# *Imaging the three-dimensional structure of forming fabrics*

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**ABSTRACT:** We developed a technique to produce three-dimensional computer models of forming fabrics. The technique consists of machining cross-sections of a fabric, imaging the cross-sections, and then reconstructing the fabric structure using computer-aided design (CAD). An application of this technique is demonstrated, showing the existence of critical distances between filaments, which computational fluid mechanics suggest may cause the coarse backing layers in fabrics to influence micro-uniformity of drainage.

***Application:*** This fabric imaging technique can provide insight into the drainage flow through a fabric, which has an effect on the microstructure of paper produced on it.

Forming fabrics play a key role in determining the properties of paper, through influencing the early part of the sheet drainage process. An obvious effect is the wire mark on paper [1]. Less obvious is the fabric's potential influence on micro-uniformity of fiber and filler distribution [2]. This influence may be caused by micro-scale nonuniform drainage through the fabric structure. Existence of such micro-scale nonuniformity in flow can be determined from computational fluid dynamics (CFD) if the micro-scale fabric structure is known accurately. However, this structural information is not yet available.

Modern fabrics are typically multilayer weaves, with a fine weave on the paper side and a coarse weave on the machine side for structural support. There has been speculation in recent years that the coarse under-layer may exert a “shadow mark” effect on drainage through the fine weave, creating micro-scale nonuniformity. Evidence for this has been suggested in recent studies of fabrics modeled as rows of cylinders [3, 4]. Under certain conditions, rows of large diameter cylinders on the downstream side of rows of small diameter cylinders induced nonuniformities in the flow entering the row of small diameter cylinders. However, the degree to which these findings may apply to fabrics is unknown because the internal structure of forming fabrics is not known with sufficient precision.

Various past studies have attempted to characterize the structure of fabrics. Some methods were based on encasing fabric samples in plastic, followed by grinding and polishing to observe the cross-sections [5, 6]. However, these methods were largely focused on two-dimensional properties, typically open-area. Another approach has been the computer-based creation of three-dimensional models of fabrics [7]. However, this approach has not fully modeled the knuckling and deformation of filaments — key factors in three-dimensional structure. Still other attempts have been based on modeling fabrics from exterior micrographs alone, but these, too, could not capture the full complexity of modern fabric designs.

Other complex materials have been modeled using approaches based on sectioning at known depths, imaging the exposed surfaces, and combining the images into a three-dimensional model. One study created three-dimensional digital volumes of paper samples in this manner using microtome slices [8]. Another study, again investigating paper, ground and polished encased samples and used Uglestad beads (monodisperse polymer beads) embedded in the sample to measure accurately the depth of material removed [9]. Yet another study, investigating metallic specimens, took precise section depths by using a modified micromill with a built-in imaging system [10]. Yet, all of the above approaches focus on much finer structures than those in forming fabrics, and therefore cannot be directly applied to forming fabrics. A recent technique, X-ray computed tomography, has also been used to generate three-dimensional images of paper samples [11], but whether this method can be applied to forming fabrics remains to be seen.

In summary, there was no suitable method available to determine the three-dimensional microstructure of forming fabrics. Our objective in this study was to develop such a methodology.

## EXPERIMENTAL

The technique we developed consists of three components: machining fabric cross-sections, imaging each newly-exposed cross-section, and reconstructing the fabric structure from these images using computer aided design (CAD).

### *Machining*

A key issue in machining thin slices from fabrics was securing the fabric with sufficient rigidity to allow machining without deformation. This was accomplished by encasing the sample in a hard-setting compound, rigid when cured, but low enough in viscosity before curing to completely permeate the fabric sample. Many epoxy compounds were evaluated and found to be unsatisfactory in preventing filaments from deforming to a degree that resulted in blurred microscopic images of the machined sections. The only compound found to be acceptable was a common polyester fiberglass resin. Dye was added to the resin to enhance the contrast between the resin and the fabric. Fabric samples potted in this resin machined cleanly and showed the interior structure of the fabric clearly.

We potted samples of fabrics, approximately 2 cm by 5 cm in size, between 1.6-mm thick aluminum plates for support during machining. While being potted, the fabric samples were strained under tension in the range of 3000 N/m to 8000 N/m, typical levels found on a paper machine. However, the resultant fabric strain was less than 1%, suggesting this tensioning may have been unnecessary. We note that for a typical fabric thickness of about 1 mm, the average fabric stress under tension would be about 5 MPa. Since this stress is about three orders of magnitude greater than the typical fluid differential pressure seen across a fabric [12], it is reasonable to assume that the fabric geometry is unaffected by the fluid hydrodynamics. Likewise, since the fabric filament material is non-hygroscopic, its geometry should not be affected by the wet environment of a paper machine. We tested only unworn fabric samples, since worn fabric samples will, of course, be geometrically different.

We carried out machining on a full-size vertical milling machine using a fly-cutter, a single-edged cutting tool. The fly-cutter was run at 1400 RPM with a feed rate of 20 mm/min. The encased fabric samples were held in a vise on the mill table. To image all filaments clearly, multiple cuts were taken across each filament. Depending on the type of fabric, this required cutting depths of 0.05-0.08 mm. Generally about 70 cuts were taken to expose a large portion of the repeating pattern of the fabric.

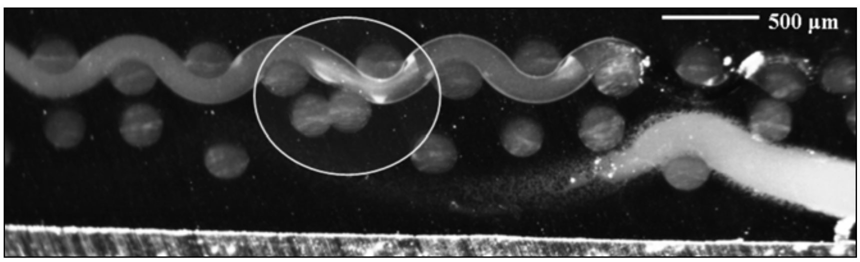
### *Imaging*

After removal of each slice of the fabric, we imaged the newly exposed cross-section, using a microscope with a digital camera attachment. Images were taken at approximately 20x magnification, imaging an area of about 5 mm on a side. A stage micrometer slide was included in every third image for calibration.

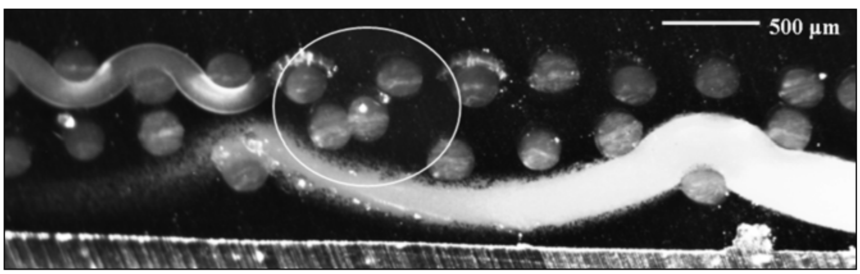
The fabric samples remained fixed to the mill table throughout the sectioning, and the microscope was moved between images in order not to interfere with the cutter. A simple jig was used to reposition the microscope in the same location, but errors occurred in placement, on the order of 0.1 mm. As a result, images had to be aligned before they could be stacked into a model. Alignment was achieved by means of a slot milled into the aluminum support plates perpendicular to the section plane, with the corner of this slot used to register the images.

### *Modeling*

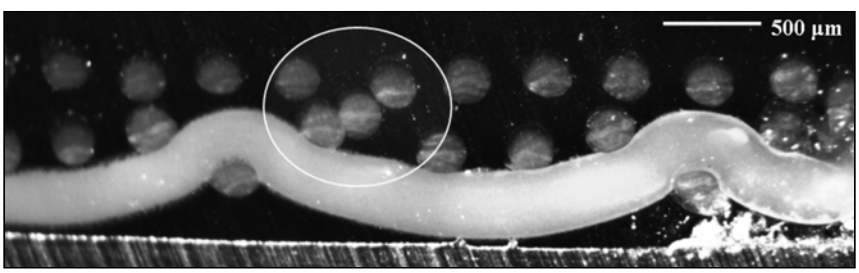
We modeled the fabric geometry in



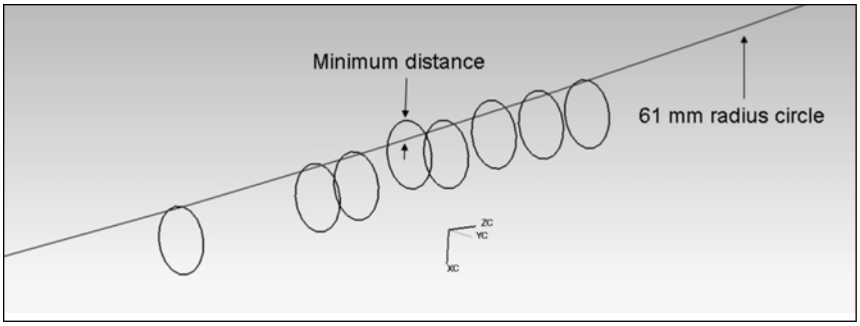

***1a. A double-layer fabric imaged in the CD-Z plane.***




***1b. The same fabric as in Fig. 1a but imaged 0.076 mm further in the machine direction.***




***1c. The same fabric as in Fig. 1a but imaged 0.152 mm further in the machine direction.***




***2. Results of an accuracy test using unwoven fabric sample arranged in a known geometry: model cross-sections of the filament are shown with the 61 mm radius of curvature circle.***

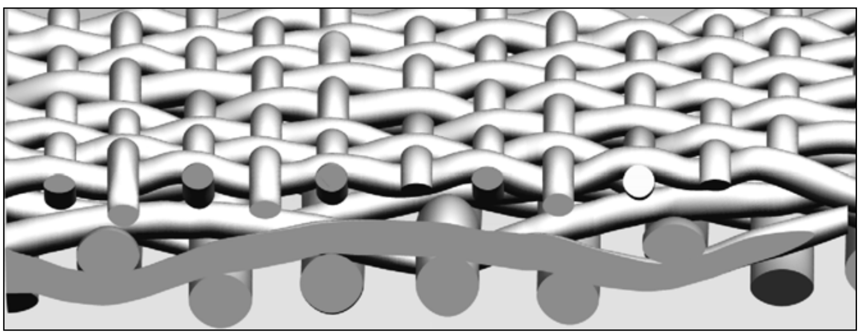
three dimensions, with orthogonal axes in the machine direction (MD), cross-machine direction (CD), and fabric thickness direction (Z). Because fabric wefts and warps run roughly perpendicular to each other, the filaments in the machined fabric surface had ellipsoidal or sinusoidal cross-sections. For example, machining a typical fabric in the CD-Z plane split the MD filaments into ellipses, and the CD filaments into sinusoidal shapes (**Fig. 1**).

We constructed three-dimensional models from the images of the fabric cross-sections. The raw images were first edited using the shape-drawing function in Microsoft PowerPoint. White ellipses were drawn around the roughly circular filaments, and straight white lines were drawn on the edges of the alignment slot. The images were then reduced to black-and-white images, with just these shapes, to simplify the image processing. We used the Matlab Image Processing Toolbox to convert the images into point data we could use to model the fabric. The software converted image pixels into matrix data; the black-and-white images became logical matrices with ones representing the white pixels and zeros representing the black. A program written in Matlab traced the boundary of the inside of each outline and calculated the best-fit ellipse through the points. The program then found the coordinates of the quarter points of that ellipse (the points at the end of the major and minor axes). In the same way, the program also searched out from the corner of the image to detect the lines on the edge of the alignment slot. Filaments that were split into a roughly sinusoidal shape had points manually selected along their boundary. These coordinate data were converted from pixel coordinates to actual distances using the micrometer scale, and exported as data files to be read by Unigraphics.

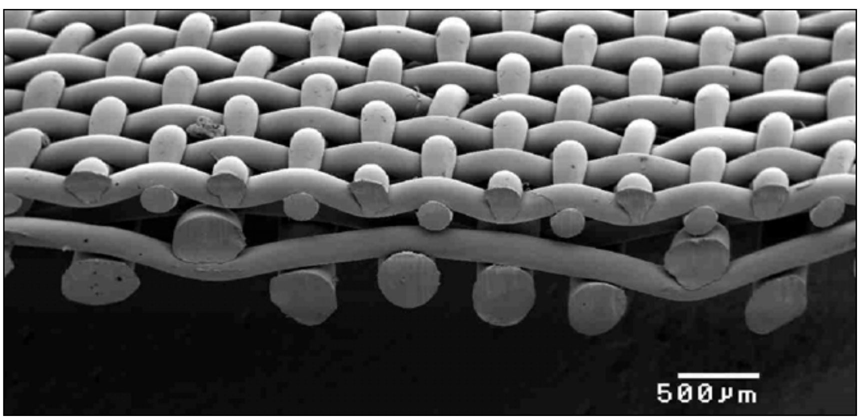
We constructed each cross-section slice as a separate part with splines fit through the point data from the images. The complete model was built as an assembly of the slice parts, which were registered by the plate slot and the milled depth. Guide splines were fit through the ellipsoid cross-sections, and one of the cross-sections was swept along the splines to form a solid. We used a similar sweep on the sinusoidal filaments. We obtained the necessary cross-section by taking a single cut and image in the perpendicular plane.

## RESULTS AND DISCUSSION

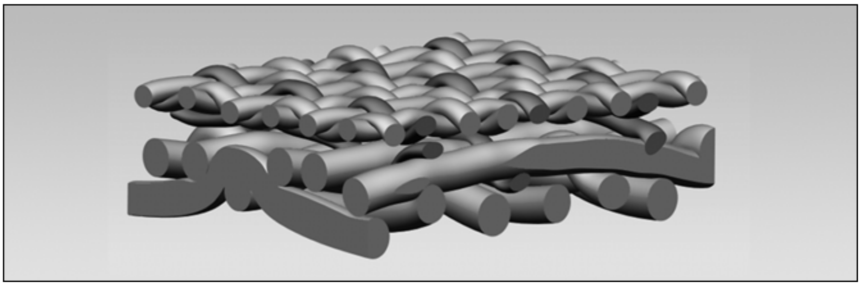
Figure 1a shows a typical CD-Z micrographic image of a forming fabric sample that has been potted and milled in the manner described above. Figures 1b and 1c show successive cross-sections of



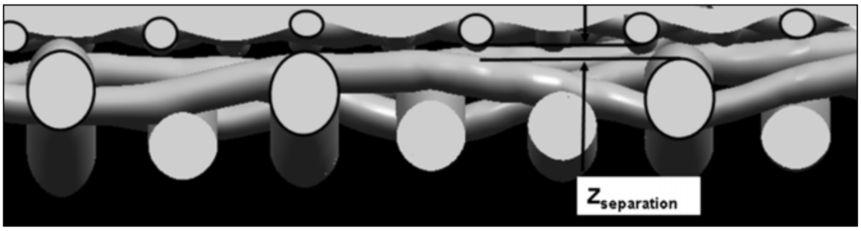
***3a. Unigraphics model of a double layer forming fabric.***




***3b. Micrograph of the actual fabric.***
*PHOTO COURTESY ASTENJOHNSON INC.*



*4.Unigraphics model of a triple-layer fabric*




***5. Cross-section view of double layer fabric model in MD-Z plane with separation of layers indicated. Filaments are outlined for clarity. Approximate dimensions: small filament diameter - 0.18mm; large filament diameter – 0.35mm; Z separation – 0.09 mm.***

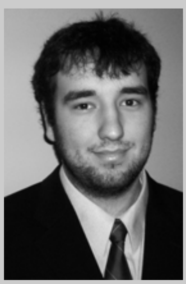
the same sample after machining off 0.076 mm and 0.15 mm respectively.The circled group of three filaments shows the changes in the fabric microstructure between the three slices.

To determine the accuracy of this technique, a known geometry of fabric filament was potted, sectioned and modeled. The sample was a single filament of polyester bent over a support to give a curvature radius of 61 mm. We cut 10 cross-sections of the filament cut at angles, similar to those produced by sectioning an actual fabric. The RMS minimum distance between the cross-sections and a 61 mm-radius circle fitted to the points was found to be 0.028 mm (shown in **Fig. 2**).This RMS deviation can be interpreted as an indication that the uncertainty of the technique is roughly 0.028 mm.

**Figure 3a** shows a complete CD-Z model of a double layer forming fabric constructed using the procedure developed in this study.The appearance of the exterior of the model shows good agreement with the photomicrograph of the same fabric (Fig. 3b). **Figure 4** shows a triple layer fabric model.

Illustrating an application of this technique, **Fig. 5** shows an MD-Z section plane of a model of a modern forming fabric with two rows of filament cross-sections highlighted, the upper row being paper-side filaments and the bottom row being machine-side filaments. Results from recent CFD studies [3] suggest that for row separations less

## INSIGHTS FROM THE AUTHORS



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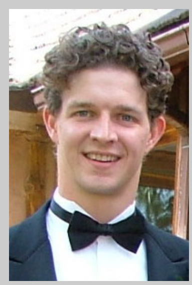

***Gilchrist***

We chose this topic for research because manufacturers had no experimental information about the internal structure of their fabrics. This research also complements other research we are conducting that involves the modeling of forming fabric flow at the scale of individual filaments.

The most difficult aspect of this investigation was figuring out a way to machine forming fabric without tearing out filaments or in other ways altering the fabric structure.Our most interesting finding was that this research enabled us to generate rapid prototype machine scale models of fabrics, which are significantly useful tools for visualizing fabric structure.

Mills will benefit directly from our findings because paper machine clothing manufacturers will be able to design superior fabrics as a result of our research. The next step is to import the three-dimensional CAD drawings into computational fluid dynamics (CFD) software and use the software to predict the flow field through the fabric.

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than 0.7x the paper-side diameter, the machine-side filaments may affect the uniformity of flow entering the paper-side. In the cross-section shown in Fig. 5, the paper-side filament diameter is approximately 0.18 mm. The Z-direction distance between the two highlighted layers is approximately 0.09 mm, or 0.5x the paper-side diameter, which is within the critical limit. In fact, for the fabric shown in Fig. 5, the highlighted filaments continued to be within the critical separation for sections spanning 0.3 mm farther in the CD-direction, which is comparable with the length of a short fiber. This suggests that conditions may exist in forming fabrics in which large-diameter machine-side filaments may affect the micro-uniformity of drainage flows entering the paper side of the fabric.

## CONCLUSIONS

We have developed a method for imaging and modeling the interior geometry of multi-layer forming fabrics. The usefulness of this new technique was demonstrated by determining information necessary for computational fluid dynamics modeling of micro-uniformity of flows into fabrics. This technique opens new possibilities for understanding the influence of fabric design on the micro-uniformity of flow in the early stages of drainage, and consequently its role in determining the microstructure of paper. **TJ**

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