Baggy paper webs: Effect of uneven moisture and grammage profiles in different process steps

Cecilia Land, Karlstad University, Sweden
cecland@yahoo.com
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Abstract

One of the problems encountered in paper converting is caused by the occurrence of “baggy webs”, which essentially is when the tension profile of the paper web is uneven. In an area with low tension the paper is longer, which results in bagginess. The baggy parts can not usually be stretched to even out the tension of the paper web in a converting machine, with the result that runnability problems are likely to occur.

The aim of the work described in this thesis was to investigate three particular stages in papermaking, namely drying, calendering and storage, and rank them according to their propensity for inducing baggy webs. The focus was placed on investigating the effects of uneven moisture and grammage profiles on the machine-direction strain difference profile.

The largest strain difference occurred when there were systematic thick streaks throughout a reel that formed ridges. Stress relaxation during storage then gave rise to a difference in MD strain of 0.14 % when the ridge height was around 2 – 3 mm. Thickness variations due to variations in grammage is also a source of moisture variation.

A difference in moisture of 5 % in the calendering stage resulted in strain differences of about 0.05 – 0.08 %. These strain differences resulted in creases being formed as early on as in the calender nip when differences in both grammage and moisture content were present. Most creases appeared when the moisture difference was 2 – 8 %. The difference in grammage could be large without creases being formed when no differences in moisture content were present.

A moisture difference of about 5 – 6 % during drying resulted in a strain difference of 0.1 % measured on isotropic samples. The moist area turned into a tight streak when the moisture difference appeared at moisture contents higher than 25 %. At moisture contents lower than 20 %, on the contrary, the moist area turned into a slack streak.

The conclusion drawn is that papermakers should concentrate first and foremost on eliminating variations in grammage, especially if these are systematic. This would also eliminate some variations in moisture content, which would solve more problems.

Keywords: bagginess, drying, calendering, grammage, moisture content, paper, profile, reels, softwood kraft pulp, storage, strain, streak, tension, web.
List of Publications

This thesis is based on the following papers:

Paper I


Paper II


Paper III


Paper IV


Paper V


The published papers were reprinted with the permission of the journals in question.
Related conference papers, not included in this thesis


Other non-related publications by the same author


Contents

1 Background 1
   1.1 Baggy webs .......................... 1
   1.2 Paper .................................. 3
       1.2.1 The manufacture of paper .......... 3
       1.2.2 Forming of a fibre network ......... 4
       1.2.3 The structure of paper ............. 5
   1.3 Web handling .......................... 6
   1.4 The runnability of paper ............... 8
   1.5 Solving baggy web problems ............. 9

2 Aim .................................. 12

3 Methods 13
   3.1 Length and strain measurements ........ 13
       3.1.1 Cathetometer ....................... 13
       3.1.2 Speckle photography ............... 14
       3.1.3 Slide calliper ..................... 15
       3.1.4 STFI thickness tester ............. 16
       3.1.5 Dial gauge set-up ................. 17
       3.1.6 Image analysis ..................... 17
       3.1.7 Summary ........................... 18
   3.2 Web tension measurements ............... 20
       3.2.1 Web Tension Profile Analyzer (WTPA) .... 20

4 Materials ................................ 23

5 Summary of the papers 24
   5.1 Moist streaks during drying .......... 24
       5.1.1 Paper I ............................ 24
       5.1.2 Paper II ........................... 28
   5.2 Calendering ........................... 32
       5.2.1 Paper III ......................... 32
   5.3 Ridges in reels ........................ 36
       5.3.1 Paper IV ......................... 36
       5.3.2 Paper V ................. 38
   5.4 Summary ............................... 41

6 General discussion 42

7 Conclusions 44

8 Suggestions for further research 45
List of Figures

1 Examples of baggy paper webs. .......................... 1
2 Schematic diagram of a Fourdrinier paper machine. ....... 3
3 Activation of a fibre segment during drying. ............... 4
4 Typical load-strain curves for paper. ...................... 5
5 Schematic diagram showing the use of a spreading roll. .... 10
6 Cathetometer with eyepiece and digital display. .......... 14
7 The random pattern used for the speckle photography measurements. ........................................... 15
8 STFI thickness tester. .................................... 16
9 Schematic diagram of the dial gauge set-up. ............... 17
10 WTPA measuring beam. .................................. 20
11 WTPA measurement principle. ............................ 21
12 Set-up for drying paper on laboratory scale. .............. 24
13 Strain profiles after drying and unloading. ................ 25
14 Moisture profile and strain profile in a sack paper machine. 31
15 Possible reasons for uneven calendering compression profile. 32
16 The MD strain due to calendering as a function of the moisture content. ................................. 33
17 Visual rating of creasing as a function of MD strain difference. .................................................. 35
18 A typical creasing pattern found in samples with uneven grammage and moisture profiles. ................. 34
19 A paper reel with ridges. ................................ 36
20 The calculated strain difference as a function of the ridge height. ................................................. 37
21 A reel with a ridge of aluminium foil. ..................... 38
22 A slack streak made by a ridge of polyethylene film. .... 38
23 The strain difference between the ridge and the rest of the reel. .................................................. 39
24 The strain-at-break in the ridge and beside the ridge as a function of the MD position in the reel. .......... 40

List of Tables

1 Specifications of machine precision required. .......... 9
2 Standard deviation of the different methods used to measure length. ........................................... 18
3 Mechanical properties in the MD of the papers tested. 23
4 Types of calendering experiments. ........................ 33
5 Summary of strain differences due to different irregularities. ..................................................... 41
1 Background

1.1 Baggy webs

A perfect paper web is absolutely flat. It is able to run smoothly through various converting machines that make sacks, printed matter or other paper products. Sometimes, however, the “baggy web” phenomenon occurs and causes problems. Baggy webs have both slack and taut parts, which can cause runnability problems in the converting process. Bagginess may manifest itself in the form of slack streaks, a baggy edge or a tight edge (Figure 1). Regardless of the distribution of bagginess in the web, baggy webs have three characteristics in common:

- An uneven tension profile
- Uneven length and strain profiles
- Out-of-plane buckling (at low tension)

Figure 1: Examples of baggy paper webs with tight streaks (above) and a tight edge (below).
These three characteristics are three manifestations of the same problem. The web tension profile and web strain profile are mirror images of each other [1]. When the web tension is high, out-of-plane buckling is temporarily stretched out, but when it is lowered the buckling may return. Problems associated with baggy webs thus tend to appear in converting, since converting machines usually have lower web tensions than the winders in paper machines.

Many different issues can arise in converting due to baggy webs. Converters nowadays generally push their machines to the limit, with the result that the operating window decreases. Baggy webs may have low web stability and at high web speeds in particular fluttering can occur if there are one or two slack edges. If one edge is slack the web tends to wander towards that edge [2] which can cause web breaks or difficulties in cutting the web edge [3]. Creases can form when a baggy web passes a nip. Bagginess may lead to misregistering in the printing process. Problems may be encountered in forming and folding when sacks, envelopes, etc., are being produced. Faulty folding in sack-making can lead to an agglutinated sack. Even if a baggy paper is runnable, it may be returned by an unsatisfied customer merely because of its baggy appearance, who thereby registers a complaint.

Very small differences in strain are sufficient to cause problems. A strain difference of 0.1 % would cause problems for any paper grade, and thinner grades may tolerate as little as 0.01 % before runnability problems occur [4]. These limits should, however, be seen as guidelines, since runnability is dependent on the distribution of the baggy parts in the web.

Streaks are classified as being tight or slack depending on their distribution in the web. The streaks are tight if the tension of most of the web is low and slack if it is high. A narrow slack streak probably leads to more problems than a narrow tight streak, since a very high web tension is required to stretch almost the whole taut paper web out to match the length of the slack streak. A narrow tight streak, on the other hand, would require much lower tension to be stretched to the same length as the rest of the web.

Baggy webs can occur with many materials. The problem is complex and paper is a complex material. It is necessary to start from the beginning in order to understand why baggy paper webs occur and their behaviour. The introduction of this thesis begins by describing paper as a material and the behaviour of webs in general is addressed. This is followed by a description of the behaviour of paper webs in general and baggy paper webs in particular.
1.2 Paper

1.2.1 The manufacture of paper

Paper is made from cellulose fibres that originate mainly from wood. The type of wood used influences the properties of the paper: softwood has long, strong fibres whereas hardwood has short fibres that provide the paper with a smooth surface. Fibres are composed mainly of fibrils, which consist of bundles of cellulose chains.

The fibres are separated by mechanical means (e.g. grinding or refining) and/or by chemical means (e.g. kraft cooking) when producing pulp. When making paper, the pulp is diluted with water to a fibre content of around 0.2 – 1 %, depending on the paper grade being made.

An overview of a paper machine can be seen in Figure 2. The diluted pulp is lead into a headbox where it is fed through nozzles onto a permeable wire. A large proportion of the water is drained off here and then some more water is removed by pressing in the press section. The remaining water is dried off using heated cylinders in the dryer section, where most of it evaporates in the free draw between the cylinders. The moisture content of the paper when it enters the dryer section is typically between 45 – 66 % [5] and the final moisture content after drying is typically 4 – 10 %.

Figure 2: Schematic diagram of a Fourdrinier paper machine [6].
1.2.2 Forming of a fibre network

At the beginning of a paper machine, water is present both in the form of free water between the fibres and bound water within the fibres. After the forming section the paper is saturated with water. As soon as air starts to penetrate the paper capillary forces make it contract as the fibres are pulled together [5] and the free water is removed. Colloidal interactions and mechanical interlocking of fibrils, known as “Campbell forces”, pull the cellulose surfaces closer together [7]. Then, in the press section, water starts to diffuse from the fibre lumen. This causes the fibres to collapse, which is beneficial for the strength of the paper. When the fibres are close enough hydrogen bonds start to form and this occurs gradually, starting at moisture contents of around 50 % [8]. Bonds are formed more easily if the fines content is high or if there is external fibrillation.

At about the same moisture content the fibres start to shrink [9], primarily in their lateral direction. The lateral shrinkage of the fibres is transformed to longitudinal shrinkage at the fibre-fibre crossings. The free segments between the bonds are then stretched, i.e. the fibre segments are activated (Figure 3). Activated fibre segments can carry a load and contribute to the tensile stiffness of the paper.

![Figure 3: Activation of a fibre segment during drying, due to lateral shrinkage of the neighbouring fibres. The cross-hatched areas represent bonds.](image)

The fibre shrinkage causes paper in-plane shrinkage if no external forces are applied to restrain the paper. It begins after most of the free inter-fibre water has been removed. A paper dried under free shrinkage becomes crumpled. The tensile strength and tensile stiffness are lower for a freely dried paper than for a paper dried under restraint. The strain-at-break and tensile energy absorption
is, however, higher for a freely dried paper.

In the wet state, the stress-strain behaviour of the fibre network is mostly deter-
dined by Campbell forces [10]. When wet paper breaks, the fibres often remain
unbroken. In the dry state the fibre network is viscoelastic and plastic and when
the dry paper breaks, the result is many broken fibres.

1.2.3 The structure of paper

The fibres in the network are oriented in all directions even though most of them
lie in the machine direction (MD), since they orient themselves along the flow
direction in the paper machine. The fibres are relatively stiff, especially in the
longitudinal direction, which makes the paper stiffer in the machine direction
than in the cross-machine direction (CD). An example of tensile test curves in
MD and CD can be seen in Figure 4 and the MD-CD tensile stiffness ratio is
typically 1.5 – 3 [11]. The fibres lie in layers on top of each other, with almost
no fibres oriented in the thickness direction (ZD). The ZD tensile stiffness is
thus very low, typically 50 – 100 times lower than the in-plane stiffness [11].

![Figure 4: Typical load-strain curves for paper (135 g/m² liner). The load per sample width is shown as a function of the strain.](image)

Paper is thus an anisotropic material, i.e. the properties differ depending on
the direction of the test being performed. It is also generally assumed to be
orthotropic, i.e. that the material behaviour can be explained by properties in
the three dimensions MD, CD and ZD. Paper, being very porous, contains a
significant amount of air. In addition to the fibres, paper generally contains fillers (e.g. clay or calcium carbonate) and other chemicals. Different types of coating can also be applied to its surface.

During measurement of mechanical properties on porous materials like paper, special treatment is required. The elastic modulus, for example, is defined as the stress divided by the strain in the linear part of a tensile test curve. Determining the stress, i.e. the force per unit area, that acts on a porous material presents a problem since the air, which comprises such a great part of the material, does not bear load at all. The “tensile stiffness index” is normally used instead of the elastic modulus. The tensile stiffness index is the same thing as the specific elastic modulus, i.e. the elastic modulus divided by the density. For a standard in-plane tensile test, this is calculated by taking the slope of the load-strain curve and dividing it by the sample width and the grammage. The tensile stiffness index is a measure of the stiffness of the fibre material, and not of the air-containing structure.

Paper is viscoelastic, which means that its tensile stiffness is affected by the loading speed. It is therefore important to choose a testing speed that corresponds to the rate of elongation in the application of interest, or at least to be aware of the difference. Stress relaxation occurs in the paper during a constant strain tensile test, which lowers the tensile stiffness measured. Using a method that is too slow for the application of interest would therefore give a stiffness that is too low. Similarly, a test speed that is too high leads to a stiffness response that is too high. The current (March, 2010) speed record of a newsprint paper machine is 2014 m/min [12]. The ISO 1924-3 method for determining paper tensile properties dictates a strain rate of 0.1 m/min. New technology has allowed the development of tensile testers with speeds of up to 6 m/min [13, 14].

Ultrasonic stiffness measurements, where a sound wave is used to load the paper, are also possible. The speed of sound in paperboard is around 210000 m/min in the MD and 120000 m/min in the CD [15]. The testing speed used in ultrasonic measurements is thus significantly higher than in both tensile tests and paper machines. The difference between stiffness measured using a standard tensile test and an ultrasonic test is 10 – 40 % for dry paper [16], depending on the type of paper and the direction. The difference is 20 – 70 % for wet paper (15 % moisture content) [16], thus making it more time-dependent than dry paper.

1.3 Web handling

A web is, by definition, a long piece of thin and flexible material. Web mechanics state that when a web passes a roller, the web path and the web tension may change. The behaviour of the web is then influenced by the way in which it interacts with the rollers, which can be traction, sliding or floating mode [17].
Most machine elements operate in “traction” mode: the web grips the roller surface through friction, causing the roller to rotate at the same periphery speed as the web. A basic rule here is the “normal entry law” [18], which states that paper in traction mode hits the rollers at a 90° angle of approach. The web tension changes during its passage around the roller according to the “band-brake equation”:

\[ \frac{T_2}{T_1} \leq e^{\mu \theta} \]  

where \( T_1 \) and \( T_2 \) are the web tensions before and after the roller, \( \mu \) is the effective friction coefficient, including air viscosity effects and \( \theta \) is the wrap angle (in radians) of the web around the roller [17, 18]. There is a less than or equal to sign, since torque effects also influences the change in web tension.

The interaction mode is denoted “sliding” when the roller rotates at a different speed to the web, and “floating” when the roller has no contact with the web (which is common in drying ovens, etc.). Although it is more difficult to predict the effect sliding has on the path of the web, the band-brake equation applies, albeit with a less than sign instead of a less than or equal to sign. In floating mode, the roller cannot change the path and tension of the web, since they are not in contact with each other.

Baggy webs act in a more complex manner, since the tight parts of the web may be in traction whilst the slack parts are not. The way in which the path of the web is affected depends on how the baggy areas are distributed in the web. A web with one baggy edge moves towards that side on the rollers [2, 19]. The effect is greatest when there is traction between the rest of the web and the roller, and a little less when the rest of the web slides. A low web stiffness gives a larger deflection. Deflection at low levels of tension depends strongly on the web tension [19].

The forces acting on a paper web are both external and internal. The most important external force is the web tension, but other forces such as gravity and friction also act upon the paper web [10]. The internal, or residual, stresses vary with the MD, CD and ZD positions of the paper, but for a paper sheet lying on a table, in equilibrium, the resultant of the residual stresses is zero. In a freely dried paper, all residual stresses are close to zero. The residual stresses in a restrained dried paper, on the other hand, are equal to the drying stress level in the end of drying, and also to the yield stress of the paper [20]. Residual stresses may give rise to distortion of the paper and may also affect the strain due to a certain tension. This could most certainly be connected to the strain differences that are present in baggy webs.
1.4 The runnability of paper

Paper is a viscoelastic plastic structure that is very sensitive to moisture. It is also non-uniform with variations in grammage and thickness. Its behaviour under changes in tension and moisture content is thus complex.

Runnability is the ability of a web to pass through a machine without any problems. Examples of converting machines for paper webs are printing presses, packaging machines and laminators. Many of these processes involve changes in moisture content of the paper. The goal of the converter is to run the paper as fast and as wide as possible in order to maximise productivity. Parameters, such as the web tension, usually have a runnability optimum. One strategy of determining the optimal web tension is to find the point of the lowest cost [21]. The cost of problems due to too high web tension (e.g. web breaks) and the cost of problems due to too low web tension (e.g. unstable web) should then be added, for each possible web tension. The web tension with the lowest cost is then used. Albeit this method is somewhat crude, it is quite useful for the industry.

Runnability can also be defined as the distance between two web defects, usually breaks. Runnability involves, however, more than just strength. Problems that may be encountered vary according to the converting process employed. Important issues include:

- Dimensional stability: in-plane or out-of-plane
- Friction properties
- Moisture content
- Stiffness: tensile or bending
- Strength

The goal, in many cases, is for the paper to have uniform properties. An even friction coefficient is often necessary for good runnability. Evenness in other properties may be beneficial for dimensional stability and for avoiding baggy webs.

In the case of baggy webs, the properties and the tension in the machine direction are the most important factors. Variations occur more frequently in the CD due to the fact that the dimensions of individual fibres change more in the lateral direction. The web tension in the CD is not, however, directly related to the MD web tension profile. Knivilä [1] claims that a local decrease in MD tensile stiffness is a measure of slackness in the sheet and that MD tensile stiffness should not vary by more than $+2.5\%$ for normal grades of paper or $+5\%$ for heavier grades.
1.5 Solving baggy web problems

It is obvious that the rollers in converting machines should be properly aligned and properly round in order to avoid distorted tension profiles. Machines are required to have a very high degree of precision (Table 1) but, an almost perfect machine is not enough, or the problem would be considered solved already.

*Table 1: Specifications of machine precision required, according to Roisum [17]. The values depend on the length-width ratio of the web and are therefore approximate.*

<table>
<thead>
<tr>
<th>Accuracy required</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Roller in-plane alignment</td>
<td>0.015</td>
</tr>
<tr>
<td>Roller out-of-plane alignment</td>
<td>10</td>
</tr>
<tr>
<td>Roller roundness</td>
<td>0.0025 – 0.25</td>
</tr>
</tbody>
</table>

Some machines are equipped with “spreading rolls” that are bent so that the slack edges (or slack centre) of a web can be stretched out temporarily, usually for only one span. The typical use of a spreader is otherwise to prevent, or remove, wrinkles as shown in Figure 5. According to the normal entry law, the web hits the bent roll at a right angle, becomes spread out and is thus flattened. Although this may work, it can also make matters worse if executed improperly. Traction is necessary for the normal entry law to apply, which may be difficult to achieve between a baggy web and a spreading roller. A spreading roll is of little use if there are baggy streaks instead of edge/centre problems. Some very thick materials, e.g. paperboard, can not be spread at all. Avoiding a baggy web is particularly important in nips and it is doubtful whether the spreading would remain within the nip.
Bagginess that appears in paper machines is usually solved by increasing the winding tension [22]. This will work just fine, but the problem is only being masked until it is time to convert the paper and the tension is lowered. Setting the tension very high, and thereby deforming the paper permanently, is an actual cure. It does, however, need to be performed uniformly. It is in fact preferable, and probably easier, to make the paper uniform in the first place. Stretching the paper permanently may also destroy the properties required of the paper. The possible sources of the problem need to be analysed instead.

The tension profile of the paper web can be influenced in many ways. It means that papermakers with baggy webs face a challenge when trying to solve these problems. They are not helped by the fact that many of these factors, listed by Kurki et al. [10], are interdependent:

- Edge flows in headboxes
- Headbox slice
- Water removal in the forming section
- Load distribution in the flat nip in the press section
- Operating conditions of press felts
- Use of steam box in the press section
- Uniform adhesion properties of a centre roll in the CD
- Uniform cylinder drying in the CD
- Basic strain behaviour between the web and roll surface

Figure 5: Schematic diagram showing the use of a spreading roll.
- Roll alignment
- Shrinkage of the paper web in the CD
- Amount of strain potential used or remaining in the paper web
- Friction factors between the web and roll or fabric surface
- Distribution of nip load in sizing and coating
- Calendering (roll surface properties)
- Paper thickness changes in the CD
- Paper moisture changes in the CD
- Use of spreading rolls
- Reeling tension
- Winding
- Storage of paper reels
- Tension changes in the paper reel (creep, relaxation)

The grammage, thickness and moisture profiles in paper are often connected. Gaining some understanding of baggy webs requires the factors to be evaluated individually to isolate the effects. The interactions also need to be studied in the future. The frontiers of research are, however, not yet there. It is necessary to start with the basics.
2 Aim

The aim of this thesis is to test three hypotheses as to why baggy webs occur. These are ranked according to their tendency to cause runnability problems due to bagginess, measured as the MD strain difference in a paper web.

The three hypotheses are:

- During drying, moist streaks are stretched together with less moist areas, causing an uneven permanent strain in MD.
- An uneven calendering load causes an uneven permanent strain in MD.
- A paper reel with ridges (uneven diameter) is subjected to an uneven permanent creep strain in MD during storage.

Moist streaks may either be present prior to the dryer section or created there due to uneven drying. Before the dryer section, moist streaks may appear due, for example, to an uneven grammage profile or uneven pressing.

Uneven calendering may occur as the result of uneven calender rolls due to wear, or because of grammage streaks in the paper. The latter can also cause the diameter of the paper reel to become uneven, a phenomenon known as “ridges”, that subjects the paper in a reel to differences in strain [23, 24]. Such a strain difference may become permanent.

This thesis concentrates on the processes, structure and properties of paper. Paper and converting machines, along with general web mechanics, are mentioned briefly as background information, but are not examined in depth.
3 Methods

The three characteristics of baggy webs provide three main ways of measuring or detecting bagginess. There are several techniques [3, 25, 26, 27] for measuring tension profiles online in paper machines or converting machines, but they are very rare within the industry. The strain (length) profile can be measured by cutting the paper in strips along the MD and measuring the length of each strip. Out-of-plane buckling can be observed visually: one method is to record the stress required to stretch the paper until it appears to be flat [22]. However, this method is operator-dependent and is not suitable for scientific studies. The methods that were used for measuring bagginess in this project are described below.

3.1 Length and strain measurements

The length profile of a paper web can be determined by cutting it into strips and measuring the length of those strips before and after a certain process. The strain due to the process in question can then be determined. A profile of strain difference is obtained when the values are recalculated to obtain an average strain of zero. Measuring the actual lengths is quite challenging as a very high degree of accuracy is necessary.

A typical baggy web could, as stated previously, have strain differences of an order of 0.1 % so a measurement accuracy of about 0.01 % is therefore desirable. This can be attained by using methods with a inherent high degree of accuracy as well as by measuring long samples, which would decrease the percental error. During length measurement, it is important that all paper strips are stretched to the same degree in order to obtain an accurate length profile. It is actually preferable that the paper is not stretched at all, since possible differences in tensile stiffness between the samples then might influence the length measured. On the other hand, the strips should be buckling-free, which requires a degree of stretching to be applied. A balance must be found between these two issues, and is handled differently in the various methods available.

3.1.1 Cathetometer

The first method for measuring lengths involved the use of a cathetometer (Figure 6), which was employed during creep tests (Paper IV). It is equipped with an eyepiece that can be moved in the vertical direction. Looking through the eyepiece, a cross-hair is visible that can be aligned with lines on a paper strip hanging about 0.5 m behind it. A position transducer with an accuracy of 0.01 mm was used to give a reading on a digital display. The repeatability of
the measurements was, however, a little low since it was difficult to position the transducer accurately. This also gave rise to a long measurement time of about 2 min, which is somewhat too long. Ten measurements on a 200 mm long sample showed a standard deviation of 0.02 mm.

This method is most useful on a laboratory scale, and especially so for creep tests, since it does not involve direct contact. Measurements can thus be performed while the sample is loaded in the MD. Loading was performed with weights hanging in clamps from the end of the sample, which also ensured that buckling was avoided.

3.1.2 Speckle photography

In speckle photography a random pattern of dots (Figure 7) is printed on the paper. The paper is photographed before and after the process of interest and a mathematical cross-correlation procedure is carried out on parts of the images in order to obtain a strain field [28].

Speckle photography has been used previously to measure in-plane strains associated with calendering [29]. This method was used for the same purpose in the present study, though the focus here was on the MD strain that requires a higher level of accuracy. Although averages of many samples were taken, the degree of measurement accuracy was simply not sufficient. The problem with the set-up used in this project [30] was probably that the camera had to be
very close to the paper in order to obtain good pixel accuracy. This, in turn, meant that the measuring area became too small to reflect what was actually happening in the paper on a larger scale. The result was a significant spread in the measurements even though very similar machine-made sheets were tested. It is possible that the dimensional stability of the paper tested was too great for changes to be registered, since this method was only tried on dry paper.

3.1.3 Slide calliper

The slide calliper used is also primarily useful on a laboratory scale, since the maximum length that could be measured was 150 mm, if not adding several measurements. Adding several measurements affects the error margin in the measurement. The slide calliper used in these experiments had an accuracy of 0.03 mm, which then corresponds to 0.02 % when measuring a length of 150 mm. There is also a certain margin of error that originates from the operator that arises from the difficulty to finding the exact centre of the point that is to be measured from. Practice improves this; one test showed a standard deviation of 0.04 mm (based on ten measurements on a 120 mm long sample) in the measurements made by the author.

Using a slide calliper offers a simple (in principle), mobile and cheap method of measurement. It is quicker to use than the cathetometer but is nevertheless time-consuming, especially if a profile is required, and only short samples can be measured. The method was used in Paper I for measuring strain profiles on samples cut into strips. It was also used in Paper III for measuring strain caused by calendering.
3.1.4 STFI thickness tester

The STFI thickness tester (Figure 8) can be used not only for measuring thickness but also for measuring length. The sample is moved forward by two rollers in the tester and a thickness reading is taken every 0.1 mm. The accuracy in this spacing depends, however, on the evenness of the rollers. The number of data points multiplied with 0.1 mm gives the length of the sample. The accuracy is then about 0.1 mm, thus making the STFI tester less accurate than a slide calliper.

![Figure 8: STFI thickness tester.](image)

No manual recording of data is necessary. It is, however, important to insert the samples perpendicularly for good repeatability. A possibly strategy here is to make several repetitions and pick the lowest, or mean, value. The main drawback of this method is the importance of avoiding improper steering, which is difficult when the samples are long. A test showed a standard deviation of 0.06 mm on ten measurements of a short sample (190 mm in length). When a 630 mm long sample was tested, however, the standard deviation was found to be 0.7 mm.

It can be summarised that although measuring length using the STFI thickness tester is a good idea, the long samples that are required for obtaining a good degree of accuracy are too difficult to handle adequately.
3.1.5 Dial gauge set-up

A dial gauge set-up, developed at Billerud Gruvön [31], was used for measuring the length profiles of full-size reels. Two parallel lines between which the length is to be measured should first be drawn on the paper web. The web is then divided into strips of suitable width (around 40 mm). A pre-defined load is then applied to the paper strips whilst the length is being measured. The load is chosen to be as small as possible to avoid stretching of the strips but large enough to avoid buckling. A load of 30 N/m was used in Paper II of this thesis.

First, a strip of medium length is placed in the equipment so that it is at the centre of the scale on the dial gauge (zero length difference). The dial gauge is then fixed in that position. The other strips can then be measured, with the result being given as a difference in length compared to the first strip. The approximate length of the first strip is then measured with a tape measure to obtain the length difference in percent.

Figure 9 shows the set-up in which the dial gauge is connected to a scale (to record the load) and to one of the clamps. The strips are mounted so that the lines on the paper correspond exactly with the lines in the clamps. The distance between the clamps was about 2 m, but it is possible to measure longer strips by either adding several measurements together or modifying the set-up. Although the accuracy of the dial gauge itself was 0.01 mm, its accuracy during practical use was estimated to be about 0.1 – 0.5 mm when measuring a sample with a length of 3 m.

![Diagram of the dial gauge set-up](image)

*Figure 9: Schematic diagram of the dial gauge set-up, showing the dial gauge (left), paper strip (centre), and clamps.*

3.1.6 Image analysis

A quick method of measurement is needed for measuring the length of moist paper, in order to avoid moisture evaporation during the actual measurement process. In this case, a special procedure, based on image analysis of scanned samples, was used. For extra care, the paper samples were kept in plastic bags.
during scanning. Four dots, one in each corner, were drawn on the sample: each had a diameter of about 5 mm. The scanning was performed before and after the process of interest was performed. In the case of Paper III, this was calendering. The samples were scanned using an Epson Perfection V750 Pro with a resolution of 600 dpi, giving a pixel size of 0.042 mm.

The centre points of the dots were determined using the MATLAB Image Analysis Toolbox (Mathworks Inc.). The strain was then calculated from the distance between the dots before and after the procedure in question was carried out. The maximum distance that could be measured was 29 cm, which was the length of the scanning area. The standard deviation of ten measurements was 0.019 mm when the dot distance was 279 mm.

This method is sufficiently accurate, easy to perform and reasonably fast. The main difficulty lies in drawing each dots accurately enough so that the centre is actually aligned in the MD. If the sample is long, the error from this issue is small.

3.1.7 Summary

The different methods available are suitable in different cases. The standard deviations of the methods used in this project, and the sample length of which is required to obtain an accuracy of 0.01 %, are listed in Table 2 as a guide. These standard deviations were determined on short samples, which means that effects arising due to longer samples are not accounted for. In the case of speckle photography, the random error due to an expression given by Sjödahl [32] is given.

<table>
<thead>
<tr>
<th>Method</th>
<th>Standard deviation [mm]</th>
<th>Sample length to obtain 0.01 % accuracy [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tape measure</td>
<td>0.5</td>
<td>5</td>
</tr>
<tr>
<td>Cathetometer</td>
<td>0.02</td>
<td>0.2</td>
</tr>
<tr>
<td>Speckle photography</td>
<td>0.5</td>
<td>5</td>
</tr>
<tr>
<td>Slide calliper</td>
<td>0.04</td>
<td>0.4</td>
</tr>
<tr>
<td>STFI thickness</td>
<td>0.06</td>
<td>0.6</td>
</tr>
<tr>
<td>Dial gauge</td>
<td>&lt; 0.5</td>
<td>&lt; 5</td>
</tr>
<tr>
<td>Image analysis</td>
<td>0.02</td>
<td>0.2</td>
</tr>
</tbody>
</table>

The accuracy of the speckle photography set-up was very low, but could possibly be improved by optimizing the speckle dimension and the optical system. The
accuracy of the STFI thickness tester was unacceptable due to the steering problems encountered when the samples were long enough to be otherwise useful. The cathetometer has a high level of accuracy but was tricky to handle.

The dial gauge was found to be the best option for full-scale or pilot tests, whereas the slide calliper and image analysis both worked well for small-scale laboratory tests. It should be noted that the length needed to obtain an accuracy of 0.01 % with the slide calliper was 0.4 m, which was impossible with the calliper used in this work, which had a length of only 0.15 m. It would require several measurements being added together for this level of accuracy to be attained with this particular slide calliper. The accuracy of the slide calliper thus appears in Table 2 to be better than it actually was, but this method is nonetheless very practical. Measuring the averages of a lot of samples makes it possible to overcome the problem of accuracy. Image analysis was the only method that was fast enough for measuring the lengths of wet samples of reasonably large size.
3.2 Web tension measurements

3.2.1 Web Tension Profile Analyzer (WTPA)

A Web Tension Profile Analyzer (Webline, Sweden) [33, 34] was used to measure web tension profiles as well as length profiles. The equipment used was a prototype which is inserted in a twin-drum rewinder at Billerud Gruvön in which reels with slack streaks were run and measured. It is the prototype is described in this chapter, rather than the current version with a different layout which is claimed to reduce some errors, e.g. vibrations. The fundamental principle on which they are both based is, however, similar. WTPA consists of a measuring beam (Figure 10) but is nonetheless a non-contacting measuring method because the web floats on a layer of air. Since the measurement is performed without any contact with any rollers, the equipment does not disturb either the tension or the path of the web. A further advantage is that slack streaks, i.e. streaks with zero or negative tension, can be measured.

![Figure 10: The WTPA prototype measuring beam seen from the side. The web is seen passing the measurement segments.](image)

The measuring beam contains 24 measurement segments: each segment is 30 mm wide, thus giving a total width of 720 mm. Each of these segments contains a LVDT (Linear Variable Differential Transformer) transducer which allows for the contact-free measurement of position. The air layer on which the paper web is floating has a thickness of about 0.1 mm when it passes the transducers. The actual measurement is based on the geometry of the measuring equipment and the impression of the LVDT transducers. The path of the web needs to be
positioned with absolute accuracy by the air bars if good measurements are to be obtained.

The length and tension profiles of the web are calculated from the segments impression force, its depth position in the web, the width of the segment, the total width of the web and the paper properties. A calibration routine is used to find the zero and maximum levels of the transducers. A correction routine, determined with finite element modelling, is used to compensate for the stiffness of the paper and edge effects. Figure 11 shows the web from the side and one of the measuring segments with the dimensions used for measuring the length profile. The local length of the web between the air bars can be calculated using Pythagoras’ theorem:

\[ L_{rel} = 100 \left( \frac{2 \sqrt{(a - L_m/2)^2 + L_z^2 + L_m} - 1}{2a} \right), \]  

(2)

where \( L_{rel} \) is the difference in web length in percent, relative to an absolutely straight web. \( L_z \) is the calibrated and edge-compensated impression depth of the web and the other symbols are defined in Figure 11.

\[ F_s = \frac{F_x}{2b \sin \alpha}, \]  

(3)

where \( F_s \) is the web tension in N/m, \( F_x \) is the downward web impression force measured and edge-compensated, \( b \) is the width of the measurement segment.

Figure 11: Measurement principle of the WTPA prototype. The dashed lines show two measurements with different lengths and tensions.

The web tension can be calculated from:
and $\alpha$ is the web angle (Figure 11). These calculations are performed for each measurement segment in order to obtain profiles. The web length profile is usually recalculated to produce an average of zero. The profile then shows how the length differs from the average length. This is also the equivalent to a strain difference profile.

The manufacturer of the equipment specifies a maximum linearity error of the LVDTs of 0.25%, and a resulting margin of error in web tension of up to 1.5%. At lower web tensions the error is smaller but, due to the sine function, the error increases at higher web tensions. This estimation of error is based on the transducers only; the geometry of the equipment is assumed to be specified with absolute precision.
4 Materials

Flash-dried bleached softwood kraft pulp, Billerud Kraft Pulp SW from the Gruvön Mill, was used to make laboratory sheets. The Formette Dynamique sheet former (DSF) was usually used in order to obtain samples with a realistic fibre orientation, although standard laboratory sheets were also used. The anisotropy of restrained dried sheets was 2 in the DSF sheets.

Three machine-made paper grades were used for tests on a larger scale: a machine-glazed (MG) paper with a grammage of 71 g/m² and liners with grammages of 80 g/m² and 135 g/m², respectively. They were all made at the Gruvön Mill from never-dried softwood bleached kraft pulp of type similar to the laboratory sheets but on different machines, and included fillers and other chemicals. The mechanical properties of the papers are listed in Table 3.

<table>
<thead>
<tr>
<th>Grammage</th>
<th>Tensile strength, MD [Nm/g]</th>
<th>Tensile stiffness, MD [kN/m²]</th>
<th>Strain-at-break, MD [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>71 g/m²</td>
<td>120</td>
<td>11.6</td>
<td>2.3</td>
</tr>
<tr>
<td>80 g/m² liner</td>
<td>110</td>
<td>10.3</td>
<td>2.5</td>
</tr>
<tr>
<td>135 g/m² liner</td>
<td>114</td>
<td>10.7</td>
<td>2.4</td>
</tr>
</tbody>
</table>

The 80 g/m² liner is two-layered, with long fibres in the bottom layer and a mixture of short fibres and broke in the top layer. The 135 g/m² liner is also two-layered, but has a mixture of long and short fibres in the bottom layer and a mixture of long fibre and broke in the top layer. The MG paper, on the other hand, is one-layered consisting of a mixture of short and long fibres.

The liners are dried in a conventional multi-cylinder drying process. The 71 g/m² MG paper is partly dried whilst restrained on a Yankee cylinder, which makes its mechanical properties somewhat different to the liners. The exact percentages of the different types of fibre vary somewhat between the papers, which also affects their mechanical properties. Anyhow, the tensile stiffness of the MG paper is somewhat higher than that of the liners.
5 Summary of the papers

5.1 Moist streaks during drying

5.1.1 Paper I

The purpose of Paper I was to investigate whether or not paper with moist streaks would acquire an uneven strain profile after drying. DSF paper sheets that were pressed but not previously dried had moist streaks added before being dried on a laboratory scale (Figure 12). The paper was dried under a prescribed strain, either in room temperature or with an IR dryer. The point at which the tension was released was also varied. After the paper was released it was cut into narrow strips. The lengths of the strips were measured after conditioning with a slide calliper and a strain profile was thus acquired. The tensile properties of the strips were then measured.

Figure 12: Set-up for drying paper on laboratory scale. The moist streaks were noted as being wavy at the start of the drying process.

To obtain good measurement accuracy, the paper was tested with the CD in the load direction. The strain and shrinkage are greater in the CD since the fibres shrink much more in the lateral direction than in the longitudinal direction. When the CD was used as the primary direction the anisotropy of the sheet was 0.5. There is no other fundamental difference between the MD and the CD other than the fibre orientation [35] if effects due to conditions during drying
are disregarded. These were not of importance here, since the CD was treated as though it was the MD during the drying process. This means that qualitative behaviour could be investigated but, if quantitative results are to be obtained, the paper should be tested in the MD.

The papers were dried under two different settings: positive and negative prescribed strain. Regardless of the sign of the strain, the moist streaks were short in length after drying when the paper was released at the maximum drying stress, i.e. before the moisture and stress had reached an equilibrium. When the paper was kept under tension until the drying stress had reached equilibrium, however, the strain profile was unaffected by the streaks. Figure 13 shows the strain profiles when the prescribed strain during drying was +2 %.

![Figure 13: Strain profiles after drying under +2 % strain and unloading. Black line: paper unloaded at maximum drying stress. Grey line: paper unloaded after drying stress had relaxed to equilibrium. Filled dots: position of the initial moist streaks.](image)

The moist streaks dried more slowly than the dry streaks, thus taking on a slack, or wavy, appearance at the beginning of the drying process (Figure 12). After drying, however, the moist streaks were shorter than the rest of the sheet. This was explained as follows: at the beginning of drying, most of the paper was under tension and was thus subjected to some plastic strain. The paper in the streaks was not under tension at the beginning of the drying process; it was only once it had become quite dry and had shrunk to the same length as the rest of the paper that it became subjected to tension. The plasticity of the paper is lower at that moisture content. The result is that the formerly moist
streaks become shorter than the rest of the paper, since they were not subjected to plastic strain at the beginning of the drying process.

The streaks were about as short regardless whether the paper was allowed to shrink or not. In the case of the paper being allowed to shrink to a certain degree, the same mechanism as described above probably occurred, but only after the paper had shrunk to the prescribed strain and started to carry a load.

The tensile stiffness profile depended on whether or not the paper was allowed to shrink during drying. When the paper was dried under a positive strain, the tensile stiffness was lower in the previously wet streaks (Figure 14). If the paper was allowed to shrink, the tensile stiffness profile was flat (except for at the edges). The paper dried freely at first until it reached the prescribed strain. The whole paper, including the moist streak, was thus subjected to the same shrinkage at the same moisture content, only at different times. Consequently, the tensile stiffness profile correlated with the strain profile after drying under a positive prescribed strain. After drying under a negative prescribed strain, on the other hand, the tensile stiffness profile did not correlate with the strain profile. It is thus clear that the tensile stiffness cannot always be used to predict runnability problems.

In the case of positive strain, the wet streak was strained together with the less moist paper. In the wet streak with 80 % moisture content, the fibre network is probably not activated by the strain but the fibres merely glide in the bonding points. The paper with a moisture content of 50 % next to the streak is, however, in a moisture region where strain affects tensile stiffness considerably [36]. An uneven tensile stiffness was therefore obtained for samples subjected to positive strain during drying.
Figure 14: Tensile stiffness profiles for two levels of prescribed strain. Both trials were unloaded at the maximum drying stress. Filled dots show the position of the initial moisture streaks.
5.1.2 Paper II

One question unanswered by Paper I was how great the differences in moisture can be without problems being encountered. Another question posed was in which part of the paper machine moist streaks disturb the runnability of the end product the most. The moisture profile in a paper machine is generally measured at the pope and, if possible, the process is adapted so that the moisture profile is even at that point. The plastic strain is, however, greatest in wet fibres [37] so the question arises whether the moisture profile should in fact be corrected earlier in the machine.

Paper II investigated the plastic strain of isotropic laboratory sheets after loading to a specified total strain and immediate unloading. The moisture content and the total strain were both varied. The samples were formed directly in the sheet former using a mould (Figure 15) and were only dried once, reaching the intended moisture content directly. The plastic strain is shown in Figure 16. The total strain should be interpreted as the draw in the machine.

Figure 15: Wet paper strips made using a mould.

Figure 16 shows that the maximum plastic strain occurred when the moisture content of the paper was between 15 – 25 %. It is, however, the most pronounced slopes of the curves that show where the paper is most sensitive to moisture streaks, which was at the dry end in particular. At the wet end the slope was also pronounced, although negative. This means that if moist streaks appear at high moisture contents, they would turn into tight streaks, whereas moist streaks appearing at low moisture contents would turn into slack streaks.
In order to interpret these results more easily, the strain difference in a paper with a wet streak was calculated. Figure 17 shows the moisture contents and moisture differences at which the absolute strain difference is above 0.1 \%, which is Roisum’s criterion for runnability problems [4]. This occurred at both the dry end and the wet end.

In the dry end of a paper machine, moisture differences usually have dried out and the draws are very low. At high moisture contents, e.g. in the press section, the draws can be quite high and the moisture differences too. Consequently, the most moisture-induced runnability problems probably occur as a result of moisture streaks early on in the machine. The origin of the problems may then be either in the forming or the press section. Whilst it is important to have an even moisture profile at the pope, it is also important to have an even moisture profile when the paper first starts to carry load and is subjected to draws.

Figure 16: The plastic strain after loading to a total strain and then unloading. The total strain (the draw) is given in the figure.
Figure 17: Contour plot of the calculated strain difference arising from the moisture difference shown for different moisture contents and draws. Contour lines for +0.1% and -0.1% strain difference are shown. The grey area is the risk zone for runnability problems.

In addition to the laboratory study, a trial was performed on a sack paper machine in which moist streaks were added in the middle of the dryer section. Figure 18 shows the strain profile plotted together with the moisture profile at the pope. The strain profile correlated clearly with the moisture profile: the moist streaks had become tight streaks, confirming the results from the laboratory study qualitatively, as well as the results from the experiments in Paper I.

Although the strain differences arising in this trial were relatively high, no runnability problems were encountered when this sack paper was converted (i.e. coating with polyethylene), despite the fact that the strain difference was greater than 0.1%. The paper web had some tight streaks, as seen in Figure 18. Presumably there would have been more problems if attempts had been made to convert a paper web with slack streaks instead.
Figure 18: Results from a trial on a sack paper machine with moist streaks added in the middle of the dryer section. The moisture profile (filled black area) taken from the pope is shown together with the strain profile after unloading (grey line).
5.2 Calendering

The load profile in the calendering section may be uneven for several reasons. The calender roll may be uneven as a result of heat or wear, or the paper may be uneven (Figure 19). It is possible that all of these factors can give rise to an uneven strain profile in the MD, and thus produce a baggy web.

![Figure 19: Two possible causes of uneven calendering compression profiles: a thick streak in the paper (left) and uneven calendering rolls (right).](image)

5.2.1 Paper III

The aim of Paper III was to investigate whether an uneven calendering load can give rise to significant differences in strain. An uneven load profile was created by calendering samples of DSF paper with thick streaks, with the MD in the calendering direction. Three types of laboratory calendering experiments were performed (Table 4). The first involved paper samples with even grammage profiles and moisture contents being calendered and the MD strain measured. In the second, samples with uneven grammage profiles and/or uneven moisture profiles were calendered and the creases that appeared was evaluated visually.

The third and last type of experiment was to calender samples of different grammage simultaneously and then measure the MD strain difference between the samples. The aim was to evaluate the effect uneven load profiles on the MD strain profile. The effect of an uneven load profile was, however, within the experimental uncertainty. The relationship between the MD strain and creasing rating was therefore determined by comparing the first two types of experiment.
Calendering conditioned samples of different grammages showed that during calendering, high-grammage samples received a negative MD strain and low-grammage samples received a positive strain. However, this effect was not found to be significant on realistically low calendering loads. When samples of different moisture content were calendered, the strain effect was greatest at around 15 – 20 % (Figure 20), which corresponds roughly to the results of in-plane plastic strain given in Paper II. The moisture content was much more important for the MD strain and the ZD compression than was the grammage.

The samples of uneven grammage and moisture profiles showed tilted creases in the area outside the streak (Figure 21). This indicates an excess of paper length outside the thick streak, i.e. the thick streak had received a greater negative strain than the thin area. All of the samples were visually assessed and were

---

**Table 4: Types of calendering experiments.**

<table>
<thead>
<tr>
<th>Moisture content</th>
<th>Grammage</th>
<th>Load</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Even samples</td>
<td>Even</td>
<td>Even</td>
<td>Even</td>
</tr>
<tr>
<td>Uneven profiles</td>
<td>Uneven</td>
<td>Uneven</td>
<td>Uneven</td>
</tr>
<tr>
<td>Separate samples</td>
<td>Even</td>
<td>Uneven</td>
<td>Uneven</td>
</tr>
</tbody>
</table>

---

**Figure 20:** The MD strain due to calendering as a function of the moisture content. Two different grammages are shown. The error bars show the 95 % confidence interval.
allocated a grade from 0 – 5, where 0 meant no creasing and 5 meant extensive creasing.

When only the moisture profile was uneven, creases only appeared parallel to the MD as a result of poor CD tension and bending stiffness, which was no evidence of MD strain differences. When only the grammage profile was uneven, no creases appeared at all. It thus seems that differences in both grammage and moisture are necessary in order to create significant MD strain differences.

Figure 21: A typical creasing pattern found in samples with uneven grammage and moisture profiles. The edge on the left hand side entered the calender first. The arrows point out the creases. The contrast has been increased in this image.

Figure 22 shows the result of combining the calendering of even samples with the evaluation of creases in uneven samples. This figure was created by using the curve fit in Figure 20 to calculate the strain difference for some specified moisture contents and moisture differences. The curve fit for the visual evaluation data (see Paper III) was then used to calculate the crease rating for the moisture difference in question. The rating could then be plotted versus the calculated strain difference.

Significant creasing appeared as early as at an MD strain difference of about \(-0.03\%\) (Figure 22), depending on the moisture content of the sample. The paper seems to be more sensitive to creasing at low moisture contents. The agreement between the points measured and the results calculated from curve fits is not perfect, but it is important to keep in mind the fact that the rating of the samples are only integral values. Almost all of the samples had a negative strain difference between the thick streak and the thin areas, but in the few samples that had a positive strain difference, a tendency towards a mirrored trend towards the positive side can be seen (Figure 22).
Figure 22: Visual rating of creasing shown as a function of MD strain difference, shown at three different moisture contents. The points show the rating of the actual samples; the lines are calculated from curve fits. The numbers on the lines show the absolute moisture difference.

The total compressive energy transferred to the paper was very high in this investigation, since the speed of the laboratory calender is low. The strain differences and the formation of creases occurred in the same nip. This may cause the paper to be more sensitive to creasing than if strain differences from the calender had caused creasing in subsequent converting. It is possible that the critical strain difference would, in that case, be higher.
5.3 Ridges in reels

A ridge is a “raised band or ring of material around the circumference of a reel” [38]. An example is a systematic local thickness increase in the paper, which then causes an uneven reel diameter (Figure 23).

![Figure 23: A paper reel with ridges.](image)

5.3.1 Paper IV

The aim of Paper IV was to investigate whether long-time stress relaxation in a ridge of a paper reel could give rise to significant differences in permanent strain. The investigation was performed on paper strips of the machine-made paper grades described in the “Materials” section. Relaxation tests were performed, i.e. the paper strips were subjected to a prescribed strain and the load was recorded. The duration of the test was 1 week, after which the strip was unloaded and the length of the strip was measured after 1 min. The plastic strain was thus determined.

This data was used for calculating the expected MD strain difference in a reel with a ridge of a certain height. A geometrical model of a paper reel was used for this purpose:

\[
\Delta \varepsilon_{perm} = A \cdot \frac{h}{r_0},
\]

where \(\Delta \varepsilon_{perm}\) = permanent strain difference, \(A\) = material parameter determined from relaxation tests, \(h\) = ridge height and \(r_0\) = reel radius.
The three different paper grades did not differ greatly in strain differences, although the MG paper was somewhat more sensitive to long-term straining. Assuming that the maximum runnable strain difference in a paper web is 0.1 %, the maximum ridge height that was allowed was 1 – 1.5 mm when the reel diameter was 1.2 m. When the reel diameter was 1.8 m, the maximum ridge height calculated was 1.6 – 2.2 mm (Figure 24). It was then assumed that separate paper strips behave in the same way as a continuous paper reel.

Figure 24: The calculated strain difference as a function of the ridge height. Two different reel diameters are shown.
5.3.2 Paper V

The calculations made using the geometrical model in Paper IV required experimental verification. Controlled ridges were created by winding thin either polyethylene film or aluminium foil into reels of the same machine-made paper grades as were tested before. A reel prepared with aluminium foil is shown in Figure 25.

![Figure 25: A reel with a ridge of aluminium foil.](image)

The reels had a diameter of 1.2 m and width of 1.4 m. The film and foil were 100 mm in width and 5 – 6 µm in thickness. The reels were unwound after one month, the film/foil was removed and the web tension profile and web strain profile were measured with the WTPA.

Slack streaks appeared in the position where the film or foil had been both before and in the region of the film/foil (Figure 26). The region of slackness before (i.e. radially outside) the film was very small: paper is compressible and its ability to even out disturbances in thickness in a reel is therefore good.

![Figure 26: A slack streak made by a ridge of polyethylene film.](image)
Figure 27 shows the strain difference between the ridge and the rest of the reel when aluminium foil was wound into the whole reel of an 80 g/m² liner reel. The strain difference was about 0.14 % at the surface of the reel where the ridge height was about 2 – 3 mm. In the middle of the reel, however, there was a part with almost no slackness at all in the reel. The strain difference then increased again, but at the very end of the reel, i.e. closest to the core, the streak was instead tight. Possibly the tight streak is the result of a “calendering effect” due to the high compression in the ZD that, in turn, results in shortening in the MD.

![Graph showing strain difference](image)

*Figure 27: The strain difference between the ridge and the rest of the reel, as a function of the MD position in a 80 g/m² liner reel.*

A strain difference of 0.2 % was calculated for the surface of the 80 g/m² liner reel when the model from Paper IV was used. The model thereby overestimates the strain difference slightly, since the experimental value was 0.14 %. Presumably shear forces between the ridge and the rest of the reel make the strain difference smaller than when separate strips are considered.

The only mechanical property that was affected by the ridge was the strain-at-break, and then only in the outer part of the reel, where it was significantly lower than in the rest of the reel (Figure 28).
Figure 28: The strain-at-break in the ridge and beside the ridge as a function of the MD position in the reel. The error bars show the 95% confidence interval.
5.4 Summary

The results obtained in the different trials are summarized in Table 5. In the case of thick streaks during storage, it was assumed that a reel diameter difference of 0.5 % also corresponded to a grammage difference of 0.5 %.

Here, trials on DSF and random sheets have been compared indiscriminately with machine-made sheets. The DSF sheets had about the same anisotropy as the machine-made sheets, with the exception of the first drying trial, when they were tested with the CD in the primary direction. Some of the DSF sheets were never-dried and some were rewetted but, as they were all made from flash-dried pulp it was assumed that they had the same degree of hornification. The DSF sheets were made from pure softwood kraft pulp and the machine-made papers were made primarily from softwood kraft pulp.

*Table 5: Summary of strain differences due to different irregularities.*

<table>
<thead>
<tr>
<th>Moisture content difference [%]</th>
<th>Moisture content difference [%]</th>
<th>Grammage difference [%]</th>
<th>MD strain difference [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moist streaks during drying</td>
<td>50</td>
<td>30</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>35</td>
<td>6</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>Thick streaks in calendering</td>
<td>8</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>Moist streaks in calendering</td>
<td>8</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>Thick streaks during storage</td>
<td>8</td>
<td>0</td>
<td>0.5</td>
</tr>
</tbody>
</table>
6 General discussion

The short summary shown in Table 5 is a great simplification of the results obtained in this thesis. The moisture content is, as shown in Papers II and III, an important variable, along with the draw or tension. The relative importance of the different factors is nevertheless apparent. Variations in thickness (e.g. grammage), which increase the risk of ridges being formed, seem to be the most important issue that must be tackled if runnability problems are to be avoided. Variations in grammage also are a source of variations in moisture content, which should be examined too.

Variations in moisture appear to be not so important in Paper I. The strain difference in the first row of Table 5, which is for paper of extremely low anisotropy with a high starting moisture difference, is still quite low. The strain difference in the MD would be even lower. In Paper II, on the other hand, moisture variations seem more plausible as being a cause of significant differences in strain, although smaller values are expected even here for the MD than for the isotropic samples tested. No runnability problems were experienced when converting paper from the machine trial with moist streaks but, the distribution of the strain differences was probably not the most harmful possible. The distribution of the strain differences is a very important issue for runnability.

Variations in moisture can also give rise to significant strain differences in calendering. The distribution of the variations in moisture should be important even here. It may be presumed that the type of nip (hard or soft) would also make a difference.

The in-plane plasticity of the paper tested is the greatest at a moisture content of around 20%. This was observed in both Paper II and Paper III. In the former, the decrease in plastic strain at low moisture contents was accompanied by an increase in tensile stiffness. At high moisture contents, on the other hand, no significant change in tensile stiffness occurred together with the decrease in plastic strain. It is unclear why the plastic strain was at its highest when the moisture content was at a medium level.

The permanent MD strain difference is thus affected in a complex way at different moisture contents and moisture differences. At high moisture contents, a wet streak became a tight streak after drying and at low moisture contents, a wet streak turned into a slack streak after drying. Judging from the shapes of the curves, the results may indicate that a large difference in e.g. moisture content gives rise to a smaller strain difference than a smaller moisture difference would. Such a high moisture difference is, however, rarely found in the industry. Generally speaking, it is probably safe to claim that reducing the differences in moisture will also reduce differences in MD strain.

Some of the experimental investigations were performed on separate paper strips
with differing degrees of moisture content, grammage, etc. rather than on paper containing streaks with differing properties. It was then assumed that the behaviour of the separate strips reflects the behaviour of a paper web with areas of these specific properties. In reality, there are shear forces between areas that shrink or strain differently. These shear forces should decrease the actual differences in strain, since the parts constrain each other. Comparing the difference in strain in Papers IV and V, calculations for strip experiments were compared to experiments using continuous paper with streaks. The strip experiments showed greater differences in strain, which was as expected.
7 Conclusions

Three hypotheses were evaluated in this work, with the following results:

- During drying, moist streaks are stretched together with less moist areas, causing an uneven permanent strain in MD.

True. Moist streaks that appear early at an early stage in the paper machine can result in the formation of short streaks. The strain differences in paper from the tested chemical pulps were great enough to cause problems when the moisture difference was at least 6% at the start of the dryer section. Although problems can also occur later in the machine, the risk is mainly theoretical, since the draws and moisture differences are then low.

- An uneven calendering load causes an uneven permanent strain in MD.

True. An uneven load profile created by calendering a paper with an uneven grammage as well as an uneven moisture profile can cause creases to form immediately in the nip. This occurred at a strain difference of about −0.03% in the MD or a difference in compression of 2% in the ZD. Paper is much more sensitive to differences in moisture than in grammage. The grammage can vary greatly without causing problems provided that the difference in moisture does not exceed 1 – 2%. More research is, however, needed on the maximum difference in grammage that can be tolerated before there is a risk of creasing.

- A paper reel with ridges (uneven diameter) is subjected to an uneven permanent creep strain in MD during storage.

This was also found to be true. Quite small ridges of around 3 mm height, when the reel diameter is 1.2 m, result in permanent differences in strain at around 0.14% at the top of the reel. The behaviour can be explained reasonably well with a geometric model using stress relaxation data. Ridges only appear if there is a systematic disturbance in thickness and are quickly evened out after the end of the disturbance.

One aim of the work described in this thesis was to rank the hypotheses according to their tendency to cause runnability problems due to bagginess. It was found that the greatest risk was posed by the ridges, followed by calendering paper with moist and thick streaks and, finally, moist streaks present during drying.
8 Suggestions for further research

In the work described in this thesis, the effect of streaks with high grammages and/or moisture contents were evaluated in different process steps. This could be developed by examining the way in which streaks of high grammage influence the web during drying, and how streaks with high grammages and moisture contents affect reels during storage. In this particular study, creases were seen to appear directly in the calender nip. Further studies performed on the formation of creases in subsequent converting after the nip are recommended, since the critical strain difference might then be different.

An expansion of this research could be to test how streaks of different fibre orientation affect the paper, e.g. by making oriented sheets and then making paper strips at different angles. The plasticity of these strips could be evaluated at different moisture contents, as in Paper II. The effects of long-time relaxation could be tested, as in Paper IV.

A model of the drying process could show how the different moisture contents of the streaks and the rest of the paper affect the resulting MD strain differences. It is necessary that the strain profile in the paper during the drying process be known if deeper understanding of the mechanism of the formation of short streaks caused by moist streaks is to be gained. This could be achieved either by modelling or making measurements. The combination of different draws at different moisture contents also requires further examination, using Paper II as a starting-point. The models of Mäkelä [39] and Wahlström [40] could be of use here, too.

The maximum strain difference that can be tolerated should be evaluated in more detail. This limit depends not only on the distribution in the web and the distance between the maximum and minimum point in the web tension profile, but also on the type of converting used. A possible approach is to create different strain profiles by using samples with different moisture distributions, dry the papers and then pass them through a calender. A nip is a hard test for a baggy web, so a conservative limit is therefore obtained that can be used as a guideline.
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Karlstad, November 1, 2010

Cecilia Land
References


Moisture streaks and their relation to baggy paper webs

Cecilia Land, Torbjörn Wahlström and Lennart Stolpe

Abstract

Significant and controlled wet streaks were imparted to laboratory-made kraft paper sheets having an initial moisture content of 50%. The sheets were then dried under a specified strain according to different drying strategies. Both the wet streaks and the drying strain were applied in the CD in order to amplify the observed effects. The bagginess of the paper sheet, or the length profile, was measured after drying and relaxation. Moisture streaks remaining after unloading resulted in short streaks in the paper. Drying of the paper beyond moisture equilibrium also led to an uneven paper length, particularly when the paper was allowed to shrink during drying. No correlation was found between the tensile stiffness profile and the permanent length profile.

Keywords: bagginess, drying, paper, shrinkage, slack areas, strain, tensile stiffness.


1 Introduction

Slack areas in paper webs are regions where the web is longer than the neighboring regions. The length difference is usually very small, but a difference of only 0.1% (1 mm/m) leads to serious runnability problems on almost any material or product [1]. Such problems appear primarily in converting processes, where the web tension is low and slack parts may not be stretched out by web tension. Problems are especially likely to appear when the paper web passes through a roller nip. The excess paper in the longer streaks gathers before the nip to eventually pass through and cause creasing. Another common problem that can appear is misregister in printing. Webs with length differences are commonly referred to as “baggy webs”.

The origin of baggy webs can vary greatly. Defects in the converting machines are often the cause; e.g. if rollers are not properly aligned the paper is unevenly stretched [1]. On the other hand, the problems can be due to variations in the
paper web. Streaks of different lengths may have been present already on the paper machine. There, paper is deformed permanently in its in-plane directions, primarily in the press and dryer sections. As an effect of water removal during drying, the dimensions of the paper web are reduced by shrinkage. If there are wet streaks in the paper when it enters the dryer, those streaks may shrink differently from the rest of the web.

The hypothesis in this study was that paper that has wet streaks would acquire an uneven length profile after drying under a prescribed strain. Mäkelä [2] presented a mathematical model showing that wet streaks can become short streaks after drying under certain circumstances. In the present study, this case was studied experimentally and in greater detail. Different prescribed strains give rise to different tensile stiffness values [3]. Drying tests were therefore performed under different strains. Different drying strategies were tested to evaluate which mechanisms are important.

2 Method

2.1 Sample preparation

Commercially manufactured, flash-dried, bleached softwood kraft pulp was beaten in a PFI mill to 17 SR and sheets were made on a Formette Dynamique sheet former. The rotational speed was 1200 rpm and the nozzle pressure was 3 bar. The tensile stiffness anisotropy (MD/CD) of restrained dried sheets was 2. One sheet was cut into two samples, each with area 350x215 mm$^2$. After pressing twice in a roll press (at 250 kPa and 450 kPa), the paper was sealed in a plastic bag to prevent moisture evaporation.

Just before drying, two wet streaks of width 35 mm were added to the sheet, evenly spaced on the paper. For this purpose, a plastic sheet template (Figure 1) was used. The moisture was added by dabbing the paper with a wet tissue, which was weighed to determine the amount of moisture added. The moisture content of the sheet was about 50% before adding the streak. The resulting moisture streak had a moisture content of about 80% which corresponds to the paper being completely saturated with water. The positions of the streaks were marked with a pen.
2.2 Drying

The paper samples with wet streaks were fastened between two heated clamps and were positioned 70 mm from an IR heater (Figure 2). This device, the Dryer Section Simulator, has previously been described by Wahlström & Lif [4]. In the present investigation, the device was inserted in a Zwick Z010 material tester (Zwick GmbH, Germany). The cross-machine direction (CD) of the paper was placed in the load direction (1-dir in Figure 2), to amplify the effects that tend to be small. Paper is more sensitive in CD than MD regarding the effects of strain, hygroexpansion and drying shrinkage on paper properties. At first, measurements with the MD in the load direction were attempted, but no effects could then be seen. Another reason for placing the CD in the load direction is that the transverse (2-dir) shrinkage is minimized, necking and thus edge slippage in the clamps is avoided, and the length measurements are less disturbed by transverse effects.

The anisotropy of the paper was thus 0.5 if the load direction is considered to be the primary direction.

After mounting, the sheet was stretched to a line load of 45 N/m which was chosen as zero strain to avoid initial slackness. The sheet was then dried under constant strain, with a heater temperature of 80 °C. Two different strain levels were tested, +2 % and −3 %. The drying span length was 150 mm.

When the paper was dry, immediately before the clamping pressure was released, two lines were drawn on the paper as close as possible to the clamps, resulting in two parallel lines with a distance of 150 mm, parallel to the clamps. To make sure that no slippage occurred in the clamps during drying, tests were at an...
early stage performed with similar lines sprayed on the paper before mounting, with spray paint and with help of a template.

After the paper had been released, it was immediately cut into 6.2 mm wide strips in the load direction, and these strips were then allowed to reach moisture equilibrium at 23 °C, 50 % RH.

2.3 Evaluation

After a minimum of 3 h, the length of each strip, between the two previously drawn lines, was measured with a high precision slide caliper (accuracy 0.03 mm) along both edges of the strip. These data were then used to obtain the profile of permanent strain in the paper.

The mean length was calculated for those strips that were positioned entirely outside the streaks; 30 mm at each edge of the paper was excluded to remove edge effects. Another mean length was calculated for the strips that were positioned entirely within the streaks. The difference between the two mean values, expressed as a percentage of the drying span length (150 mm), was defined as the permanent length difference. A 95 % confidence interval for the length
difference was also calculated.

Some experiments were performed without length measurements to determine the moisture content gravimetrically. In this case, the clamped areas were removed after drying and the dried paper was then cut along the borders between the earlier wet and dry positions, leaving five measuring positions (1 – 5 in Figure 1). Each part was cut into two pieces and average moisture values were calculated for each position. The moisture contents were determined both immediately after releasing the paper and after conditioning.

At least 48 h after drying, the tensile properties were measured on the paper strips with an Instron 4411 (Instron Corp), in accordance with ISO 1924-2 but with span length 100 mm and width 6.2 mm. Average tensile stiffness values were computed for the paper regions referred to above.

3 Results

3.1 Drying strategies

The two different strain levels tested represent two different strain situations in the dryer section. A positive speed difference in the dryer section results in a positive strain. The negative strain simulates a negative draw in the dryer section, when the paper is allowed to shrink in MD to a certain degree.

For each strain level, five different drying strategies (Table 1) were tested. Two aspects were varied: the criterion for releasing the paper, and the drying method. The paper was released either at the load peak (Figure 3) or after the load had leveled out. The two drying methods used were IR drying and room-temperature drying.

Drying with an IR dryer was used to dry the paper to below its equilibrium moisture content (overdrying). Without IR, it was only possible to dry to equilibrium with the ambient humidity (23 °C, 50 % RH). In some cases, the drying method was changed from IR to room temperature at the load peak, in order to further explore the drying mechanisms.

At the load peak, streaks with different moisture content remained (Figure 4), but when the load curve had leveled out, it was concluded that the streaks and the surrounding paper had reached the same moisture content. This conclusion can be drawn because no further shrinkage or relaxation then occurs. The moisture status at the point of release is summarized in Table 1.

During drying, the load typically changed with time as shown in Figure 3. In the initial phase of the test, the applied strain, +2 % and −3 %, was reached.
Figure 3: Load during drying at the different strain levels. The drying was performed according to drying strategy 2 (described in Table 1).

Table 1: Drying strategies (DS) for both positive and negative strain. Peak and Level are defined in Figure 3.

<table>
<thead>
<tr>
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<th>DS 1</th>
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<th>DS 3</th>
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<td>Start to Peak</td>
<td>IR</td>
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<td>Room</td>
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<tr>
<td>Peak to Level</td>
<td>-</td>
<td>Room</td>
<td>IR</td>
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<tr>
<td>Release at</td>
<td>Peak</td>
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<tr>
<td>Moisture status at release</td>
<td>Overdried, streaks (Previously remaining overdried)</td>
<td>Equilibrium</td>
<td>Overdried</td>
<td>Streaks</td>
<td>Equilibrium</td>
</tr>
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</table>

In the case of a positive strain, the paper relaxed somewhat in the beginning whereas in the case of negative strain the load started at zero. In both cases, shrinkage and thereby stress buildup then started. At a certain point, the rate of stress increase is equal to the rate of relaxation and the load curve passes through a maximum. Thereafter the stress decreases. When the paper has reached its final dryness (about 90%) the shrinkage and the associated stress buildup stop and only relaxation occurs. The speed of relaxation decreases and finally the curve starts to level out.
3.2 Length differences

During drying, buckling was seen in the moisture streaks, indicating that they were longer than the rest of the paper. With time the buckling gradually disappeared as the streaks were shrinking and was gone well before the peak in Figure 3.

When the paper strips were cut after drying, no cockling or bagginess was visually observed in the location of the moisture streaks. The measurements of profiles of permanent length (Figure 5) show, however, that in most cases the strips located in the moisture streaks had become shorter than the rest of the paper.
Figure 5: Examples of measured length profiles for drying strategy 1 (black line) and drying strategy 5 (grey line). The filled dots show the position of the moisture streaks. Both experiments were performed at a prescribed strain of +2 %.

Figure 6 shows the permanent length differences after drying according to the different drying strategies. The greatest length differences were observed when there were streaks of different moisture left when the paper was released (drying strategies 1 and 4).

There were also length differences in the paper without remaining moisture streaks if the paper had been overdried (drying strategies 2 and 3). Even when the paper was brought to moisture equilibrium while still in tension (drying strategy 2), the length differences remained, at least in the case of negative prescribed strain.

There were no length differences when the paper was dried to moisture equilibrium and was kept under tension until the load curve had leveled out (drying strategy 5). After the paper had been dried to moisture equilibrium, and without any remaining stress relaxation potential, there was nothing that could cause length differences to appear.

This applies if the paper is tensed under straight conditions, so that no slackness is created by improperly aligned clamps or rollers in a paper machine. In some experiments, the clamps were not properly aligned and a tilted profile was observed. These profiles were mathematically treated to remove this trend and thus isolate the effects from the streaks.
Figure 6: Permanent length difference (average values) between the paper beside and within the streaks. The drying strategies are explained in Table 1. The error bars show a 95% confidence interval for the length difference. One point represents one experiment.

Figure 7 shows the tensile stiffness in the streak and non-streak positions. The tensile stiffness did not vary greatly with drying strategy, which is in agreement with Persson et al. [5] who saw no change when drying at different temperatures, and with Östlund [6] who only saw small variations in elastic modulus in a similar study.

Under a positive strain, there was a difference in tensile stiffness between the streak and non-streak positions, whereas in the case of negative strain there was no difference.
Figure 7: Average tensile stiffness in streak positions and in the rest of the paper. The results are shown for the two different prescribed strains during drying. The error bars show 95% confidence intervals.

4 Discussion

4.1 Mechanisms

The paper is able to change in length only after the tension has been released, hence length differences can only arise thereafter. The length after release could however be affected by physical changes in the paper created while the paper was under tension.

Drying strategies 1 and 4 led to moisture streaks remaining in the paper. After drying with strategy 1, the whole paper was dryer than corresponding to moisture equilibrium with the laboratory climate. The paper was then free to change its dimensions by hygroexpansion after being released. After drying strategy 4, the paper was still moist. It was then allowed to change dimensions by drying shrinkage.

Because of the different moisture contents in the different positions, these dimensional changes give rise to length differences. The moisture difference at the time of release was \(0.5 - 1\%\) in both cases, which seemed sufficient to give significant length differences. The load curve had not leveled out, so that an uneven stress relaxation might also lead to length differences in those cases. The remaining moisture streaks seem however to be a more probable reason for the length differences. These length differences appear in addition to the ones caused by the physical changes in the paper.

The physical changes in the paper depend on the strain level, as the two strain
settings were quite different. Under a positive strain there was tension in the whole sheet throughout the drying period, although it was slightly lower in the wet streak.

When shrinkage was allowed, the whole paper dried freely in the start of the experiment under zero tension. As the shrinkage progresses, the paper beside the streaks first starts to bear a load and thereafter the streaks also start to bear a load. The whole paper is thus subjected to the same shrinkage process at the same moisture contents, but at different times. The wet streak dries freely for a longer time than the paper beside the streak, but this does not seem to affect the tensile stiffness profile. This has earlier been shown for papers dried under restraint [7].

In the case of a positive strain, however, the wet streak was strained together with the less moist paper. In the 80% wet streak, the fiber network is probably not activated by the strain, but the fibers merely glide in the bonding points. The paper with 50% moisture beside the streak is however in a moisture region where strain affects the tensile stiffness considerably [8], and an uneven tensile stiffness profile was obtained in the case of positive strain during drying.

The difference in tensile stiffness between wet streaks and positions beside the streak within a sample was approximately the same for a given strain level, regardless of the drying strategy (with the possible exception of drying strategy 5). Consequently, there is no unequivocal correlation between the tensile stiffness profile and the length profile. This indicates that a uniform MD tensile stiffness profile in a paper web is no guarantee against bagginess.

It is also unknown exactly how baggy different paper grades can be without causing runnability problems. The 0.1% length difference mentioned earlier is not an absolute limit. It merely represents a level at which any web, paper or other material typically has problems [1]. Problems can appear at much lower length differences, especially for thin paper webs, and depends on the type of converting process. The bending stiffness of the paper is probably an important parameter. Also, how the length differences are distributed on the paper should affect the runnability. A web with a few slack streaks is probably more sensitive to problems than a web with a few short streaks.

After overdrying, moisture hysteresis occurred. The equilibrium moisture content after overdrying was higher in the streak positions (Figure 4, drying strategy 1), so that the paper beside the streaks could not take up moisture to the same level as the lesser dried streaks. This should actually result in smaller length differences, since the hygroexpansion in the paper adjacent to the streaks would be lower and they would be shorter. The length differences were however as high, or even higher, after drying with strategy 1 than after drying with strategy 4 which involved no overdrying. Overdrying thus worsens the problem.

This was also observed after drying with strategy 2, where the stress and mois-
ture status at the time of release resembled those after drying strategy 5, where no length differences were seen. In strategy 2, where the paper was previously overdried, short streaks were however present. The moisture hysteresis is probably accompanied by a length hysteresis, which means that the short streaks remain in drying strategy 2. The mechanical properties, on the other hand, were not particularly affected by overdrying.

The measurements show the length after tension release, and they were performed after relaxation, and sometimes moisture changes, on free strips. The changes occurring in the strips are hard to separate from physical changes in the paper during drying under tension. A hypothesis to evaluate in future studies is that during drying, the dry parts of the sheet bear a higher load than the wet parts. Then the dry paper is subjected to a higher plastic strain than the wet parts, and when the paper is fully dry the former wet streaks are tighter (have a higher tension) than the rest of the paper. A logical conclusion of this hypothesis is that a paper web with dry streaks would turn into a paper web with slack streaks after drying.

### 4.2 Relation to paper machine

It is a well known fact among papermakers that baggy webs can occur in the paper machine. The most well known example are the “slack edges” often occurring on edge reels of the machine reel, but slack areas in other parts of the web can also occur. There is reason to believe that uneven CD moisture profile during drying can cause such length differences and this work aimed at investigating this hypothesis.

The causes of uneven moisture profile can be several, but uneven moisture profile from the press section seems to be the most evident one. Uneven temperature profile on drying cylinders as well as uneven tension profile or uneven permeability profile of the drying wires could also contribute. An uneven moisture profile early in the drying section might not be detected as an unacceptable unevenness in the final moisture profile due to the equalizing effect of the drying process.

The conditions in these experiments may deviate from those in a paper machine. The aim of this research was however to study how the different mechanisms interact. This is done best by exaggerating, like using a large moisture difference and applying the load in the CD of the paper. Exaggeration was particularly necessary in this study, when working with very small length differences that were difficult to measure.

The initial moisture difference in these experiments was very high. However, the differences in permanent length difference are probably occurring at a lower moisture content, when the fiber-fiber bonds are getting strong enough to give a considerable elastic strain. This lower moisture content also means that there
was a lower difference in moisture, since the wetter parts of the sheet dry faster. The moisture difference of $0.5 - 1\%$ that remained when the paper was removed was of an order that might be found after drying in a paper machine.

The drying rate in these experiments was low compared to that of a paper machine, but the drying time and temperature do not influence the tensile stiffness of the paper if the time and temperature are varied together [7]. The other mechanical properties would probably not be affected either. It is possible that length differences might be affected, however, since they did not fully correlate with tensile properties.

Because of the low drying rate, it could be argued that moisture migration between the streaks and the rest of the paper occurs. This does not seem to have occurred to a significant degree. After drying partly (drying strategy 1 and 4) the remaining moisture streaks were still situated in the same locations. This was seen in moisture measurements. The length measurements also support this claim, since they showed an exact match between the location of the moisture streaks and the short streaks (Figure 5).

The length difference that arose from the streaks was well over 0.1 \%, indicating that this is an issue that the papermaker needs to deal with to avoid bagginess. In these experiments, the paper was oriented in the CD which magnifies the effect, but a paper oriented in the MD should also show such tendencies, especially if the pulp is highly beaten. These papers were made of pulp with quite a low degree of beating. For restrained dried papers the same physical behavior prevails in MD and CD, it is just a matter of the number of fibers in the different directions.

Measuring the paper oriented in the CD was necessary to get sufficient accuracy in the length measurements. To further improve the accuracy, the samples were cut in many strips (about 50). Still, an even greater accuracy would have been desirable. For making trials with greater accuracy, perhaps even with the MD in the load direction, a very long distance between the clamps would be needed. To perform such experiments there are many practical details that need to be solved. Drying evenness, for example, may be hard to achieve. Also the slide caliper would need to be replaced with some other method and there are not many appropriate methods with as good accuracy.

An almost equally important reason to do the measurements in the CD was to avoid transversal shrinkage. In a free draw in a paper machine the boundary condition for the paper is dynamic and determined with rollers. Using clamps and a static boundary condition, as in this study, fixes the ends completely and no transversal shrinkage is allowed close to the clamps. In the middle of the sheet however, the paper shrinks and necking occurs. Necking results in the paper edges becoming bent during drying. This disturbs the length measurements, primarily near the edges. By putting MD in the transversal direction, the
transversal shrinkage was very low and thus the problem described was avoided.

Based on the present results, it is suggested that the cure for bagginess caused by moisture streaks would be to keep the paper locked in position until the moisture and possibly also stress differences are evened out (drying strategy 5). That is of course difficult to achieve on a paper machine. In the paper roll however, the paper is locked in position but the paper is under MD strain only in the outer layers of the roll. Further down into the roll there is about zero MD strain but a great radial pressure instead. The time in the roll would thus not help to even out bagginess caused by moisture streaks, in the major part of the roll. Even if considering the outer part only, there is another problem. If the roll diameter is uneven, the MD strain would be uneven and the storage time would induce baggy web problems, rather than reduce them [9, 10].

5 Conclusions

In this study, wet streaks were applied in the CD of a kraft sheet in order to amplify observed effects related to baggy paper webs. It was found that moisture streaks entering the dryer section can lead to short streaks in the paper, depending on drying strategy. The most serious problems appeared when the paper still contained streaks of different moisture contents when released from the drying unit. When shrinkage was allowed to take place during drying, the short streaks were even shorter. Overdrying worsened the problem. The qualitative mechanisms shown here, primarily from drying strategy 1, should also apply on a paper machine. Especially the statement that wet streaks leads to short streaks should apply.

The short streaks in the paper web were not always accompanied by a difference in the tensile stiffness profile. The problem is complex and involves e.g. the degree of strain during drying. It is concluded that runnability problems cannot be predicted by measuring the tensile stiffness profile.

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References


Cecilia Land. Baggy paper webs: Effect of uneven moisture and grammage profiles in different process steps
Plastic strain of moisture streaks at different moisture contents

Cecilia Land, Torbjörn Wahlström, Lennart Stolpe and Luciano Beghello

Abstract

An uneven moisture profile in the paper web during drying can cause runnability problems due to slack areas in the paper web. This study aims at identifying the moisture level at which it is most important to keep the moisture even. This was evaluated with a laboratory study of plastic strain after loading wet paper samples to strains between 0.3 – 4 % and unloading. The papers tested were made from softwood bleached kraft pulp and the moisture content varied between 9 and 50 %. The plastic strain was highest at a moisture content of 20 – 30 %, but the sensitivity to moisture variations was highest at a moisture content of 10 – 20 %. The paper was also sensitive to moisture variations above a moisture content of 30 %.

According to calculations based on the laboratory results, moist streaks appearing at a high moisture content would turn into short streaks, and moist streaks appearing at a low moisture content would turn into long streaks. A machine trial with moist streaks applied at high moisture resulted in short streaks in the paper, confirming the qualitative results of the laboratory study.

Keywords: baggy web, draw, moisture, paper, plasticity, strain

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1 Introduction

Moisture streaks in the paper machine can lead to MD strain differences and thus runnability problems with the finished paper. Strain differences in paper webs are commonly referred to as baggy webs [1], and these can cause problems such as creasing during converting.

The strain profile after drying paper with moist streaks was evaluated in a
previous study [2]. Formette sheets with wet streaks were then dried in the laboratory under both positive and negative prescribed strain. The moist streaks were introduced in the sheets just after pressing, at 50 % moisture content, and the moisture content of the streak was 80 %. Regardless of the sign of the prescribed strain, the moist streak turned into a short streak. This is presumably because the paper is still under a positive tension due to drying shrinkage.

The wet streaks in the previous study were significant, to demonstrate the qualitative behavior of wet streaks. The magnitude of the moisture differences that can cause problems is not however known. They depend on the rheological properties of wet paper at different solids contents.

The strain imparted to the paper in different parts of the paper machine, the draw, is governed by the speed difference between different machine elements and the drying shrinkage of the paper web. The draw can vary between 2 and 5 % after the press section [3] and it can also be negative, primarily in sack paper manufacture where a high strain-at-break of the paper is desired.

The total strain imparted to the paper web has an elastic part and a plastic part, of which the plastic part remains after unloading. The web is more plastic if the fiber moisture content is high [4].

The tensile strength and tensile stiffness of wet papers has been extensively studied in the literature [3, 5, 6] and there are several standard methods, e.g. SCAN-CM 35:81 for testing never-dried samples and ISO 3781 for testing rewetted samples. Relaxation tests on wet paper have also been reported [3, 7, 8]. The elastic and plastic strain of wet paper is sometimes mentioned but very seldom measured. The aim of the present study is therefore to determine the plastic strain at different moisture contents and use these data to predict runnability in subsequent converting. Such data could answer the question of the position in the paper machine at which it is most important to maintain an even moisture profile.

2 Materials and Methods

2.1 Laboratory tests

Bleached softwood kraft pulp (flash-dried) was beaten in a PFI mill to 20 SR. A mold, in accordance with the specifications in SCAN-CM 35:81, was used in a standard laboratory sheet former to produce paper strips directly, eliminating the need to cut wet paper. The dimensions of the strips produced were 20.0x130 mm and the grammage was 145 g/m². Sheet forming and pressing were otherwise performed according to ISO 5269-1.
The samples were left on drying plates for specified times at 23 °C, 50 % RH to obtain different sample moisture contents. The plastic strain was then tested with two different methods in a Zwick Z050 material tester (Zwick GmbH, Germany), with a test strip span length of 80 mm. This was the maximum length that could be clamped successfully. No pre-drying of the clamped areas was used, since the solids content was high enough to prevent excessive water leakage in the clamps. Each sample was weighed directly after the test and then oven-dried in order to measure the moisture content. The grammage was determined by reconditioning the samples and weighing them again.

The first method (Figure 1a), hereafter referred to as “the standard tensile test method”, was a standard tensile test (ISO 1924-3), except that the span length was 80 mm. The elastic strain, calculated from the tensile stiffness, was subtracted from the total strain to give the plastic strain:

\[
\varepsilon_{pl} = \varepsilon_{tot} - \frac{\sigma(\varepsilon_{tot})}{E}
\]

where \( \varepsilon_{pl} \) = plastic strain, \( \varepsilon_{tot} \) = total strain, \( \sigma(\varepsilon_{tot}) \) = load per width at \( \varepsilon_{tot} \) and \( E \) = tensile stiffness. In the literature this approach has been used in some investigations [8, 9]. In the present investigation, the plastic strain was calculated with total strains of 4 %, 2.8 %, 2 %, 0.8 % and 0.3 %, which were chosen from typical speed differences found in paper machines.

The second method (Figure 1b), hereafter known as “the unloading method”, was a test where the strain was increased to the same total strain levels as above, and the sample was then unloaded with a speed of 100 mm/min. The paper strip was considered to be unloaded at a load of 5 N/m, which was also the pre-load applied in the tests. The remaining strain at that load was recorded as the plastic strain. Other settings of the material tester and the sample dimensions were the same as in the standard tensile test method.

In the standard tensile test method, it was sufficient to do one tensile test at each moisture content and then calculate at different points on the curve, while in the unloading method one test for each strain level, 4 %, 2.8 %, 2 %, 0.8 % and 0.3 %, was performed. In Figure 1, the arrows mark the plastic strain at a total strain of 4 %.
Figure 1: Two methods of evaluating plastic strain, shown with data from a moisture content of 9%. (a): A standard tensile curve, load as a function of total strain, is shown together with the tensile stiffness line, load as a function of elastic strain. The plastic strain is then the total strain minus the elastic strain calculated from the stiffness, noted with an arrow. (b): A tensile curve with unloading is shown. The dotted line marks the total strain and the arrow marks the plastic strain.

2.2 Machine trial

A trial was also performed on a sack paper machine, during the manufacture of an uncreped 70 g/m² unbleached kraft paper. Four wet streaks of different widths were then applied to the web, with a dampening unit in the middle of the cylinder dryer section, where the moisture content was about 35%. After the moisture streaks had been applied, the paper was further dried on cylinders and then in a fan dryer with permitted shrinkage.

The moisture profile of the paper web was measured at the pope and a long paper sample was taken from the top of the reel. Two parallel lines were drawn across the web at a distance of about 4 m and the sample was then conditioned at 23 °C, 50 % RH. The sample was cut into MD strips, and the length of each strip between the lines was measured with a micrometer screw setup described below. A MD length profile was thus obtained.

To measure the length of each paper strip, a paper strip of medium length was first inserted in the setup, shown in Figure 2. The lines on the strip were aligned with lines on each clamp, and the position of one of the clamps was adjusted until the load on the paper strip was 30 N/m. This was measured with a spring gauge fixed to the movable clamp. The position of the micrometer screw was recorded to the nearest 0.01 mm.

The next strip was then inserted in the setup and the clamp was again adjusted until the correct load was reached, and another micrometer screw reading was
taken. The difference in length between the two strips was thus obtained. To obtain the length difference as a percentage, the absolute length of the first strip was measured with a tape measure. The length difference profile, or strain difference profile, could then be calculated by subtracting the average value.

To measure the length of 4 m long strips in this setup, each strip was measured as the sum of two measurements. First 2 m was measured and a line aligned with the clamp was drawn. The rest of the strip was then measured.

To test the runnability during converting of the paper, it was coated with polyethylene (PE). No measurements were performed but visual observations.

![Figure 2: Setup for measurement of length profile.](image)

3 Results

3.1 Laboratory tests

The results obtained by the two different methods for evaluation of plastic strain differed, as the standard tensile test gave a very unclear trend. The curve obtained by the unloading method seems to be the maximum curve which the data from the standard tensile test sometimes reached (Figure 3).

At a low moisture content however, the plastic strain was larger in the standard tensile test method (Figure 3). The determination of plastic strain using Equation (1) assumes that the slope during unloading is the same as during loading, and this did not seem to be a good assumption at all moisture levels. The dry papers, in particular, exhibited quite a large non-linear relaxation, which was missed when the plastic strain was calculated using Equation (1).

At high moisture contents, another problem appeared in the standard tensile tests. It was then difficult to measure the tensile stiffness accurately since the slope is difficult to define when the elastic region is very small. This leads to unstable plastic strain results. The data from the unloading tests were much
more well-defined. Consequently, the study continued with tests based solely on unloading.

![Figure 3: A comparison of the different methods to determine plastic strain. The total strain was here 2.8%. Each point represents one measurement.](image)

Figure 4 shows the plastic strain as a function of the moisture content. The maximum plastic strain was observed at moisture contents between 20% and 30%.

The average measured grammage of the samples was 145 g/m² with a coefficient of variation of 6.6%. Even though the scatter was large, the plastic strain curves were very smooth (Figure 4). The grammage did not thus affect the total, plastic or elastic strain.

![Figure 4: The plastic strain after loading to a total strain and then unloading. The total strain is indicated in the figure.](image)
Figure 5 shows the tensile stiffness of the samples. Below the moisture content of \(20 - 30\%\), the tensile stiffness increased abruptly.

![Figure 5: The tensile stiffness index of all paper samples as a function of moisture content.](image)

The interpretation of the laboratory results is easier if a paper web with a certain moisture content with a moist streak is considered. The plastic strain difference in such a paper can then be calculated from data in Figure 4. To visualize the effect of moisture level and draw, contour plots of the strain difference were constructed, as shown in Figure 6. When the moisture difference between the streak and the paper was 1\%, the strain difference was below 0.06\% for all the draws and moistures tested. This means that there would probably be no runnability problems according to Roisum’s 0.1\% strain difference criterion [10]. When the moisture difference is 5\% however, the plastic strain difference can be higher than 0.1\%, at least when the moisture content is low. It can also be seen that the effect of draw levelled out at draws higher than about 2 – 3\%, depending on the moisture content.
Another example is shown in Figure 7, where the effect of moisture difference is shown at different moisture contents and draws. The data for a draw of 0.3 % are not shown, since the strain difference at that draw level never reached 0.1 %.

It was only at a low moisture content, 15 % or below, that the strain difference could exceed 0.1 % (Figure 7). At a moisture content of 30 – 35 %, the strain difference could become lower than −0.1 %, if the moisture difference were higher than about 6 % and if the draw were high. These two risk zones are seen in Figure 7 as grey areas.

In a paper machine, the paper is subjected to several draws at different moisture
contents. An example of speed differences typically applied for the pulp used is shown in Table 1. The total strain difference thus arises stepwise, but the result is probably not a direct sum of the individual strain differences. During drying, the width of the moist streaks decreases and the result should be several streaks of different lengths. A hypothetical representation of this is seen in Figure 8. Figure 8a shows hypothetical moisture profiles of a web with a wet streak during drying, and Figure 8b shows a possible resulting strain profile after drying. Since the sign of the strain difference changed during drying, the moist streak could result in two short streaks, or rather a double-peaked short streak.

Table 1: Examples of draws (speed differences) in the making of kraft paper without “clupak”, and the resulting strain difference according to the present laboratory study. *Estimations.

<table>
<thead>
<tr>
<th></th>
<th>Draw content</th>
<th>Moisture difference</th>
<th>Plastic strain difference</th>
<th>Cumulated sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Press</td>
<td>2.8</td>
<td>50*</td>
<td>6*</td>
<td>−0.1</td>
</tr>
<tr>
<td>Dryer section</td>
<td>0.8</td>
<td>40*</td>
<td>5*</td>
<td>−0.03</td>
</tr>
<tr>
<td>Pope</td>
<td>0.3</td>
<td>10*</td>
<td>2*</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Figure 8: (a) Hypothetical moisture profiles of a wet streak during drying. (b) A possible resulting strain profile after drying. The dotted lines show the edges of the streak at three different times during drying.

### 3.2 Machine trial

Figure 9 shows the moisture profile at the pope and the strain profile after conditioning. There was a clear correlation between the moist streaks and the strain profile. There was no evidence however of any double-peaked short streaks.
Possibly this effect is small, especially in the sack paper case where the winding strain is small to preserve the stretchiness of the paper. The strain difference was about −0.1 % when the moisture difference in the dry paper product was 4 − 5 % (Figure 9).

Figure 9: Moisture profile at the pope (black, filled area) and strain difference (grey line) plotted as a function of the position in CD from the front side of the sack paper machine.

During converting (PE coating) of this paper, there were no runnability problems at all, although tight streaks could be observed in the paper web when the web tension was low.

4 Discussion

4.1 Laboratory tests

At all strain levels, the largest plastic strain was observed at moisture contents between 20 % and 30 % (Figure 4). This is not in agreement with the conventional belief that wet webs are more plastic than dry webs, since there was a maximum in plastic strain at about 25 % moisture content. What has actually been reported is that wet fibers are more plastic than dry fibers [4].

At 20 − 30 % moisture content, the plastic strain showed only small variations with varying moisture content (Figure 4). This means that although the plastic strain was high in this region, the paper was not very sensitive to moisture variations, making this region less important for runnability. Lätti et al. [9] suggests instead that the moisture region most critical for runnability is at a moisture content between 15 and 35 %, where they found that the largest tension variations in the web, due to moisture variations, occur.

At a higher and especially at a lower moisture content than 20 − 30 %, the plastic strain was lower, but the slopes of the curves were more pronounced (Figure 4), meaning that the paper is more sensitive to moisture content vari-
ations above and below 20 − 30 %, as also suggested in Figure 7. At a high moisture content, the slope was negative, and at a low moisture content, the slope was positive. Interestingly, it thus seems that if a moist streak is introduced in the beginning of the machine at a high moisture level, it would become a tight (short) streak, whereas if it is introduced at a low moisture level, by for example uneven drying on the final cylinders, the moist streak would become a slack (long) streak. The former is supported qualitatively by the previous study [2] which showed that when moist streaks were added to a paper at a moisture content of 50 %, they became short streaks.

It is unclear why the plastic strain was lower both at higher and lower moisture contents than 20 − 30 %. Clearly, a lot of morphological changes occur in the bond region in the end of drying. Below the moisture content of 20 − 30 %, the tensile stiffness increased abruptly (Figure 5) during the sharp decrease in plastic strain (Figure 4). During the plastic strain decrease above 20 − 30 %, there was no corresponding change in tensile stiffness.

The paper was most sensitive to moist streaks at the dry end (Figure 7), but there the draws are typically low and the moisture difference is also at its lowest due to the higher drying speed in the wet streaks. The moisture profile is therefore more even at the dry end of the paper machine than at the wet end. Consequently, the most problems probably originate in the wet end, when a wet streak present early in the machine becomes a short streak after drying. A dry streak early in the machine should then, logically, become a slack (long) streak after drying.

4.2 Laboratory study: Sources of error

The results in this laboratory study apply for papers dried under restraint that were unloaded in a wet state. This leads to an underestimation of the plastic strain. During the drying of paper under a positive strain, a part of the elastic strain is “frozen in” and becomes plastic [11]. The underestimation in the present study compared to drying in a paper machine has two origins. First, the frozen-in strain is smaller because the paper was not dried before unloading. There was thus less opportunity for the strain to be frozen in during the restraining. Second, the frozen-in strain is smaller because the paper was dried under restraint to achieve the desired moisture content, instead of under a positive strain. Note that since the plastic strain is underestimated in these trials, the strain difference may possibly also be underestimated.

The plastic strain was determined immediately when reaching 5 N/m, but if there had been a delay between the straining and final strain measurement the plastic strain would have been somewhat lower. To measure without delay is more realistic, since paper is not unloaded between manufacturing and converting. If anything, the plastic strain should be higher due to stress relaxation.
during storage in the reel. This is another possible underestimation of the plast-
ic strain.

If the contour plots had been drawn with plastic strain data from a standard
tensile test, the results would have been quite different. The sensitivity at low
moisture contents would have been lower.

At a total strain of only 0.3 %, the plastic strain in Figure 4 was actually nega-
tive, suggesting that the paper has become shorter than it was before straining.
This could be a measurement error, since the total displacement was very low
in that test (0.24 mm). It is likely that the plastic strain is actually zero. On
the other hand, the unloading level in the measurements seems to have high re-
peatability, which suggests that there is a physical explanation, possibly related
to release of dried-in strains.

4.3 Machine trial

In the machine trial, the correlation between strain profile and moisture profile
was very high (Figure 9). A wet streak introduced at 35 % moisture content
resulted in a short streak. This is in qualitative agreement with the findings
from the present laboratory study and previous results [2].

The moisture profile at the pope was quite uneven. Since the strain profile was
measured after conditioning it could be influenced by free shrinkage occurring
after unloading. Paper webs are not unloaded in this way before going to con-
verting, which means that the strain profile in the machine trial was somewhat
unreliable. The laboratory results showed however that there actually is an ef-
fect due to different moisture contents during restrained drying. In a web, the
strain difference is also influenced by the fact that the wet streaks bear a lower
load than the dry parts. All these effects should be considered when trying to
answer the question of why papers with moisture variations can become baggy
webs.

Even though the strain difference in the sack paper was high, it was possible to
wind and coat the paper with polyethylene without any runnability problems.
It is clear that the 0.1 % criterion that was suggested by Roisum [10] is only
a guideline, since the runnability must depend on how the strain difference is
distributed in the web and, on the converting process itself. A printing press is
probably more sensitive to slack areas than a PE coater. A narrow slack streak
is more likely to cause creasing than the narrow tight streaks in this study,
which seemed to stretch during converting to the same length as the rest of the
web. The laboratory study suggested that problems most likely arise early in
the machine, where dry streaks lead to short streaks. To have good runnability,
dry streaks early in the paper machine should thus be avoided.
4.4 Comparison

The laboratory and machine trials are very different in e.g. drying strategy and the data cannot be directly compared. Nevertheless, some similarities can be found in the results.

The draw at the end of the cylinder dryer section was about 0.7 %, at a moisture content of about 32 %. A probable moisture difference there was about 10 %. If the laboratory results are applied to these settings, the calculated strain difference was −0.05 %. After this point in the machine, the paper was subjected only to negative draws. This makes it even harder to compare with the laboratory study. Previous results [2] showed that the strain differences arising under permitted shrinkage are about as high as the strain differences arising under a positive strain during drying. This is possibly because the paper is subjected to a positive tension anyway due to drying shrinkage. If it is assumed that the strain difference depends only on the absolute value of the draw, the calculated cumulative strain difference was −0.19 %, which is greater than but still of the same order as the measured strain difference in the sack paper. Considering that the measurements were performed on paper samples that had relaxed after the paper machine, the calculated result from the laboratory study is surprisingly reasonable.

5 Conclusion

The plastic strain should be determined by unloading of strained samples, since the results tend to be unreliable if calculating plastic strain from the tensile stiffness.

The plastic strain of sheets made from bleached softwood kraft pulp is highest at a moisture content of 20 – 30 %, but the paper is most sensitive to moist streaks at a moisture content of 10 – 15 % and below. However, at those moisture contents, moist streaks are less pronounced and the draws are lower. In practice, the most problems probably have their origin at high moisture contents, above 30 %, e.g. as a result of uneven dewatering at the wet end or in the press section.

According to these results, the moist streaks appearing at a high moisture become short streaks, and the moist streaks appearing at the dry end become long streaks. Long streaks are believed to be the most harmful. Consequently, the most important issue for runnability is to avoid dry streaks early in the machine.
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References


MD strain and bagginess due to calendering

Cecilia Land, Lennart Stolpe, Torbjörn Wahlström and Luciano Beghello

Abstract
Uneven calendering was evaluated as a possible cause for machine-direction (MD) strain differences in paper webs. Sheets of kraft pulp with uneven grammage and moisture profiles were calendered in the laboratory and strain differences were evaluated by rating the creases formed. These results were compared with calendering trials on samples with a uniform moisture content and grammage, where the MD strain due to calendering was measured.

The results show that both grammage and moisture differences are needed to create strain differences large enough to cause creases. Creases appeared at a thickness-direction (ZD) compression difference of 2 %, or a MD strain difference of 0.03 %. To avoid creases, the moisture variation in the paper should not exceed 1 – 2 %. The grammage difference can be quite large without causing creases, as long as the moisture difference is low.

Keywords: baggy webs, calendering, creases, grammage, moisture, paper, profile, runnability.

1 Introduction
Problems can arise in paper converting processes if the paper web is slack, or baggy, in certain areas. When the paper reel is wound up in the mill, the web tension is rather high and the baggy areas are not noticeable. During converting however, the web tension is much lower and the slack areas can cause problems. Creases and misregister are examples of such problems. There are a number of process steps that may contribute to bagginess and one of them is calendering.

Calendering results in a smoother and thinner paper, but the in-plane dimensions are also changed [1, 2]. In the MD, paper can interestingly become either slightly longer or slightly shorter as a result of calendering. This is possible since paper is a fibre network structure rather than a solid material. Regardless of whether the paper gets longer or shorter, if the calendering compression profile is uneven, the paper can experience an uneven MD strain during calendering.
Factors that may cause an uneven compression profile are uneven calender rolls, or an uneven grammage or moisture profile in the paper. Streaks of higher grammage can, in turn, cause moisture streaks, since they require a longer drying time.

In an earlier study [3] it was shown that creasing can occur already during calendering, if the paper has streaks with high grammage. Creasing occurred primarily when there were also differences in moisture content in the paper. Without moisture differences, creases did not appear below a grammage difference of 35 %.

In the present study, the strain difference necessary to cause such creases was investigated. First, paper sheets with a uniform grammage and moisture content were calendered with different line loads, to see how the grammage and moisture content affect the MD strain. Samples with controlled uneven grammage and moisture profiles were then calendered to evaluate when creasing occurs. The results of these two experiments were compared to see how large MD strain difference is required to give rise to creases.

2 Materials and Methods

2.1 Sheet forming

Flash-dried bleached softwood kraft pulp was beaten to 17 SR in a PFI mill. Sheets were made with a Formette Dynamique sheet former (DSF), with a rotation speed of 1200 rpm and a stock pressure of 3 bar. The sheets were pressed twice with a roll press at pressures of 250 kPa and 450 kPa. The drying method and grammage were different in the different trials, see below. The tensile stiffness anisotropy of sheets dried under restraint was 2.

For comparison purposes, a commercial 135 g/m² liner made with bleached softwood kraft pulp was also tested. The sample was taken when the calender nip was open. The paper was conditioned at 23 °C and 50 % RH.

2.2 Trial plan

Three different types of calendering tests were performed and these are described in more detail in the separate sections, and in Table 1. To investigate the MD strain due to calendering, samples with varying (uniform) moisture content and grammage were produced. The purpose was to find a relationship between ZD compression and MD strain.
In the second part, the behaviour of paper with uneven profiles was studied. Paper samples with uneven grammage and/or moisture profiles were calendered to see when creasing occurred. By comparing these results with the results from the first part, it is possible to estimate the strain difference at which creases occur.

In the final trial, several separate samples with different grammages were introduced simultaneously into the calender nip. The purpose was to see if the uneven load profile would lead to results significantly different from those obtained when calendering separate samples.

The variables in these experiments were thus grammage, relative difference in grammage, moisture content, absolute difference in moisture content, and line load during calendering. These variables are hereafter referred to by the abbreviated expressions in Table 1. Grammage was always measured at 23 °C and 50 % RH on samples conditioned from the dry side.

Table 1: An overview of the different experiments and variables. The different shades of grey in the drawings denote the grammage, where dark grey means high grammage.

<table>
<thead>
<tr>
<th>Even samples</th>
<th>Uneven profiles</th>
<th>Samples together</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grammage</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[g/m²]</td>
<td>a) 57 – 328</td>
<td>mean around 100</td>
</tr>
<tr>
<td></td>
<td>b) 58 and 110</td>
<td>90 and 140</td>
</tr>
<tr>
<td>Grammage difference</td>
<td>0 %</td>
<td>5 – 55 %</td>
</tr>
<tr>
<td>Moisture content</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>a) 8 %</td>
<td>Varying</td>
</tr>
<tr>
<td></td>
<td>b) 8 – 48 %</td>
<td>8 %</td>
</tr>
<tr>
<td>Moisture difference</td>
<td>0 %</td>
<td>0 – 15 %</td>
</tr>
<tr>
<td>Line load</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[kN/m]</td>
<td>a) 50 – 400</td>
<td>100 and 200</td>
</tr>
<tr>
<td></td>
<td>b) 100</td>
<td>100 and 200</td>
</tr>
</tbody>
</table>

2.3 Uniform samples

First, paper sheets of uniform grammage (57 – 328 g/m²) were produced. The sheets were dried under restraint on a steam-heated cylinder dryer (KMW, Sweden) with a dwell time of 140 s. The samples were then conditioned at 23 °C, 50 % RH. Samples with a width of 8.0 cm and a length of 60 cm were prepared, and their lengths were measured with a high-precision slide calliper.
(accuracy 0.03 mm). Both edges were measured and all the distances were measured twice. Immediately after calendering, the length was measured again. The average engineering strain in MD (hereafter referred to as MD strain) was calculated from two samples taken from different sheets.

The grammage was determined by weighing each sample. The structural density of the samples was determined by dividing the grammage by the structural thickness. To investigate the effect of density, a 95 g/m² sample with a lower density than that of the other sheets was produced by pressing with a lower pressure in the second pressing, 250 kPa instead of 450 kPa. The tensile stiffness orientation (TSO) angle was measured with an L&W TSO tester (Lorentzen & Wettre, Sweden).

Paper samples with different moisture contents were also evaluated. The grammages tested were 58 and 110 g/m². The wet paper sheets were cut into two halves and dried under restraint in a STFI plate dryer (Fibertech, Sweden). The wet samples required a faster strain measurement method to avoid moisture evaporation. Dots ca 5 mm in diameter were first drawn on the sample near all the corners. The samples were then conditioned at 23 °C and different humidities between 10 and 98 % RH.

Each moist sample was put in a plastic bag and scanned in a desktop scanner (Epson Perfection V750 Pro) with a resolution of 600 dpi. The sample was removed from the plastic bag, calendered, and then quickly put back in the plastic bag and scanned again. In these trials, the calendering line load was 100 kN/m. The sample width was still 8.0 cm, but in order to fit the paper into the scanner, the sample length was 29 cm. The thickness of uncalendered and calendered paper was measured with the STFI thickness tester, immediately after calendering. The centre points of the dots in the corners of the sample were determined with the Image Analysis Toolbox in MATLAB (Mathworks Inc). The MD strain due to calendering was then calculated from the distance between the centre points.

2.4 Samples with uneven profiles

The samples with uneven profiles were also manufactured with the Formette Dynamique sheet former. To produce streaks with a higher grammage the spray nozzle was stopped in the middle of the sheet for specified times between 5 and 20 s. The width of the resulting streaks was approximately 5 cm.

The sheets were pressed in the same way as the uniform sheets, and then cut in half perpendicular to the grammage streak and dried under restraint in a STFI plate dryer (Fibertech, Sweden). Different drying times between 1 and 2.5 min were chosen, depending on the grammage difference, in order to obtain relevant moisture differences in the paper.
After drying to the intended moisture profile, the sheets were trimmed to a width of 16 cm and a length of 31 cm. The moisture contents in the streak and beside the streak were determined gravimetrically on samples with dimensions of ca 3x3 cm. The sheet was then immediately calendered. Later, these small samples were dried and reconditioned and used for grammage measurement.

The creases were visually assessed after all the samples had been calendered, by sorting the samples into six different groups ranked from 0 to 5, where the rating 0 meant no creases.

For comparison, some samples were fully dried and conditioned before calendering. Other experiments were performed without grammage streaks but with added moisture streaks. These streaks were added with a wet tissue before drying. Otherwise the procedure was the same as that for the samples with uneven grammage.

### 2.5 Separate samples calendered together

When paper with thickness variations is calendered, the thickness profile is evened out but the compression profile is uneven. A higher pressure on the thicker regions would affect the MD strain there, whether positive or negative. Therefore, a calendering trial with a grammage-streaked paper, but cut at the grammage boundaries, was performed. The purpose was to compare the difference in MD strain between these regions of the sample and the results of the other experiments.

The three samples were placed beside each other and introduced simultaneously into the nip. In order to achieve this, the three paper samples were taped trailing after a stiff board piece, which kept the paper samples parallel with a separation of 1 – 2 mm while passing through the nip.

In this trial, the length of each of the three samples was measured before and after calendering with the slide calliper. This test was performed with the paper conditioned at 23 °C, 50 % RH, since it takes too long time to measure the lengths of three samples without moisture evaporation, even if the scanning method were used. The grammage difference between the streak and the rest of the paper was 55 %.

### 2.6 Calendering parameters

All samples were calendered with a soft-nip laboratory calender (DT Paper Science Oy, Finland) with MD in the calendering direction. Different line loads between 50 kN/m and 400 kN/m were used (Table 1). The roll temperature
was 23 °C (the roll was non-heated) and the calendering speed was 34 m/min. In all the experiments, the thickness profile was measured immediately before and immediately after calendering with a STFI structural thickness tester (TJT Teknik, Sweden). The average non-elastic ZD compression due to calendering was calculated for the high-grammage area and the low-grammage area in the paper, and the difference between these values was called the “ZD compression difference”.

3 Results and discussion

3.1 Uniform samples: Effect of line load and grammage

Figure 1 shows the non-elastic ZD compression at different line loads for the uniform paper samples conditioned at 23 °C, 50 % RH. A line load of 100 kN/m corresponds to a ZD compression of 8.5 %. The ZD compression was independent of the sheet grammage and both the DSF sheets and liner acted in the same way. Sheets with a higher thickness have a higher compressive stiffness in ZD [4], but this seems to be irrelevant in the case of the non-elastic ZD compression tested here.

For the uniform samples, the MD strain was linearly dependent on the ZD compression (Figure 2), as previously shown by Lif et al. [2]. In the present study, different grammages were tested and they gave rise to different slopes. The paper with the lowest grammage showed a positive strain after calendering.
whereas the papers with a higher grammage showed a negative strain.

The 135 \( \frac{g}{m^2} \) liner and the DSF sheets were made of similar fibres, but the forming and drying processes are completely different. Consequently the liner had a strain-compression slope of \(-0.0053\), which is more pronounced than the slopes of all the DSF sheets (Figure 2). The liner was thus more inclined to deform during compression, suggesting that it may be more sensitive to bagginess.

Figure 2: The average MD strain due to calendering shown as a function of the ZD compression. Data for DSF samples of different grammages and a 135 \( \frac{g}{m^2} \) liner are shown. The error bars show the 95\% confidence interval. The vertical line shows the line load 100 kN/m.

The TSO angle differed by only about 1° between the different grammages, indicating that differences in fibre orientation were probably not the reason for the differences in MD strain. It would be interesting to carry out similar experiments with different anisotropies, to see whether the MD strain-ZD compression slope changes. It seems plausible that it will, but by how much is unknown.

Figure 3 shows the MD strain as a function of grammage. Surprisingly, there was a grammage for which there was no MD strain, and this was independent of the line load. This grammage was 106 \( \frac{g}{m^2} \) for the DSF sheets. Possibly there is also such an optimal point for other paper grades. Such a paper would experience no runnability problems due to calendering.

The variation in strain with variations in grammage is probably due to differences in behaviour in the surface and in the bulk. Paper with a high grammage, with a higher ratio of bulk material to surface material, seems to shrink in the MD due to ZD compression. Thin papers, consisting mostly of surface, expand in the MD. Compression in ZD of a paper with a non-homogeneous structure can have two different effects.
One effect is a compression of single fibres resulting in an expansion of the fibres, principally in their lateral direction. This would lead to an expansion in both MD and CD of the sheet, especially in CD due to a larger number of fibres along the MD axis.

The other effect is an increased entanglement of the fibres in the sheet when the free segments of the fibres are pressed into voids in the fibre network. This leads to a contraction of the sheet in both MD and CD [5, 6]. The entanglement effect is probably more pronounced in the bulk of the sheet, while the single fibre compression is more pronounced in the surface of the sheet, since the surface fibres have voids on only one side. With increasing grammage, the single fibre compression would have a progressively smaller influence on the MD and CD strain. The single fibre compression is especially significant for CD strain.

The MD strain planed out at high grammages, as shown in Figure 3. Due to practical difficulties during sheet-making, 57 g/m² was the lowest grammage that was tested. It was not therefore possible to see whether the strain curve (Figure 3) also levels out at the low end when the length is affected by only single-fibre compression.

![Figure 3: MD strain due to calendering, as a function of grammage, shown for different line loads. Interpolation from data in Figure 2.](image)

3.2 Uniform samples: Effect of density

In general, a low-grammage laboratory sheet has a lower density than a high-grammage sheet [7] and this was also the case here (Figure 4). It can therefore be argued that the variation in MD strain with grammage is due to variations in sheet density. The sample with low density, denoted with “Low pressure” in Figure 4, showed an MD calendering strain of $-0.04\%$ after calendering at
100 kN/m, which is much lower than the strain of the other 95 g/m² sheets. The MD strain thus increased with increasing density at constant grammage. This agrees with the CD strain results of Baumgarten [1], which showed that the CD plastic strain increased with increasing density for a gravure paper grade calendered under a given line load.

Sheets with a higher density, due to a higher grammage, instead had a lower MD strain. This trend thus went in the direction opposite to that of the trend due to density at constant grammage. The density differences between the sheets did not thus cause the grammage trend but actually masked it. Without the density differences, the differences in MD strain between the different grammages would be greater than those shown in Figure 2 and Figure 3.

A low density thus seems to enhance the fibre entanglement effect of the calendering. This is expected since, at high density, the fibres are more entangled before calendering due to the higher pressure during the pressing of the wet sheet.

![Figure 4: MD strain due to calendering as a function of structural density for DSF sheets conditioned at 23 °C, 50 % RH prior to the calendering.](image)

3.3 Uniform samples: Effect of moisture content

Figure 5 shows the MD strain due to calendering for papers with different moisture contents. The paper contracted in MD at most moisture contents and there was a minimum point at 15 – 20 %. This is not necessarily because the shrinkage is greatest there, but rather because the plasticity is greatest there. The in-plane plasticity of the paper tested here was determined in a previous study [8]. The plasticity was found to be greatest between 20 – 30 % and to decrease both above and below this moisture interval. The behaviour in the
The present study agrees roughly with that observed in the previous study, where isotropic sheets were tested.

The ZD compression instead increased with increasing moisture content and levelled out at about 20\% moisture content (Figure 6). An exception was at a high moisture content above 40\%, where the ZD compression was lower. The qualitative behaviour at low moisture content corresponds to previous results for newsprint [9] although the curve there tends to level out already at a moisture content of 12\%. The plastic MD strain and ZD compression thus did not follow the same behaviour with variations in moisture content.

The difference between different grammages was significant neither in the MD strain nor in the ZD compression, at a line load of 100 kN/m. This corresponds to the behaviour of conditioned paper, where the grammage effect was significant only at higher loads (Figure 2).
Figure 6: Plastic ZD compression measured after calendering at 100 kN/m, as a function of paper moisture content. Two different grammages are shown. The line is an exponential curve fit and the error bars show the 95% confidence interval.

3.4 Samples with uneven profiles: Observations

Most of the samples with uneven grammage profiles also had uneven moisture profiles, since the thicker parts of the paper need a longer time to dry. Figure 7 shows a typical creasing pattern after calendering. The vertical lines in the streak are due to load variations along the MD in the calender nip and are not of interest here. Nor is the wavy shape of the sample of interest, since it appeared after storage in a conditioned environment after calendering and measurement.

After calendering, the samples with an uneven grammage and an uneven moisture content exhibited creases in the thin part of the paper. The creases were inclined outwards and backwards from the streak towards one or both edges (Figure 7), indicating that there is an excess of paper length beside the streaks. The streak with high grammage and high moisture content had evidently become shorter due to calendering, which corresponds to the results for the uniform paper samples.

The creases did not appear until after about 15 cm (Figure 7). The angle then increased for about 10 cm, after which the creases suddenly changed and became almost aligned with the MD. The interpretation is that the strain difference builds up gradually until it is large enough to cause creasing. At the end of the sample, the CD tension could no longer be maintained and the paper entered the calender in a wavy state. If a continuous paper web were calendered, there would be less tension problems and there would probably be angled creases.
along the whole web.

Figure 7: A typical creasing pattern obtained after calendering, where the left edge went first into the calender. Arrows point to the creases. This sample had a grammage difference of 10%, a moisture difference of 2%, and was rated as a 4. The contrast has been increased in this picture.

The visual evaluation of the creasing showed, with few exceptions, that a moisture difference between 2 and 6% gave the greatest amount of creasing (Figure 8). At larger moisture differences, the creasing remained at a lower level. The grammage difference had no great effect on the rating (Figure 8). The trend line, a 4th degree polynomial, was valid for all moisture contents tested, which varied between 5% and 10% besides the streak.
When sheets with moist streaks but no grammage streaks were calendered, another type of creasing appeared. Creases then occurred only inside the moist streaks and parallel to MD. It was concluded that these creases occurred because of poor tension in the sheet in CD during the passage through the nip, due to the low stiffness in the moist streak. These creases were thus not attributed to strain differences.

3.5 Samples with uneven profiles: Measurements

Figure 10 shows the difference in permanent compression between the streak with a high grammage and the rest of the paper. At a moisture difference of $1 - 5\%$, the compression difference was much higher than at either a lower or a higher moisture content. This corresponds roughly to the result of the creasing evaluation, where most creases appeared between 2 and 8\%.

When there was no moisture difference there was only a low compression difference and it increased only slightly with grammage. Even at such a small moisture difference as $1 - 3\%$, the compression difference increased to $11 - 12\%$, even with relatively small grammage differences. Increasing the moisture difference to $3 - 5\%$ increased the compression difference further, but increasing the moisture difference even more again resulted in lower compression differences. This is probably because the absolute moisture content was not the same in all the samples. There is a correlation between the moisture difference and the absolute moisture content of the paper. This limitation would also occur in

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*Figure 8: The visual rating of the samples, where 0 means no creasing and 5 extensive creasing, plotted as a function of the difference in moisture content between the moist streaks and the surrounding paper. The line is a 4th degree polynomial curve fit to the data.*
a paper machine. In Figure 9, the moisture content and compression of the different parts of all the papers is shown more clearly.

Consequently, a probable reason for the relatively uniform compression of the samples with very high moisture differences is that they have a high moisture content, where the compression-moisture relationship has levelled out. Figure 9, like Figure 6, shows that the compression was higher at a higher moisture content, but above a moisture content of $15 - 20\%$, the higher moisture did not lead to any increase in the compression.

![Figure 9: Calendering compression (non-elastic) in ZD as a function of paper moisture content. Each arrow represents one sample, where the starting point shows the value beside the streak and the end point shows the value in the streak. The legend shows the difference in grammage between the streak and the rest of the paper.](image)

To see how important the moisture content was, a conditioned sample (8 % moisture content) was compared with a non-conditioned sample with virtually no moisture difference (5 % moisture content). The sample with the higher moisture content, denoted “0 % (cond)” in Figure 10, showed a higher permanent compression difference than the non-conditioned samples (denoted “<1 %” in Figure 10). This is not surprising since the sample with the higher moisture content should show a more plastic behaviour.

When paper with wet and thick streaks is calendered, two effects occur. Firstly, the thick streak bears a higher load than the thinner parts of the paper. This causes the high-grammage streak to be compressed more than the low-grammage parts of the paper. Secondly, wet fibres show a more plastic behaviour than dry fibres. This causes the high-grammage streak to remain compressed after unloading more than the low-grammage parts of the paper. The moisture difference was much more important than the grammage difference (Figure 8; Figure 10), but a small grammage difference was nevertheless required to obtain the tilted
creases.

Figure 10: Samples with grammage streaks, calendered with a line load of 100 kN/m. ZD compression difference as a function of difference in grammage. The legend shows the moisture difference between the streak and the rest of the sheet.

There are some possible experimental errors in the experiments with streaked papers, causing variations in the results. Drying of the samples might have introduced unwanted moisture differences in addition to the difference due to the grammage streak. The experiments had to be performed quickly to avoid moisture evaporation, and in the worst case, cockling. The STFI thickness tester does not perform well when measuring cockled papers. The grammage streaks were hard to locate in the case of small grammage differences, both visually and in the thickness profiles. Consequently, the lowest reported grammage difference was 5%. Despite these difficulties, the experiments were reasonably repeatable and the results can be used to estimate the critical strain difference.

### 3.6 Critical strain difference

The critical strain difference with respect to creasing was determined by comparing the streak trials with the measurements on separate samples with different moisture contents, i.e. by comparing the data in Figure 5 and Figure 8. Combining these two relationships gives a relationship between crease rating and MD strain difference, as shown in Figure 11. Grammage was not used as a variable here, since the grammage had been shown to have no significant influence on the MD strain when calendering separate samples at 100 kN/m (Figure 5). The effect of moisture difference was much larger.

Significant creases appeared at unexpectedly low strain differences, already at about $-0.03\%$, depending on the moisture content (Figure 11). Roisum [10]
claims that a strain difference of 0.1%, or 0.01% in the case of thinner webs, is sufficient to cause runnability problems in converting. The sheets tested here were not particularly thin. A possible explanation for the difference in critical strain is as follows. The pressure pulse in the laboratory calender is wide due to the slow speed, and the compressive energy acting on the paper during calendering is thus high. Both the strain differences and the creasing then appeared in the same calendering nip. The paper may then be more sensitive to creases than if strain differences from the calender had caused creasing in subsequent converting.

Almost all the samples showed a negative strain difference between the thick streak and the thin areas, but in the few samples that had a positive strain difference, a tendency towards a mirrored trend towards the positive side can be seen in Figure 11. The data points differ somewhat from the calculated trends and this is probably due to the difficulty involved in performing controlled calendering trials on paper with moist streaks. Also, the observed rating was only integral values.

![Figure 11](image)

*Figure 11: Visual rating of creasing shown as a function of MD strain difference, at three different moisture contents. These moisture contents were measured besides the streak. The points show the rating of the actual samples while the lines are calculated from curve fits from Figure 5 and Figure 8. The numbers on the lines show the absolute moisture difference.*

MD strain differences seem to be caused by a combination of grammage differences and moisture differences. Most important were the moisture differences; although the grammage differences applied here were very large, their effect was fairly low. Previous results [3] show that completely dried sheets with grammage profiles do not develop creases during calendering. The present results confirmed this, and showed also that streaks that were moist without being thicker did not cause the tilted creases that are characteristic of strain differences. It should be noted that all these experiments were performed on sheets and not on contin-
uous webs. A MD web tension during calendering can influence the MD strain and thus the MD strain differences in the web.

### 3.7 Effect of calendering separate samples together

The critical strain was determined on separate uniform samples, but it is possible that the MD strain is affected if the load profile during calendering is uneven.

Table 2 shows a comparison between the trial types in terms of ZD compression difference and MD strain difference. The comparison showed that the higher line load, 200 kN/m, gave a lower non-elastic ZD compression difference than 100 kN/m, which was expected since the compression-load curve had a lower slope at high line load (Figure 1). The MD strain was not, however, significantly affected by the line load (Table 2). These values apply for conditioned paper with 55 % grammage difference. The behaviour of samples with moisture differences is more complex.

When several samples were calendered together, the ZD compression in the streak was larger than the compression beside the streak. When the samples were calendered separately, the compression was the same at all positions. The MD strain difference should thus be larger when several samples are calendered together, but the MD strain difference was not statistically significant even though the grammage difference was very high. It is thus better to use the results for separate samples in the comparison with streaked sheets and estimation of the critical strain difference. These results were more reliable.

Table 2: The ZD compression difference and the MD strain difference for the different experiment types, when the grammage difference was 55 % (90 g/m² and 140 g/m²), the moisture content was 8 % with no moisture differences. The 95 % confidence interval is also shown.

<table>
<thead>
<tr>
<th>Line load [kN/m]</th>
<th>Even samples</th>
<th>Uneven profiles</th>
<th>Samples together</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZD compr. 100</td>
<td>0 %</td>
<td>8.2 ± 0.5 %</td>
<td>7.0 ± 0.2 %</td>
</tr>
<tr>
<td>difference 200</td>
<td>0 %</td>
<td>3.7 ± 0.6 %</td>
<td>4.7 ± 0.2 %</td>
</tr>
<tr>
<td>MD strain 100</td>
<td>−0.018 ± 0.02 %</td>
<td>(No creases)</td>
<td>0.0037 ± 0.02 %</td>
</tr>
<tr>
<td>difference 200</td>
<td>−0.022 ± 0.02 %</td>
<td>(No creases)</td>
<td>−0.016 ± 0.03 %</td>
</tr>
</tbody>
</table>

In this study, the plastic MD strain and the plastic ZD compression were measured. In the case of ZD compression, the plastic compression is the most relevant parameter to determine since the paper has time to relax in ZD after

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In this study, the plastic MD strain and the plastic ZD compression were measured. In the case of ZD compression, the plastic compression is the most relevant parameter to determine since the paper has time to relax in ZD after
the calender nip and in the converting machine. Regarding MD strain, however, the paper is under tension after the calender and in the converting machine, and in the reel the paper is constrained in MD, under about zero strain. There is thus no time for relaxation in MD before converting. The MD strain differences measured in this study should therefore be seen as minimum values.

4 Conclusion

The MD strain during calendering is affected by sheet grammage, density and moisture content. A high grammage results in shrinkage in MD during calendering, probably because fibres are more easily entangled in the bulk. A low density also favours MD shrinkage. The effect of high-grammage streaks during calendering is however significant only at high line loads.

The tilted creases attributed to strain differences occur during calendering only if both moisture differences and grammage differences are present. The creases appear when the difference in ZD compression is at least 2 % or when the absolute MD strain difference is at least 0.03 %. To avoid creases, the difference in moisture content should not exceed 1−2 %. The grammage difference can be quite high without causing creases, as long as the moisture difference is low.

References


Paper IV

Cecilia Land. Baggy paper webs: Effect of uneven moisture and grammage profiles in different process steps
Modeling of bagginess due to storage of paper reels with ridges

Cecilia Land, Lennart Stolpe and Luciano Beghello

Abstract
Paper is subjected to stress relaxation during storage in reels. Ridges in the paper reel subject the paper in the ridge to a higher strain than the paper adjacent to the ridge. The strain difference can become a permanent strain difference, resulting in a baggy web after unwinding. A geometrical model based on stress relaxation test results was used to determine when the bagginess is substantial enough to cause problems. The results showed that runnability problems will appear if the ridge is about 1 − 2 mm high. This applies for a reel with a diameter of 1.2 − 1.8 m stored for one week.

Keywords: bagginess, creep, ridges, paper, relaxation, runnability, viscoelasticity.


1 Introduction

Paper reels sometimes have ridges [1] due to cross-direction (CD) variations in thickness. During storage of the reel, the paper in a ridge is subjected to a higher strain than the paper beside the ridge, due to the diameter increase along the ridge [2]. This may result in a permanent non-uniform strain (or length) profile in the paper web [3]. Webs with non-uniform length are commonly referred to as baggy webs, and they can give runnability problems during converting.

When the baggy paper is unwound, the longer part of the web buckles out of plane to accommodate the extra length, because it cannot push and stretch the adjacent tight bands [4]. This buckling gives rise to problems such as creases and misregister when the paper is converted.

Information about baggy webs is scarce in the literature. Little research has been published, but some knowledge exists among troubleshooters [5]. Roisum [4] claims that a web where the length varies by only 0.1 % leads to severe bagginess on almost any material. The present study was based on this estimate as a limit for runnability problems.
So far, the literature contains some bagginess characterizations [6] and some studies of how baggy webs behave [7, 8], but few studies of the possible causes. Baggy webs can have a number of causes but it is unclear which of them gives the greatest problems.

In this study, we investigated whether storage of a paper reel with ridges can be a cause of baggy webs. Our hypothesis was that the paper in the ridge position develops a permanent strain that is significantly greater than that of the rest of the paper. The aim of the investigation was to find a relation between the ridge height and the permanent strain difference, and what ridge height could cause runnability problems. Three different paper grades were investigated.

We performed creep and relaxation experiments on paper strips to determine the time-dependent behavior and the data obtained were used as input in a geometrical model of a paper roll, to determine the difference in permanent strain between paper in the ridges and adjacent paper without ridges.

Creep tests are performed under constant load while relaxation tests are performed under constant strain. We did the creep tests as a “worst case” first study, since a creep study could be performed much more efficiently in time. If there were no significant strain differences after a constant load test, there would be no strain differences after a constant strain test, since during a constant strain test the load decreases with time. The loading mode in a reel is presumably constant strain rather than constant load.

2 Materials and Methods

Three different commercial paper grades made from bleached chemical pulp were tested. Two liners with grammages of 80 g/m² and 135 g/m² were compared with a 71 g/m² machine-glazed (MG) paper. The liner grades consisted of two layers with different compositions of short and long fibers, while the MG paper contained a mixture of short and long fibers. The tensile properties of the papers were determined according to ISO 1924-3. All tests were performed at 23 °C, 50 % RH.

2.1 Creep tests

The tensile creep tests were performed under constant load on paper strips (10x500 mm²) hanging with weights in clamps in the lower end. All the paper strips were taken in the machine direction (MD). The load levels corresponded to 10 %, 30 % and 50 % of the tensile strength of each paper. At least four samples were tested at each load level.
The length of the strip, between two lines with a spacing of 200 mm in the unloaded state, was measured with a cathetometer after specified times up to 1 week. The cathetometer was equipped with an eyepiece which could be moved in the vertical direction to be aligned with the lines on the paper. A level transducer with an accuracy of 0.01 mm recorded the vertical position of the eyepiece, corresponding to the lines on the paper strip. The initial length of the strip was measured under a load of 0.2 N, which was applied in order to straighten the sample. The data were fitted to exponential functions of the following form:

\[ F(\varepsilon) = C_{1,t}(1 - \exp(-C_{2,t} \cdot \varepsilon)) \]  

where \( F \) is the load, \( \varepsilon \) is the strain, and \( C_{1,t} \) and \( C_{2,t} \) are time-dependent curve-fitting constants. The data were then replotted as isometric creep curves (load versus time at constant strain, as shown in Figure 1) to allow comparison with relaxation curves.

![Figure 1: Construction of isometric creep curves for the 135 g/m² liner. The left graph shows load during creep tests as a function of the strain. Curve fit according to Equation (1). For clarity, only three curves are shown. Isometric creep curves (right graph) can be made by taking data from all available times at an arbitrary strain. Time is on a logarithmic scale.](image)

### 2.2 Relaxation tests

Relaxation tests were carried out in an Instron 4411 material tester. The test strips had a width of 15 mm and the span length was 150 mm. The test time
was 1 week. For each paper, five different strain levels between 0.1\% and 1\% were applied. One strip was tested at each strain level. After each test, the paper strip was left to relax unloaded for 1 min, after which the final length was measured with a high-precision digital slide caliper (0.03 mm accuracy). Five length measurements were made and an average value was reported. The 95\% confidence interval was determined for the difference between the length before and after the test. Data from relaxation tests were used as input data to a geometrical strain difference model.

2.3 Geometrical model

If there is a ridge in a paper roll, the roll circumference is locally higher there. The difference in circumference, $\Delta o$, is given by

$$\Delta o = o_{\text{ridge}} - o_0 = 2\pi (r_{\text{ridge}} - r_0) = 2\pi h$$

where $h$ is the height of the ridge and $r$ is the reel radius. The strain difference, $\Delta \varepsilon$, is then

$$\Delta \varepsilon = \varepsilon_{\text{ridge}} - \varepsilon_0 = \frac{2\pi h}{r_0}$$

where $\varepsilon_0$ is the wound-in strain assumed to be constant across the web. $\varepsilon_{\text{ridge}}$ is the sum of $\varepsilon_0$ and the strain resulting from the diameter increase.

To assess the magnitude of the permanent strain difference associated with this strain difference, relaxation tests were carried out. A straight line was fitted to the plot of measured permanent strain, $\varepsilon_{\text{perm}}$, versus applied strain, $\varepsilon$, during the relaxation test:

$$\varepsilon_{\text{perm}} = A \cdot \varepsilon + B$$

where $A$ and $B$ are paper-dependent fitting constants.

Assuming that this can be applied to the reel conditions, the expected permanent strain difference in the paper between ridge and non-ridge positions is then

$$\Delta \varepsilon_{\text{perm}} = A \cdot \frac{h}{r_0}$$

3 Results and discussion

The creep experiments showed that there were significant differences in permanent strain when different loads were applied. The hypothesis that a significant strain difference develops during storage was thus supported by the creep tests and the investigation proceeded with relaxation experiments.
The results of the creep and relaxation tests are shown together for comparison in Figure 2 at a strain level of about 0.5 %, an arbitrary number which may reasonably occur in a reel. For the liners, the slopes of the relaxation curves were lower than the slopes of the creep curves. This was expected since, in the constant strain case, the load decreases with time and is thus lower than in the constant load case.

In the case of the MG paper, the curves matched each other after a fairly short time. In the case of the 80 g/m² liner, the relaxation curve approached the creep curve at the end of the experiment, whereas the curves for the 135 g/m² liner did not reach such a point during the time of the experiment. It seems likely that they would have if the test had lasted longer.

Both the creep tests and the relaxation tests showed that, at a given strain, the MG paper carries a relatively higher load in proportion to its tensile strength than the liners (Figure 2). Correspondingly, the tensile test showed that the MG paper had a higher tensile stiffness index (Table 1). The MG paper also tended to show a higher permanent strain after the test than the liners (Figure 3).

Figure 2: Isometric creep curves plotted together with relaxation curves. Time is on a logarithmic scale.

Up to about 0.1 % applied strain (the intercept on the x-axis in Figure 3) there
was no permanent deformation in any of the paper grades. When applying the strain difference model, we assumed that the web strain during winding was above or equal to that strain level. This assumption simplifies the model greatly and is generally reasonable. Without this assumption, there was only a slight difference in the results at very low ridge heights.

Figure 3: The permanent strain as a function of the applied strain during the relaxation tests. The test duration was 1 week. The error bars show the 95% confidence interval. Curve fit according to Equation (4) with fitting constants shown in Table 1.

Table 1: Curve-fitting constants and MD tensile properties for the three paper grades.

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>Tensile strength [kN/m]</th>
<th>Tensile stiffness [kN]</th>
<th>Tensile stiffness index [kNm/g]</th>
</tr>
</thead>
<tbody>
<tr>
<td>71 g/m² MG</td>
<td>0.55</td>
<td>-0.055</td>
<td>8.6</td>
<td>827</td>
<td>11.6</td>
</tr>
<tr>
<td>80 g/m² liner</td>
<td>0.49</td>
<td>-0.059</td>
<td>8.9</td>
<td>826</td>
<td>10.3</td>
</tr>
<tr>
<td>135 g/m² liner</td>
<td>0.42</td>
<td>-0.044</td>
<td>15.4</td>
<td>1445</td>
<td>10.7</td>
</tr>
</tbody>
</table>

Figure 4 shows the strain difference that would arise according to the model due to a ridge of a given height. A given ridge height cause smaller strain differences if the reel diameter is large. This applies since it is the percental diameter difference that is important. The reel diameters investigated here were 1.2 m and 1.8 m, but results for other reel diameters can easily be calculated with Equation (5), as long as the strain ε_{ridge} in Equation (3) do not exceed ca 1 %, the maximum measured strain.

The MG paper was most sensitive to ridges; a ridge height of about 1.1 mm, or 1.6 mm for the larger reel, being sufficient to cause a strain difference of 0.1 %.
Figure 4: Calculated strain difference in the paper web after storage for 1 week and unwinding for different ridge heights on different papers. Calculation according to Equation (5), for reel diameters of 1.2 m and 1.8 m.

(Figure 5). The liners were somewhat less sensitive, but as shown in Figure 3 the difference between all paper grades are small and the experimental error is quite high. If there are differences between the paper grades, it can be due to the fact that they were made from different furnishes with different machines. Particularly the drying method may cause differences, since the MG paper was partly dried restrained on a Yankee cylinder, while the liners were dried in a conventional dryer section.

Figure 5: The maximum runnable ridge height if the strain difference limit is assumed to be 0.1 %.

The liners were similar in tensile stiffness index (Table 1), but when considering the actual stiffness the liner with high grammage was much stiffer. The
difference in calculated strain difference between the liners was however not much greater than the difference between the MG paper and the 80 g/m² liner. These two grades were similar in tensile stiffness, but nevertheless differed in calculated strain difference. The viscoelastic behavior of the paper is thus not fully explained by the tensile stiffness. Instead, relaxation trials are needed to evaluate papers with regard to strain difference.

We assumed that the permanent strain in relaxation tests can describe the behavior in the outer layers of a reel, where the MD stress is tensile. It is a well-known fact among paper suppliers that problems with bagginess are always greater in the outer layers of a paper reel. Deeper into a good reel, the MD stress is usually zero or slightly compressive [9]. Regardless of the stress level, there is however still a length and strain difference, as long as there is a ridge.

The tensile stress could give rise to a small thickness difference in the paper. This effect was not included in this study, since our study sought to determine how high the ridges are allowed to be, not how thick the paper is in the ridges.

There are also ZD compressive forces in a reel, which vary with the reel diameter. The ZD compression is larger closer to the reel core. This compression may affect the paper length, but this effect was assumed to be small and was neglected in these calculations.

We assumed that it is possible to predict the strain profile by making measurements on separate paper strips. In the paper reel, where the paper in the ridge is continuously connected to the non-ridge paper, the different positions affect each other. Shear forces probably arise in the boundary between the ridge and the rest of the reel. If the shear forces restrict the strain differences appearing, the critical ridge heights would be somewhat higher than the values reported here. In a future study we shall compare the results presented here with measurements on paper reels.

Further research is needed in order to determine the maximum paper strain difference that can be run in different kinds of paper converting machines. Different machine elements are sensitive to different degrees, thus a more complex analysis than using Roisums criterion of 0.1 % would be interesting to perform.

### 4 Conclusion

The strain difference in a roll with ridges was determined with a simple geometrical model. The critical ridge height for runnability problems was between 1.1 mm and 1.5 mm for the papers tested, when the reel diameter was 1.2 m. When the reel diameter was 1.8 m, the critical ridge height was 1.6 – 2.2 mm. The calculation showed that MG paper was more susceptible to permanent
strain differences due to ridges than the liner grades. The critical strain difference was assumed to be 0.1 %.

The calculated critical ridge heights are very small, and could certainly occur in actual reels. The critical ridge height in practice would probably be somewhat higher. Still, significant strain differences can appear during storage. Ridges are thus a plausible cause for baggy lanes in paper.

Relaxation trials are needed to evaluate papers with this kind of model, since the tensile stiffness did not fully explain the long-time behavior. After a long time, creep tests could also explain the relaxation behavior of the paper.

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References


Bagginess due to storage of paper reels with artificially fabricated ridges

Cecilia Land, Jonny Widstrand, Torbjörn Wahlström, Lennart Stolpe and Luciano Beghello

Abstract

Ridges can appear in paper reels due to thickness profile variations. To create and study such ridges, thin foil strips were wound into paper reels. The web tension profile and web strain profile due to these ridges were measured in different MD positions of the web in the reels, after storage for one month. A ridge with a height of $2 - 3$ mm resulted in MD strain differences of about $0.14\%$ in the outer surface of an $80\,\text{g/m}^2$ liner reel with a diameter of $1.2\,\text{m}$. When the thickness disturbance was removed, the reel diameter quickly evened out. In the outer part of the reel, the strain-at break was lower in the ridge than in the rest of the reel.

Keywords: baggy webs, paper, reels, ridges, tensile properties, tension profile.

1 Introduction

Cross-direction variations in thickness, due to e.g. grammage variations, can cause ridges in paper reels [1]. During storage of the reel, the portion of paper in a ridge is subjected to a higher strain than the paper beside the ridge, because the diameter of the reel increases along the ridge [2]. This can produce a permanent non-uniform strain (or length) profile in the paper web. Webs with a non-uniform length are commonly referred to as baggy webs, and they can lead to runnability problems during converting.

A reel is wound under tension, but the MD tension in a paper reel is positive only close to the reel surface. Deeper into the reel, the MD tension is transformed to ZD compression, and the MD tension is then close to zero or slightly negative [3]. In a ridge however, it is possible that the tension is positive even further into the reel.

In a previous study, Land et al. [4] calculated the plastic strain differences in a reel with a ridge of a certain height. The calculation was based on reel geometry and paper relaxation properties. Three different paper grades were evaluated,
and a ridge height of 1 – 2 mm led to a strain difference greater than 0.1 %, which is a criterion for when runnability problems occur [5].

The purpose of the present study was to evaluate how ridges influence the strain profile in real paper reels. Controlled ridges were made in paper reels by winding thin foil strips into the paper reels. We evaluated the strain differences and tension differences in the web, and compared the results with the previous model [4]. The tensile properties at different reel positions were also measured.

2 Materials and Methods

Three different commercial paper grades made from softwood kraft pulp were tested: a 71 g/m² machine-glazed (MG) paper, an 80 g/m² liner and a 135 g/m² liner. The paper reels were 1.2 m in diameter and 1.4 m in width. The total web length on the reels was then about 16000 m for the MG paper, 14000 m for the 80 g/m² liner and 7500 m for the 135 g/m² liner. Properties of all the materials can be found in Table 1. The paper grades were the same as those previously tested [4].

<table>
<thead>
<tr>
<th></th>
<th>Structural thickness [µm]</th>
<th>MD tensile stiffness [kN/m]</th>
<th>ZD compressive modulus [GPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>71 g/m² MG</td>
<td>76</td>
<td>827 [4]</td>
<td>0.006</td>
</tr>
<tr>
<td>80 g/m² liner</td>
<td>90</td>
<td>826 [4]</td>
<td>0.009</td>
</tr>
<tr>
<td>135 g/m² liner</td>
<td>150</td>
<td>1445 [4]</td>
<td>0.01</td>
</tr>
<tr>
<td>Polyethylene film</td>
<td>7</td>
<td>-</td>
<td>0.7 [6]</td>
</tr>
<tr>
<td>Aluminium foil</td>
<td>6.3</td>
<td>-</td>
<td>90 [7]</td>
</tr>
</tbody>
</table>

Thin foil strips with a width of 10 cm were wound into these reels, with a Vari-Dur twin drum rewinder (Jagenberg). In the first trial, polyethylene (PE) film was wound into the three reels, in three different MD positions. A strip with a length of 200 – 300 m was wound into each position. The positions were: close to the core, in the middle of the reel, and in the surface of the reel, as seen in Figure 1.

In a second trial, aluminium foil was wound into an 80 g/m² liner reel throughout the whole reel. Aluminium foil was chosen due to difficulties in acquiring PE films of sufficient length. PE and aluminium both have a significantly higher compressive stiffness than paper (Table 1) and can thus be assumed not to be deformed. The thicknesses of the film and foil were chosen to be as low as possible in order to give a thickness difference of the same order as that which may accompany a grammage variation.
All the reels were stored in the storage room of the mill, without climate control, for one month. After storage, the reels were unwound and the foil or film was removed. A prototype of the Web Tension Profile Analyzer (Webline, Sweden) [8] was used for web tension profile and web strain profile measurement. In the case of the reels with film in three positions, the rewinder was stopped after half the length of each film strip and samples were taken for measurement of tensile properties and thickness. For the reel with aluminium, a sample was taken every 2000 m.

After unwinding, tensile strength, tensile stiffness and strain-at-break were measured on paper strips according to ISO 1924-3, in different CD positions in order to obtain profiles. The structural thickness profile was measured with a STFI thickness tester (TJT-Teknik AB, Sweden). For practical reasons, these measurements were performed a week after unwinding. The ZD compressive modulus of the paper grades was also measured on paper samples that were not from these reels. A stack of 10 paper sheets was then subjected to a compressive load of 3 MPa in a Zwick Z005 material tester (Zwick GmbH, Germany). A fixture with circular compression plates with an area of 1000 mm$^2$ was used. The samples were loaded up to 3000 N with a crosshead speed of 50 mm/min. The gradient of the load-strain curve was then determined by linear regression between 30 and 2500 N. The machine compliance was first measured and subtracted from the results. All these measurements were performed at 23 °C and 50 % RH.
3 Results and discussion

3.1 Observations

In the foreground of Figure 2, the ridge on the reel with an aluminium strip throughout the reel is seen. The ridge height was estimated to be about 2 – 3 mm by measurement of the photograph and relating the height to the width of the ridge (100 mm). Behind the reel, the unwound web is seen.

Figure 2: The 80 g/m² reel with a ridge (marked) due to aluminium foil.

During unwinding, there was a clear slack streak in the CD position where the foil had been. Another observation was that corrugations occurred, primarily on one side of the ridge (Figure 3). These corrugations in the reel occurred occasionally. The surface roughness was perceived by touch to be higher in the ridge than next to it, when the paper was in the reel. After unwinding, no roughness difference was perceived.

Figure 3: The 80 g/m² reel with aluminium ridge, about 2000 m from the outer surface.
3.2 Thickness and tensile properties

The thickness measured after unwinding was affected by neither the ridge nor the MD position in the reel. The ZD compression occurring in the reel was thus elastic. This applied at all positions in all the reels. The roughness that could be perceived in the ridge might depend on that fibers were rising from the paper during removal of the film/foil, due to adhesion between the film/foil and the paper. The surface roughness might otherwise be an effect of the MD strain acting on the paper. Whatever the case, the roughness effect disappeared before the measurements were made.

While the paper was still in the reel, however, there was obviously some ZD compression, especially in the inner part of the reel and especially in the ridge. Otherwise the ridges would have been much higher. If there had been no extra ZD compression of the paper in the ridge position, the aluminium ridge in the 80 g/m² reel would have been about 4 cm high instead of 2 – 3 mm. The compressive modulus is much lower for paper than for the film and foil (Table 1), and all the compression must thus have occurred in the paper.

Of the tensile properties, only the strain-at-break differed significantly between the ridge and the rest of the reel, and only in the outer part of the reel (Figure 4), where the ridge was relatively high. The paper in the ridge was subjected to long-term stress relaxation, which deformed the paper permanently and lowered the strain-at-break. The effect was greater further out in the reel, where the permanent strain in the ridge was higher. The explanation of the decrease in strain-at-break in the ridge is that the paper was already permanently deformed during storage and less ability to strain thus remained. Beside the ridge, the strain-at-break was more or less constant throughout the reel, except closest to the core. There, the strain-at-break was clearly lower than further out in the reel, in all CD positions.
3.3 Web tension and strain

The slack streak observed in the paper was also very clear in the web tension profiles. Figure 5 shows the web tension profiles in the reel with aluminium foil. The streak was most slack in the outer part of the reel, and the slackness declined as the height of the ridge decreased. In the middle of the reel, there was a part that was less slack and the slackness then appeared again about 4000 m from the core. Possibly there was another defect in the reel that caused this. In the very end of the reel, the ridge gave rise to a tight streak instead of a slack streak.

When only shorter pieces of PE film were used, the slack streak was significant only in the position close to the core, which is opposite to the results obtained with foil throughout the reel. The explanation is probably that the 200 – 300 m of film that was wound into the paper reel closest to the core consisted of more laps of paper than in the middle and at the outside of the reel. The ridge build-up was thus greatest close to the core. Longer film pieces would presumably have caused more slackness due to a larger ridge build-up. 200 – 300 m is quite a small part of a 14000 m long reel.

During unwinding, slack streaks were found before the actual thickness disturbance, i.e. radially further out than the PE film. The slackness increased closer to the film and reached a maximum at the start of the film. The slackness then gradually decreased as the height of the ridge decreased. Towards the end of the films, the reel diameter and tension profile had evened out. These observations were made at the “core” position, where the slack streaks were significant. Similar tendencies were seen in the “middle” position also. An exception to this...
behavior was the tight streak that appeared closest to the core.

Table 2 shows data for the recovery of the slack streak at the “core” position. The film thickness is the total thickness of the PE film in the “core” position. This is not an exact measure of the ridge height, since the effect of extra paper compression in the ridge is not accounted for. The film region thickness is the total thickness of the paper and the film at the “core” position. The compression of the paper is not taken into account either here. The maximum strain difference due to the ridge was at the start of the film. The recovery length is the distance in meters outside the ridge until the slack streak disappeared from the web tension profile.

The strain difference was the highest for the MG paper and the 80 g/m² liner, and was significantly lower for the 135 g/m² liner (Table 2). In the previous study [4], the paper with the largest strain difference was the MG paper, the 80 g/m² liner was the second and the 135 g/m² liner had the smallest strain differences. In that study, the difference between the MG paper and the 80 g/m² liner was about as great as the difference between the 80 g/m² liner and the 135 g/m² liner. The strain difference due to the PE ridges can unfortunately not be calculated with this model, since there is no accurate estimation of the ridge height. If the height of the PE film is taken to be the ridge height, the model would still not be possible to use, since the material parameter is not determined for the strain that would appear in a reel with such an unrealistically high ridge, relative to the reel radius. The reel radius here would be the film region thickness (Table 2) plus the core radius.

Paper is a compressible material, and the reel thus needed quite a short distance to recover to a uniform thickness. If the ridge had consisted of paper instead of
PE, the recovery would have been even faster since paper is more compressible than PE. It is surprising that the 135 g/m² liner needed the longest distance to recover, since in that case the film is thinnest relative to the paper thickness and the strain difference was also the lowest. The relatively long recovery length could be because the ZD compressive stiffness was relatively high in the 135 g/m² liner (Table 1). Between the different paper grades, the recovery length was ranked in the same order as the ZD compressibility.

Table 2: Distance for recovery of slack streak due to PE film, and the maximum MD strain difference, for the different paper grades at the “core” position (see Figure 1). The thickness of the film in the ridge and the uncompressed thickness of the whole film region (film+paper) are also shown.

<table>
<thead>
<tr>
<th>Film thickness [mm]</th>
<th>Film region thickness [mm]</th>
<th>Maximum strain difference [%]</th>
<th>Recovery length [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>71 g/m² MG</td>
<td>3.2</td>
<td>38</td>
<td>0.12</td>
</tr>
<tr>
<td>80 g/m² liner</td>
<td>3.8</td>
<td>53</td>
<td>0.13</td>
</tr>
<tr>
<td>135 g/m² liner</td>
<td>3.2</td>
<td>72</td>
<td>0.088</td>
</tr>
</tbody>
</table>

It was unexpected that the slack streak turned into a tight streak closest to the core. This was only in the last 80 m, approximately, of the reel and was observed in all the trials. The ZD compression is very high there and there is a hard core on one side which does not compress as much as the paper. A possible explanation is that the high ZD compression causes a negative MD strain there, as sometimes occurs in calendering [9]. Nevertheless, the thickness measured after unwinding in the ridge position was not different from the thickness in the rest of the reel.

Figure 6 shows the strain difference between the ridge and the rest of the reel for the 80 g/m² liner with aluminium foil. When foil was wound throughout the reel, the strain difference was about 0.14 % at the surface of the reel (Figure 6). The web strain profiles are the mirror images of the web tension profiles and both measurements thus show the same behavior in the reel. Consequently, deeper into the reel, the strain difference decreased but then increased again unexpectedly about 5000 m from the core, and closest to the core the strain difference was negative.

It is surprising that the strain difference in the reel with the aluminium foil was so small compared to the strain difference due to a small PE ridge close to the core. In the 80 g/m² liner reels, at 300 m from the core, the strain difference was 0.13 % in the reel with PE and about 0.01 % in the reel with aluminium. There, the strain difference did not reach 0.13 % until in the outer part of the reel. The aluminium foil was somewhat thinner than the PE film, but the difference is not large enough to explain this behavior. A possible explanation is that in the reel with aluminium foil, the ZD compression on the ridge is higher than in the reel.
Figure 6: Strain difference between the ridge and the rest of the reel as a function of MD position in the 80 g/m² liner with aluminium foil throughout the reel.

with PE, since a large amount of aluminium foil is outside the “core” position. A high ZD compression could result in MD contraction as previously stated [9]. The effect would then be a smaller strain difference close to the core in the reel with aluminium foil, as was measured.

According to previous calculations based on stress relaxation [4], the strain difference in the 80 g/m² reel containing an aluminium strip with a ridge height of 2–3 mm would be about 0.2 % in the surface of the reel after one week’s storage. The measurement in Figure 6 showed 0.14 % after one month’s storage, which is of the same order but nevertheless the calculations seem to have overestimated the problem. In the reel, there are probably shear forces between the ridge and the paper beside the ridge and those might restrict the strain at least at the edges of the ridge. The strain in the ridge used for the calculation shown in Figure 6 is the average value of the three measurements made inside the ridge, and not only the strain in the center of the ridge, which always was the highest.

An interesting issue is that the ZD compression in the reels was elastic, but the MD strain differences and differences in strain-at-break were permanent. There is a great need for further research in this area.

4 Conclusion

A systematic thickness disturbance in a paper reel gives rise to a ridge, but the ridge evens out very quickly if the thickness profile is evened out. The paper in the ridge develops a decreased strain-at-break if the ridge is high enough, but
other mechanical properties or permanent thickness are unchanged.

A ridge with a height of 2 – 3 mm on an 80 g/m² liner reel with a diameter of 1.2 m gave rise to a strain difference of 0.14 %. The strain difference is affected by the stress relaxation behavior of the paper, and by shear forces between the ridge and the rest of the reel.

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**References**


