Evaluating an Improved Method to Determine Layered Fibre Orientation by Sheet Splitting

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ABSTRACT

First the most commonly applied methods are reviewed. Then a new method is introduced employing the laminate method for sheet splitting, a high resolution scanner for imaging and fibre segment image analysis for fibre orientation measurement. One advantage of the new method is that it permits arithmetic correction of uneven sheet splitting which reduces noise in the FO measurement.

The main part of the paper is devoted to the evaluation of the new method. Repeatability of the measurement is good. The influence of the sheet splitting process on the measured fibre orientation is assessed by analyzing isotropic laboratory handsheets and oriented machine made sheets. Only minor influence of the sheet splitting on the result is found for handsheets, the measured fibre orientation was nearly isotropic. For oriented paper differences of the measured FO between sheet splitting in MD and CD was found. Overall the effect of sheet splitting on the measured results was lower than expected.

The experiments indicate that the influence of sheet splitting on the measured FO is, although undoubtedly existing, certainly low enough to permit meaningful results. It is discussed, that the predominantly layered structure of the fibres in paper is the reason why sheet splitting can be applied in combination with fibre orientation measurement.

1 INTRODUCTION

Sheet splitting has been used in different ways for paper testing because it enables z-directional analysis of the sheet structure. For example z-directional filler distribution and formation [1] or forming layer mixing [2] are examined by sheet splitting. Within the last ten years several methods to measure fibre orientation through the thickness direction of paper have been introduced. These methods have been used to investigate paper problems [3, 4, 5, 6] like curl, centimeter waves or cockling which are, to a different extent, related to fibre orientation. Sheet splitting has two main advantages compared to other z-directional FO measurement techniques like confocal laser scanning microscopy [7] or polarized light based surface fibre orientation measurement [8]. It permits two-dimensional analysis of the FO and it has a large enough sample area to detect structures in the centimeter scale which is relevant for the analysis of cockling or FO streaks.

In this paper first a review on the existing methods is given, where the pros and cons of these methods are discussed. Then an improved z-directional fibre orientation measurement method is introduced. It combines favourable methods for sheet splitting, layer imaging and image processing. The main innovation of the method is, that uneven sheet splitting is corrected arithmetically, thus obtaining a better reproduction of the true 3D layered fibre orientation. Finally the main topic of the paper is addressed, the evaluation of the new method. As the paper samples are torn apart during the sheet splitting process, the question arises if the orientation of the fibres measured in the split layers still reflect the original fibre orientation in the sheet. No conclusive answers could be found in the literature. This question is treated here from three perspectives

- Repeatability of the method
- Measurement of unoriented sheets. Any orientation measured in such sheets must descend from the sheet splitting.
- Measurement of oriented sheets. For that purpose the tearing direction during the sheet splitting was lead in MD and CD and the impact on the measured FO was studied.

2 RELATED RESEARCH

A tabular compilation of the key characteristics of the reviewed sheet splitting based fibre orientation measurement methods is presented in Table 1.

As early as in the 1950ies sheets were split with adhesive tape in order to investigate z-directional sheet structure [9]. The authors produced up to 20 layers from a newsprint sample by repeatedly putting adhesive tape on both sides of a paper sheet and tearing it in two halves. Although in this early work the focus was set on assessment of formation in different layers of the sheet, the variation of fibre orientation in the splits caused by wire shake was already observed.

One of the first publications where fibre orientation in various layers of the sheet was analyzed appeared in 1969 [10]. The author split paper in four layers using a Beloit Sheet Splitter [11]. With this method 8-12 layers can be obtained from an 80 $^{g}/_{m^2}$ sheet. In the splits the author determined the fibre orientation distribution in each layer from visual evaluation of stained fibres in the paper. Additionally he estimated fibre orientation anisotropy from zero span tensile testing of the split layers.

	Dyeing of sample	Splitting method	Imaging	Determination of fiber orientation	Sample area	Number of layers
Kallmes 1969 [10]	-	Beloit splitter	-	zero span tensile testing, visual inspection	-	6-10
Bando et al. 1995 [12]	yes	Adhesive tape	-	Visual inspection	3×3 cm^2	8
Erkkilä et al. 1998 [13]	-	Adhesive tape	Scanner	Gradient vector field histogram	5×15 cm^2	8-12
Thorpe 1999 [16]	yes	?	Microscope	Hough transform	2.5×2 cm^2	13
Knotzer 2000 [19]	-	Laminating device	Microscope	Skeletonization and segment angle measurement	1×2 cm^2	60-200
Lloyd & Chalmers 2001 [5]	-	Adhesive tape	Scanner	Gradient binarization and edge segment angle measurement	5×20 cm^2	10-15
Ono et al. 2002 [17]	-	Adhesive tape	Microscope	Skeletonization and segment angle measurement	?	6-12
Söderberg & Lucisano 2005 [2]	-	Laminating device	Scanner	Gradient vector field histogram	up to 10×20 cm^2	8-12
Hirn 2006 [4]	yes	Laminating device	Scanner	Skeletonization and segment angle measurement	3.5×8 cm^2	60-200

Table 1. An overview of sheet splitting based methods to measure fibre orientation in different z-directional layers of the sheet. The number of layers refers to a sheet with 80 $^{g}/_{m^2}$.

Several decades later a Japanese group adopted tape splitting [12]. They stained paper samples with a toluene based dye to attain well visible fibres in the individual splits. The paper was divided in eight layers, in each layer FO anisotropy was determined by manual counting of the number of fibre crossings in each layer.

One of the most widely used layered FO measurement methods was first described byErkkilä et al. [13, 14]. They also use tape splitting. An important innovation of their approach is that they evaluate fibre orientation using digital image analysis. Imaging of each layer is performed with a scanner operated at 800 dpi. At this resolution individual fibres are just recognizable. Fibre orientation measurement is not performed by identification of individual fibres in the image, instead the FO is quantified by analyzing the texture of the image. Orientation angle and intensity of the texture is calculated from a gradient vector field of the image pixels [14, 15]. In a subsequent publication [3] the same group also introduced layered formation analysis and local measurement of fibre orientation. Local fibre orientation is measured in 3×3mm^2 large subareas, for each of these subareas FO angle and anisotropy is determined. This local FO measurement permits visualization of fibre orientation structures, which is widely used to analyze paper defects like cockling or finger ridges [3, 5, 6]. Also the intensity of small scale turbulence in the forming zone is studied by analyzing local fibre orientation in the split sheets.

In [16] an unspecified method for sheet splitting was applied. The author split 2.5×2 cm^2 large samples of copy paper in 13 layers. The individual layers were imaged using a microscope and a CCD camera. For image analytical measurement of the fibre orientation in the split sheets a Hough Transform [15] was applied.

Curl and cockling was investigated [5] by analyzing layered fibre orientation. The authors applied Erkillä's tape splitting method to split samples of size 5×20 cm^2 in 10 to 15 layers. For fibre orientation measurement they use a somewhat different image analysis technique. It also identifies the edges of fibres but it measures orientation of individual fibre segments. In this paper also local fibre orientation for samples of size 2×10 cm^2 was analyzed.

A conference publication briefly describes an additional method [17]. The paper samples are split in several layers using adhesive tape. The layers are photographed in background illumination using a microscope and a CCD camera. The images are binarized and the fibre center lines are identified. The center lines are approximated by a string of line segments and the orientation angle of the individual segments is measured. The angles of all segments are summed up to find the fibre orientation distribution.

Also widely used is a lamination based sheet splitting procedure introduced by a Swedish group [18, 2]. Lamination based sheet splitting will be described in section 3. The authors split an 80 $^{g}/_{m^2}$ sheet into 8-12 layers, sample sizes up to 30×40 cm^2 can be achieved. They compute local fibre orientation for arbitrarily sized subareas in each layer as well as overall layer fibre orientation also using gradient field image analysis [13, 14]. Furthermore they analyze formation and wire mark geometry in the split layers. This method is, along with the one of Erkkilä et al. [13], state of the art in sheet splitting based paper structure analysis.

2.1 Discussion of the Reviewed Literature

Comparing these methods with respect to their technical characteristics we find significant differences, see Table 1.

Sheet splitting method. The Beloit Sheet Splitter is clearly the most difficult to use splitting technique. It requires considerable skill of the operator to obtain splits of acceptable quality. Tape splitting [2, 5, 9] permits splitting in more layers and provides more even splits. The downside of tape splitting is that it is limited regarding sample size and number of possible splits. The laminating method [2, 4, 19, 20] has the main advantage that it is very flexible. It can be used for small and large sample sizes, standard office laminating devices cover paper formats up to 30×40 cm2. Furthermore it is easily possible to vary the basis weight of individual splits. Thus an 80 g/m2.sample can be split in up to 200 layers.

Imaging method. Scanner imaging [2, 4, 5, 13] is clearly superior to microscope imaging because of the much larger field of view, and thus much larger possible sample size. Large sample size is necessary to detect FO structures in the centimeter scale. Also for good repeatability the measurement area should be considerably larger, see section 4.1. The main advantage of microscope imaging [16, 17, 19] used to be the better optical resolution but within the last few years affordable scanners have reached an optical resolution of 3500dpi and more, so they are well able to image individual fibres.

Please note that these are high resolution scanners. Common office scanners feature a pixel size corresponding to 2400dpi, however their optical resolution is much below. Cheap scanners are not able to depict objects in the range of their pixel size, instead small objects appear highly blurred.

Image Analysis for fibre orientation measurement. The gradient field image analysis approach which is the most widely used today is very efficient for two reasons. First it does not involve complex image processing procedures like object segmentation or complex filtering. More important, the method does not identify individual fibres. Thus it is sufficient to split a sheet in 8-12 layers, compared to other image analysis methods which require 50-100 splits. Also images with a resolution of 800dpi are sufficient which reduces scanning time, especially for large area samples.

On the downside this method is very sensitive to small scale noise [18] which is introduced by small objects in the image like for example fibre debris or filler particles. Also gradient field image analysis is affected by uneven background illumination as it occurs in microscope imaging as well as with cheap flatbed scanners. Image analysis algorithms based on *segmentation* [4, 5, 17] identify the fibres or the fibre edges in the image. As an effect from this segmentation the background pixels are discarded [15] from the subsequent image analysis. Thus

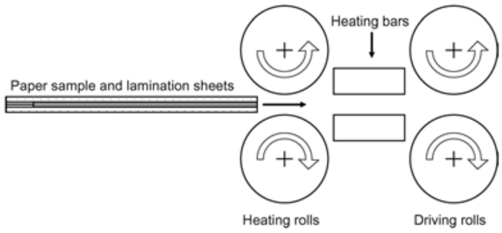


Figure 1. Lamination of a paper sample in a commercial hot laminator [2].

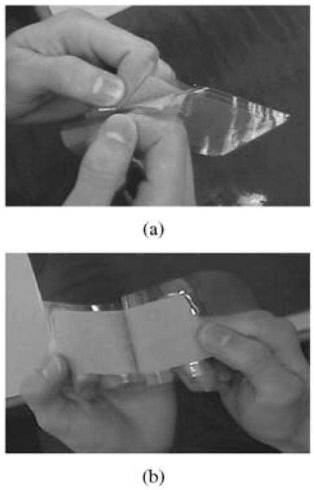


Figure 2. Working principle of laminate sheet splitting. Both paper surfaces adhere to the laminating film and the sheet is torn in two layers.

moderate changes in background illumination do not affect the results from these algorithms. In conclusion fibre orientation should be measured from fibre segments [5, 11, 14] or other larger structures [18] instead of pixelwise gradient field computation. This reduces small scale noise and provides robustness against background illumination inhomogeneities.

3 OUR METHOD

For layered fibre orientation measurement we use laminate sheet splitting and flatbed scanner imaging. The fibre orientation in the split layers is measured on line segments approximating the fibres.

First the sample is dyed for improved contrast of the fibres in the individual layers. We use Cartaren Black, a cationic dye from Clariant. In a laboratory trial it proved to be superior because it penetrates very well into the sheet, even in high coat weight papers. After dyeing the sample is pressed in a sandwich of very high mesh wire and dried at room temperature.

Originally the laminating method for sheet splitting was introduced by Knotzer [1, 19, 20]. The paper sample (grey) is sandwiched between two laminating foils and inserted in the laminator, where moving rolls transport the sandwich through the device, see Figure 1. On its way, the sample is heated, hot melt glue applied to the inner part of the

(a) (b) (c)

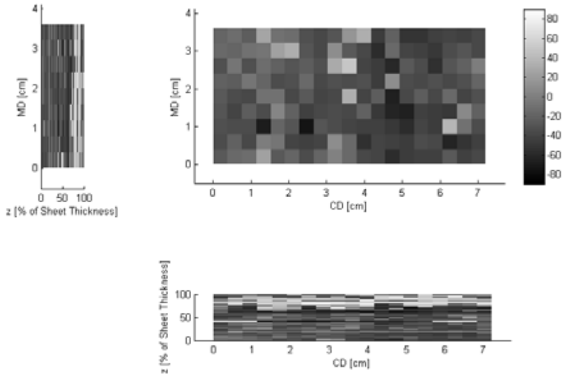
Figure 3. For measurement of fibre orientation the fibre center lines (b) are divided into segments with a length of 130µm (c) and the orientation angle of each segment is measured.

laminating foils melts and firmly attaches the transparent plastic film to the paper surface. Penetration of the laminate glue into the paper is controlled by heating temperature and the transport speed through the laminator. Suitable choice of these parameters also enables splitting of coated papers. After lamination the sample is split in two halves by hand as illustrated in Figure 2. By repeating this procedure the paper is split to increasingly thin layers, usually to roughly 1 $^{g}/_{m^2}$, that is 60-100 layers for an 80 $^{g}/_{m^2}$ paper. With this technique layers with only a few fibres per square millimeter can be obtained, for some experiments layers covered with as little as 0.4 $^{g}/_{m^2}$ were produced. Most of the methods reviewed in the previous section fix the sample on two rolls and split it in the outgoing roll nip, e.g. [2]. Such a procedure reduces the influence of laboratory personnel manually performing the split. However we found, that the influence of manual splitting on the result is remarkably low. Experiments regarding this issue are treated in detail in section 4.

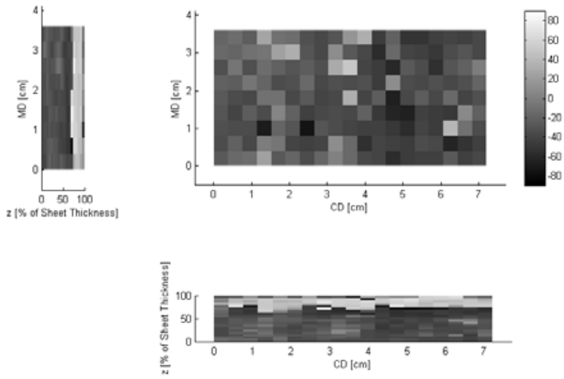
In order to obtain a sufficient field of view a high definition film scanner for medium format photography is employed. It is a high end scanner with a very even field of illumination. The fibre layers are scanned at a resolution of 3300 dpi, due to the high resolution and the many layers individual fibres are well discernable in the images, see Figure 3(a). Maximum sample size is presently 3.5×8 cm^2 due to scanner hardware limitations.

Image analytical measurement of the fibre orientation [4, 15] is outlined in Figure 3. Fibres in the image are detected by Otsu's thresholding algorithm and the fibre center lines are found by skeletonization. These fibre center lines are approximated by line segments. The orientation angle of the line segments is measured, collecting all the segment angles yields the fibre orientation distribution. By fitting an ellipse to this distribution fibre orientation angle and anisotropy are found. The direction of the major axis is the FO angle and the ratio of major- to minor axis length $^{a}/_{b}$ is the anisotropy.

Fibre segment image analysis requires splitting in many layers, because if the fibre mat is too dense there are many intersections between fibres, which leads to incorrect positioning of the line segments approximating the fibres. Choosing a fibre segment



(a) Raw data without arithmetic correction.



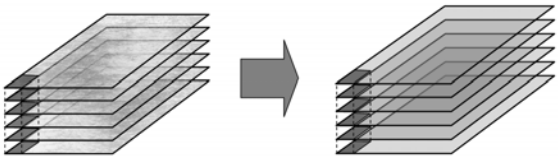
(b) After arithmetic correction of uneven sheet splitting.

Figure 4. Effect of arithmetic correction of uneven sheet splitting. The fibre orientation angle of the same sample is depicted before (a) and after (b) arithmetic correction of uneven splitting.

length of 130µm was a compromise between two conflicting requirements which are discussed elsewhere in detail [4]. On one hand the applied polygon decomposition algorithm works better with smaller segment length. The larger the segment length the less segments can be identified by the decomposition algorithm. On the other hand the resolution of the segment angle measurement increases with longer segments. For example a segment length of two pixels can only depict four different segment positions, thus yielding an angular resolution of 45°. For the chosen segment length of 130µm both, an angular resolution of ~3.8° is obtained as well as enough segments can be measured to obtain good statistics. However segment lengths of 150µm and 170µm were also tested and gave nearly equivalent results.

Finally a 3-dimensional model of the extracted fibre orientation in the sheet is built. The contours of the original sample are well visible in each split layer, see Figure 5(a). From that information the MD- and CD- position of each fibre segment with respect to the sample edges is recorded. The z-position is defined by the number of the split layer containing the fibre segment. From this data a three dimensional layered fibre orientation model of the sample is compiled. Fibre orientation angle and anisotropy from rectangular subregions of the

(a) Uneven splitting of one layer.



(b) Illustration of arithmetic correction of uneven sheet splitting.

Figure 5. Uneven sheet splitting requires arithmetic correction of the fibre mass distribution.

specimen can be computed [4], in this way local fibre orientation maps of the specimen are generated. An exemplary result gives Figure 4(a). It shows the fibre orientation angle of a sample in three different views. The MD-CD view depicts the local FO angle for $3.6{\times}3.6\text{mm}^2$ subareas of the paper. The CD-z view and the MD-z view give the local fibre orientation angle across the sheet thickness direction. Similar plots are generated for FO anisotropy, e.g. see Figure 9.

3.1 Arithmetic Correction of Uneven Sheet Splitting

Image 5(a) also shows, that the sample layers may split unevenly, which is a general problem with sheet splitting, e.g. [5]. It occurs in varying intensity, leading to an incorrect z-directional position of the fibres in the 3D-layered model, because the z-coordinate corresponds to the layer number. This is demonstrated by Figure 4(a), here the z-directional FO is divided in 60 layers. In the MD-z and CD-z view a remarkable change of the FO angle in the top 40% of the sheet is visible. Still the plot is somewhat noisy due to uneven splitting causing erratic changes in the measured fibre orientation.

For that reason the fibres are arithmetically evened out according to a procedure illustrated by Figure 5(b). First the total specimen area is divided into subareas, for these subareas ultimately the local fibre orientation is determined. Fibre segments within a defined subarea (dark) are summed up over all layers. This gives the cumulative fibre length of the paper within the subarea. Then the fibres are, under preservation of their z-directional order, evenly distributed between all layers of this subarea. This procedure is repeated for each subarea of the sample. From this corrected FO model, the fibre orientation can be computed and visualized for a user defined amount of layers in the sheet. In Figure 4(b) the raw data from Figure 4(a) was arithmetically corrected for uneven splitting and the FO was recomputed for a sheet divided in 20 layers. As an effect much of the noise has disappeared and the structure of the sheet becomes more clear.

3.2 Discussion of Our Method

In the context of the reviewed methods the chosen approach uses an effective splitting technique and state of the art scanner imaging. Sample size is today limited to 25 cm^2 but can be easily increased by a scanner with a larger field of view. For image analysis not the gradient field approach was chosen, rather more robust measurement of separate fibre segments is performed. Additionally arithmetic correction of uneven sheet splitting reduces noise in the measurement. All these benefits are of course gained on the expense of considerably higher time effort caused by the large number of split layers this method requires. One sample with standard size $3.5{\times}8\ \text{cm}^2$ takes 4 hours of time for splitting and scanning, image analysis requires a runtime of a few hours on a desktop PC.

4 EVALUATION

The focus in this section is set on the influence of the sheet splitting procedure on the results. Specifically it is examined if the splitting induces systematic repositioning of fibres in the layers or if it adds noise to the measured fibre orientation.

4.1 Repeatability

Analyzing repeatability of the method should answer two questions. First we need to know if the chosen sample size is large enough to get a reproducible fibre orientation measurement across the sheet thickness direction. It is well known that local fibre orientation varies largely below centimeter scale [3], so for good repeatability the measurement area must be considerably larger. Second we get information about the noise introduced by the measurement method.

Repeatability was tested with 80 $^{g}/_{m^2}$ fine paper. Four samples, each with an area of $3.6{\times}7\ \text{cm}^2$, were taken from two different profiles at the same CD position of the paper machine. Samples A1, A2 were extracted in close distance, A3 and A4 were

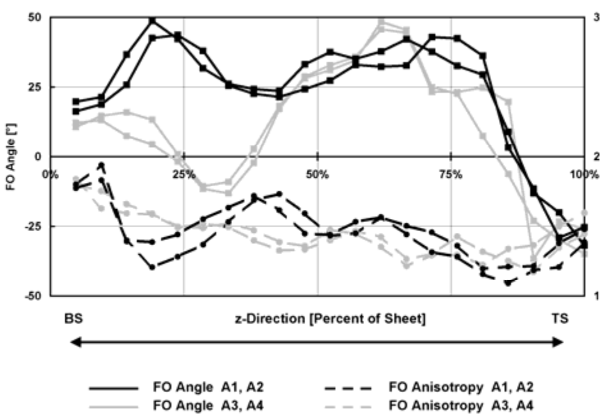


Figure 6. Repeatability of z-directional layered fibre orientation measured with 80 $^{g}/_{m^2}$ fine paper.

also cut out close to each other but from a different CD profile than A1 and A2. It can be assumed that the adjacent samples A1, A2 respectively A3 and A4 were formed under the same flow conditions, so they should exhibit a similar z-directional fibre orientation. The samples were split in about 80 layers, after arithmetic correction of uneven splitting the fibre orientation was recalculated for 20 layers in the sheet. As a matter of fact the adjacent samples A1, A2 and A3, A4 do have very similar z-directional fibre orientation angle and anisotropy curves, see Figure 6. This proves that the sheet splitting process introduces negligible stochastic noise to the measurement, repeatability is good. Furthermore the chosen sample area of 25 cm^2 seems sufficient for a reproducible measurement of z-directional fibre orientation.

4.2 Analyzing Handsheets

As it has been proved that random effects of the sheet splitting on the measured FO are low, it must be examined if there are *systematic* effects. Systematic influence of the splitting or laminating process on the measurement is plausible, because the repeated splitting and laminating movement could likely reposition fibres. In order to examine this, laboratory handsheets were analyzed. The fibre orientation of handsheets should be totally random. Consequently all fibre orientation measured in this experiment descends from the splitting process itself.

In order to obtain quantitative information about the influence of the sheet splitting a designed experiment for an analysis of variance (ANOVA) was carried out which is illustrated in Figure 7. Four handsheets were made on a laboratory handsheet former. Four rectangular specimen were cut out from each handsheet. These specimen were split length- and crosswise (denoted SL vs. SC) respectively laminated length- and crosswise (denoted LL vs. LC). Splitting lengthwise means, that the movement of delamination is carried out parallel to the long side of the specimen. Laminating lengthwise means, that the specimen is moving through the laminator parallel to its long side. Beside the main factors splitting and laminating the test design permitted the control of two nuisance factors. In this way the impact of the nuisance factors can be removed from the calculation of the ANOVA. Our nuisance factors are the number of the handsheet and the position (A, B, C or D) of the specimen in the laboratory sheet former. In summary the ANOVA quantitatively determines the influence of the main factors splitting direction and laminating direction and decides if the nuisance factors sheet former position and handsheet number have an influence or not.

Figure 8 gives the measured FO for the varying splitting and laminating directions. It shows the

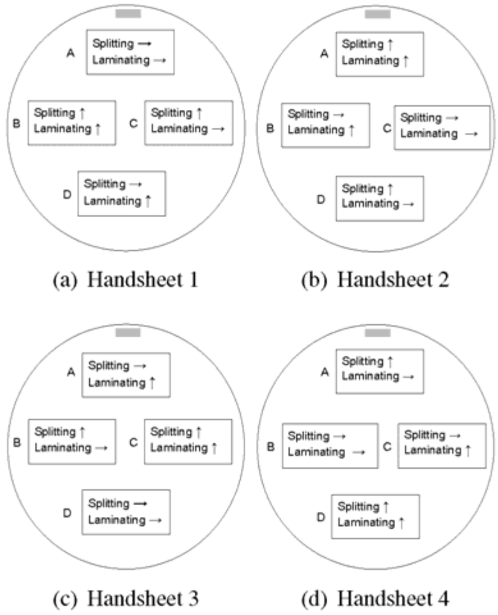


Figure 7. Experimental design to quantify the influence of the sheet splitting process on the measured fibre orientation. Specimen taken from four handsheets were split length- and crosswise and also laminated in length- and crosswise direction.

ellipses fitted to the fibre orientation distributions. Each ellipse represents one of the four combinations of splitting- and laminating direction. Surprisingly the splitting as well as the laminating shows little impact on the measured FO. All four combinations of splitting and laminating direction have an FO angle between -15° and -30° and an anisotropy between 1.09 and 1.20 which is close to a circular perfect random distribution (anisotropy of 1). Still there is a small systematic effect in the

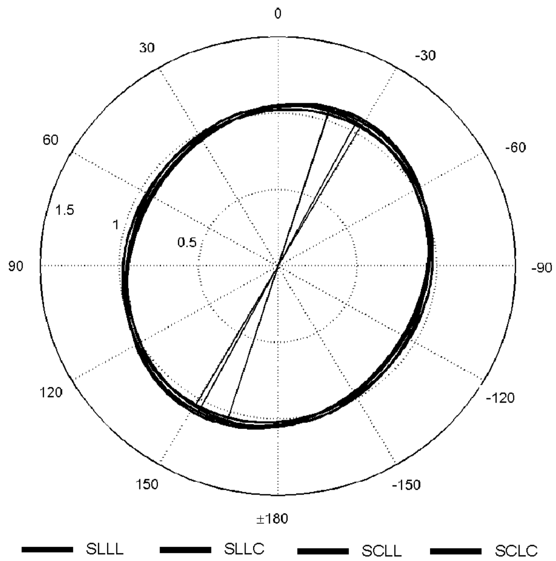
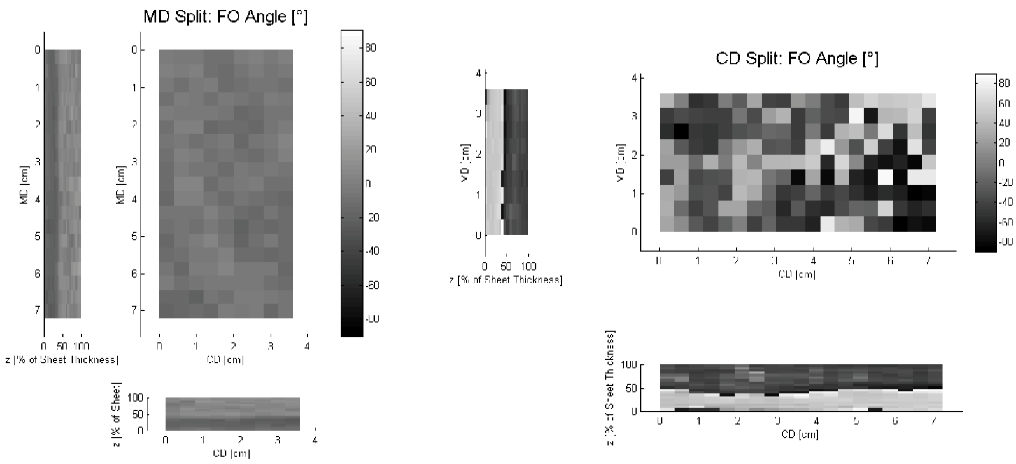
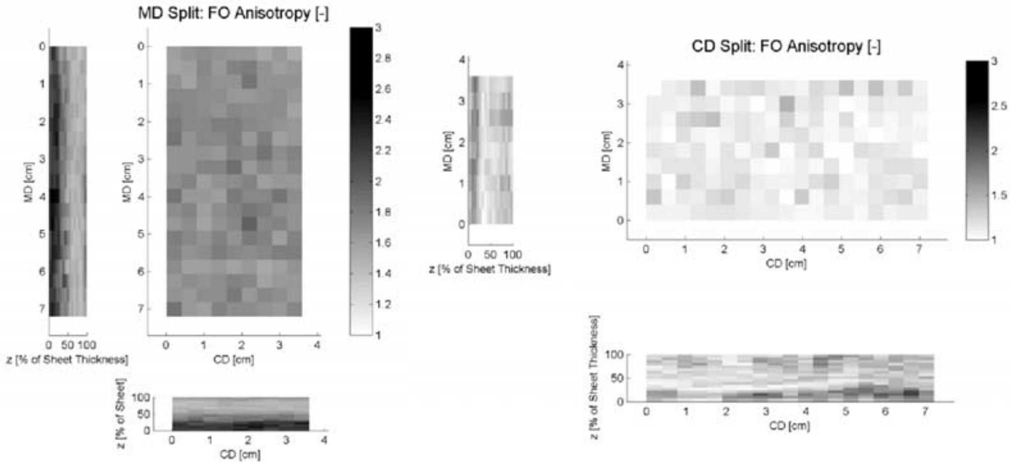


Figure 8. A summary of sheet splitting fibre orientation measurement in handsheets. Although sheets were split and laminated in lengthwise- as well as crosswise direction, hardly any influence on the measured fibre orientation can be observed: the fibre orientation is close to a perfect random circular distribution.



(a) Fibre orientation angle measured from MD splitting (left) and CD splitting (right).



(b) Fibre orientation anisotropy measured from MD splitting (left) and CD splitting (right).

Figure 9. Effect of splitting in MD or CD for wood free coated paper produced on a commercial paper machine. MD splitting imposes less change on the measured fibre orientation in the samples than CD splitting.

splitting, all FO angles are rotated clockwise. The ANOVA of the results revealed, that neither the variation of laminating nor splitting direction was responsible for this rotation. Instead the model gave a systematic offset (intercept) of -20° for the angle and 1.17 for anisotropy. Surprisingly the nuisance factor ’position of the specimen on the handsheet’ was highly significant. Thus the main proportion of the orientation can be attributed to the samples in position A on the handsheets, all other positions did not have significant orientation. One could speculate that there is a slight systematic flow in this position of the laboratory sheet. However, this assumption is not proven.

In conclusion little systematic effect of the sheet splitting on the fibre orientation measured on handsheets could be detected. The splitting method which is actually implemented as our standard, Splitting Lengthwise and Laminating Lengthwise (SLLL), induces an anisotropy of 1.09 and an angle of -28° to the measurement, including the sample from position A in the handsheets. Again this is an isotropic, nearly perfectly circular random distribution. It can be interpreted as follows: on average 4.5% of the fibres were moved by an average angle of -28°. Discarding position A on the handsheet from the analysis no significant orientation was introduced by our method.

4.3 Analyzing Oriented Sheets

Another test on the effect of the sheet splitting procedure on the measured FO was realized for machine made paper. The experiment was carried out with woodfree coated paper produced on a hybrid former, the tensile MD-CD ratio was 1.9. The paper was split in two different ways, the splitting direction was MD respectively CD. So the splitting direction coincided with the principal fibre orientation respectively it was perpendicular to it.

The results are shown in Figure 9(a) for FO angle and Figure 9(b) for FO anisotropy. The left diagram shows the FO angle/anisotropy in an MD split sample, the right diagram in a CD split sample of the same paper. Overall anisotropy is considerably higher for the MD split, than for the CD split, 2.4 for MD vs. 1.3 for CD. Still the z-directional characteristics of FO anisotropy remain unchanged, anisotropy increases towards the bottom side of the sheet. For the fibre orientation angle, the principal characteristic - a disruption of the FO in the bottom

40% of the sheet - is also visible in MD split as well as CD split. The change in FO angle sign between MD- and CD splits is due to sample rotation by 90°. So although the same specific z-directional inhomogeneities are found with MD and CD splits, the absolute differences are large. The large variation in FO angle values and the low anisotropy measured in the CD splits leads to the conclusion, that this splitting direction significantly alters the fibre orientation. The values for MD splits are much more plausible. On the top side the FO angle is between 0° and +10° in the bottom 40% of the sheet it is around -20°. Overall anisotropy with a value of 2.4 is somewhat higher than the MD-CD tensile ratio with 1.9. As fibre anisotropy does not correspond exactly to tensile MD/CD it is unclear if and how many fibres were realigned by the splitting procedure. Anyway splitting in machine direction is advisable for layered fibre orientation measurement.

In conclusion the change of the splitting direction did influence the measured fibre orientation for machine made sheets. Still splitting in machine direction delivers plausible FO angle values and FO anisotropy at least does not contradict MD/CD tensile ratio.

4.4 Discussion of the Evaluation Experiments

A hypothesis to explain the differing results between handsheet experiments and machine made paper might be the fact that laboratory handsheets are formed at an extremely low consistency of about 0.04% where little flocculation takes place in the suspension. Thus filtration is the principal forming mechanism which produces a nearly perfect *layered sheet structure* [21]. Opposed to that forming on a paper machine produces a somewhat more *felted structure* due to more flocculation. The difference is that layered structures can, at least in theory, be split without repositioning fibres, which is impossible for felted structures. In a classic publication [22] a mix of 80% layered and 20% felted structure has been suggested for machine made paper. This difference in the degree of felting between handsheets and machine made paper could explain some of the additional influence from sheet splitting in machine made paper. Still paper forms a predominantly layered structure. It is noteworthy, that this layered structure of paper is the key reason why sheet splitting based fibre orientation measurement is possible at all.

5 CONCLUSIONS AND OUTLOOK

The introduced method to measure layered fibre orientation employs state of the art methods for sheet splitting, layer imaging and fibre orientation image analysis. Laminate splitting is the most flexible splitting technique regarding sample size and number of split layers. Scanner imaging permits high resolution images with large field of view, further improvements in this technology are still to be expected. For image analysis a stable, noise resistant approach has been chosen. However the chosen image analysis algorithms require splitting in 80-150 layers which is costly and time consuming. Therefore the largest potential for further developments lies in development of an image analysis approach that permits splitting in fewer layers.

A characteristic feature of the introduced method is arithmetic correction of uneven sheet splitting. It has been demonstrated to effectively reduce noise from the inherently inhomogeneous splitting procedure. Arithmetic correction permits analysis of layered fibre orientation with high z-resolution. Please note that this feature depends on actually detecting and counting of individual fibres. In order to preserve this functionality a possible new image analysis approach must also be able to detect individual fibres or fibre segments.

The influence of the sheet splitting on the measured fibre orientation has been studied extensively. It has been shown that the repeatability of the method is good. Sheet splitting does not introduce stochastic noise to the measurement. Splitting of isotropic laboratory handsheets showed minor influence on the measured FO. The samples still exhibited a nearly isotropic orientation after splitting. Analyzing machine made paper with splitting in machine direction and cross direction showed significant differences. Results suggested much more plausible results for splitting in MD. Considerations regarding sheet forming theory lead to the concept, that it is the highly layered structure of the fibres in paper that enables sheet splitting based z-directional fibre orientation measurement.

In conclusion the experiments indicate that the influence of the sheet splitting process itself on the measurement results is low enough to justify further development and application of this method. Although being elaborate and expensive sheet splitting will remain an important method to analyze z-directional fibre orientation.

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