An instrument to assess the biaxial stress during paper drying

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ABSTRACT: To investigate the effect of drying stresses on the properties of paper, the author developed a biaxial stress monitoring device. The objective was to design an instrument to control stress and shrinkage during drying which would also operate independently and simultaneously in both directions of the plane of a sheet. The exposed sheet should be sufficiently large to allow standard mechanical paper testing of the dried sheet. Experimental work confirms that the new instrument fully meets expectations.

KEYWORDS: Cross direction, design, drying, hygroexpansivity, machine direction, measuring instruments, monitoring, paper, paper properties, shrinkage, stresses, test methods.

Drying of paper influences its many physical properties. To understand the fundamental mechanism which affects paper quality during drying, accurate data acquisition under controlled drying conditions is a key requirement. Earlier writings have described the general trends of strength development during drying *(1–3)*. There is also a well-known, close relationship between paper dryness and the level of shrinkage during drying *(4)*. It is possible to control the level of shrinkage by varying the drying stress level *(5)*. Application of these relationships has provided the conceptual base for development of instruments to examine the level of drying stress or shrinkage as a function of paper dryness *(6)*. Such work has used modified stress–strain instruments. The modification normally involves using wider clamps and a sophisticated electronic device to control the distance between the clamps. The Swedish Pulp and Paper Research Institute (STFI) has performed extensive studies in this area *(7–10)*.

A common feature of the applied measuring devices for assessing drying stress in paper currently available is that they control the stress in only one direction at a time. This limitation characterizes the operating mode of the standard stress–strain instruments. There is evidently only one investigator who examined the concept of a biaxial load on paper *(11)*. Biaxial loading is experimentally difficult. Severe limitations in this early attempt caused a lack of further interest in the instrument. Before some early reports of measurements of biaxial drying stress phenomena, there had been discussion of the associated mathematical characteristics based on the knowledge of the thermodynamic properties of paper *(12)*.

Recently, there have been considerable efforts to achieve better cross direction (CD) shrinkage control during papermaking which have resulted in modified paper machine design *(13–16)*. It appears that the modification of the dryer section may continue with the objective of achieving total control of paper shrinkage, i.e., drying of paper with CD dimension control.

Because of this technological trend, it is important to investigate the relationship between drying stresses applied in CD as well as machine direction (MD) and the properties of the paper. To address this problem in a controlled way will require proper laboratory equipment.

Work began at our organization to develop a biaxial stress monitoring device for paper using as a basis the extensive work at STFI and the previous attempt for sheet drying

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biaxial stress control *(11)*. The objective was to design an instrument to control stress and shrinkage during drying which would also operate independently and simultaneously in both directions of the plane of a sheet. **Figure 1** indicates a specimen with controlled shrinkage in only one direction of the test sheet using a stress–strain instrument technique and another specimen with controlled shrinkage in both directions of the plane of the test sheet using the newly developed instrument. An additional design objective was that the sheet being exposed to different drying strategies should be sufficiently large to allow standard mechanical paper testing of the dried sheet.

Requirements of a biaxial testing instrument

Biaxial loading of paper is experimentally difficult. The previous technique to control drying stress was to allow varying shrinkage of the paper. The challenge is how to achieve stress control in both directions of the plane of the paper in a controlled fashion independently and simultaneously while ensuring development of uniform property profiles in the sheet at the same time. It is necessary to hold the test sheet in a position such that no local differences in dryness or load develop. The clamps that grip the test sheet must therefore be able to move with a minimum of friction as the sheet is shrinking. The friction in other movable parts must similarly be negligible. It is also important that one can record the stress generated in the dried sheet entirely by fitted strain gauges. Uniform drying of the entire test sheet area is necessary to obtain a homogeneous sheet.

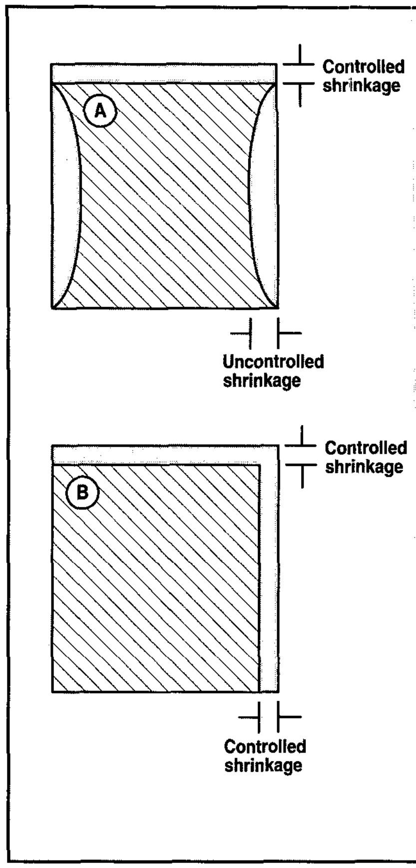
A test instrument must allow experiments of test sheets which have been dried freely, restrained, or strained at different dry solids content. An accurate and continuous measurement of the dryness of the sheet is a prerequisite. The sheet must have even and known dry solids content throughout the drying sequence.

Completion of the basic concept of a new instrument will require a control system which makes it possible to control the stress conditions in both the x and the y directions independently and simultaneously. It is also necessary to be able to introduce changes in the stress or shrinkage levels of the test sheet in a desired sequence.

A testing instrument capable of satisfying the requirements specified so far would allow a wide range of fundamental studies related to paper drying. Clearly, the study of phenomena related to commercial drying rates and drying times as low as 5 s would also be interesting. High drying rates will cause moisture gradients in the sheet. These may cause stress and shrinkage differences in the x, y, and z directions of a sheet which would impede scientific evaluations of the results. The drying operation during a multicylinder drying section involves the two sides of a paper sheet having alternate contact with a hot steel cylinder. This causes rapid evaporation of moisture from both paper surfaces. It also establishes a very complex temperature gradient in the z direction.

The object of our design was to fix the test sheet in a way such that the drying is equal from both sides to facilitate fundamental studies. This design strategy implies this instrument will not be able to study many aspects of industrial drying.

1. Comparison of shrinkage of sheets using a stress–strain instrument technique (A) and the newly developed test instrument (B)

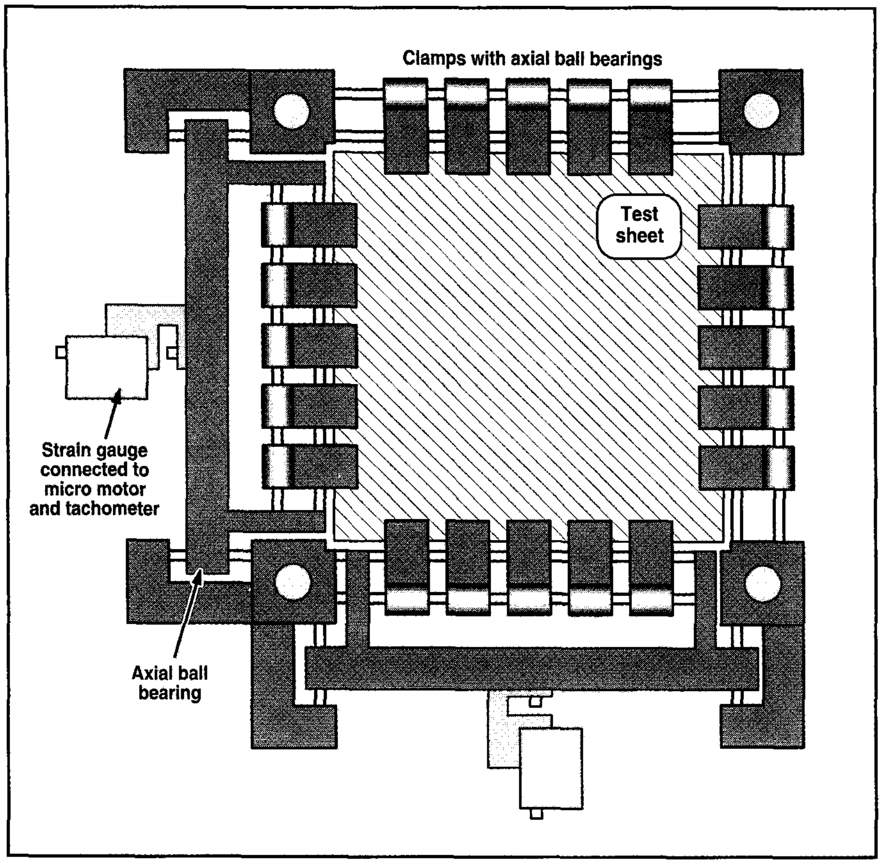


Building the biaxial testing instrument

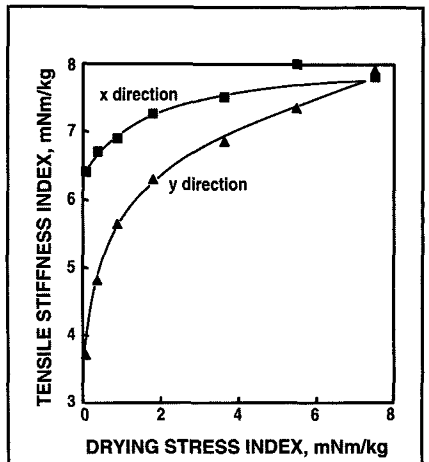
The basic concept of the instrument is the arrangement to hold the square (180 mm x 180 mm) test sheet shown in **Fig. 2**. Pneumatically operated clamps mounted on axial ball bearings hold the sheet at all four edges allowing movement with a minimum of friction along rods parallel to the four edges. Two adjacent rows have axial ball bearings allowing the rows to move freely on rods in the x and y directions. The rods holding the clamps attach to a frame which can move perpendicular to the direction of the rods using two micro motors. A strain gauge connects each motor and the corresponding rod allowing measurement of the generation of the drying stress. Optoelectronic tachometers control and monitor the distance between each pair of opposite clamp rows. To avoid breaking of the paper at the zone around the clamps, heating elements mounted on the clamps preheat these areas.

Monitoring the weight change of a "second" sheet of identical quality as the test sheet allows measurement of the dryness of the test sheet as the photograph of the instrument in **Fig. 3** indicates. The Plexiglas box surrounding the basic construction described above also contains a

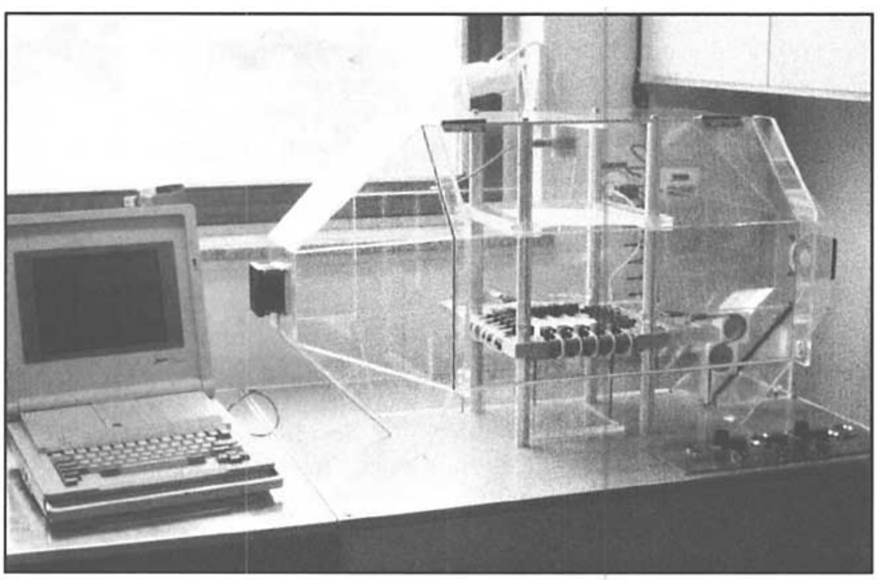
2. Diagram of the mechanical clamping device for the biaxial test instrument



4. Tensile stiffness index of the test sheet vs. drying stress index preset in the y direction



3. Photograph of the test instrument



weight system to make this possible. Two fans operating alternately ensure air exchange in the box. Extensive studies have demonstrated that the rates of drying of the test sheet and the "second" sheet are equal.

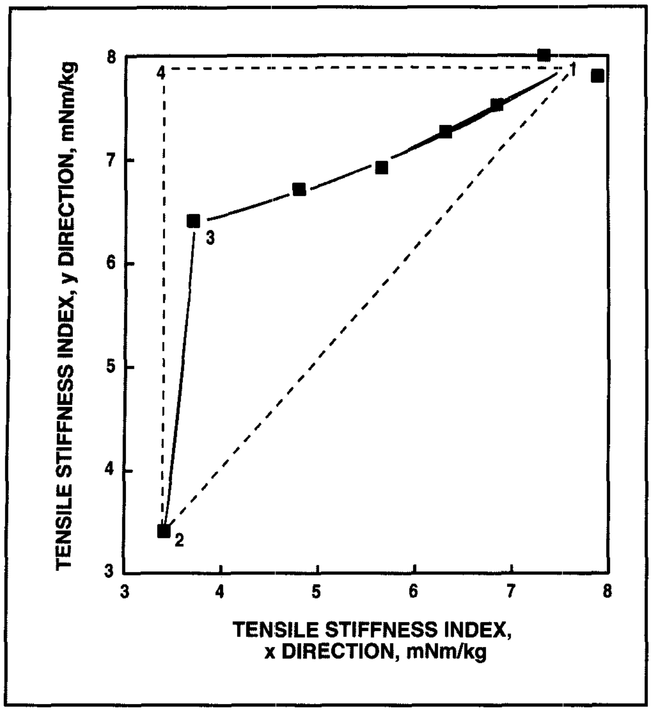
A control device registers and transforms the acquired data for storage in a personal computer. Using the computer, it is possible to either preset or interactively operate a variety of experimental parameters, e.g., levels of dryness.

The temperature, the relative humidity, and the movement of the air flowing through the box surrounding the instrument determine the sheet drying rate. Drawing air from a conditioning box provides alteration of the air humidity to extreme levels to test for the biaxial hygroexpansion of paper. A future paper will present results from these experiments.

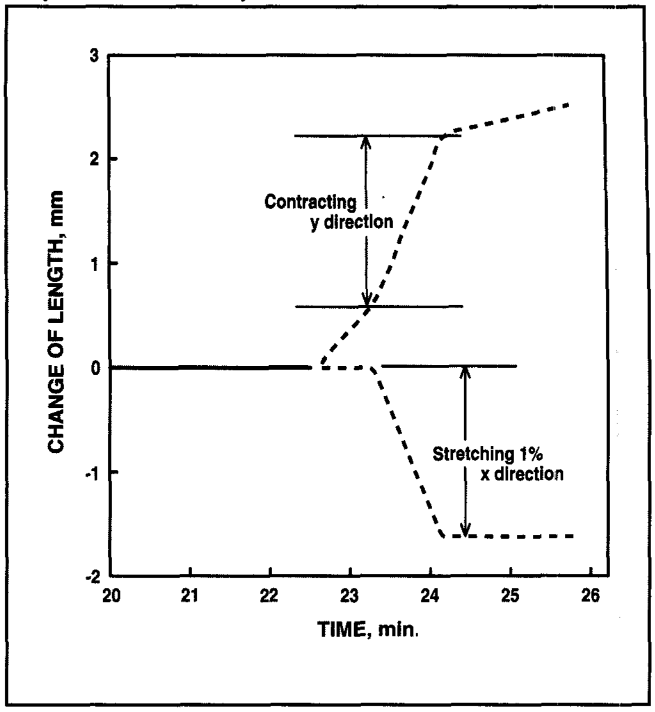
Experimental results

This section provides examples of appropriate use of the new instrument to illustrate its functions. Another paper will discuss the detailed

5. Tensile stiffness index in the x direction of the test sheet vs. tensile stiffness index in the y direction



6. Change of length vs. time when stretching a test sheet 1% in the x direction immediately after having released the drying stress in the y direction at 65% dry solids content



physics behind the phenomena. The reported measurements of the drying process used bleached long fiber sulfate pulp beaten to °SR 40 in a PFI mill. The test sheets had random fiber orientation and 35% dry solids content after wet pressing. Total drying time in the new test instrument was 25 minutes. The dry basis weight of the test sheets was 60 g/m^2.

In the first series of experiments, the paper underwent drying with constant restraint in the x direction and variable stress levels in the y direction. Varying the drying stress from restrained drying to free drying gave different stress levels. "Free drying" with this instrument means drying with the sheet subjected to a low stress of 14 N/m. This is so because the instrument operates by controlling the stress or force in the test sheet.

Figure 4 shows that tensile stiffness does not develop independently in the x and y direction of the sheet. This is probably due to Poisson effects. Increased stress in the restrained direction induces enhanced contraction in the other direction.

Earlier investigation has reported the relationship between tensile index (mNm/kg) and applied drying stress index (mNm/kg) for different pulps and levels of beating to be linear *(11)*. The results in **Fig. 5** show that such a linearity does not exist for sheets from the same type of pulp. In the figure, the numeral 1 represents restrained drying in both directions and 2 represents free drying in both directions. The numeral 3 indicates restrained drying in the x direction and free drying in the y direction. The numeral 4 shows the expected result, if there was no interaction. The points between numerals 1 and 3 represent results when varying the drying stress in the y direction. The maximum drying stress in the restrained direction presumably drops when the sheet can shrink in the opposite direction. This confirms the relationship shown in Fig. 4.

A second series of experiments investigated the existence of contraction caused by straining of the sheet. If a wet sheet at 65% dry solids content stretches 1%, the sheet will contract 1% in the other direction. The distance the clamps have to move to maintain the preset stress in the sheet measures this as **Fig. 6** illustrates. For the paper samples in these experiments, i.e., this particular kind of fiber and this paper dryness with an isotropic fiber distribution, the Poisson ratio appears to be 1. When drying a test sheet under restraint, the development of the drying stress in one direction will act in the other direction as if the sheet was under strain. This causes a phenomenon like the Poisson effect.

Several similar experiments have shown a good reproduction of the experiments. Subsequent papers will report these results. In experience to date, the instrument works accurately and reliably.

Conclusions

Our experiments show that the newly developed instrument functions fully according to expectations. The instrument measures stress and shrinkage during drying with a high degree of accuracy. Measurements indicate that it is possible to relate mathematically paper properties to shrinkage and drying stress levels. This will enable research scientists to link paper properties to the development of biaxial stress during drying. ◼

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