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EFFECTS OF WET STRAINING AND DRYING ON FIBER ORIENTATION AND ELASTIC STIFFNESS DIRECTIONALITY

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ABSTRACT

Ultrasonic determination of in-plane stiffness directionality has received wide acceptance in the paper industry to assess headbox performance and fiber misalignment problems. With this diagnostic tool, however, machine process variables after the forming section are not considered, and the principal stiffness orientation may not always agree with the preferential fiber orientation. In this work, effects of wet straining and drying were studied on 80 g/m^2 oriented handsheets manufactured with a small fraction of dyed fibers. Results indicated that stiffness directionality can deviate from fiber orientation when the fibers are initially offset.

INTRODUCTION

Ultrasonic testing of cross machine paper strips has received wide acceptance in the paper industry as a tool for assessing machine and product performance. The traditional application involves determining the orientation and anisotropy of the sheet by measuring the elastic stiffness in several in-plane directions. The principal stiffness orientation is commonly interpreted as an indirect measurement of the preferential fiber orientation, and is therefore used

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to assess headbox performance and fiber misalignment problems. With this diagnostic tool, however, the effects of machine variables such as wet straining and drying on both fiber orientation and stiffness directionality are at best ignored.

In general, the elastic stiffness, C, is described by:

$$C = \rho v^2 \qquad (1)$$

where ρ is the material's apparent density and v is the velocity of ultrasonic waves. By measuring C as a function of the angle from the machine direction (MD), the results can be displayed as a polar diagram (Fig. 1) [1]. With the shape approximating a cosine distribution function, the key components describing the plot are the MD, CD, MAX, and MIN elastic stiffnesses as well as the angle that the principal axis makes with the MD. This directional angle is often referred to as the polar angle.

As illustrated in Fig. 1, the principal stiffness direction may be skewed from the machine direction. This condition can cause performance problems such as stack lean [2], twist curl, and twist warp [3, 4]. The origin of skewed polar plots has been traced to transverse flows in the forming section which cause fibers to align at an angle to the MD. Such transverse flows can vary across the paper machine as a result of changes in slice screw settings or nonuniform stock pressures in the headbox. Baum has shown that elastic stiffness measurements are highly sensitive to machine process variables [5]. Therefore, the resulting polar plots and their respective orientations are responsive to process changes as well [6].

True fiber orientation is much less easily determined. While several indirect methods like ultrasonics are available [7], the only direct method of measuring fiber orientation involves the detection of dyed fibers dispersed throughout the sheet [7,8].

Limited work has been done to characterize the response of fiber orientation to paper machine variables after the forming section. As paper travels through the draws of the machine, an increase in anisotropy is observed. Early literature proposed that this increase was due to the fibers and fibrils becoming more aligned, indicating an actual reorientation of structural elements [9]. However, no increase in the orientation of fibers due to straining of paper through the dryer section was observed by Danielsen and Steenberg [10], nor in later laboratory investigations by Schulz [11].

Given that elastic stiffness properties are highly sensitive to machine variables, they may not always be a good indicator of fiber orientation. The aim of this project was to study the impact of wet straining and drying and to qualify the circumstances in which stiffness directionality is representative of fiber orientation.

EXPERIMENTAL PROCEDURE

Handsheet Making

The bleached Kraft softwood pulp used in this study was obtained in dry-lap form. The pulp was soaked, defibered, and beaten at 3% consistency in a 5 pound laboratory Valley beater to a freeness of approximately 570 CSF. In order to use image analysis techniques for determining fiber orientation, dyed fibers equivalent to 0.25% OD fiber weight were added to the slurry before sheet making. The dyed fibers were obtained from the original stock sample to ensure the same fiber length distribution was maintained.

All of the sheets were manufactured to a target basis weight of 80 g/m^2 on a Formette Dynamique sheet former. The wire speed (800 m/min) and jet pressure (2.0 bars) were held constant, providing the same anisotropy ratio for each sheet. In order to simulate fiber misalignment with respect to the MD, samples were cut out with a scalpel at 0, 5, 10, and 15 degrees. The net result of an induced offset was a fiber orientation that deviated from the drying frame machine direction. The samples were placed between blotters and pressed at 50 psi for 5 minutes resulting in a solids level of about 45%. Following the pressing cycle, a biaxial straining device was used to induce various straining levels up to 2.4% and to control the drying restraints (MD/CD or MD). Sheets were dried using a heater dryer hood placed over the apparatus.

The experiments incorporated a factorial design with three factors and multiple levels. The design factors and their respective levels are listed in Table I.

Additional samples were prepared to specifically evaluate the impact of wet straining. The wet straining levels included 0, 0.8, 1.6, and 2.4%. Each of these samples was cut out with an initial 15 degree offset of fiber orientation.

After drying, the sheets were conditioned and tested in a controlled environment of 23°C and 50% R.H. Ultrasonic measurements were made to characterize the in-plane stiffness properties. An automated imaging system [12] was then used to determine the fiber orientation by detecting the orientation of dyed fiber segments. The felt and wire side distributions were not significantly different. Therefore, fiber orientation measurements were obtained on the wire side only. Both the stiffness and image analysis measurements were represented as polar plots with increments of 10 degrees. The directional angle of the distributions was then determined by calculating the direction of the major axis of the moment of inertia.

RESULTS AND DISCUSSION

Wet Straining - Biaxial Restraint

Biaxial restraint provides the only condition in which shrinkage can be eliminated as a variable, for the shrinkage is zero in both directions. With biaxial restraint and no straining of the samples, the measured stiffness orientations are identical to the fiber orientations (Fig. 2). Thus, under conditions of full restraint the sheet is stabilized. The drying stresses that develop are uniformly distributed with no preferential alignment. The result must therefore be a stiffness plot which mirrors the main orientation of the fiber distribution.

When samples are exposed to wet straining before drying, a major difference develops between the two measurement techniques (Fig. 3). The stiffness polar plots are essentially "straightened out" by the straining action. For example, samples that contained an initial fiber orientation offset of 15 degrees had a stiffness orientation of only 9 degrees from the MD after processing. This reorientation of the stiffness distribution occurs despite no significant effect on the measured fiber orientations.

The main fiber orientations do not show any realignment because significant bond formation has already taken place at 45% solids, and the fibers are essentially immobilized. However, with regard to elastic stiffness, significant effects can still take place. Htun et al. [13] have shown that the cellulose structure of paper has a maximum mobility in the solids content range of 40-55%. At this level, the fiber wall components of paper are soft and plastic. Therefore, straining causes flow in the cell wall matrix allowing the cellulose chains to be straightened and oriented in the straining direction. At higher levels of organization, the wet straining straightens dislocations, kinks, and bends between points of bonding. The straightening of these fiber segments increases the elastic stiffness in the direction of the applied straining.

Schulz [11] and van den Akker [14] proposed that applied tension during drying enhances the stress distribution in the network. The improved efficiency of stress transfer along the fiber lengths creates more active load bearing elements and increases the stiffness in the direction of the applied tension. The net result of both mechanisms is a stiffness polar plot that is reoriented toward the MD by the effects of wet straining.

The magnitude of wet straining is also an important variable. With biaxial drying restraint and the initial offset angle held constant at 15 degrees, the difference that develops between the two orientation measurements is totally dependent on the degree of straining (Fig. 4). This of course is due to the sensitivity of the elastic stiffness and the insensitivity of fiber orientation to such treatment. Regression analysis showed that 90% of the variance was explained by the wet straining.

Uniaxial Drying Restraint

Samples were dried under uniaxial restraint to simulate the conditions at the edges of a paper machine where CD shrinkage takes place. With uniaxial drying restraint, a difference in orientations again develops between the two measurements (Fig. 5). The difference is comparable to that which occurred when wet straining was used with biaxial restraint. Thus, conditions of nonuniform drying restraint are as significant as when straining is induced. The combination of wet straining with uniaxial drying restraint produces the largest discrepancy between the stiffness and fiber orientations as shown in Fig. 6.

With sheet consolidation, swollen fibers become bonded at crossings. The transverse shrinkage of one fiber during drying forms microcompressions in a crossing fiber as proposed by Page and Tydeman [15]. In the direction of restrained drying, fiber segments between crossing points are strained and straightened by longitudinal shrinkage and by the few microcompressions that nevertheless form [16]. This causes a tightening of the sheet structure and a high stiffness in the direction of restraint. In the freely dried direction, there is no limitation on the degree of microcompressions that form. The gross shrinkage that develops causes fibers to adopt a more curled form resulting in a low stiffness. With a reduced stiffness in the CD and enhanced MD stiffness, the stiffness polar plot appears to be reoriented toward the MD with the principal stiffness direction no longer aligned with the main fiber orientation.

Machine-made papers are continually strained in the MD throughout the manufacturing process as they are transferred through open draws. Straining in the MD on a paper machine has tremendous implications for CD properties. While CD shrinkage always takes place, this shrinkage can be reduced by MD straining through better contact with the dryer cylinders. On the other hand, the MD straining causes CD contractions due to the Poisson's effect. The net result on CD properties, or which mechanism predominates, is dependent on the dryer section design. With the experimental drying frame, the MD straining led to CD contractions with no limiting effect on CD shrinkage through better contact with the drying surface.

Given the draws and drying on a traditional paper machine, the degree of fiber orientation misalignment will always supersede that of the stiffness orientation. In the wet straining experiments in which the final stiffness orientation was measured at 8 degrees, the fiber orientations were at least an additional 5 degrees off axis. Commercial papers with stiffness plots oriented as much as 15 degrees off axis have been documented [4, 6]. The results presented here suggest that with stiffness orientations of 15 degrees, the fiber orientations would be expected to be on the order of 20 degrees or greater.

Initial Fiber Orientation

The impact of the initial orientation offset of the samples can be deduced from Figs. 2 through 6. In every case except one, as the initial offset was increased, the difference between the two orientations became greater. The only exception was when the samples were dried under biaxial restraint without first being strained.

Analysis of Variance (ANOVA) was utilized to statistically analyze the results. It showed that drying restraint, initial orientation offset, and wet straining all had a significant effect on the development of a difference between the stiffness and fiber orientations. The initial offset had nearly three times the effect of the other variables. This is followed in importance by the percent wet straining and the drying restraint conditions.

CONCLUSIONS

The stiffness and fiber orientations, although closely related, are clearly different properties of paper. Wet straining and drying restraint have no significant effect on fiber orientation. However, these process conditions and the initial fiber offset all have a significant effect on a difference developing between the two orientation measurements. The only conditions in which the stiffness orientation represents fiber orientation are 1) when the major axis of the fiber distribution is perfectly parallel with the machine direction (0 degree offset angle) or 2) when there is no wet straining and the sheet is dried under biaxial restraint. In instances such as the latter, the effect of an initial fiber offset is insignificant.

These results suggest several implications. The most important of these is that the principal stiffness orientation should not be interpreted as being the same as the main fiber orientation. Thus, the use of ultrasonic analysis of cross machine strips to diagnose headbox performance can be misleading. With new headbox designs striving to decouple the control of fiber orientation from CD basis weight, care must be taken in the means of analyzing performance or in interpreting results. The stiffness orientation will always be superseded by the angle of fiber orientation. The difference, though significant in the middle of the web where drying occurs under biaxial restraint, is further heightened at the edge of the web where uniaxial restraint occurs.

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TABLE I SHEET DESIGN FACTORS	
Initial Fiber Orientation	0, 5, 10, and 15 degrees
Wet Straining Level	0 and 2.4%
Drying Restraint	MD/CD and MD

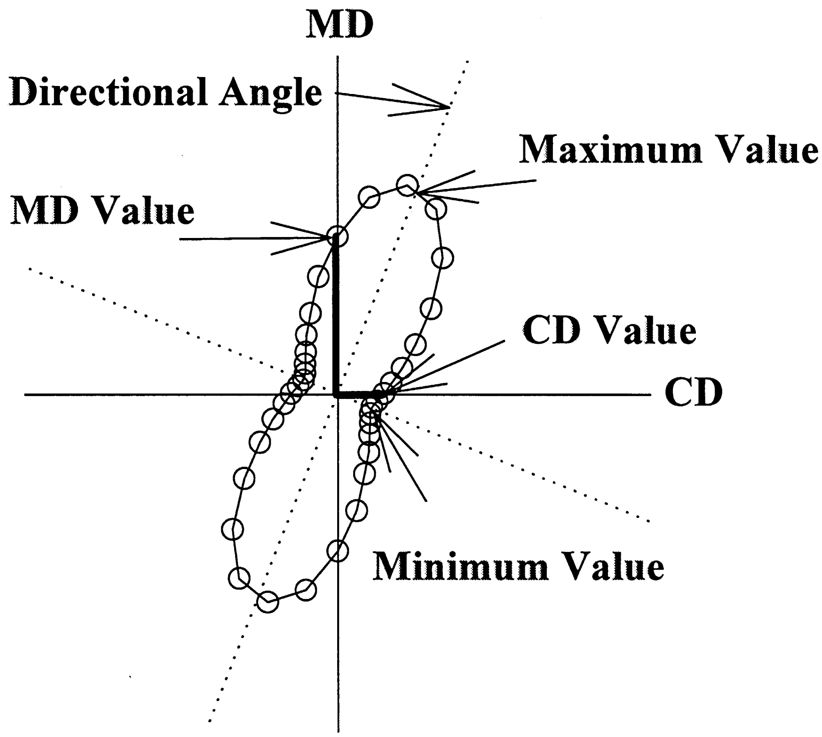

Fig. 1. Typical ultrasonic stiffness polar diagram.

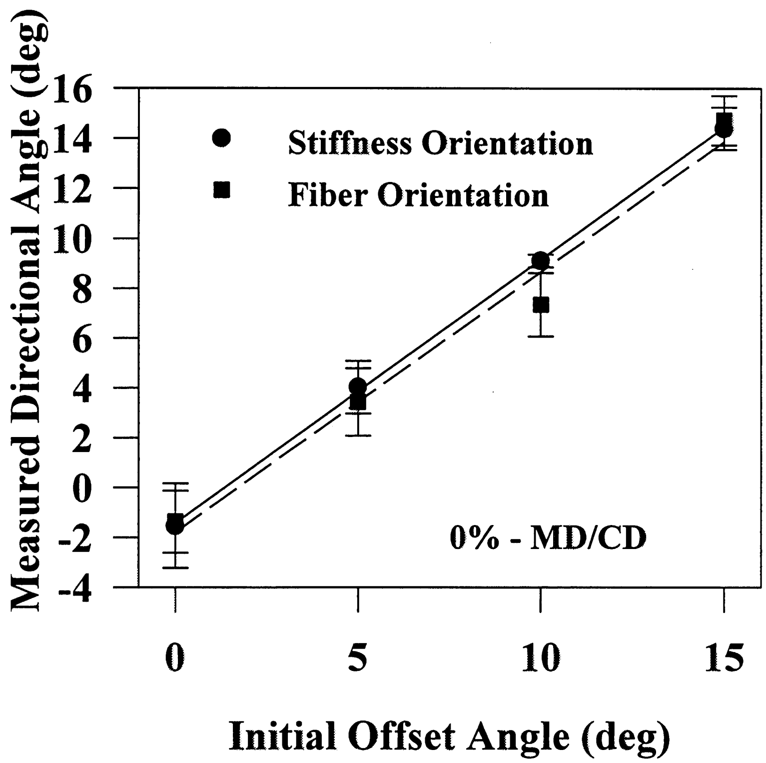

Fig. 2. Stiffness and image analysis angles when 0% straining and biaxial restraint conditions are specified.

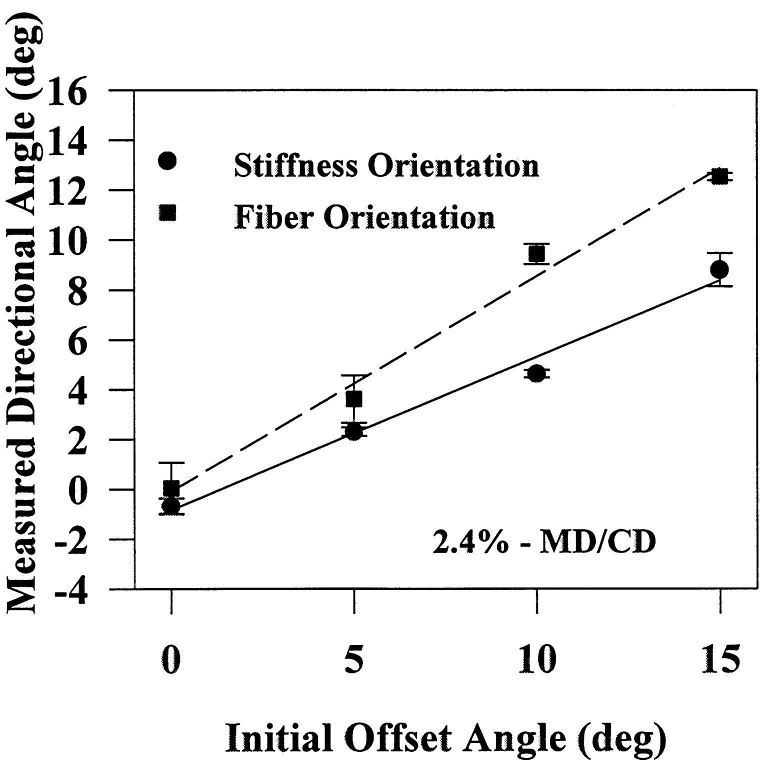

Fig. 3. Stiffness and image analysis angles when 2.4% straining and biaxial restraint conditions are specified.

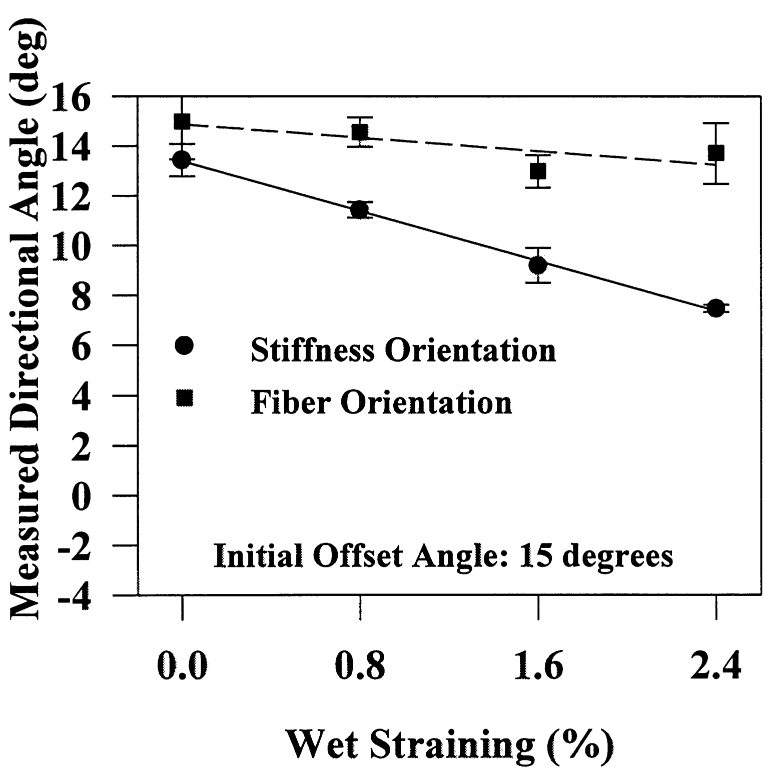

Fig. 4. Stiffness and image analysis angles as a function of wet straining when the initial offset angle is 15 degrees and biaxial restraint is considered.

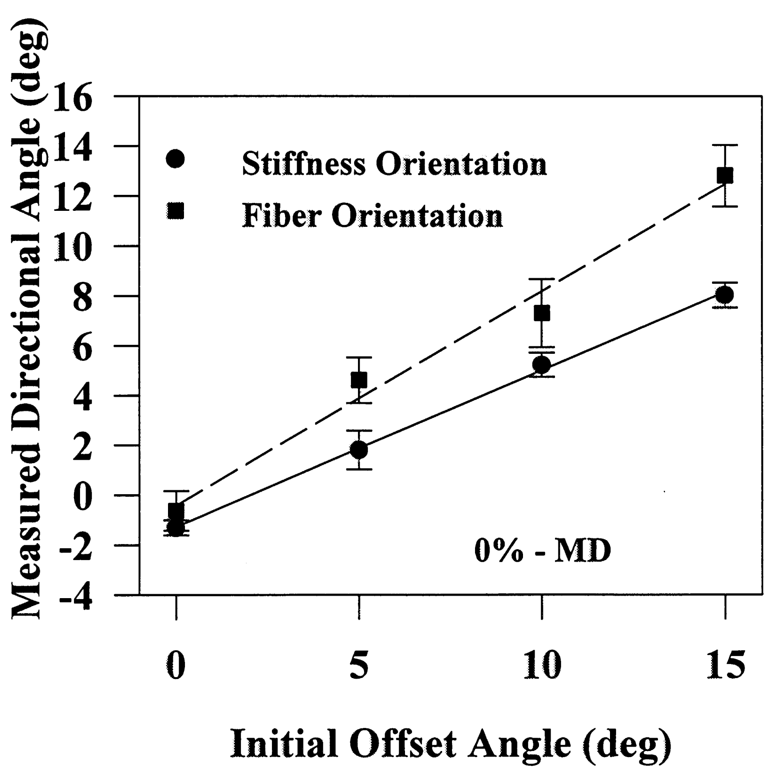

Fig. 5. Stiffness and image analysis angles when 0% straining and uniaxial restraint conditions are specified.

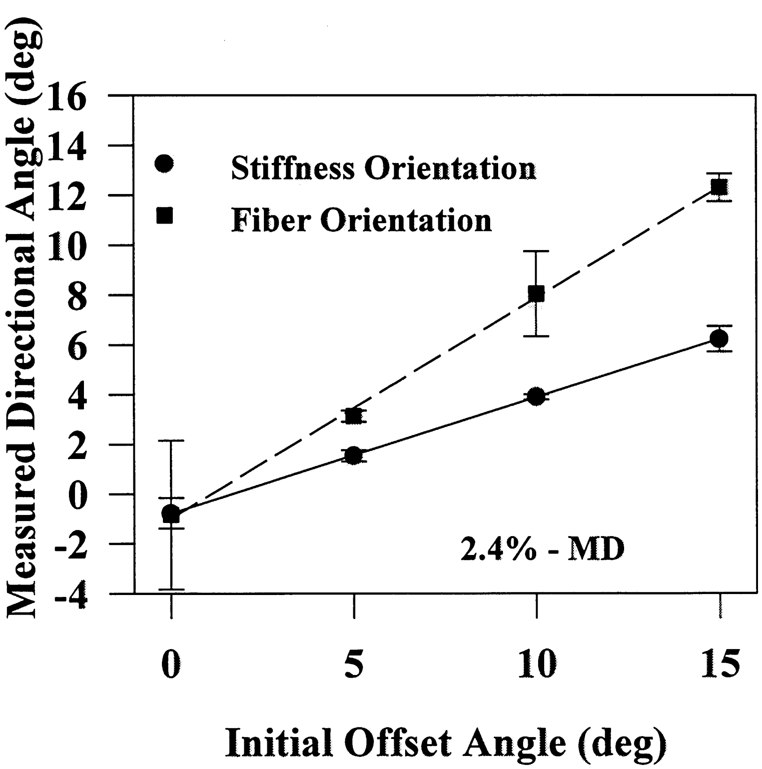

Fig. 6. Stiffness and image analysis angles when 2.4% straining and uniaxial restraint conditions are specified.