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A LABORATORY INVESTIGATION ON THE ORIGIN OF MACHINE DIRECTION MICROSTRIATIONS

Marco F.C. Lucisano[1] *and Hannes Vomhoff*

Innventia AB – Box 5604 – SE-11486 Stockholm (Sweden)

1 SUMMARY

This paper is based on a laboratory-scale experimental study of machine direction microstriations (MDM) on board surfaces. We developed a pressing and drying simulator in which we can replicate some of the phenomena which are believed to be the origin of MDM: density stratification in wet pressing as well as in-plane restraining conditions during drying. Our laboratory experiments showed that we could generate surface features, visually similar to those classified as MDM in industrial paper production. In particular we could replicate the elongated appearance, the characteristic wavelength interval (1–4 mm) and the occurrence on one surface only.

The most important parameter in respect to the absolute amount of surface roughness was the in-plane restraining conditions during drying. Biaxial restraining resulted in much lower surface roughness and prevented the occurrence of MDM. MDM started to appear as soon as uniaxial shrinkage was permitted. Interestingly, however, shrinkage perpendicular to the main direction of fibre orientation in an oriented paper sheet caused a less pronounced occurrence of MDM in spite of a larger absolute value of shrinkage. The surface presented topography features parallel to the restraining direction. The press felt surface, in our investigation the coarseness of the batt fibres, influenced the surface roughness of paper, however at a characteristic length that was much smaller than that of MDM.

[1] To whom correspondence should be addressed: marco.lucisano@innventia.com.

2 BACKGROUND

The term "Machine Direction Microstriations" (MDM) refers to elongated microscopic buckling appearing as ridges and valleys parallel to the machine direction of paper (*Figure 1*). MDM generate quality problems in converting processes which rely on the surface properties of the substrate, e.g. polymer extrusion. Additionally, the relatively small surface defects constituting MDM are usually very clear and disturb print quality, since the human eye is extremely sensitive to gloss variations. In spite of the widespread occurrence of MDM in industrial papermaking there are no reports of successful attempts of generating MDM in a laboratory environment. Thereby the number of investigation directly elucidating the mechanisms of MDM generation is limited after the first description by MacGregor and Conners [1].

2.1 Modes of out-of-plane deformation

In absence of a generally accepted quantitative definition of MDM, we assume that a basic criterion for stating that a sample presents MDM is the occurrence of ridges and valleys elongated in MD, with a characteristic wavelength (in CD) in the range 1–4 mm. A second criterion for deciding the occurrence of MDM is that they can be observed exclusively on one side, implying that the topography of one surface of the sample is generated independently of that on the other surface, as illustrated in *Figure 2*.

MDM are not the only mode of out-of-plane deformation effecting paper products (*Table 1*). All modes of deformation are related to non-uniform shrinkage and irregularities in shrinkage, yet they differ as to their in-plane length scales, shape and depth of deformation. The literature present no general approach to describe or predict which mode of deformation is likely to appear in a given paper.

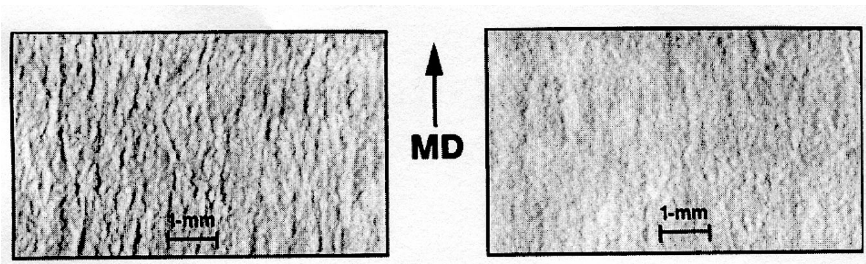

Figure 1. Micrographs of the two surfaces of a paper sheet, with MDM on the felt side of the paper (left) but not on the smooth roll side (right) [1].

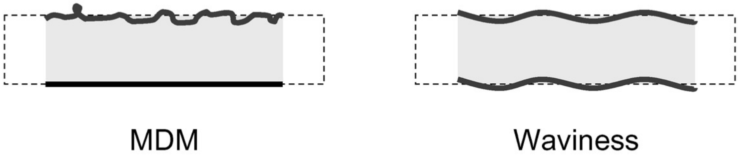

Figure 2. Schematic of the difference between MDM and waviness. The two sides of the sample have different surface topography in presence of MDM. On the contrary, the two surfaces of a paper affected by waviness share the same pattern of out-of-plane deformation.

Table 1. Modes of out-of-plane deformation of paper.

	Length scale	*Description*
Microstriations (MDM)	<1 cm	Appear as tiny ridges and valleys on one surface of the paper, highly oriented in machine direction. Cause reduced print quality and performance in converting.
Waviness/ fluting	1–3 cm	Appear as a series of macroscopic elongated parallel peaks and valleys. Can be observed with the same intensity on both surfaces of the paper. Noticeable to the naked eye. Involve the entire thickness of the web. Caused by uneven or excessive shrinkage during drying. Can result in problems with sheet feeding on printing machines.
Cockle	0.5–5 cm	Small-scale out-of-plane deformation with comparably low degree of orientation. Caused by in-plane irregularities in shrinkage during drying. Connected to formation, density, grammage, fibre orientation and drying patterns.
Curl and twist	>5 cm	Macroscopic large-scale out-of-plane deformation, caused by asymmetric fibre distribution, and non-symmetric in-plane stresses and shrinkage along the thickness direction of the sample. Negative effects on runnability in converting.

2.2 Stratification and differential shrinkage as a cause of MDM

The original hypothesis links the most probable mechanism for MDM to two-sided uneven shrinkage during the drying process. Additionally, the paper web entering the drying section of a paper machine has often a moisture and density profile in thickness direction, which is a result of the mechanical forces removing water in the press nips. This phenomenon, called stratification, was originally described by MacGregor [2, 3] as the change in vertical distribution of fibre and filler material resulting from fluid shear forces during a dynamic wet pressing process. In a single-felted press nip, density increases locally as water leaves the paper web from the surface in contact with the press felt. This generates two gradients: the moisture content increases in the direction from the felt side to the solid roll side, whereas the local density increases in the opposite direction. The existence of stratification has been observed in laboratory experiments, e.g. Burns *et al.* [4, 5], and measured in dry paper [6, 7]. Indeed, empirical observations suggest that MDM tend to appear on the surface pressed against the felt in the last nip, regardless of which side was in contact with the forming wire.

The hypothesis on the generation of MDM is formulated as follows: when one surface of the paper starts drying and shrinking, the rest of the sheet can comply with the deformation, being still wet (*Figure 3*). In the successive stages of drying, the remaining portions of the sheet shrink as they dry. Yet the paper layers that dried first have limited possibilities to shrink in plane and comply with the deformation by micro-buckling, which generates MDM. The highly-oriented nature of MDM is believed to be a result of the

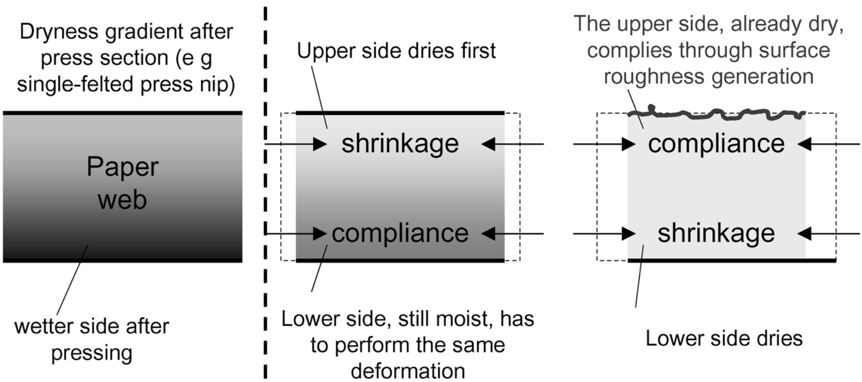

Figure 3. Differential shrinkage in drying as a result of stratification in pressing as the postulated mechanism for MDM. Felt on top side.

combination of the prevalent fibre orientation in MD with the different restraint conditions in MD and CD during machine drying. This hypothesis has to be considered a conceptual model for helping to understand the generation of MDM. However, this model neglects other important phenomena, such as the shrinkage properties of different plies in paperboard or the effects of their fibre orientation.

2.3 Characterizing MDM

Visual observations and measurement of a paper surface are the two most common ways to assess the presence of MDM in a paper sample. Early investigations showed that there is no correlation between the surface structure of a sample with MDM and the surface topography of the felt with which it was in contact in the press section. Additionally, the surface images of paper samples with MDM show no periodic pattern [1]. Surface profilometry and micrographic analysis of cross sections are two tools that have been used to characterize MDM. SEM examination of cross sections shows that the paper surface against the press felt, the side that was affected by MDM, was more densified than the other side. This observation agrees with the general understanding of stratification in wet pressing. Soft x-ray photographs reveal no in-plane mass variation that could be correlated with MDM, which suggests localized density variations in the thickness direction and/or variations of local topography [1]. This occurrence, together with the postulate that the two surfaces of a sample with MDM do not replicate each other locally leads to the unverified hypothesis that MDM might be connected to local micro-delamination in the paper web.

The current study presents a novel laboratory pressing and drying simulator designed to replicate some of the phenomena believed to cause MDM. After a validation of the method, we present an investigation on the effects of wet pressing strategy, in-plane restraint, directionality of drying and fibre orientation on the generation of MDM.

3 MATERIALS AND METHODS

3.1 Pressing/drying simulator

A laboratory pressing and drying simulator was used in the experiments. In the simulator, a circular paper sample was pressed in a press nip and then dried using heated surfaces (*Figure 4*).

The press nip could be configured either as a double-felted or single-felted press nip. The shape, peak stress, and duration of the press pulse could be

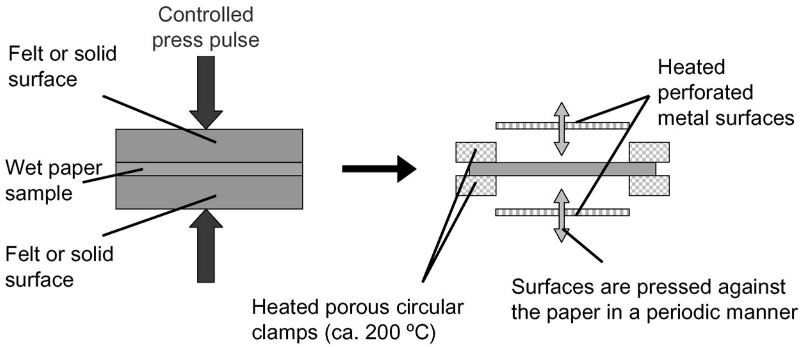

Figure 4. Working principle of the pressing and drying simulator.

controlled. Within less than 2 s after the press pulse, the sheet was transferred into the drying part of the simulator. Here the sample was clamped with the help of a pair of heated, circular, porous rings in order to obtain complete restraining during drying. The sample was then dried by pressing heated, perforated surfaces on both sides of the wet sample. The heated surfaces consisted of a 1 mm thick steel plate, with a special pattern of openings etched into it (top right portion of *Figure 5*). The surfaces were mounted on the top of two beakers, which were heated with hot air with the temperature of up to 250°C.

During drying, the heated surfaces were pressed against the wet sample for a certain time, and then lifted off the sample for the same time to allow for evaporation. The surfaces were then rotated clockwise by 15° before being pressed onto the sample for the same time as in the previous position, lifted off the sample and rotated counter-clockwise by 15°. Given this special procedure, the sample was heated by conduction every second drying pulse. In the remaining time, water could evaporate from the surface of the sample. This drying procedure was repeated until the paper sample was completely dry. The number of cycles for obtaining a completely dry sample was determined in pre-trials. The total drying time for a sample was of the same order of magnitude as that in a drying section of a paper or board machine.

In the present study, the total drying time for the 240 g/m^2 sheet was 96 s. It consisted of 8 sequences with a duration of 12 s, 3 s contact time and 3 s evaporation in both positions of the drying beaker. The air fed from the hot air blowers to the drying beakers had a temperature of 160°C.

The temperature in the upper and lower hot air blowers could be controlled independently of each other, thereby simulating both symmetric and non-symmetric drying conditions.

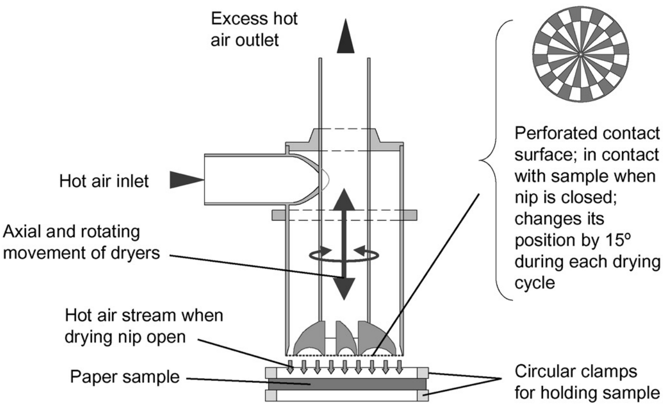

Figure 5. Schematic of the dryers with the perforated contact surfaces.

Laboratory experiments were performed on circular samples with a diameter of 79 mm. Individual samples were punched out of either standard handsheets or French dynamic laboratory sheets and stored refrigerated in sealed plastic bags.

The circular clamps of the pressing/drying simulator kept the sample in biaxial restraint during drying. Uniaxial restraining conditions were generated by introducing two parallel cuts with a sharp blade prior to pressing and drying (*Figure 6*).

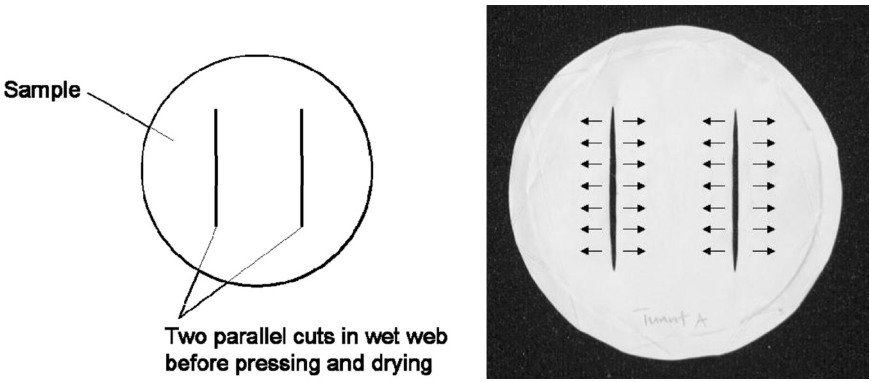

Figure 6. Schematic of the method to obtain uniaxial restraining during drying (left); the cuts opened when the sample shrinked in a direction perpendicular to the cuts.

3.2 Experimental conditions

This study is based on two sets of experiments. Initially we investigated the influence of restraining conditions, pressing and non-uniform drying in thickness direction on the surface roughness, and in particular on the generation of MDM. The second study targeted the influence of the fibre orientation on the surface roughness.

In the first series of experiments we prepared 240 g/m^2 webs by couching together four 60 g/m^2 isotropic handsheets in the wet state, prepared as in ISO 5269-1. The furnish consisted of a mixture of 40% bleached softwood (24,6 SR) and 60% hardwood (17,1 SR).

The pressing simulator was configured to replicate a single-felted press nip, with either a fine felt (FF), 1300 g/m^2 of a mixture of 17 µm/20 µm (3,1 dtex/4,2 dtex) batt fibres in the surface layer, or a coarse felt (CF), 1500 g/m^2 of 61 µm (44 dtex) batt fibres in the surface layer. The simulator was programmed to generate a 25 ms shoe-press pulse (Metso type, with plateau) with a peak pressure of 5 MPa. The dryness upon entering the press nip was approximately 18%, whereas the outgoing dryness was 39,3% with the coarse felt and 38,8% with the fine felt. All experiments were duplicated.

We used the drying simulator to reproduce three drying conditions: (i) symmetric, (ii) non-symmetric with heat supplied exclusively to the felt side of the sample, and (iii) non-symmetric with heat supplied only to the smooth side of the sample. In all cases the temperature of the hot air feeding the dryers was set to 160°C. All experiments were duplicated.

The second set of experiments was also performed with 240 g/m^2 webs prepared by couching together four 60 g/m^2 sheets in the wet stage. These where either isotropic handsheets (IS), prepared as in ISO 5269-1, or French dynamic (FD) laboratory sheets with tensile strength anisotropy 3,3. The furnish consisted of a mixture of 40% slightly beaten bleached softwood (20 SR) and 60% slightly beaten hardwood (20 SR). When working with French dynamic sheets, we prepared two different sheet structures. Whereas the two surface plies always shared the direction of main fibre orientation, the central portion of the sheet could be either aligned with the surfaces, or rotated by 90° (*Figure 7*). In both cases, we define the machine direction of the surface plies as the machine direction of the entire structure.

The pressing simulator was configured to replicate a double-felted press nip, using fine felts (FF), 1300 g/m^2 of a mixture of 17 µm/20 µm (3,1 dtex/4,2 dtex) batt fibres in the surface layer of the press felt. The simulator was programmed to generate a 25 ms shoe-press pulse (Metso type, with plateau) with a peak pressure of 6 MPa. The dryness upon entering the press nip was approximately 19% whereas the outgoing dryness was 45%. The dryer was

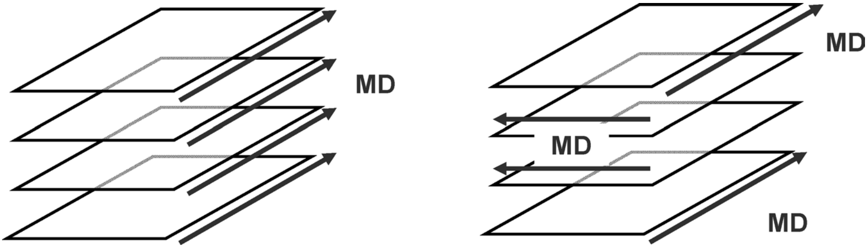

Figure 7. Schematic of the structures of the oriented sheets: (left) All plies were oriented in the same direction; (right) the centre plies were arranged perpendicular to the surface plies.

configured for symmetric drying conditions, with the hot air feeding the dryers set to 160°C. All experiments were duplicated.

An overview on the sample designation and the positions of the cuts relative to the machine direction is shown in *Figure 8*.

3.3 Evaluation

The topography of the paper surfaces was characterized with the OptiTopo, a non-contact system that provides three-dimensional images of a paper surface [9, 10]. The system takes two images of the same surface at a low angle of illumination, from left and from right, respectively. The images are combined

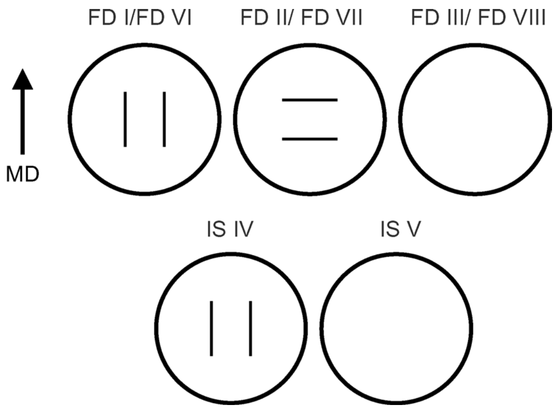

Figure 8. Sample designation and location of cuts relative to the machine direction: French dynamic laboratory sheets (above), isotropic handsheets (below).

to obtain a gradient image, from which the topography is determined. However, when using the OptiTopo, one should be aware of that only topographical features oriented approximately perpendicular to the direction of illumination become visible. Thus, the OptiTopo method performs a directional filtration of the topographical information. However, as MDM are known to cause an oriented surface structure, the OptiTopo method was adopted to detect the main changes in topography.

The OptiTopo system we used is equipped with a CCD camera with a resolution of 1024 × 1024 pixels. The sample area analyzed in the first set of experiments was 16 mm × 16 mm, corresponding to a pixel size of 15,6 µm. For the second series of experiments, we measured on 23 mm × 23 mm images, which is equivalent to a pixel size of 22,5 µm.

4 RESULTS

4.1 Generation of microstriations

The first goal of our investigation was to determine whether our pressing/drying simulator could generate surface topographies similar to those described as Machine Direction Microstriations (MDM) in industrial paper samples.

Visual inspection of samples dried in uniaxial restraint showed elongated surface roughness structures along the direction of the restraining (*Figure 9*). Digital images of these surface features could be acquired with the OptiTopo, when the illumination was positioned perpendicularly to the restraining direction (hereafter labelled "across cuts", top image in *Figure 9*).

In contrast to that, no clear surface roughness orientation was visible when the direction of illumination was rotated by 90° (hereafter labelled "along cuts", bottom image in *Figure 9*). The comparison between the two directions of illumination provided evidence of the preferred directionality of the surface roughness features, which was our first criterion for determining the presence of MDM.

A second criterion to determine that a surface roughness feature can be described as MDM was that the two surfaces of the sample are not a replica of each other. Accordingly we characterized both surfaces of a sample with the OptiTopo technique. A visual comparison of the OptiTopo gradient images and the study of their spectral description showed that the surface roughness of the two surfaces of the samples believed to be effected by MDM evolved independently of each other (e.g. *Figures 12* and *13*). Thereby our initial investigations suggested that the pressing/drying simulator could be used to generate MDM in a laboratory environment. Accordingly, we

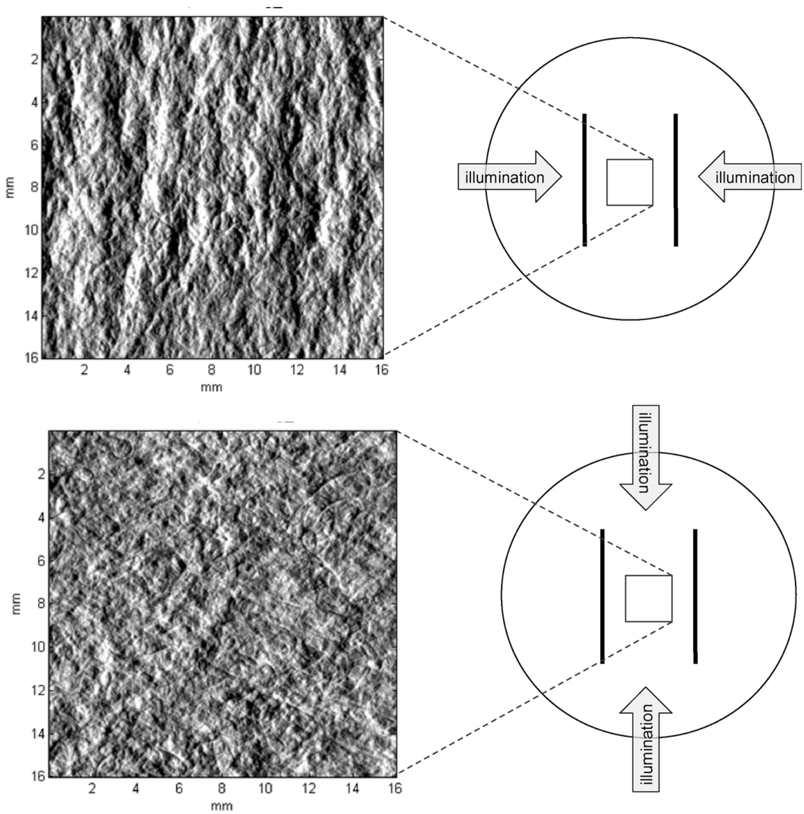

Figure 9. Example of the topography measured with two illumination directions in the OptiTopo: (above) illumination positioned perpendicularly to the restraining direction "across cuts"; (below) illumination positioned parallel to the restraining direction "along cuts". The sample was an isotropic laboratory sheet.

proceeded with experimental studies of effects of restraining conditions and of pressing and drying strategies on the surface topography of the samples.

4.2 Influence of restraining during drying

A second result of our investigation was that the restraining conditions during drying were the single most important parameter determining surface roughness in the length scale that was investigated. We pressed standard laboratory paper sheets before drying them under either (i) biaxial restrained conditions or (ii) uniaxial restrained drying.

When the web was dried in full restraint (*Figure 10*, top left), the sheet was much smoother than if the sheet was allowed to shrink in one direction (*Figure 10*, top right and bottom). In the latter case, the surface roughness was predominantly oriented in the machine direction, satisfying the first condition for determining the occurrence of MDM. However, also a considerable amount of non-oriented surface roughness could be observed, which is evident when comparing the left and right images in *Figure 10*. The differences in surface roughness were quantified in a frequency analysis (*Figure 11*).

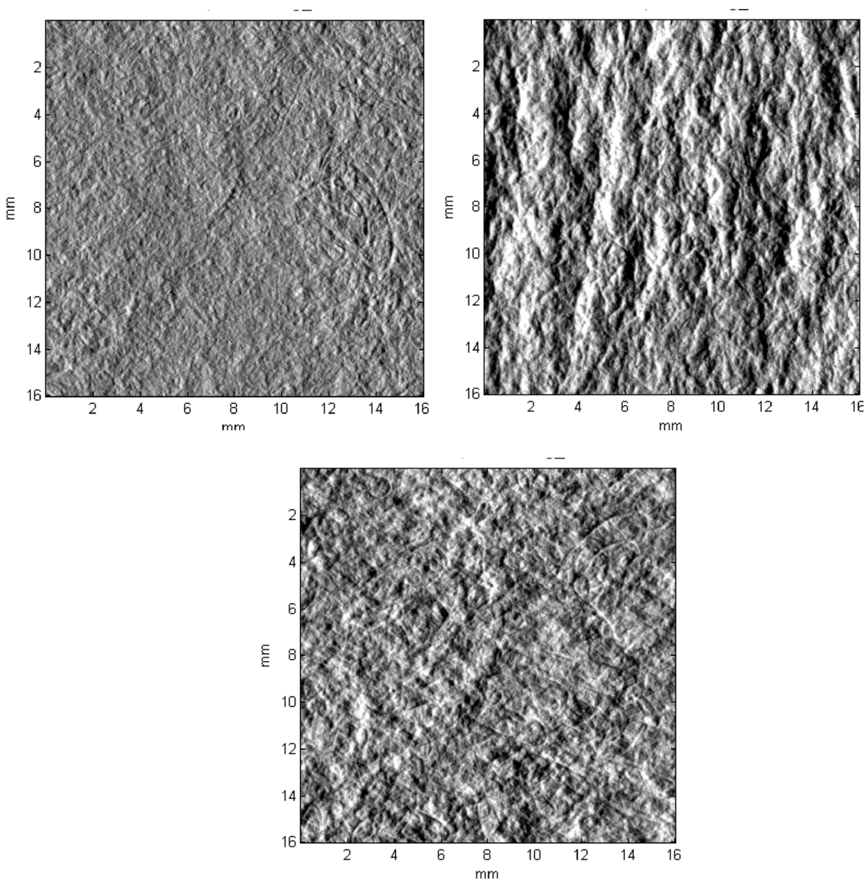

Figure 10. Influence of the restraining conditions during drying on the surface topography of an isotropic laboratory sheet: biaxial restraint (top left), uniaxial restraint with illumination across cuts (top right and bottom), and uniaxial restraint with illumination along cuts. Symmetric drying.

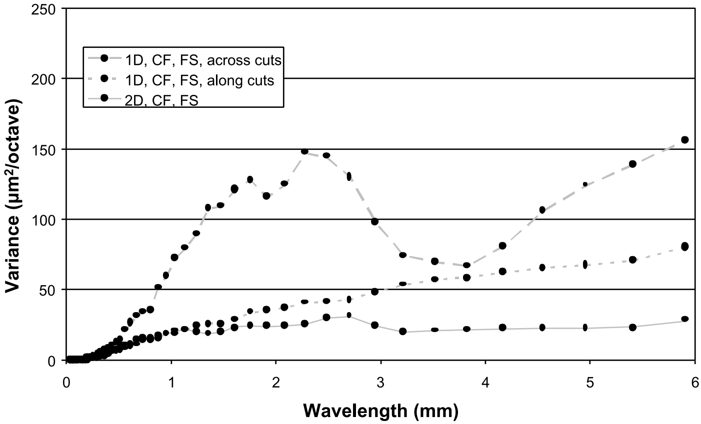

Figure 11. Wavelength spectra of the surface topography of the images in *Figure 10*. Effect of drying restraint on the surface topography of isotropic laboratory sheets: solid line = biaxial restraint (2D), broken line = uniaxial restraint (1D), illumination across cuts, dotted line = uniaxial restraint, illumination along cuts. Symmetric drying.

In the industrial papermaking process, the preferred orientation of the MDM coincides with the machine direction of the paper machine. The fibre orientation is therefore often linked with the appearance of MDM. In the present study, however, an isotropic laboratory sheet was used with no preferred fibre orientation. This led to the conclusion that one-dimensional shrinkage was the main cause for the occurrence of MDM.

4.3 Influence of press nip configuration

We studied the effect of the press felt on the surface topography after drying, by simulating a single-felted press nip with either a coarse felt or a fine felt (*Figure 12*).

Pressing with a coarse felt resulted in higher surface roughness than pressing with a fine felt. The felt surface was much rougher than the roll side of the paper, especially at smaller wavelengths. Interestingly, MDM could be clearly discerned for both felts. It appears that the batt fibres of the coarse felt contributed to the surface roughness by simply indenting their shape into the sample surface, resulting in a higher surface roughness. However, this surface roughness had a different length scale than that of the MDM. Furthermore, it should be pointed out that the spatial resolution of the OptiTopo is nearly the same as the diameter of the batt fibres of the fine felt. Thereby, although

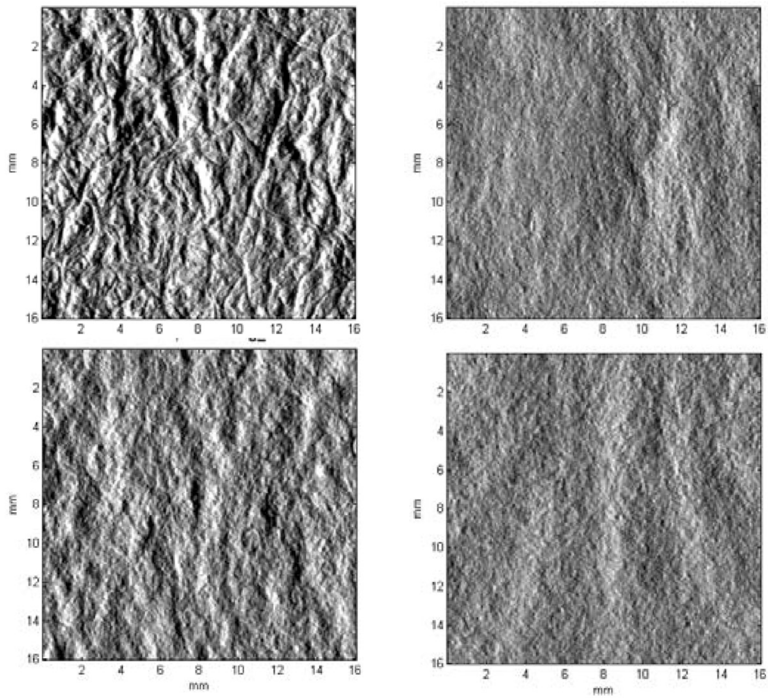

Figure 12. Influence of the single-felted press nip configuration on the surface roughness: coarse felt, felt side (top left) and smooth side (top right), and fine felt, felt side (bottom left) and smooth side (bottom right). Samples dried under uniaxial restraint, illumination across cuts, symmetric drying.

it is possible that the batt fibres of the fine felt caused similar indentations, these would not be detected with the chosen spatial resolution of the OptiTopo method.

Figure 13 presents the frequency analysis of the topography of the experimental conditions of *Figure 12*. A peak at approximately 2,5 mm is clearly discernible.

4.4 Influence of drying

The upper and lower drying systems in our pressing/drying simulator could be controlled independently of each other. We used this possibility to investigate the effects of symmetric and non-symmetric drying on the occurrence of MDM, as well as the effect of the direction of drying in the non-symmetric

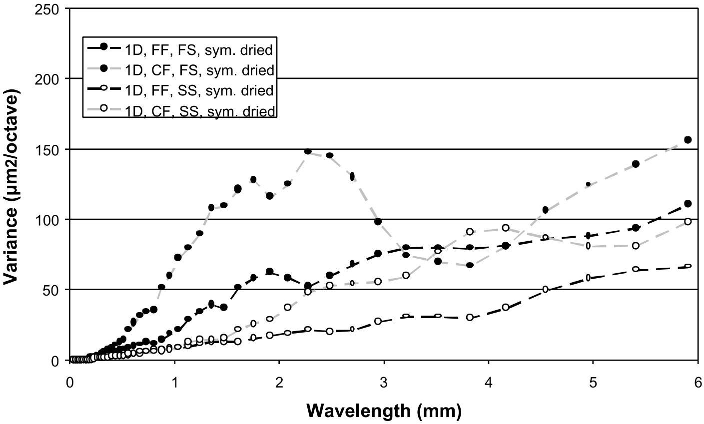

Figure 13. Analysis of the topography of the four images in Figure 12. Effect of pressing configuration on the surface topography of isotropic laboratory sheets: filled circles = felt side (FS), open circles = smooth side (SS), black line = fine felt, grey line = coarse felt. Samples dried under uniaxial restraint. Illumination across cuts. Symmetric drying.

cases. We performed the investigation for samples dried either in full restraint or with uniaxial restraint. Additionally, experiments were performed both with the fine felt and with the coarse felt.

MDM were evident in all samples after drying with uniaxial restraint, regardless of which pressing felt was used (*Figures 14* and *15*). The surface roughness on the felt side for both press felts was highly oriented and perpendicular to the direction of shrinkage. Additionally, the roughness characteristics of the felt side and smooth side of the samples differed from each other. Thereby we concluded that the surface roughness generated in our experiments could be classified as an occurrence of microstriations.

The results obtained with the two types of felt were qualitatively similar. Samples pressed with a coarse felt had higher roughness on both surfaces and somewhat more pronounced MDM on the felt side of the sample. The effect of the coarse felt, as compared with the fine felt, was evident in the wavelength range between 1 and 3 mm as well as above 4 mm.

One goal of our experiments was to test if it was possible to influence the occurrence of MDM as late as in the drying section, after generation of a material density profile by stratification in wet pressing. Accordingly, we changed the directionality of drying from symmetric to non-symmetric, supplying heat either from the felt side or the smooth side of the sample.

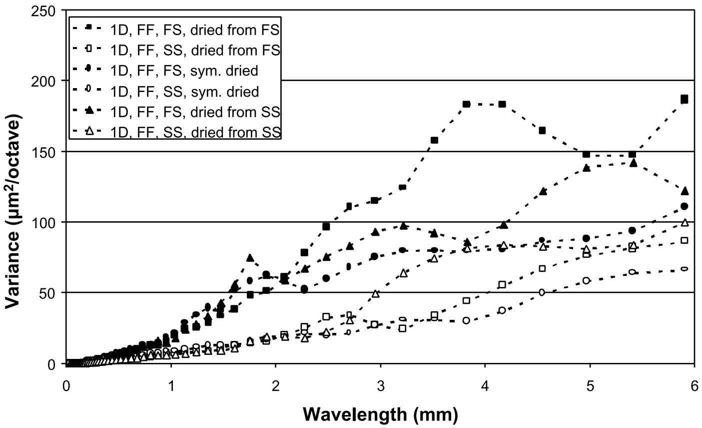

Figure 14. Influence of direction of drying for samples pressed in a single-felted nip with a fine felt (FF). Circles = symmetric drying, squares = drying from the felt side, triangles = drying from the smooth side. Filled symbols = felt side (FS), open symbols = smooth side (SS). Drying under uniaxial restraint, illumination across cuts.

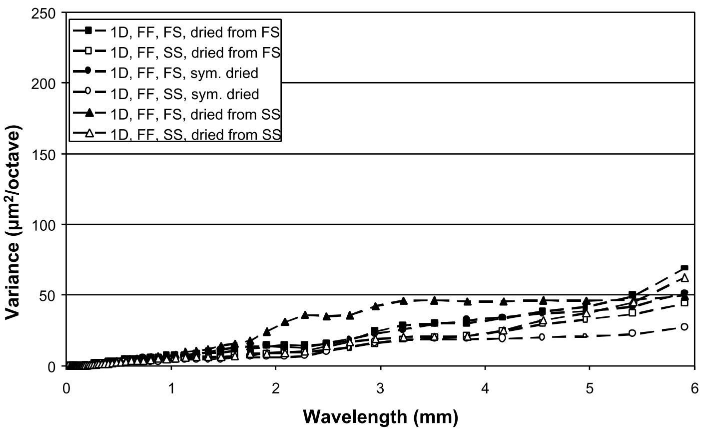

Figure 15. Influence of direction of drying for samples pressed in a single-felted nip with a fine felt (FF). Circles = symmetric drying, squares = drying from the felt side, triangles = drying from the smooth side. Filled symbols = felt side (FS), open symbols = smooth side (SS). Drying under uniaxial restraint, illumination along cuts.

Our experiments showed some effect of the directionality of drying on the surface topography of the samples. When comparing with a symmetric drying case, both MDM and surface roughness increased considerably on the felt side of samples pressed with a fine felt and dried from the felt side. On the other hand, reversing the direction of heat supply from the felt side to the smooth side reduced two-sidedness to some extent but did not decrease the roughness of the felt side surface. No additional insight into the effect of the directionality of drying after single-felted pressing could be obtained from experiments with a fine felt.

4.5 Influence of fibre orientation

In the second investigation we studied the influence of fibre orientation on the occurrence of microstriations in paper. The development of surface roughness and microstriations was characterized with the OptiTopo, taking images both with illumination parallel to the cuts and with illumination perpendicular to the cuts.

As an effect of the orientation of the cuts relatively to the fibre orientation, we could confirm the expected result that the cuts opened much more when placed in parallel with the MD (shrinkage 8%) than when placed in CD (shrinkage 4%, *Figure 16*).

Visual inspection of the samples after drying and characterization with the OptiTopo showed oriented surface topography features, which we classified as MDM (*Figures 18* and *19*). Additionally, we observed that the orientation

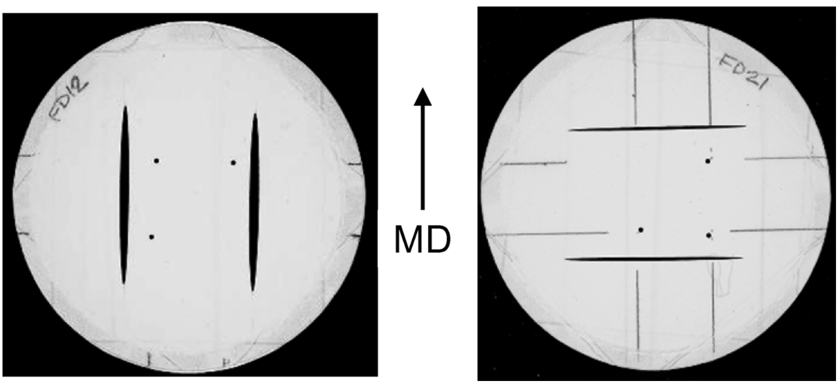

Figure 16. Influence of fibre orientation on the amount of shrinkage during drying: cuts along machine direction (left, "FD I") and cuts across machine direction (right, "FD II").

of microstriations was parallel to the direction of restraint, i.e. MD in samples with cuts placed in MD and CD in samples with cuts placed in CD. This finding confirmed our earlier results that the restraining conditions are the main parameter influencing MDM.

A second interesting result of this comparison was that microstriations were more evident on the samples with cuts in CD, in spite of the fact that the samples with cuts in MD had a much larger amount of shrinkage. If MDM are described as local micro-buckling phenomena of the paper structure, which was originally suggested in [1], this observation agrees with the observed behaviour of oriented paper sheets upon compression in MD and CD. In fact, strain-to-failure in compression in an oriented paper web is always larger in CD than the corresponding parameter in MD for non-isotropic paper sheets [11]. Indeed the CD to MD ratio for the strain to

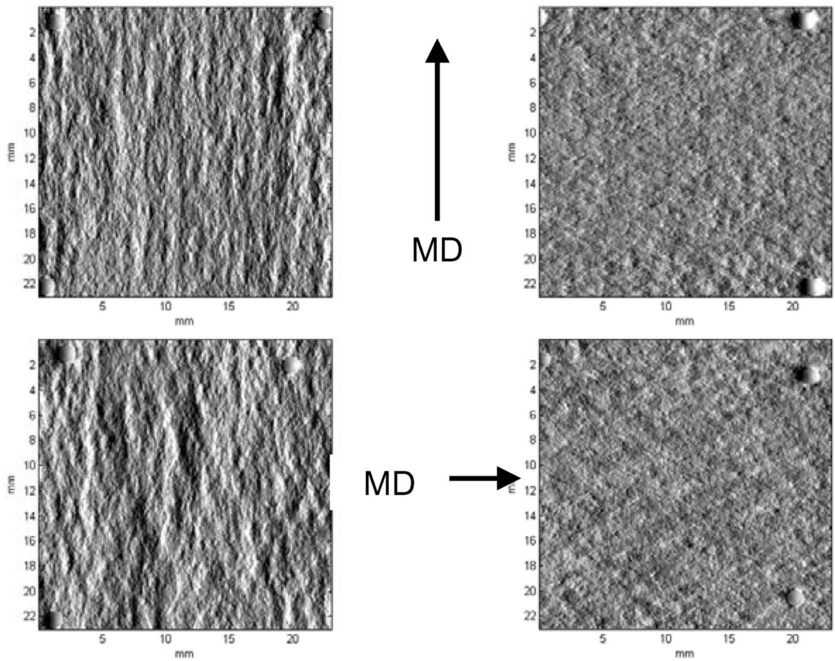

Figure 17. Influence of fibre orientation on the obtained surface roughness: cuts along machine direction (upper row, "FD I") with illumination across cuts (left) and illumination along cuts (right), and cuts across machine direction (lower row, "FD II") with illumination across cuts (left) and illumination along cuts (right). Single-felted press nip with fine felt, drying under uniaxial restraint.

failure can be as high as 2,5 for a French dynamic sheet with anisotropy of 3,3. Therefore, it is conceivable that local buckling of the structure which generates MDM would be more severe upon shrinkage in MD than when loading in CD, even if the compressive strain is more limited.

We compared the surface topography of oriented samples with cuts placed in CD with the topography obtained from isotropic samples prepared from the same pulp mixture (*Figure 19*). The comparison showed that the surface characteristics were very similar for these two cases, in spite of the significant difference in fibre orientation.

Interestingly, the surface roughness for the isotropic sheet is worse than that of the oriented sheet with the cuts along the orientation of the fibres. This allows the conclusion that an increased fibre orientation actually can lead to a reduction in respect to the generation of MDM.

Multi-ply structures are used in the practice of papermaking to optimize the performance of the final product with respect to the use of raw materials, e.g. in multi-ply paperboard. The furnish and properties of the plies in commercial products can vary significantly across the thickness direction of the paper. We have prepared an extreme model structure by couching together four French dynamic sheets as illustrated in *Figure 7* (right): the main direction of fibre orientation of the two centre plies was rotated by 90° with respect to the fibre orientation of the two surface plies. We used these samples

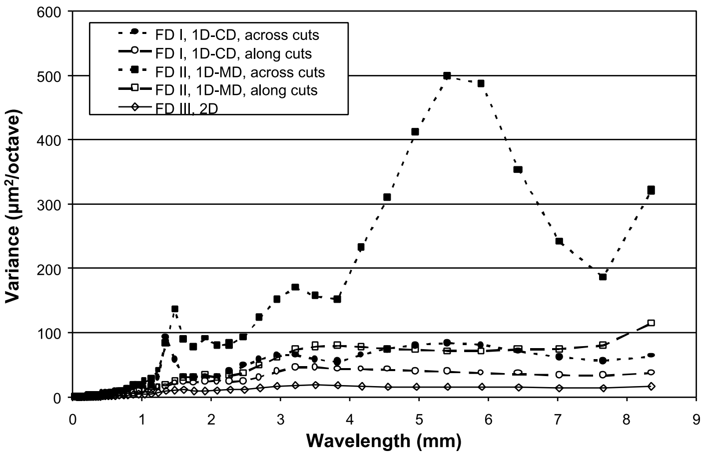

Figure 18. Influence of the fibre orientation on the topography: "1D-XD" = uniaxial restraint during drying, shrinkage allowed in XD. "2D" = biaxial restraint during drying. "across cuts" = illumination perpendicular to the cuts, "along cuts" = the illumination parallel to the cuts.

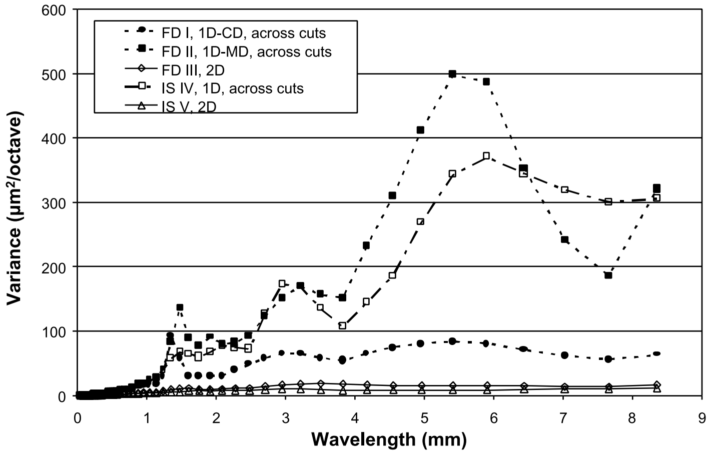

Figure 19. Influence of the shrinkage conditions for oriented (FD) and isotropic (IS) sheets. "1D-XD" = uniaxial restraint during drying, shrinkage allowed in XD. "2D" = biaxial restraint during drying. "across cuts" = illumination perpendicular to the cuts, "along cuts" = illumination parallel to the cuts.

to repeat the experiment illustrated in *Figure 18*. The measurements confirmed the results obtained for samples with uniform fibre orientation distribution, although the effects were more limited. With respect to the orientation of the surface plies, allowing shrinkage in MD resulted in more evident microstriations than allowing shrinkage in CD.

5 CONCLUSIONS

This paper described a laboratory-scale experimental study of machine direction microstriations (MDM) on paper and board surfaces. We designed a wet pressing and drying simulator in which we could replicate some of the phenomena which are believed to be the origin of MDM: stratification in pressing as well as in-plane restraining conditions in drying.

In absence of a generally accepted quantitative definition of MDM, we set two criteria for stating that a sample presented MDM: (i) the occurrence of ridges and valleys elongated in MD, with a characteristic wavelength (in CD) in the range 1–4 mm; (ii) the topography of one surface of the sample shall be generated independently of that on the other surface.

The first result of our investigation was that we could generate MDM, by selecting appropriate pressing and drying conditions. We characterized paper

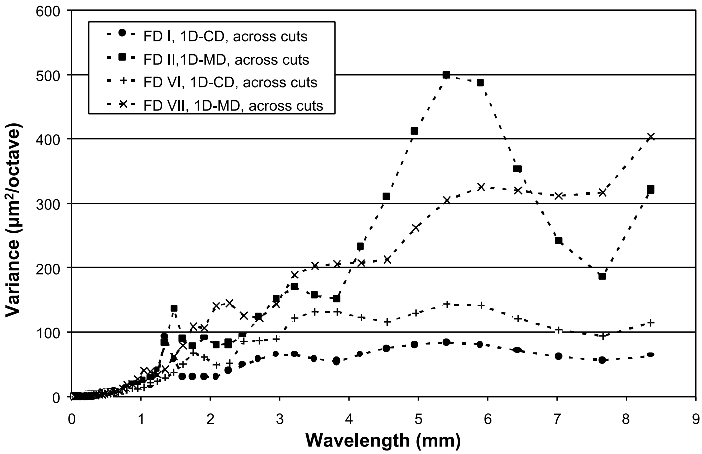

Figure 20. Influence of fibre orientation profile on MDM and surface roughness; FD I and FD II had uniform fibre orientation, FD VI and VII had a non-uniform fibre orientation where the fibres in the middle of the sheet were oriented perpendicular to the fibres at the surface. "1D-XD" = uniaxial restraint during drying, shrinkage allowed in XD. Illumination perpendicular to the cuts.

samples with the OptiTopo, a topography measurement system that provides three-dimensional images of a paper surface. When the variance of the surface topography was plotted as a wavelength spectrum, MDM appeared in the wavelength range between 1 and 4 mm, often with a peak at approximately 2 mm. It could be speculated that the presence of the 2 mm peak could be linked to fibre length, so that surface buckling by MDM might be related to a characteristic length of a structural elements in the paper web. Future investigations with varying furnish could provide additional insights in this matter.

In a first series of experiments we characterized the effects of restraint during drying, pressing strategy and directionality of the drying operation on the generation of MDM. The restraining conditions in the dryer were the most important process parameter in respect to influencing surface roughness. Complete restraining of the sample during drying resulted in a relatively smooth paper surface. A considerable amount of surface roughness was generated, as soon as one of the directions of the paper sheet was allowed to shrink during drying.

In our study of the effects of wet pressing, we could reproduce the industrial observation that MDM appear on the press felt side of the paper. Additionally, when we compared a felt with fine batt fibres with a felt with coarser batt fibres, we observed that the surface structures generated by the latter were more severe.

We investigated whether we could influence which side of the paper would be affected by MDM by changing the directionality of drying. We compared symmetric drying with non-symmetric conditions, where heat was supplied either from the felt side or from the smooth side of the sample. In our experiments all samples presented MDM on the felt side of the paper regardless of the directionality of drying. This occurrence might be correlated with the fact that we used one single press pulse to increase dryness from 18% to 39%, which might result in unrealistic levels of stratification upon pressing. Also, although we simulated single-sided drying by supplying heat to the wet paper from one surface only, our equipment could not prevent evaporation from the opposite surface. Accordingly, future investigations shall focus on clarifying the role of drying on the generation of MDM.

In a second series of experiments we studied the effects of fibre orientation on the generation of MDM and surface roughness. Here we allowed French dynamic samples to shrink upon drying in either MD or CD. In spite of the fact that samples presented a larger degree of shrinkage in CD than in MD, the surface features generated upon drying were more prominent when shrinkage was allowed in MD. The fibre orientation on the middle portions of a multi-ply structure had some influence on the behaviour of the surface. With respect to the orientation of the surface plies, allowing shrinkage in MD resulted in more evident microstriations than allowing shrinkage in CD.

6 ACKNOWLEDGEMENTS

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Transcription of Discussion

A LABORATORY INVESTIGATION ON THE ORIGIN OF MACHINE DIRECTION MICROSTRIATIONS

Marco F.C. Lucisano and *Hannes Vomhoff*

Innventia AB – Box 5604 – SE-11486 Stockholm, Sweden

Torbjörn Wahlström Stora Enso

I do not know if I understood correctly. You created this roughness on one side of the paper and you dried different amounts from both sides of the paper, but did you show that you could move the roughness from one side to the other? It is well known in board production that by drying more or less from one of the sides of the paper you can change the side where the roughness will appear.

Marco Lucisano

We did try to do that experiment and this is the result. We could influence the extent of machine direction microstriations (MDM) on the side that was affected by MDM, but we did not manage to move them to the opposite side of the paper. This could be because of the fact that in our simulator, when we do supply heat from one side, we are still allowing evaporation from both sides. So we do not strictly control the direction of evaporation – so it could be a limitation in our experimental setup.

Torbjörn Wahlström

But evaporation happens from both sides, also in real production.

Marco Lucisano

Yes, it does.

Discussion

Torbjörn Wahlström

You showed a model for how this roughening is created. Was this based on your own direct observations, or taken from the literature (Figure 3 in the paper in the proceedings, ed.)?

Marco Lucisano

This is essentially what has been described in the literature 20 years ago and it is something that looks reasonable.

Torbjörn Wahlström

Actually, I have been thinking the other way around, that you have a rough surface on both sides and when they shrink, the final shrinkage is happening to the right there. The surface is then in a partially restrained state and thereby gets more smooth. That is just another way to see it, but it would be interesting if you could make direct observations.

Marco Lucisano

Yes. One thing that we cannot do right now, but we are planning to investigate if it is possible, is that we are not able to look at the surface during the time of drying. It would be very interesting to be able to do that. For the time being, the apparatus is closed for the entire duration of the drying stage, and it is not designed to be interrupted at different stages. So for the time being, we cannot do it, but it would be very interesting.

Torbjörn Wahlström

Yes, I also must comment that I do not like this term "machine direction microstriation". I would prefer something like "shrinkage-induced roughness" – why do we suddenly have a new term for roughness.

Marco Lucisano

We have it since '89, so we decided to keep it. There is a good term in Swedish "krynk", but I don't think there is one in English.

Torbjörn Wahlström

With "krynk" you are referring to a severe ditch type of surface roughness, I suppose. I have also been studying this special type of surface roughness and found that it appears when the paper is shrinking and is very deep ditches appearing more often in heavier weight board grades. In a laboratory study, I found that you do not really need drying against a surface to get that severe roughness effect, meaning it is not necessarily gradient dependent. We also found that it was appearing where there were sharp gradients in basis weight. Have you tried any matching towards the basis weight map?

Marco Lucisano

Yes, we have tried some matching, but we could not find any good correlation. Or actually, to put it correctly, we could find some correlation in some specific cases and then it completely disappeared in others. So we took away that part of the work because we could not make sense of it. So it appears to be the case sometimes and in some our experiments not at all.

Torbjörn Wahlström

Okay! Thank you.

Ilya Vadeiko FPInnovations

So if I understood correctly, in all your experiments, you felted only one side of the paper, and that was the side where you observed the striations, is that correct?

Marco Lucisano

Yes, basically it was stronger on one side of the paper, yes.

Ilya Vadeiko

Then coming back to the beginning of your presentation where you showed the image of felt and used it to discard the idea that the felt could have any effect on the striations. I just wanted to make a comment that if you take an impression of the felt at much higher load, you see clear pattern of the felt base.

Marco Lucisano

Yes.

Discussion

Ilya Vadeiko

And I do not want to make the point that there is a mechanical indentation from the felt base on the paper surface, but there is an open question where the wavelength that you observed in the striation is coming from and it could be related to the wavelength of the felt base.

Marco Lucisano

We have actually looked at that issue as well and in some of our experiments if we were a little bit too violent with pressing, we did see indentations of the deeper structure of the felt, not the surface structure of the felt and thus your comment is perfectly correct. The structure that you see here on your left hand side is the surface structure of the felt, and if we were to press to a much higher load, then you would observe even a deeper structures appearing, so.

Ilya Vadeiko

Yes, but I am not talking about the mechanical indentation on paper surface, I am saying that maybe the felt base has an effect on the pattern of fibre contacts and that could have relation to the actual appearance of indentation depending on the drying conditions. Do you agree on that?

Marco Lucisano

It could, yes.

Steve I'Anson University of Manchester

I used to work for Scapa and we were often being told that this was due to the felt base cloth for exactly the reasons that have just been described, and so we used Fourier transform image analysis to look at these surfaces illuminated in this way. I also looked at the frequencies that would have come from the felt base cloth. There is absolutely no relationship whatsoever. This has got nothing to do with the felt base cloth. It is not slightly hidden, those frequencies just aren't there in this pattern, so I think you can happily discount that one.

William Sampson University of Manchester (from the chair)

Qualitatively these structures, although they are of different wavelengths, do not look unlike what Pasi Lipponen was showing us this morning. So do you think that this is one phenomenon occurring at different scales?

Marco Lucisano

I do not know. It would be intriguing if you could have a general theory of out-of-plane deformation of everything. But, essentially, it is the same driving force that manifests itself with different wavelengths and different deformations.

Jean-Claude Roux University of Grenoble

We can certainly make a parallel with the paper from this morning. If you remember one of my comments, I took the example of drying occurring at different locations on the cross-machine direction and when this occurs, we describe exactly what you presented, which I believe is excellent. So in that case, we can generate cockling effects. I saw that in the industry and when this occurs in the thickness of the sheet of paper, you generate this MDM. So probably, and I do not know if this is your research into the future, we can make a global theory which can describe all these out-of-plane and in-thickness phenomena.

Ramin Farnood University of Toronto

Thank you for your interesting talk. I just have a quick question and that is, did you have a chance to look at moisture non-uniformity in your mill trials, specifically, using infrared imaging; and if so, did you see any correlation with MDM?

Marco Lucisano

I cannot answer, unfortunately, meaning probably yes.