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ON THE RELATIONSHIP BETWEEN CURL AND COCKLING

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ABSTRACT

The paper concerns itself with the effect of pre-curl (induced curvature during the wet state) on cockling when paper is dried. Laboratory experiments are carried out on copy paper to identify this interplay between induced curvature and cockling. Using the uniform wave-like deformation that occurs during the intermediate stage of drying in narrow paper strips as a proxy for the extent of cockling, it is demonstrated that increased pre-curl in MD, alleviates cockling. In addition, under two contrasting drying boundary conditions of free drying on a flat table and hang drying without weights, it is seen that free drying induces more cockles than hang drying. As a corroboration of the experimental observations, numerical experiments are carried out on flat (varying tensile loads) and curved specimens (varying radii), using moisture-induced deformations together with an orthotropic elastic material model. Using the Hausdorff distance metric to compare the deformed and undeformed geometries, it is shown that, both pre-curl in MD and tensile loading in CD, alleviate cockling. The results of these experiments could be useful for after-market applications of paper, like printing, where pre-curl could be induced mechanically to reduce or prevent cockling.

1 INTRODUCTION

Curl and cockles are among the main dimensional stability issue of paper. The origin of curl has been attributed to a number of factors among which the inhomogeneous fibre orientation (REF) and drying non-uniformities (REF). A common occurrence is a curl in the cross-machine direction due to changes in relative humidity [1, 2, 3]. Cockles are described as a series of out-of-plane deformation in the sheet due to strain non-uniformity induced by moisture change. From a mechanical perspective, cockling has also been considered as local buckling, driven by drying rate as an applied force with the local basis weight distribution and fibre orientation impacting the cockle shape and distribution. Numerical simulations have been used to understand the effect of these parameters on the cockling phenomenon [4, 5, 6].

An interesting, yet relatively unexplored, aspect of moisture-induced dimensional instability is the relationship between curl and cockling. In this work, an attempt is made to understand the influence of curl on cockle through evaluating during drying under different conditions – cockle formation on cylinders of varying curvatures. The primary hypothesis is that the initial phase of cockling is driven by geometric stiffness and not by local inhomogeneities. To this end, the behaviour of paper samples during room temperature drying from wet to dry state and hot air drying from 5% moisture content to 1% moisture content under different drying boundary conditions is studied. Subsequently, numerical experiments have been conducted to verify the results observed during the experiments.

2 METHODS

The laboratory experiments consist of experiments with paper strips of three different dimensions of which the first two will be referred to as narrow strips (15 mm × 200 mm and 60 mm × 120 mm) and the third as wide strips (180 mm × 110 mm).

2.1 Experiments with Narrow Strips

Rectangular strips of two different sizes (15 mm × 200 mm and 60 mm × 120 mm) are cut from 75 gsm copy paper in the MD, CD and 45-degree direction. Two cylinders of diameters 35 mm and 150 mm are used to introduce pre-curl of different curvatures to the samples. In the first series of tests, samples are wetted and dried under three dissimilar conditions: (i) on two cylinders of different diameters, (ii) on a flat table and (iii) drying in the air by hanging (without a weight). In another set of experiments, hot air drying from room temperature conditions (5% moisture content) to less than 1% moisture content is carried out on a flat table and cylinder. In order to maintain the curvature during drying, the paper strip is made to hold its shape (while being free to move) by strips of paper that are not in contact with the test sample (Figure 8d).

There are two distinct stages observed during drying. In the first stage, uniform and even cockling is observed, driven by local buckling, and subsequently inhomogeneous deformation. The number of cockles is counted during the first stage of drying.

2.2 Experiments with Wide Strips

The narrower strips used in experiments as described in the previous section are convenient for comparing cockling propensities by evaluating waviness. This waviness is not what is typically referred to as cockling and it does not appear in a sample with a smaller aspect ratio. Instead, cockling manifests itself as sporadic distortion without a distinct wavelength. An additional set of experiments were carried out wherein a wide strip of paper of dimensions 180 mm × 110 mm are dried under three separate conditions: (i) Drying on a flat surface, (ii) Drying on a cylinder (Figure 1) and (iii) Drying on circular edge supports (Figure 2). The idea

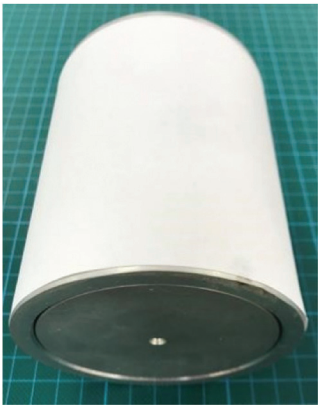


Figure 1. Drying of wide strips on a metal cylinder of diameter 95 mm.

(a) (b)

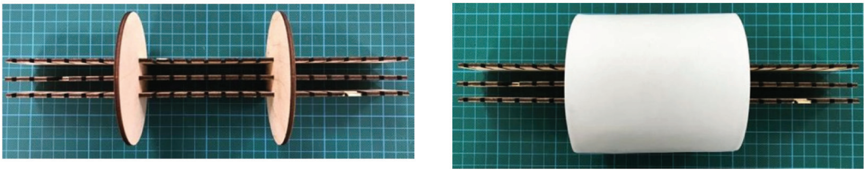


Figure 2. Drying setup to avoid adhesive force from a steel cylinder (a) Fixture (b) Drying.

Table 1. Summary of the cases for laboratory experiments

Case Number	*Sample type*	*Dimensions* [mm]	*Drying type*	*Boundary conditions*
E1	Narrow strip	15 × 200 60 × 120	Free drying at room temperature	On cylinders On flat table Hanging without weight
E2	Narrow strip	60 × 120	Hot air drying at room temperature	On cylinders On flat table
E3	Wide strip	180 × 110	Free drying at room temperature	On cylinders On flat table On circular edge supports

behind performing this test is to exclude the adhesive forces as a contributing factor and to see if the effect of curvature extends to the sporadic cockling.

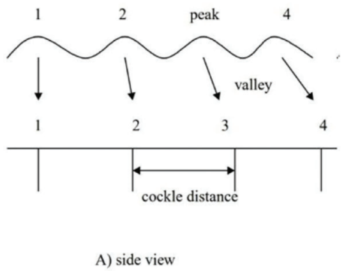
The cases considered in the laboratory experiments are summarised in Table 1.

2.3 Counting of Cockles

In literature, cockles are defined as the non-uniform and randomly distributed local deformations noticeable when the paper has dried. From an experimental point of view, making a numerical estimate of this non-uniform distribution is difficult. When a narrow strip of paper is wetted, it is observed that the moisture-induced deformations manifest themselves as uniform wave-like deformations at an intermediate stage of drying before going on to becoming non-uniform and random distributed local deformations. In the set of experiments which are carried out in this paper, the counting of cockles is based on counting the number of waves (peaks) in this intermediate stage where this uniform wave-like deformation is noticeable. The method of counting was introduced by Paik et. al. [7], and a representation of this counting is shown in Figure 3. In general, it has been observed that an increase in the number of waves in the intermediate stage of drying corresponds to an increase in the random local deformations in the fully dried state. It must be noted that this wave-like pattern is observable only on narrow strips of dimensions 15 mm × 200 mm and thus all counting of cockles in experiments is restricted to this specimen size only. While the extent of non-uniform random deformation is comparable between the narrow and wider strips, the wider strips do not exhibit uniform deformation during the intermediate stage thus precluding counting of cockles.

Drying temperature and drying rate have a definite effect on the observed number of cockles, and it has been shown previously by Paik et. al. [7] that number of cockles increases with an increase in drying rate. We do not focus on "temperature" as a parameter in this work.

(a)



(b)

Figure 3. (a) Top view of uniform wave-like deformation at an intermediate stage in drying and (b) Schematic representation of the counting of cockles [7].

2.4 Numerical Experiments

We used a non-linear finite element analysis to reproduce the conditions necessary to induce cockling. Numerical simulations enable accurate evaluation of the cockling amplitudes under well-controlled and repeatable conditions. The methodology of inducing cockling is based on the work presented in [8] which assumes the existence of hygroexpansion variations during the drying process modelled, in this case, as moisture variations. It is important to note that similar hygroexpansion variations can also be modelled through varying hygroexpansion coefficient. The geometry of the considered flat sample is shown in Figure 4.

Due to assumed symmetry, only a quarter of the web was considered. The paper was modelled with an elastic, orthotropic, moisture-dependent material, and 4-node fully integrated shell elements. The element size was 1.7 mm × 1.7 mm and was selected to ensure mesh convergence. The material properties were adapted from [9] with E-moduli in the MD and CD as a function of moisture shown in Figure 5.

The in-plane Poisson's ratio ν_{12} and shear modulus G_{12} were calculated using the following approximations [10] at given moisture.

$$\nu_{12} = 0.293.\frac{E_1}{E_2} \tag{1}$$

$$G_{12} = \frac{1}{\frac{1+\nu_{12}}{E_1} + \frac{1+\nu_{21}}{E_2}} \tag{2}$$

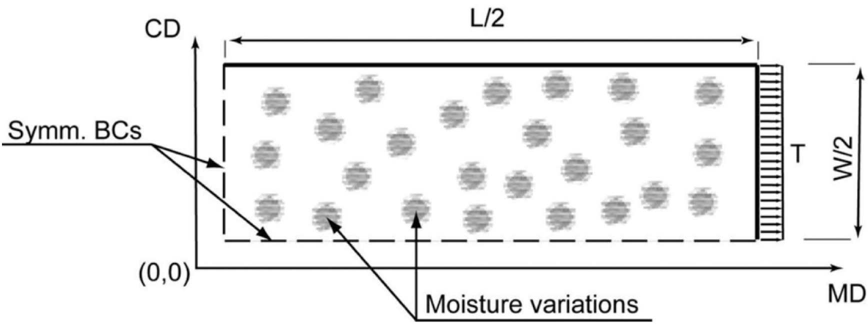


Figure 4. A quarter of the sample with randomly distributed moisture variation spots (MD orientation case, L = 30 cm, W = 10 cm, the diameter of the moisture variation sport is 6 mm, the thickness of paper t = 44 microns).

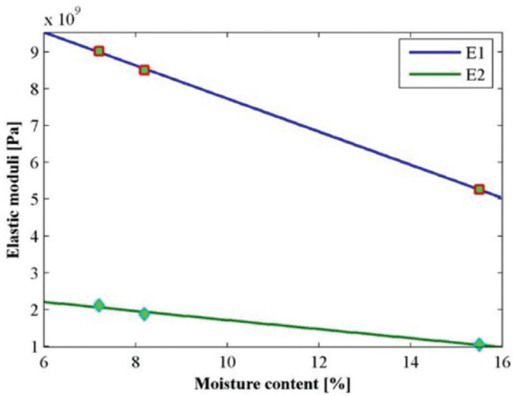


Figure 5. Elastic constants versus moisture content (E1 is in the MD and E2 in the CD).

The hygroexpansion coefficient with respect to the change in moisture content expressed in per cent in the MD and CD were assigned to $\alpha_1 = 0.05 \cdot 10^{-2}$ and $\alpha_2 = 0.15 \cdot 10^{-2}$ respectively. The local moisture variations were modelled by introducing randomly distributed rounded spots having a diameter of 6 mm with a given moisture difference of 0.8 per cent. The spots covered 40% of the paper surface.

Two main cases are considered in the numerical experiments: (i) Flat geometry with tension and (ii) Curved arc geometry without tension. In order to model the curved geometry with varying curvatures, a strip of constant length is mapped into a curved configuration of varying radii of curvature. For the case of curved

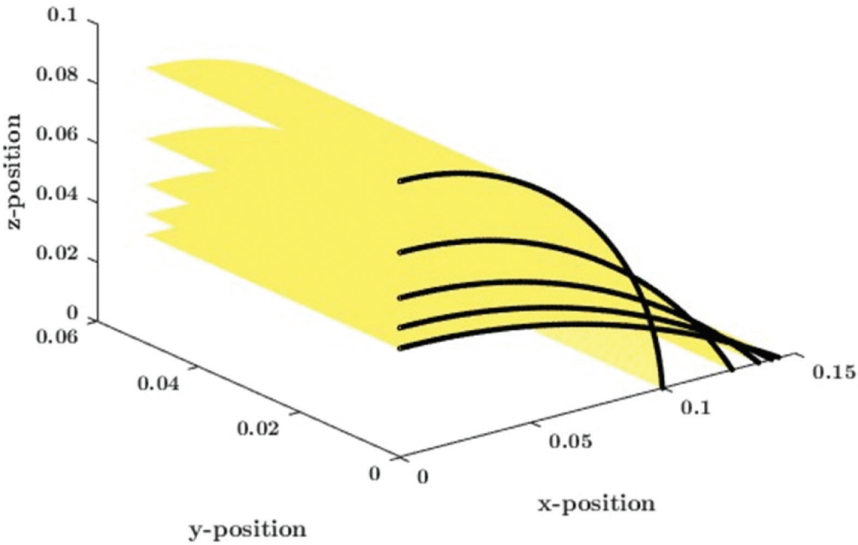


Figure 6. Curved surfaces of varying radii used to introduce pre-curl in MD and CD.

Table 2. Summary of considered cases

Case number	*Geometry*	*Orientation*	*Tension* [N/m]	*Radius* [mm]
N1	Flat	MD, CD	5, 55, 105, 155, 205	
N2	Curved	MD, CD	–	10, 15, 20, 25, 30

geometry five different radii are considered (shown in Figure 6) and for the case of flat geometries, five different values of nominal tension are simulated. For both cases, simulations are carried out in both CD and MD. The cases are summarized in Table 2.

In order to quantify the extent of cockling observed during the numerical experiments, the "Hausdorff Distance" metric is used. In image analysis, this metric is often used to measure the degree of resemblance between two objects (images) and the smaller the distance metric, the closer is the resemblance of the two objects [11]. For our case, we are interested in comparing the deformed configuration after moisture-induced deformations resulting in fluting and cockling with the original undeformed configurations (flat and curved). Thus, we expect the Hausdorff distance to provide an objective measure of the extent of deformation that is induced in the various numerical experiments that are considered here. A comparatively smaller value of the Hausdorff distance would indicate a closer resemblance of the deformed geometry to the undeformed geometry and thus a lesser extent of cockling.

The deformed and undeformed geometries are specified by the respective node sets and their spatial coordinates. Considering the spatial co-ordinates (or point sets) of the two geometries, let $\{p_{,1}, p_2, p_3, \ldots p_n\}$ be the set of points on the undeformed surface S and $\{q_1, q_2, q_3, \ldots q_n\}$ be the set of points on the deformed surface S', the Hausdorff distance is defined as $H(S, S') = \max\,(h(S, S'), h(S', S))$ where $h(S, S)') = {}^{\max}{}_{p \in S\, q}{}^{\min}{}_{\in S'} \parallel p - q \parallel$ and $\|p - q\|$ is the underlying distance norm (in our case, the standard Euclidean distance). In essence, the minimum of the distances between a point in S and every point in S' is computed. This is done for every point in S and subsequently, the maximum of the set of these minimum values is computed. This process is repeated for S' to S. The maximum of the two maximum values is then the Hausdorff distance.

3 RESULTS

3.1 Experiments with Narrow Strips

Twenty samples were considered for each orientation and drying condition in all the tests. The drying setup on cylinders of different diameters is shown in Figure 7.

3.1.1 Effect of Pre-curl on Cockle

The results in terms of the average number of cockles (Case E1), as counted during the first stage of drying, are tabulated in Table 3. The cockles appearing at the first stage of drying and the appearance of the strip at the end of drying is shown in Figure 8a. The effect of pre-curl is evident in the reduced number of cockles for the case of the smallest cylinder diameter as opposed to flat table drying. It was also observed that the strips of dimensions 15 mm × 200 mm are

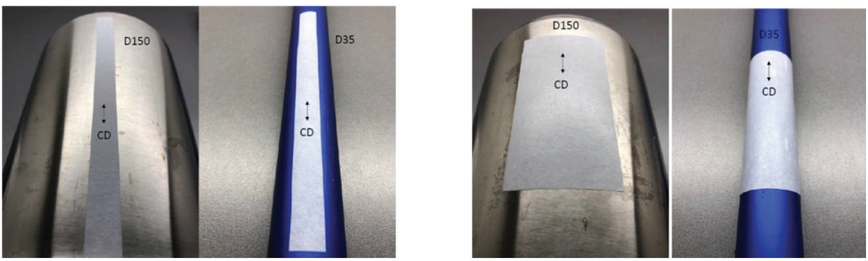


Figure 7. Drying on cylinders with two different diameters (a) Sample size 15 mm by 200 mm (b) Sample size 60 mm by 120 mm.

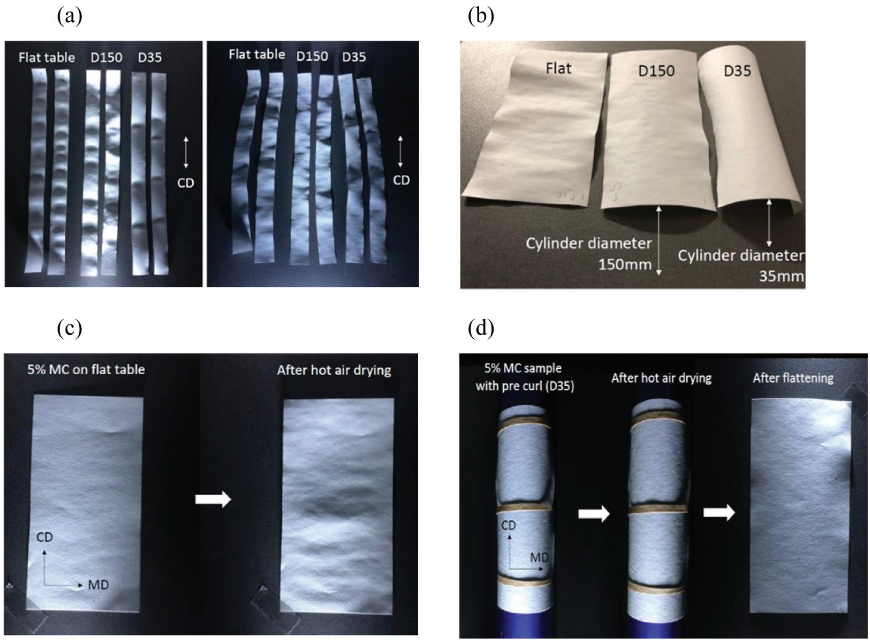


Figure 8. (a) Uniform first cockles and final shape at the end of drying; (b) Absence of cockles on a wider strip with increased curvature. Hot air drying on (c) at table; (d) cylinder with pre-curl

Table 3. Average number of cockles in the CD oriented samples depending on the degree of curvature of the pre-curl for narrow strips of dimensions 15 mm × 200 mm. Note: D150 and D35 denote cylinders of diameter 150 mm and 35 mm, respectively.

Case Number	*Drying*	*Boundary condition*	*Number of cockles* (Mean ± Standard Deviation)
E1		On flat table	10 ± 1.56
E1	Free drying at room temperature	On cylinder (D150)	6.1 ± 1.21
E1		On cylinder (D35)	3.7 ± 0.92

unable to maintain the given curvature during the entire drying process, and thus 60 mm × 120 mm strips were also trialled. As is shown in Figure 8b, no cockling is observed for the sample with the highest pre-curl as compared to the sample dried on a flat table. Hot air drying (Case E2) of the narrow strips of dimensions 60 mm × 120 mm showed similar results (Figure 8c and Figure 8d).

3.1.2 Effect of Drying Boundary Conditions and Fibre Orientation on Cockle

The results for two different drying conditions – flat table and hang drying – are tabulated in Table 4. Samples that are hang dried (Figure 9), owing to the gravity effect [12], showed a fewer number of cockles as opposed to the samples that were dried flat. Cockling occurs due to local shrinkage and expansion of the paper network and the shrinkage force is in turn related to the fibre orientation. This is apparent in Figure 9 where the cockle shape follows the fibre orientation with the 45-degree samples having the peaks and troughs of the waves being oriented along the fibre direction.

Table 4. Average number of cockles observed during drying on a flat table and hang drying for narrow strips of dimensions 15 mm × 200 mm.

Case Number	*Drying*	*Boundary condition*	*Number of cockles* (Mean ± Standard Deviation)		
			MD	CD	45
E1	Free drying at room temperature	On flat table	3.8 ± 0.41	10.3 ± 1.89	7.9 ± 0.97
E1		Hanging without weight	1.9 ± 0.72	4.9 ± 1.02	3.8 ± 1.15

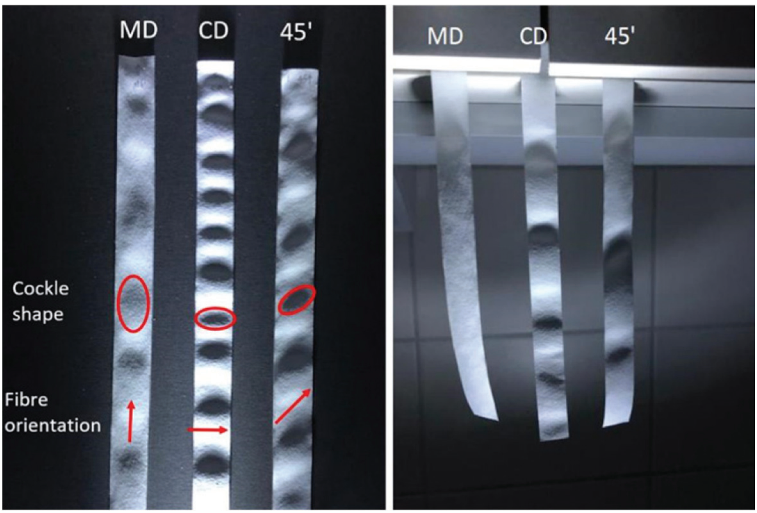


Figure 9. Cockle shape on samples from table drying (left) and hang drying (right).

3.2 Numerical Experiments and Experiments with Wide Strips

The first set of simulation results represents flat samples (Case N1) under tension. Figure 10 shows the deformed state of paper with a small tension (needed to achieve numerical stability). It is apparent that the condition for creating sporadic cockling was achieved with a tension of 5 N/m in MD. Increasing tension to 105 N/m in MD transformed cockling to fluting, which was previously reported in [8]. Maintaining a tension of 105 N/m in CD, however, showed the least distortion and we attribute this to the effect of stress-stiffening in the CD direction, in other words, the increase of bending resistance due to applied tension. In Figure 11, the Hausdorff distance metric, calculated between the undeformed and deformed geometries plotted against varying levels of tensile loading, is presented.

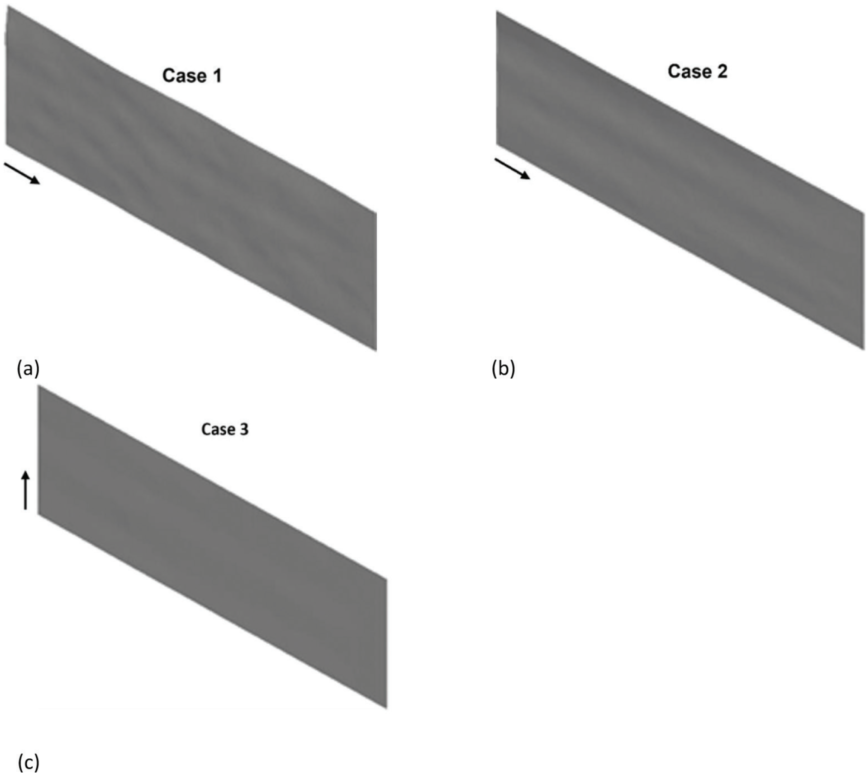


Figure 10. Deformed configuration geometries of the specimens from numerical experiments. The arrows indicate the machine direction. (a) MD orientation with 5 N/m tension, (b) MD orientation with 105 N/m tension and (c) CD orientation with 105 N/m tension.

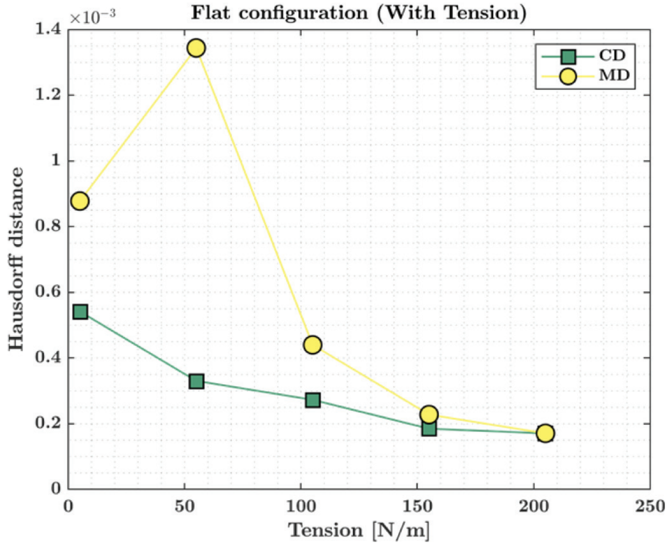


Figure 11. Hausdorff distance metric calculated between the undeformed and deformed configurations for the flat geometry at varying tensile loads in CD and MD.

Two distinct observations are made: i) As mentioned above, at a tensile load of 105 N/m, there is a transition from cockling to fluting which is represented by the increased dissimilarity between the undeformed and deformed geometries oriented in MD and ii) Tensile loading in CD alleviates cockling. The complete set of undeformed and deformed geometries for Case N1 is presented in Figure 16 Appendix 6.1.

Figure 12 shows the deformed state of paper for the curved geometries with the pre-curl in CD and MD (Figure 12a Figure 12b). A similar stiffening effect can be achieved through changing geometrical shapes when curvature is introduced into the paper. The corresponding results from experiments with wide strips are presented in Figure 12c and Figure 12d. The case of pre-curl oriented in MD shows the least out-of-plane distortion which is attributed to geometrical stiffening due to the presence of curvature. The experiments with wide strips showed similar behaviour. On the top edge of Figure 12c, which corresponds to pre-curl in CD, the excessive out-of-plane distortion as compared to the pre-curl in the MD (Figure 12d) can be clearly noted.

While visual observation clearly shows that that pre-curl in the MD has indeed alleviated the outof-plane distortions, it is rather difficult to quantify these variations experimentally on wide strips. However, once again, for the numerical case of curved geometries, the Hausdorff distance metric (shown in Figure 13) is used

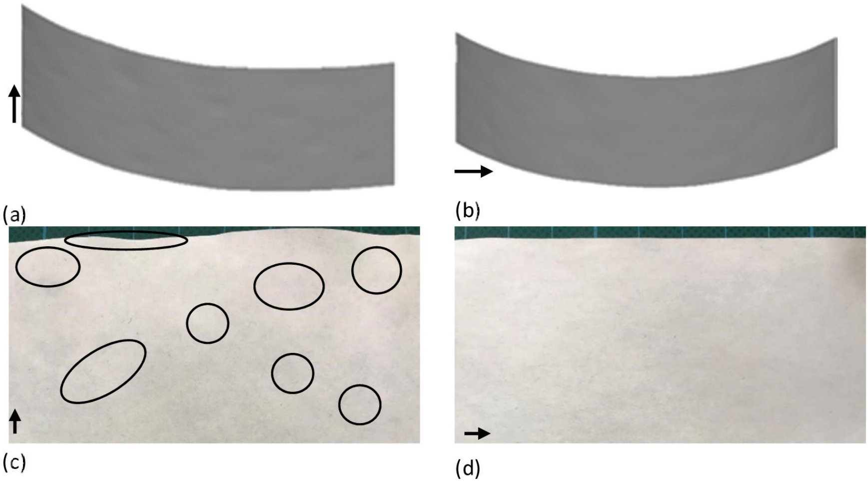


Figure 12. Deformed configuration geometries of the curved specimens from numerical experiments. The arrows indicate the machine direction. (a) Pre-curl in CD, (b) Pre-curl in MD. Wide strips dried on circular edge support with pre-curl in (c) CD and (d) MD.

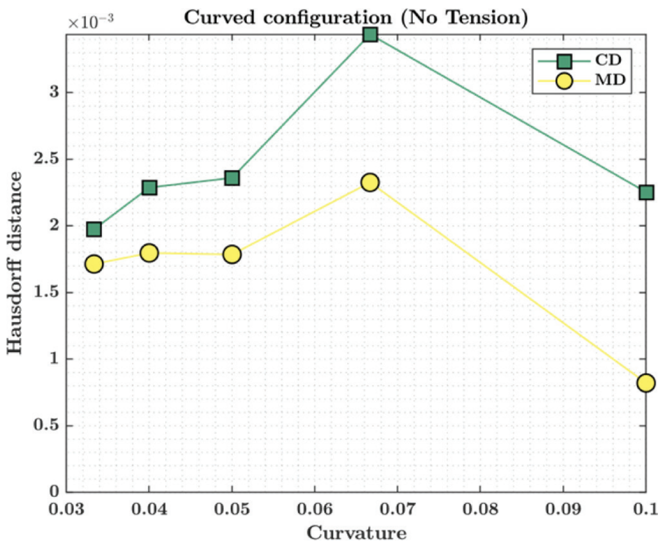


Figure 13. Hausdorff distance metric calculated between the undeformed and deformed configurations for the curved geometry at varying curvature in CD and MD.

to compare the undeformed and deformed configurations. Firstly, the results show that the deformed configurations for the case of curvature in MD are more similar to the undeformed configuration than the counterpart in CD. Secondly, an increase in curvature (reduction in radius), appears to reduce the extent of deformation only for the CD samples.

There is an observed anomaly in Figure 13. At an intermediate curvature, the extent of cockling is seen to be increasing. In Figure 14, the deformed and undeformed edges for the curved geometry with radius 15 mm is shown. In addition to the local deformations that are introduced by moisture variations, the numerical experiments capture some global deformations as well which are geometry dependent. The distance metric that is used looks for similarity between the final deformed configuration and the original undeformed configuration. A consequence of this is that geometry dependent global deformation is accounted for in the distance metric, an effect which is not present in the lab experiments. However, we wanted a single metric that would capture local deformations for both the flat and curved geometries and the Hausdorff metric, to the best of our knwoledge, is the one that was most suited. Thus, the results of the distance metric from parameteric study of curved geometry is to be seen as being indicative of the trend that cockling is reduced with pre-curl in MD as seen between the lowest and highest radius of curvature considered in the study. The complete set of undeformed and deformed geometries for Case N1 is presented in Figure 16 Appendix 6.2.

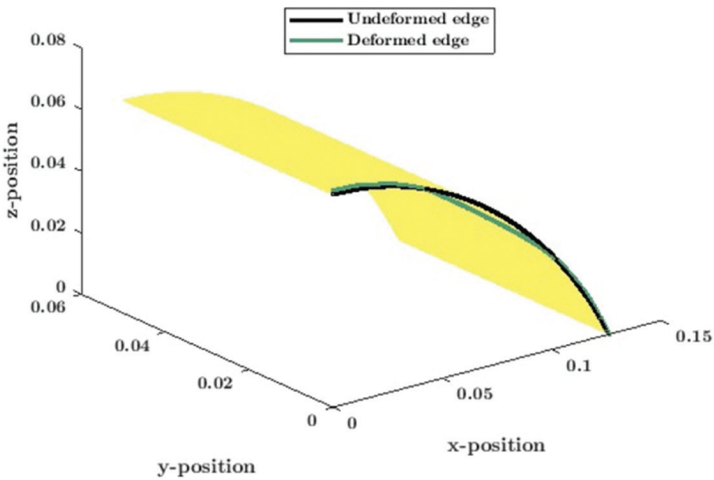


Figure 14. Highlighted edges of the deformed and undeformed configurations for curved geometry with radius 15 mm.

In the numerical experiments, it was proved that both, applying the tension in CD and introducing curl along the MD direction reduced cockling amplitudes. In the case of curl, the cockling propensity was reduced by the geometry (geometric stiffening) of the sample rather than by the stress-stiffening effects as the bending stresses are relatively low in a bent configuration.

3.3 Numerical Experiments and Experiments with Narrow Strips

As the narrow strip exhibited a different appearance of distortion, with a distinct structural waviness, particularly at an intermediate drying state. This observation raised the question of whether there is a single or competing mechanism in case the aspect ratio becomes large. We examined this case by considering a different geometry. A narrow strip (Length = 15 cm and Width = 1 cm) was subjected to similar conditions to the one in Case N1, but without symmetrical constraints. The applied moisture difference between the spot and the rest of the paper strip was 4%.

This numerical experiment showed that random shrinkage differential may indeed create the waved pattern and, similarly to the physical experiment, it has lower amplitudes and greater wavelength in the strip with the MD being along the longest linear dimension of the sample. It is important to note, that we did not measure the mechanical properties of the sheets considered in the physical experiments and, therefore, they may likely do not match those considered in the numerical tests. The purpose of the tests was to reproduce and quantify the trends observed experimentally rather than matching them exactly.

4 CONCLUSIONS

The main conclusion, as seen in the experiments, is that introduction of pre-curl (or drying in a state of curvature) in MD reduces cockling. By using a combination of the numerical and experimental observations performed on the orthotropic

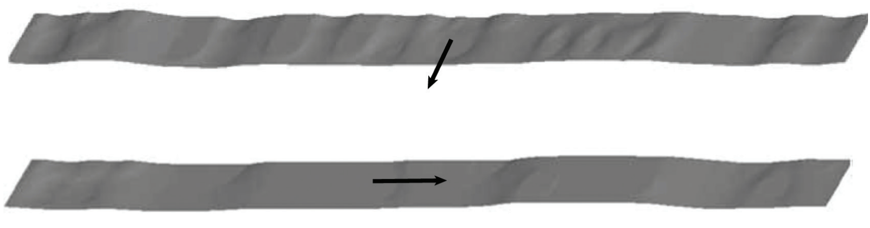


Figure 15. Distortion of a narrow strip after shrinkage with random shrinkage differentials applied as varied moisture. The arrow shows the MD.

commercial sheets, we showed that cockling can be effectively inhibited by both the stress- and geometrical stiffening in the CD direction. The stress-stiffening effect can be achieved by applying the tension in the CD. The geometrical stiffness can be achieved by introducing curvature in the MD.

Recalling that the cockling is induced by local buckling, the reported results suggest that with the given hygroexpansion coefficients, the local bending rigidity in the CD plays a crucial role in controlling the magnitude of cockles induced by drying non-uniformities. The practical outcome of this observation is the ability to control cockling amplitudes and the number of cockles by either pre-curl in the MD or tension in the CD.

The experiments with the narrow strip showed what could be considered a regular wave-like deformation at an intermediate stage during drying. The amount of these wave-like deformation has been observed to be correlated to the eventual extent of cockling [7] when drying is complete. This effect is seen under both flat and hung drying conditions. This begs the question of whether there are different drying mechanisms at play during different stages of drying. The wave-like formations intuitively point to a global phenomenon. This prompted trying to alleviate the wave formation by introducing curvature to explore the effect of global stiffness on this wave-like formation. It was seen that pre-curling in MD did indeed alleviate it. However, past literature has indicated that cockling as a phenomenon is predominantly driven by local inhomogeneities and the like.

However, the complementary numerical experiments induced cockling by introducing local variations in hygroexpansion showed that the wavy pattern can be also induced by random hygroexpansion variations. The limitation of the numerical studies is ignoring inelastic deformation and therefore not being able to capture the retention of cockling amplitudes upon restoration of moisture balance.

5 REFERENCES

[1] L.E. Eriksson, S. Cavlin, C. Fellers and L. Carlsson, "Curl and twist of paperboard-theory and measurement," *Nordic Pulp and Paper Research Journal*, vol. 2, no. 2, pp. 237–262, 1987.

[2] P. Glynn, H.W.H. Jones and W. Gallay, "The fundamentals of curl in paper," *Pulp and Paper Magazine of Canada*, vol. 10, no. 60(10), 316-323, 1959.

[3] P.H. Viitaharju and K.J. Niskanen, "Chiral curl in thin papers," *Journal of Pulp and Paper Science*, vol. 5, no. 20, 1994.

[4] P. Lipponen, A.L. Erkkilä, T. Leppänen and J. Hämäläinen, "On the importance of in-plane shrinkage and through-thickness moisture gradient during drying on cockling and curling phenomena," in *Advances in Pulp and Paper Research, Transactions of the XIVth Fundamental Research Symposium*, Oxford, 2009.

[5] P. Lipponen, T. Leppänen and J. Hämäläinen, "On the role of drying induced cross-machine shrinkage on paper cockling phenomenon," *Nordic Pulp & Paper Research Journal*, vol. 24, no. 1, pp. 60–65, 2009.

[6] A. Kulachenko and T. Uesaka, "The effect of fibre orientation streaks on out-of-plane instabilities in paper," in *61st Appita Annual Conference and Exhibition*, Gold Coast, Australia, 2007.

[7] K.H. Paik and W.S. Nam, "Cockle depending on drying conditions and local basis weight distribution" *Journal of Pulp and Paper Science*, vol. 27, no. 5, pp. 177–181, 2001.

[8] A. Kulachenko, P. Gradin and T. Uesaka, "Basic mechanisms of fluting formation and retention in paper," *Mechanics of Materials*, vol. 39, no. 7, pp. 643–663, 2007.

[9] A. Kulachenko, P. Gradin and T. Uesaka, "Tension Wrinkling and Fluting in Heatset Web Offset Printing process. Post buckling analyses," in *Advances in Paper and Science Technology, Trans. Of the XIIIth Fund. Rese. Symp.*, Oxford, 2005.

[10] G.A. Baum, C.C. Habeger Jr and E.H. Fleischman Jr, "Measurement of the orthotropic elastic constants of paper," *IPC Technical Paper Series*, 1981.

[11] D.P. Huttenlocher, G.A. Klanderman and W.J. Rucklidge, "Comparing images using the Hausdorff distance," *EEE Transactions on Pattern Analysis and Machine Intelligence*, vol. 15, no. 9, pp. 850–863, 1993.

[12] I. Kajanto, "Finite element analysis of paper cockling," in *Products of Papermaking, Trans. of the Xth Fund. Res. Symp. Oxford*, Oxford, 1993.

6 APPENDIX

6.1 Deformed and Undeformed Configurations of Flat Geometries

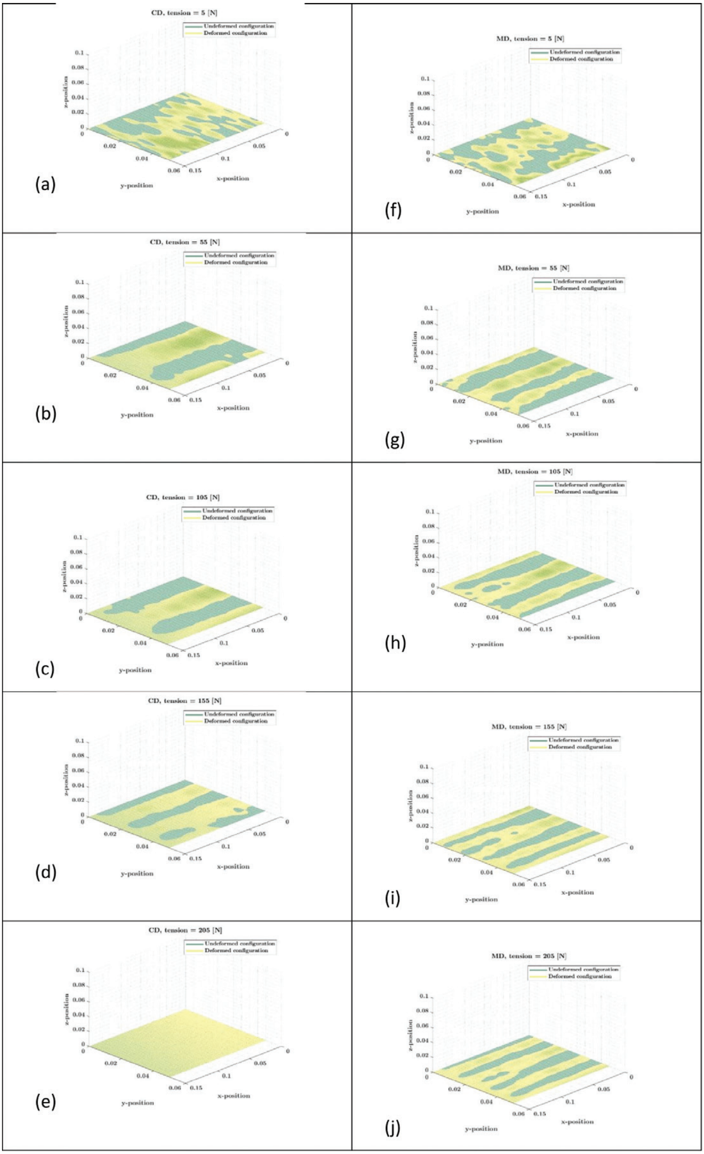


Figure 16. Visualisationof the differences between deformed and undeformed geometries of the flat configuration. (a)–(e) Tension in CD, (f)–(j) Tension in MD.

6.2 Deformed and Undeformed Configurations of Curved Geometries

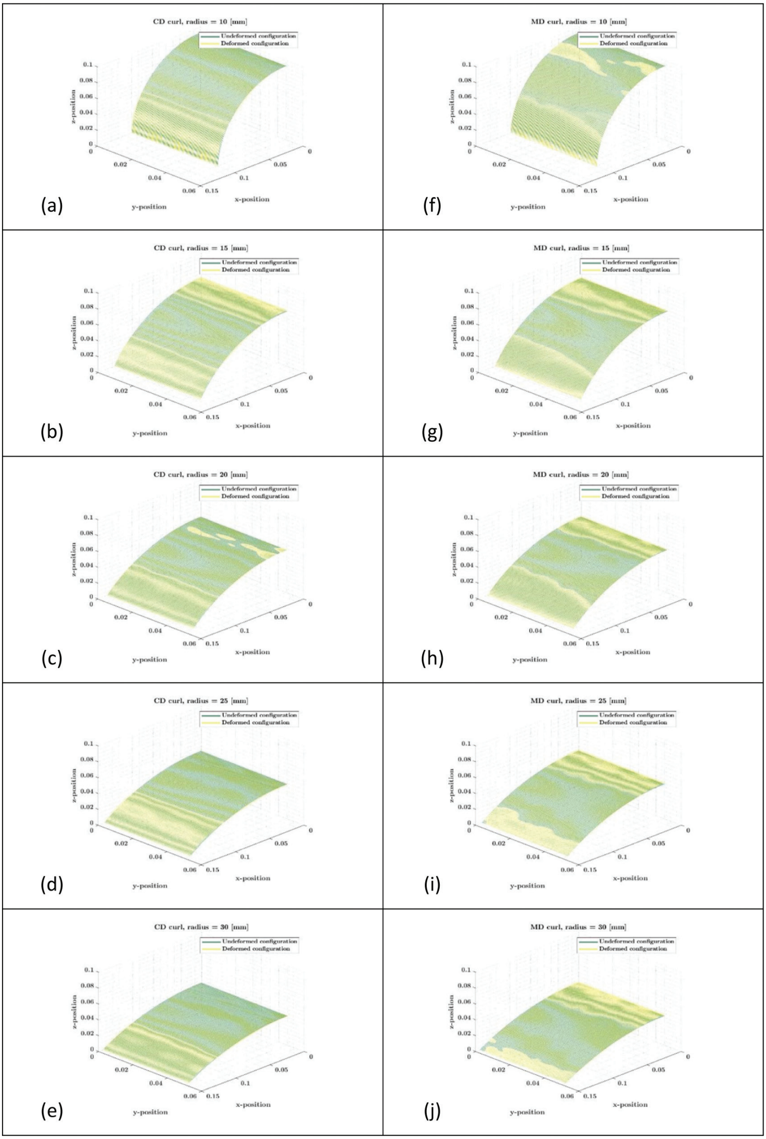


Figure 17. Visualisationof the differences between deformed and undeformed geometries of the flat configuration. (a)–(e) Pre-curl in CD, (f)–(j) Pre-curl in MD.

ON THE RELATIONSHIP BETWEEN CURL AND COCKLING

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Louis Saes Canon Production Printing

Thank you for the very nice presentation. I was wondering in the experiment you will have some kind of inhomogeneous moistening and in the numerical simulations you cannot prescribe the same moisture distribution and end up with the same result. So could you explain a bit better how you did that?

Artem Kulachenko

First of all, we never claimed that we can reproduce the experimental conditions because you have to know the variation in this particular sheet and the drying, assuming that is non-uniform, once you got to the air drying. It is out of control. So, the idea of performing numerical experiments is to demonstrate similar trends. We know how to promote cockling numerically and even how to transfer the cockling pattern to the fluting pattern. The way we do it is by promoting the local strain variations by assuming we have moisture variations. Those variations exist in paper. They have to be there because the sheet is non-homogeneous but what exactly happens in the experiment – whether this is a hygroexpansion differential or it is a moisture differential, we do not know, and we are not aiming to reproduce it exactly. We want to reproduce the trends and in our case the trends that will show the effect of the curl and the trends that will show the effect of tension.

Discussion

Louis Saes

Okay, I understand, so the inhomogeneity that you introduced is more or less statistically or randomly chosen?

Artem Kulachenko

Yes, exactly.

Louis Saes

It is not a pattern?

Artem Kulachenko

It is a random pattern, so it is not something that goes into jet streaks from the headbox for example. They are completely randomly spaced. The only thing that we ensure from our experiment is that we have the same coverage because that is the factor. We use the same coverage in all of our experiments so that the amount of area occupied by those spots is the same in all the experiments.

Markus Biesalski Technical University of Darmstadt

Very inspiring talk and now if I would come up to you saying can we work together and you give me some ideas how to actually control the pitch of certain geometric elements by controlling the flexure or rigidity of fibres and where you put them and so on. Do you think this is possible? Can you control this?

Artem Kulachenko

Well, I would not say control; it is very difficult to control anything in the system which is very inhomogeneous. Surely, when you go to micromechanics, you have several factors that you can use. For example, you can change the hygroexpansion, fibre orientation and other things.

Markus Biesalski

May I ask you the second question? Did you look into hysteresis effects?

Artem Kulachenko

Hysteresis in what?

Markus Biesalski

In the cockling, and if you just change the moisture in a controlled fashion and also with hygroexpansion or hydroexpansion?

Artem Kulachenko

Once the cockling is created, it is set. You cannot undo it unless you re-moisten and dry it under pressure. Only then you can make it flat again. Otherwise, it is not reversible and, in fact, even when you subject it to moisture cycling, cockles stay in the same location.

Jukka Ketoja VTT Technical Research Centre of Finland Ltd

I once checked myself that moisture differences actually induce quite high stresses in a web compared to the applied web tension. So in order to have the stress stiffening to prevent cockling, would you need to have a higher tension than the stress induced by the moisture differences, or how is it caused?

Artem Kulachenko

Yes, it is a good point. We never compared those with the actual stresses induced by drying. When you dry freely, the net force is zero. When the net force is zero, the stresses on a continued level cannot be large but when it comes to the local scale, it is quite difficult to evaluate and measure. My feeling is that you do not need to have so much stress to prevent cockling formation because the stress stiffening in fact is very efficient. As an example, you can demonstrate it on an A4 sheet. It has a low flexural resistance, but a slight addition of tension immediately increases the stiffness against the normal force. But how much of that is required? It could, of course, be experimentally detected. Numerically, we saw the more the better but the effect starts very early as you can see in the figure showing the measure we use to quantify cockling against varied tension.

Jukka Ketoja

I would like to have another question. What do you think is the role of the size of the inhomogeneity?

Artem Kulachenko

Yes, so it does matter, but not to a large extent. This is something that we looked at in the case of fluting and we probe everything from 3 mm to 12 mm. We saw that there was an effect, but it was not drastic as long as the coverage remains the same. That means it is not extremely sensitive to the size of these variations within reasonable ranges.

Torbjorn Wahlstrom Stora Enso

This is very comprehensive work, with a lot of results to digest in a short time. I really enjoyed how you have addressed various boundary conditions and modelling to understand what is happening. I have a comment and maybe a question. In the experimental work there are different boundary conditions acting on the sheet in different experiments. For example, in the curved structure there are the narrow and wide papers and in some case the strip was hanging with added tension. My question is, did you measure the shrinkage that actually happened in those different conditions? The shrinkage has been mentioned also in other presentations during this conference and seems to be viewed as increasingly important. It is quite easy to measure the shrinkage that happens by measuring the dimensions of the sample before and after drying or make markings and measure them or measure the change in grammage. Did you follow the shrinkage and can it be included also in the modelling?

Artem Kulachenko

It can be included in the modelling and we did measure shrinkage, but we did not report it. And I think there is a point in comparing the shrinkage with tension and without tension just to see how much the tension affects that. That is not something that we've done, but it is possible to do. I think you will be seeing expected trends there.

Torbjorn Wahlstrom

Okay, thanks. To mention something also about restraint drying, in many cases we take it for granted that our samples are restrain dried; for example when we put them under some wire with a certain tension. In the ISO method when we put the hand sheets on the polished metal we get very good restrained drying, zero shrinkage, but as soon as we do something else, I would say it could be good to make a check if the dimensions change since it has such a large effect on paper properties.

Artem Kulachenko

Yes, I totally agree. And this is something which we should sometimes be clear about when we refer to constrained drying. Constrained drying in the lab conditions is very different to what we have in the paper machine. Coming back to the question about tension, the reason I believe that you do not need a lot of tension is our experiments with the hung samples. There it was just its own weight causing nominal tension and we still see the impact. So, the tension does not need to be large to cause the effects anyway.

Douglas Coffin Miami University

When you freely hang strips to dry, there is going to be some differential shrinkage. My experience has been that the CD samples were curled quite a bit. The 45 degrees will twist quite a bit, and the MD will get a little curvature around the length. I maybe saw a little of bit of that in your picture, but it did not seem to be too severe, so I just wonder if you could address this?

Artem Kulachenko

We see that too as the global curve.

Douglas Coffin

But was it ever severe? Because then when you flatten it back out, you could change the patterns?

Artem Kulachenko

Yes, it is indeed the case we have not quantified it. So, in our case, we did not consider it to be severe. It could come from the dried-in strains or other factors.

Douglas Coffin

It's very different shrinkage from one side to the other orientation.

Artem Kulachenko

It could be the case, but it was not severe enough to affect this pattern. Yes, I understand what you are pointing at. If we promote curl during drying, it could be the reason why there is less locking. When I thought about this, I saw the increase in wavelength as we approached the upper part of the strip. Obviously, we have slightly more tension there. So that is what indicates that it is the tension that matters. Also, in the numerical experiment, we saw similar effects. Very little tension is needed to reduce cockling.

Discussion

Douglas Coffin

I have a comment that goes along with the stiffening. An old papermaker once said to me when we were looking at cockle coming off of their machine on their sheeted paper that he could remove the cockle. He would just take the paper and bend it, and all of the cockle popped out. So, I have done that over the years and for some papers, a little bit of curvature will pop all of the cockle out. However, when you let go, it comes back again. I think this related to your idea of stiffening.

Artem Kulachenko

I have not done those experiments and it would be interesting to see. Of course, it is possible to explain that. We basically force the paper to be flat, but the stresses are there. You change the stress state by changing the geometry and you see cockles popping up. Moistening will cause a similar effect, I am sure.