiffness
orientation of each sample was in the range from +1.5 to -2.0. The temperature of each dryer was fixed at 100 °C; the drum dryer speed was 6 m/min and the drying time was 1 min for both driers.

Experimental Conditions and Procedures
If rewetting, bending, and rapid (heat) drying are considered, a maximum of eight possible experimental combinations can be conducted; the five most meaningful were selected (Table 1). Before starting procedures 1 ~ 5, the curls already existing in the samples were measured. The measured curl data are presented as “Before” data in Figures 5 ~ 9.

Procedure 1: Effect of Bending without Rewetting
The sample sheets were bent in the machine direction on a drum dryer without heating (Figure 2). One group of samples was wrapped with the wire side as the outer layer (CDTS) and the other group with the wire side as the inner layer (CDWS). Four corners of each sample were fixed with Scotch tape for 4 h and paper strips were then cut from the sample sheets (Figure 3). The paper strip size was 0.5 cm (MD or CD) by 16 ~ 20 cm (CD or MD). The curls of the paper strips were measured and recorded in terms of their radii.

Procedure 2: Effect of Bending with Rewetting under Slow Drying
The samples were water-sprayed on the wire side and attached to the drum dryer, as in procedure 1, and dried at room temperature without heating. One group of samples was wrapped around the drum in the shape of the CDTS and the other group in the shape of the CDWS (Figure 2). The samples were air-dried for 4 h and then the curls of the paper strips were measured in the MD and CD.

Procedure 3: Effect of Flattening with Rewetting under Slow Drying
The samples were sprayed on the wire side and fixed on a flat dryer without heating. The samples were dried for 4 h at room temperature and then the curls of the paper strips were measured in the MD and CD.

Procedure 4: Effect of Bending with Rewetting under Rapid Drying
The same procedure as that for procedure 2, but with heating at 100 °C for 1 min, was conducted. One group was dried on the wire side and the other on the top side.

Procedure 5: Effect of Flattening with Rewetting under Rapid Drying
The same process as that for procedure 3, but with drying at 100 °C for 1 min, was conducted. One group was dried on the wire side and the other on the top side.

Results
The experimental results are summarized in Figures 5 ~ 10. The curl values are expressed in terms of the inverse curl radius in cm⁻¹ units, so smaller values indicate smaller curls. The curl radii of the test samples were recorded before and after each test. The p values of the t-test were also computed to check the reliability of the data.

Effect of Rewetting on Curl
Without rewetting, only the CD curl was changed as a result of bending; the MD curl remained relatively unchanged after 4 h of bending (Figure 5). For the CD curl, the CDWS samples showed wire-side curl and the CDTS samples top-side curl as a result of the bending effect. For MD curl, the bending was not a critical factor in terms of the t-test results: 0.947 for CDTS and 0.827 for CDWS (Figure 5). Most converting mills use a decurler to control the curl. However, the decurling process cannot control MD curl; it only affects the CD axis of the curl.

Effect of Bending on Curl
All top-side drying samples (CDTS) exhibited less curl in both the MD and CD than did the wire-side-dried samples (CDWS). The bending effect was different for the slow-dried samples compared to that of the rapid-dried samples. More curls were observed in the bending samples during slow drying. However, less MD curls
Figure 5. Effect of rewetting under the same bending and slow drying conditions (pro. 1 vs. 2).

Figure 6. Effect of bending under the same rewetting and slow drying conditions (pro. 2 vs. 3).

Figure 7. Effect of bending under the same rewetting and rapid drying conditions (pro. 4 vs. 5).

Figure 8. Effect of drying rate under the same rewetting and bending conditions (pro. 2 vs. 4).

Effect of Rewetting on Curl

were recorded in the bending samples during, rapid drying. During flat drying, the difference between the MD and CD curls was smaller with slow drying than with rapid drying (Figures 6 and 7). In the case of wire-side drying, the bending samples gave more CD and less MD curl than did the flat-dried samples because of the bending effect (cf. Figures 6 and 7).

Effect of Drying Rate on Curl

Again, the CDTS samples showed less curl than did the CDWS samples. During bending drying, the curl patterns were very similar between the slow and rapid drying samples, with the exception of the CDTS CD curls (Figure 8). Without bending, less CD and more MD curls were observed with the rapid drying samples (Figure 9). In all cases, more MD curls were observed on the rapid drying samples because of the high drying rate.

Effect of Pre-Curl on Curl

During procedure 5, both the MD and CD curls were lowest on the top-side pre-curl samples and greatest on the wire-side pre-curl samples (Figure 10). The other procedures showed the same order in terms of curl; top-side pre-curl samples the least curl, wire-side pre-curl samples the most curl.

Discussion

The laboratory test results were applied to the real mill CCP process. Because CDTS bending gave the best results, this procedure was used in process 2 (Figure 1). The rewetting and drying were achieved using a steam-box and rapid air drying (caused by the rapidly moving sheet), respectively. The results were improved tremen-
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Figure 9. Effect of drying rate under the same rewetting and no bending conditions (pro. 3 vs. 5).

Figure 10. Effect of pre-curl on the final curl (pro. 5).

Curl can take place on any paper under certain conditions. One-side rewetting is administered during some converting processes, such as with CCP, and curl in the MD and CD would be expected. Bending is a decisive factor in controlling curl during rewetting and drying. However, CDTS and CDWS bending gave totally different results in terms of MD and CD curls. The CD and MD curls are discussed in the following section.

CD Axis Curl
If water is sprayed onto the wire side and the sheet then reeled in the shape of CDTS [Figure 11(a)], the curl becomes small compared with the CDWS [Figure 11(b)]. For CDTS, the wet wire side swells and then shrinks during drying. At the same time, the wire side expands, because of CD axis bending, as the paper sheet is reeled in the MD. Therefore, the drying shrinkage force and the bending moment are offset, thus minimizing the CD curl. If the sheet is reeled in the shape of CDWS [Figure 11(b)], the wire side is compressed by the bending moment. The drying shrinkage force also exists during drying [15]. The shrinkage force and the bending moment work together on the wire side, resulting in a bigger CD curl.

With flat drying, the amount of curl is different from that of the bending drying samples. Because of the given boundary condition, the bending moment is smaller with flat drying, but the drying shrinkage is the same as that with bending drying; thus, CDTS flat drying [Figure 11(c)] gives more wire-side curl than did that of CDTS bending drying [Figure 11(a)], and CDWS flat drying [Figure 11(d)] gives less wire-side curl than did that of CDWS bending drying [Figure 11(b)]. These results are shown in Figures 6 and 7. One exception was for CDTS bending during slow drying: because of the long drying time, the curl cures on the top side.

MD Axis Curl
The bending drying samples showed less MD axis curl.

Figure 11. Mechanism of CD curl on a drum dryer during a moisture change. (a) CDTS curl during CDTS bending drying, (b) CDWS curl during CDWS bending drying, (c) CDTS curl during flat drying, and (d) CDWS curl during flat drying.
than did the flat drying samples during rapid drying (Figure 9), and more MD curl during slow bending drying (Figure 8). However, each CDTS bending drying sample exhibited less MD curl than did those of the CDWS bending drying samples. There are two possible reasons for this behavior. One is due to the boundary conditions during drying and the other is due to increased bending stiffness in the cross machine direction during bending drying in the machine direction.

Different boundary conditions are one way of explaining the curl. Gravity influences the curl through the weight of the sample causing bending [16]. After spraying on the wire side, both edges of the sample were fixed onto a plate in the shape of MDTS [Figure 12(a)] and MDWS [Figure 12(b)]. The MDTS samples exhibited less curl than did the MDWS samples. The wet wire side tries to expand in the CD, but the restricted conditions at both edges prevent it from doing so. Instead, a downside curl appears for both sample cases because the downside is blocked by the plate [Figures 12(a) and (b)]. The final curl under the conditions of Figure 12(a) is smaller than those in Figure 12(b) when using the same method as that described above for the MD curl. If different boundary conditions are given to the samples, the opposite results are obtained. The curl in Figure 12(c) is larger than that obtained under the conditions in Figure 12(d), as the bending moment takes place upside because of gravity [16].

Figures 12(a) and (b) depict situations similar to those occurring in the roll during reeling.

Therefore, the minimum curl can be achieved when the bending moment and drying shrinkage work oppositely, as shown in Figures 11(a), 11(c), 12(a), and 12(d). This situation explains why less curl occurs on the samples with CDTS than that with CDWS and with drum, rather than flat, rapid drying.

Higher drying rates increase curl-like cockle [17]. Thus, the drying rate is an additional reason why more curl appears on wire-side drying samples than on top-side drying samples when the wire side is wet. Because of the water spray on the wire side, the drying rate for the wire side is higher than in the case of the top side.

As bending increases, the moment of inertia increases the stiffness [18]. Because of bending in the machine direction, the bending stiffness in the cross machine direction increases. As a result of the increased stiffness, the curl becomes smaller. The following experiment describes the tensile strength increases in the CD by bending in the MD during the drying of a wet sheet. A series of 170 g/m² samples were prepared with a size of 17 by 17 cm, fixed on a flat plate and a drum with a radius of 15 cm in the machine direction (CD axis bending), dipped in water for 10 min, and then dried in a drying oven at 105 °C. The bending drying samples showed higher tensile strengths with lower strain values than did the flat drying samples (Table 2).

### Conclusions

The effect of bending drying on the curl in the MD and CD was examined for one-side-rewetted sheets. CD axis bending drying with a moisture change affects both the MD and CD curl. Bending itself has only a mechanical effect on the CD curl, and little effect on the MD curl without a moisture change, because no bending moment and drying shrinkage occur in the cross machine direction. The relationship between the bending moment and drying shrinkage determines the curl direction and its amount. The geometric boundary conditions during

### Table 2. Effect of Bending Drying on Tensile Strength in the Cross Machine Direction

<table>
<thead>
<tr>
<th>Tensile strength (N) in the CD</th>
<th>Bending drying samples</th>
<th>Flat drying samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>58.7</td>
<td>56.8</td>
</tr>
<tr>
<td>t-test p value</td>
<td>0.004</td>
<td></td>
</tr>
</tbody>
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Number of samples: 60

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**Figure 12.** Mechanism of MD curl on a drum dryer during moisture change. (a) MDTS curl during CDTS bending drying, (b) MDWS curl during CDWS bending drying, (c) MDWS curl at both-edges-fixed condition, and (d) MDTS curl at both-edges-fixed condition.
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drying determine the bending moment direction (Figure 12). Bending a sheet with the wet wire side as the outer layer (CDTS) can reduce the curl further than that of CDWS bending drying. The pre-curl is reflected in the final curl, and this property could be used for controlling the curl. Top-side pre-curl samples gave the lowest amount of curl, flat samples were next, and wire-side pre-curl samples gave the most.

References