Some impacts of paper making on paper structure

Michael A. MacGregor[1]

Abstract

What we do in paper making often changes the paper structure in completely unexpected ways and that is the common thread in all the experiences discussed in this paper. Inside the headbox, fibers align generally in the paper making direction—but some in perfect streaks called fiber orientation streaking. During forming the fibers and small particles are arranged into a 3-dimensional structure that has a huge disparity in its principal dimensions. Though paper is a highly layered structure the fibers are still slightly tilted inside the sheet, with the leading or trailing ends nearer to the outer layers depending on the rush or drag and pointing to the outside or inside depending the headbox jet cross flows. Pressing then modifies this structure by densifying more the water exit side and by also redistributing small particles (and sometimes fibers) inside the sheet. Like pressing, drying is also a densification process that causes unexpected structural changes otherwise not occurring if strictly an evaporative drying process. We know too little about how the paper expands (springs back) after pressing, redensifies during evaporative drying, and finally how the dried structure then responds to the finishing operations. So, we still don't truly understand the best ways to optimize the bulk, strength, dryness, and smoothness interrelationships. Intense paper making operations almost always lead to degraded paper structure such as MD Microstriations, cockle, shrinkage roughening, and others. To study the effects of all these paper making operations on paper structure it would be valuable to noninvasively sense the paper interior at a resolution sufficient to reconstruct in good detail the fiber and pore structure in all three dimensions. Though still not possible, this would lead to better understanding of the paper mechanical properties and fluid penetration of all kinds.

Keywords

Web consolidation, pressing, drying, impulse drying, Condebelt drying, press drying, MD microstriations, cockle, fiber tilt, fiber orientation streaking, skin, membrane, springback, redensification, delamination, finger ridging, stratification, flashing, fluting, 3D reconstruction

Introduction

Compared to many products, paper has orders magnitude difference between its characteristic dimensions—infinity in length, meters in width, and only microns in thickness. Therefore, both measurements and understanding must occur at a scale relevant to each problem of interest.

Paper making as a continuous process has occurred for several centuries. Today's paper mill is a highly complex multivariate nonlinear dynamic system that presents those in charge with numerous surprises and challenges. There is much in the paper mill that is deterministic[2] but a paper mill is also rife with chaotic behavior not easily explained (cockles being a good example). Order and chaos [1] act in concert to give the final structure for any given reel of paper.

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[1] MacGregor Paper Consulting
8 Pierce Court
Appleton, WI 54914
http://www.mac-paper.com/

[2] Explainable by classical physics and therefore predictable in time and/or in space.

Discussed here are several personal experiences on commercial machines, most of them astonishing surprises at the time. The driving force for solving all these problems, almost none of which could have been discovered or duplicated in the research lab or on the pilot machines, was not just the intellectual challenge of overcoming them but large profit loss at the mill level.

A common thread in all these experiences is that *process intensity is almost always the enemy of ordered*[3] *paper structure.*

Fiber orientation streaking

Fiber orientation is the cause of problems such as finger ridging in coated and supercalendered paper, fluting in the printing press, runnability problems in the corrugator, and severe out-of-plane-ness problems in general.

It is emphasized that in this section we are not discussing basis weight streaking but fiber orientation streaking. The same number of fibers per unit volume can pass by a given location but may be oriented differently in different places or at different times.

Only fluid shear force inside the headbox [2] can align fibers in the sheet with the perfection displayed in Figure 1. The fluid shear from secondary flows in the headbox has only recently come under great scrutiny [3-6] because the resulting fiber alignment causes numerous optical and mechanical problems in the paper structure and its end-use performance.

Fiber orientation streaking is easily observed on the wire side surface of brown grades like linerboard, often termed “galvanizing” or, in Europe, “water snakes” (Figure 2). The paper surface in the streaked area is denser and this causes greater light absorption (a darker appearance). Mainly, however, when the viewing direction and the incident light are both coincident with the streak (Figure 2, upper) there is no light scattering off the sides of lined-up fibers back into the eye. The streak, therefore, appears darker than the surroundings that do scatter light no matter the viewing or lighting direction. On the other hand, when the incident light and viewing direction are perpendicular to the streak, significant light reflects off the sides of the lined-up fibers into the eye, making the streak appear lighter than the surroundings (Figure 2, middle). The area surrounding the streak appears the same brightness level no matter from what direction the light arrives or the sample is viewed because always a similar number of fibers are scattering light.

The streaks do *not* correlate with a basis weight variation as indicated either with transmitted light, Figure 3, or by measurement. Instead, they are a *surface*[4] fiber orientation phenomenon (Figure 4).

White grades prevent making the above observations because the high reflection intensity overwhelms the light scattering effect from fiber sides and edges. Although the optical behavior described above provides the most sensitive method for observing fiber orientation streaking (in brown paper at least), surface fiber orientation measurements [7] or a recent tape delamination technique coupled to image analysis [8] can also reveal them and how far into the sheet they penetrate.

The streaks can originate inside a distributor-roll headbox as in the linerboard example (Figure 5) or inside a hydraulic headbox as in the coating base stock example (Figure 6). Each headbox type gives its own characteristic steak pattern or texture[5] and, to date, it has

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[3] “Ordered” in this context means either uniform or intentionally nonuniform but without faults in the structure.

[4] The fiber orientation streak lies in the layers at and just below the paper surface.

[5] A ‘pattern” is an oriented repetitive (cyclic) variation in one or more dimensions whereas a “texture,” though having orientations, is a characteristic organization of

proven difficult or impossible to eliminate them.

Prominent streaks from a distributor-roll headbox result from a combination of basic design and hydraulically overloading the headbox [9, 10]. The fibers line up during the 50 % flow contraction through the distributor roll holes, immediately followed by a stretching flow field in the high-contraction nozzle (Figure 5). Their coherency preserved by this stretching flow, the streaks leave the slice and are immediately formed into the sheet wire side (25 % or more of the sheet is formed within the first meter on the forming board). The only way to reduce the streaks is to shorten the wakes by significantly lowering the headbox flow rate (consistency) and suffer a formation loss, usually not an option in a commercial setting.

Nothing else attempted so far has eliminated the galvanizing that occurs with a distributor-roll headbox. Changing the distributor roll settings (rpm, direction, position) has virtually no effect. Spiral-drilled distributor rolls only reduce the perceived effect of the streaks during reeling—not eliminating the streaks themselves. Intense pressure forming does reduce the streaks by forcibly breaking them up on the forming board but in the process also destroys the sheet formation and gives unacceptable retention.

In the case of a hydraulic headbox the streaks can arise from spinning and other types of secondary flows [5]. These flows are thought to contain a core of highly aligned fibers that, like the air-padded headbox, escape the headbox and form immediately into the sheet. Streaks are also postulated to form by an interaction of these headbox secondary flows with the forming wire(s) during and after impingement [5, 11], Figure 6. Without actually measuring local fiber orientation inside the headbox (not currently possible) the validity of either postulation is unknown. In either case, the fiber orientation streaks originate inside the headbox with the secondary flows superimposed over the main flow but the details of these flows are the subject of continuing research.

The streaks inside the headbox are not stable in space or time but intertwine in the sheet thickness direction, chaotically alternating from the top to the bottom of the sheet [12-14]. The streak spacing needn't exactly equal the headbox tube spacing to still be related [5]. Ongoing work at several research institutes and also the machinery builders hopefully will eventually give us a better understanding of secondary flows, fiber orientation streaking, and the means to eliminate them.

In one paper mill, after arduous work (during 1995-96) to eliminate all processes back to the hydraulic headbox, fiber orientation streaking was finally pinpointed as the cause of finger-ridging in the coated and supercalendered paper. The ridges, a deterministic phenomenon easily seen at the supercalender reel (Figure 7), had a height difference of only about 1000 - 1500 µm from peak to valley at the outer circumference of the finished reel (12,500 layers!). This extremely small caliper difference (<0.1%) attributable to the streak in each layer makes them nearly impossible to detect using even the most sensitive offline basis weight or caliper sensors (vast quantities of data—represented by the reel-building process—are required to average out noise[6]).

In this example, the only fundamental sheet property that we could find to agree with the dominant finger ridging spatial frequencies (Figure 8) was the surface fiber orientation mapping (Figure 9 and Figure 10). This for the first time implicated fiber orientation streaking from the hydraulic headbox as the

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elements that can have a wide range of spatial frequencies.

[6] Variations in space and time that have an equal probability of occurrence.

cause of finger ridging and not basis weight or other common sheet properties.

Due to its different structure, the oriented streak is thought to take on coating differently and to calender differently, resulting in an imperceptibly different caliper (this postulation needs experimental proof). How to effectively eliminate fiber orientation streaking is not yet completely understood.

From research initiated by Assi-Domän Kraftliner to solve a "water snakes" problem identified as fiber orientation streaking in their linerboard [15] a triangular step was affixed to the headbox nozzle floor a short distance ahead of the slice [16]. This step, first tried much further upstream on a commercial headbox by Kiviranta [17], was meant to destroy the bottom boundary layer and break up the fiber orientation streaks before leaving the headbox. The step, generally not well known, has been applied with varying success to paper machines and grades having finger-ridging or galvanizing problems.

For headboxes with turbulence tube bundles Aidun has received a patent [18] for a device to produce counter-rotating swirling in tube pairs meant, hopefully, to cancel secondary flows that lead to fiber orientation streaking. The efficacy of this has not been reported. For now, fiber orientation streaking remains a challenging problem as a growing number of paper makers come to realize that many of their sheet structure problems like finger ridging and out-of-plane-ness originate during the forming process.

Fiber "tilt" and "grain" in paper

Paper is a highly layered structure but there is some degree of intermixing between the layers, not only due to the fiber orientation streaking discussed above but also to the dynamics of the forming process itself. It is believed that the shear during the dewatering process[7] results in the fibers being tilted slightly out of plane, giving the paper a grain structure analogous to that of wood. Some operators believe that this grain affects runnability in the coaters and in nips (like a printing press) that contain a viscous or tacky medium where sheet delamination could result.

When operating in the "drag" forming mode the fiber end (or loop) further from the headbox (the leading end) is formed first into the mat and slightly more to the outside surface. The remainder of the fiber is formed into adjacent layers more inside and backwards in the sheet, giving the wire side a backward-tilted grain structure that reaches through to the felt side (Figure 11.). The opposite is the case for the "rush" forming mode.

No method presently exists to measure the degree of fiber tilt in paper. Instead, surface tape peels can *indicate*, with many paper grades, the presence of grain and, by the amount of fiber pulled out, even give a subjective idea of the tilt degree. The tape adhesive attaches to the fiber ends and pulls more fibers out when working against Z-direction strength than against the fiber tensile strength (individual fibers are normally stronger than Z-strength), Figure 11.

The tape peel method tells the true running direction of the paper if the machine rush or drag is known. For a Fourdrinier machine operating in the drag mode the true running direction is best indicated on the wire side by more fiber removal when the tape is peeled against the grain back towards the headbox, the anti-machine-direction.

Long before the advent of modern fiber orientation sensors, tape peels could also

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[7] During dewatering the water moves *down* toward the wire but it also moves *forwards/backwards/sideways* with respect to the forming fabric, depending on the jet speed and direction.

indicate the general sheet fiber orientation using a “tape peel rosette” (Figure 12). In this LWC example the machine was operating in drag and the slice ends were pinched to counteract the effect of CD shrinkage in the dryer section. The fiber leading end is, therefore, formed first into the mat and the trailing end deeper and more towards the machine centerline due to the combined effects of drag and the jet crossflow caused by the pinched slice. Thus, the tape peels out more fiber in the anti-machine-direction and in toward the machine center (Figure 12). Facing the reel and looking down on the sheet, the fiber orientation sense is in the outward direction on the Drive Side. This result is confirmed with actual geometric fiber orientation measurements for this paper (Figure 13).

It is believed by some observant paper machine operators that coater breaks can be affected by the fiber tilt phenomenon. A square sheet and a sheet with forward-tilted grain both give the coater blade a greater chance to catch fiber ends and break down the sheet. A forward-tilted grain also increases the coating directionality for a process that is already directional without fiber tilt [19]. Coating the felt side first of a Fourdrinier sheet made in drag decreases the propensity for breaks. This is not only because of increased MD tensile strength (the conventional wisdom) but also because the blade runs *with* the grain on the felt side and can’t catch fiber ends. If the wire side is coated first, then operating in drag can actually increase coater breaks (compared to equal rush) due to the blade running against the grain.

One side of a Fourdrinier paper (usually the wires side), due to the grain structure, may have a greater tendency to delaminate (peel back) than the other. Again, if there is a choice, subsequent processes should account for this possibility.

For gap formers the grain usually runs forwards (in the machine direction) on both sides from the combined effects of two-sided drainage and headbox jet deceleration in the converging gap (even when running in rush). This makes the tape peel about equal on both sides, with more fiber pulled out in the anti-machine-direction. Coater breaks could be more and delamination in subsequent processes like printing could be worse unless the paper is rereeled to run with the grain.

Two-sided forming, which inherently produces a weak central region due to the combined effects of two-sided dewatering and grain structure, can make delamination a serious issue. If there is a choice, paper should be delivered with the grain in the same running direction as subsequent processes.

3D reconstruction of the paper structure

One of the main points of this article is that paper must be thought of as a 3-dimensional structure.

We have for millennia dealt with one-dimensional data (for example, temperature vs. time). We have also for a long time worked with two-dimensional data (mapping), even rendering this as a three-dimensional surface for better visualization. However we have never simultaneously measured the paper in all three of its dimensions at good resolution.

Much information is lost when viewing or measuring paper in a single plane or even when attempting to separately combine information from several planes. For example, the extremely tight surface seen in Figure 14 cannot be deduced from the paper cross-section. In fact, none of the plane views can be accurately derived from the others.

If we could routinely noninvasively sense the paper at a voxel size of less than 1 µm we could then much better measure and understand paper structure. A three-dimensional volume rendering of paper could tell us much about the pore structure and would be extremely useful for confirming various paper structure models. It could also, for example, elucidate the fiber tilt phenomenon discussed above that presently has no means of measurement. Most important, an accurate volume rendering would not only provide useful images but also allow objective measurements.

Several groups are attempting to perform a three-dimensional reconstruction of paper but the resolution still needs improvement. For example, the most recently reported x-ray microtomography work has a resolution of about 5 µm [20, 21], very suitable for today's medical applications and, to some extent, for studying certain paper and board structure. However, this is still too low to accurately discriminate the passageways and small particles between collapsed paper fibers.

We several years ago attempted to perform a three-dimensional volume reconstruction using light microscopy of 1 µm-thick serial cross sections combined with image analysis [22]. We found that invasively creating and maintaining a valid reference mark for registering the cross sections and then making nearly-artifact-free cross sections is probably impossible. This precludes proper data set registration for the subsequent volume rendering process, making the resulting image very noisy (Figure 15, upper). Mathematically aligning the data set using recent automated image analysis methods [23] prior to the rendering also proved impossible due to the image complexity and the rather large artifact errors. Anyway, this alignment procedure introduces its own artifacts.

Figure 15 (lower) shows two volume renderings of a single wood shive isolated from the paper serial cross-sections. The individual cross sections of this prominent feature were manually aligned for this exercise using an image-editing program prior to volume rendering. This of course introduces some subjectivity and is not a practical method for rendering the entire volume. So, it remains a matter of time until higher resolution is available, probably only occurring as the medical or another industry pushes the noninvasive sensing envelope further.

A "skin" (membrane) associated with pressing and drying

The porosity and density of the paper surface (however defined[8]) play a central role in its fluid penetration, mechanical, and optical behavior during coating, converting, and printing operations. Z-direction (paper thickness) density gradients during and after the wet pressing event have long been predicted by theory and also roughly measured on several occasions [24, 25]. The exact shape or sharpness of the surface density gradient, however, has neither been predicted nor accurately measured.

It has been long known that a fiber network density gradient can exist in paper due to wet pressing [26]. However, the serial cross sections obtained for the previously discussed volume rendering work give strong evidence that a very thin (1 - 2 µm) membrane can exist on the side of the paper where most of the water was pressed out (Figure 16). This phenomenon we believe would be difficult, if not impossible, to replicate in the laboratory or even on pilot machines because neither utilizes an integrated pressing and drying process.

We define a membrane as a thin contiguous structure that lies very near (above) or directly upon the paper surface, replicating it similar to

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[8] The term "surface density" implies that the paper surface is not a discrete entity but a *region* having different properties than the interior.

a plastic shrink-wrap. It needn't completely cover the paper surface but we think contiguity requires that the membrane be uninterrupted over a reasonably large area relative to fiber dimensions, with few discontinuities (break lines or gaps) or large holes. We believe these requirements have been met for the sample investigated and that this is the first time such a phenomenon has been reported [22].

Figure 17 shows the results of an experienced microscopist's careful examination of one cross-section using information from numerous ones on either side of the one shown. These cross sections allow a reasonably accurate definition of the first contiguous object[9] (entity) encountered when entering the cross-section. The interior pixels were removed to provide greater clarity.

It has never been possible until now to detect in the cross section the sharp density gradient implied by the surface views. The very thin structure seen on top is the first time that the paper cross-section has agreed well with the highly densified surface view of that side of the paper (Figure 14). Underneath the skin lies a dense network of collapsed fibers.

The skin appears for many consecutive cross sections. Sometimes it lies directly on the surface fibers, sometimes it is set a small distance away, and other times it spans relatively long distances from fiber to fiber. In any case, it seems to replicate the underlying fiber structure, making it extremely difficult to detect as an entity in the surface view and even in cross-section—probably one of the reasons it has escaped notice until now.

The other side of the paper consists of uncollapsed fibers, numerous passageways into the interior, and no evidence of a membrane. It is astounding that only about 60 µm separates these two surfaces that have such dramatically different structure.

The underlying Z-direction fiber network density gradient has previously been thought to control the fluid penetration behavior [27] but this work raises the question whether the skin has even more influence. This work was performed on only one commercial 50 g/m^2 lightweight-coated base sheet. Therefore, while its existence we feel has been unequivocally shown here, more research is needed to determine how widespread this phenomenon is, what coverage the membrane has, of what material it consists, how it is formed, and whether the membrane is actually critical to the fluid penetration behavior.

Differential shrinkage and out-of-plane-ness

Differential shrinkage occurs when one part of the paper dries and shrinks before another, resulting in nonuniform shrinkage strains. This occurs on different scales and also within and between sheet planes.

Cockles and its relative, ***wrinkles,*** (Figure 18) are an extremely complex phenomenon, perhaps one of the better examples of chaotic behavior in the paper mill. Cockles are the frustrating kind of a problem that, once into a siege, the paper maker can't extricate himself but when he wants to produce them for study he can't make them happen. It is as though a number of paper making variables must come into conjunction, each at the proper level, before the phenomenon either disappears or reappears.

On the fundamental level, cockles are due to differential shrinkage strain in the sheet plane but a myriad of variables, not all obvious and not all acting linearly, can affect this. The nonuniform strain initiates at the critical shrinkage point in the dryer section (about 60% dryness) and arises from localized differences in sheet structure, basis weight,

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[9] The term "object" implies 3-dimensionality and this requires numerous serial cross-sections to determine.

and/or moisture. Sheet structure includes the local fiber content and condition (even including during what time of the year the wood was cut or ground), porosity, density, and fiber alignment such as fiber orientation streaks.

So-called “shrinky” furnishes are more prone to cockles, not just from the high fiber shrinkage tendency but also because these furnishes don’t give up their water easily. A more open sheet with less hydrated fibers and fewer fines gives up its water everywhere easily. A sheet like this is postulated to arrive at the critical point in the dryer section with inherently more uniform moisture and thus not cockle as easily. The water retention value (WRV) is a good method to monitor a furnish for its cockling propensity because it indicates how easily the water is given up. Monitoring the fines content using a Britt jar (*not* Canadian Standard Freeness) has also proved useful.

Intense drying, especially in the early dryers, promotes cockles and wrinkles. It is hypothesized this amplifies the in-plane moisture differences before these enter the critical shrinkage zone. The lighter parts of the sheet dry and shrink in place before the surrounding heavier wetter regions. The latter regions ultimately shrink more and draw the lighter parts out of plane. The out-of-planeness is not due so much to the lower basis weight[10] (usually, it’s only several per cent lower) but to the nonuniform shrinkage.

Dryer felt tension has also proven to be an important variable in helping to desensitize the machine to cockle. Most paper and board machines were designed with far too low felt tension capability and many machines are being operated today at only half of what is really needed. All this is exacerbated as machine speeds are increased but nothing is done to upgrade the dryer section.

Basis weight variations that can lead to cockle arise from many causes. Bad formation is certainly one possibility for small-scale cockle. Another source of basis weight variation is pressure fluctuation from the headbox [28] or a headbox that is vibrating (especially in the machine direction). These variations can lead to “wave building” on the Fourdrinier that amplify the original basis weight variation [29].

Our recent work has indicated that headbox-related cockle is associated with short-term variations that most people are probably unconcerned with. It is believed that a threshold basis weight and/or moisture gradient and amplitude are needed to produce cocklefields or wrinklefields—the same basis weight/moisture amplitude spread out over longer wavelengths (lower frequencies) will not likely produce cocklefields unless the amplitude is unusually high.

Depending on the machine speed, 85 Hz and above seems to give MD spacings critical for cockle and wrinklefields (10 cm to 20 cm). Amplitudes in these frequencies may not appear excessive in a pulsation or vibration spectrum but still lead to cockle or wrinkle fields even when much stronger lower frequencies don’t.

There are other variations in the sheet structure that might lead to cockles. Press vibration can cause a moisture and sheet density fluctuation at the frequencies critical to cockle fields. Moisture fluctuations from the forming process can also lead to cockles, not just from the moisture variation but also from the paper structure variation. Fiber orientation streaking certainly leads to cockle or wrinkle as Figure 2 attests and is discussed by Waech [6]. Anything that affects the local sheet porosity can also lead to cockles. All this requires that great consideration be given to the condition and control of the furnish

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[10] Even a uniform basis weight sheet will cockle in the presence of nonuniform moisture.

coming from the pulp mill and to the forming, pressing, and drying processes.

MD Microstriations , like cockles, also arise from differential shrinkage—this time between the outside layer(s) and the remainder of the sheet [24].

MD Microstriations (MDMs) are tiny (much less than 1 mm) MD-oriented fissures in the paper surface seen best in grazing light (Figure 19). It is difficult to believe that they survive the coating and even the supercalendering processes but this is because they are so small and strong that it takes impossible calendering pressures to remove them.

Viewed in the microscope, MDMs give the paper surface a characteristic rough leathery appearance reminiscent of elephant skin. For a coated sheet the microstriation valleys are covered with up to ten times more coat weight than the adjacent ridges. MDMs appear in the print because the thicker coating and the thicker ink film over the microstriation valley[11] both lead to slower ink tack buildup here. This gives uneven ink trapping in offset lithography (Figure 20, upper) while the topography of the ridges and valleys give a nonuniform gloss distribution (Figure 20, lower). In rotogravure printing there can be skipped dots. All of this greatly reduces information transfer and lowers the print quality [30].

MDMs cannot be removed from the basesheet or hidden once they have developed in the main dryer!

MDMs are a sheet structure problem caused by the web consolidation process and *not* the direct fault of felt marking as is commonly believed. However, it is not a coincidence that MDMs appear on the paper side that has the most felts (e.g., the top side for a Tri-Nip-type press). This is the paper side through which most of the water is pressed. The wet pressing action densifies the water exit side, making a thin layer that is much denser and drier than the rest of the sheet (Figure 14). In essence, two completely different sheets enter the dryer section—they happen to be joined! The dense dry layer shrinks less and much sooner during the evaporative drying process than the bulk of the sheet. The latter shrinks more, drawing the thin layer into compression (it is thought) and causing the micro-scale buckling and delaminating that gives the wrinkled surface seen in Figure 19.

MDMs are, therefore, the fundamental result of a differential CD shrinkage between the dense outer layer and the remaining sheet but the detailed mechanisms need further research. Changing the felt design will *not* help MDMs (although that can help other types of marking). A smoothing press *might* help somewhat, but only by creating a slightly more uniform z-direction sheet density and dryness into the dryer and not by the smoothing action (MDMs are created during the drying process). Reducing the density gradient from wet pressing (extremely soft covers or an extended nip) and using the gentlest paper drying and the greatest CD restraint possible seem to offer the best chances to improve MDMs.

Consolidation—the role of springback and redensification

Consolidation on a commercial paper machine is an “integrated process”[12] but not in the laboratory or on the pilot machine. Therefore, while the latter can nicely predict water removal during pressing, most sheet properties cannot be predicted accurately.

Burton and Sprague [31] were the first to measure during a dynamic compression event

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[11] Coating shrinkage during drying makes the valleys slightly lower than the ridges.

[12] All processes occurring in a certain time and space sequence.

the Z-direction density gradient development during pressing (stratification) described by MacGregor [26]. Burton's data showed a substantial and sudden overall sheet density loss (springback") as the compressive stress was released—30 to 40% within milliseconds (Figure 21). Not surprisingly perhaps, most of the springback occurred in the dense layers adjacent to the porous plate (water exit side); near the end of the pressure pulse, almost *none* of the large mid-nip Z-direction gradient predicted by MacGregor remained.

Vomhoff's recent work with wet compressed paper [32] also demonstrated a large and quite rapid (within 1 sec) springback once the compressive stress was *completely* removed. In both studies the expansion behavior was furnish-dependent—mechanical pulp expanding faster than chemical pulp.

These results verify that nobody has really ever observed or measured a freshly pressed sheet—only a pressed sheet after expansion.

Despite the above measurements of high springback on freshly pressed paper, countless photomicrographs of *dried* paper like the one in Figure 14 show a very dense water exit side. In addition, a z-direction gradient has been measured in dried paper on several occasions [24, 25]. How does the pressed paper change from the expanded condition to its final state? A review of the literature shows this has not been systematically studied.

Wahren points out the interesting observation that laboratory or pilot-pressed paper reaches a lower final density compared to the commercial machine unless the pressed paper sample is recompressed against a drying cylinder and then held under light but continuous normal pressure by felt tension until dry [33]. He describes a laboratory device for properly studying the mechanical properties of the pressed and dried paper (as opposed to merely performing press water removal studies). Only when the final sheet density is the same as occurs on the commercial machine can other properties (e.g., bending stiffness, tensile stiffness, tensile strength, extension, light scattering coefficient, etc.) be properly assessed or predicted.

It is well to recall that, on a commercial machine, significantly greater shrinkage occurs in the sheet thickness direction (up to 25%) than in its width direction (usually much less than 10%, even at the edges). Thus, drying on a commercial machine can also be viewed as a densification process, one where the structural variation on one side of the sheet can be transmitted down through to the other side. This is nicely shown in Figure 22 where the top side texture entering the dryer section appears almost as strongly on the previously-flat bottom side upon drying [34].

However, significant Z-direction shrinkage densification cannot occur unless the paper fibers are *continuously* held close enough together for receding menisci to create sustained capillary pressure (Campbell force). It does not require large compressive stress to initiate and sustain the capillary pressure because the fiber network has a "memory" of its compressed condition in the press nip—the various fiber crossings are more easily brought back together again and held under light compressive stress after they have once been compressed.

The short interval between the press and the dryer sections of a commercial machine (typically several hundred milliseconds, much less than the 1 sec shown in Vomhoff's work) probably limits paper springback, especially for chemical furnishes. The ensuing compression from the dryer fabrics then acts together with sustained capillary pressure to draw the structure together and promote bonding (sheet consolidation) during the evaporative drying process.

It is impossible to know exactly how much the dense water-exit-side surface expands after leaving the press nip. It is also unclear how faithfully the original Z-direction density distribution during wet pressing is regained during the drying process (redensification). Figure 14 and measurements [24] imply that at least certain characteristics of the gradient are recovered. While the water exit side of the pressed paper is always significantly denser than the smooth roll side after the paper leaves the dryer section of the commercial machine, it is unknown how deeply into the sheet the redensification gradient extends or if it remains only at the surface.

The Press Drying process [35, 36] though never commercialized, possibly offers the ultimate consolidation process for densification and bonding because the pressed sheet is recompressed in numerous heated nips while being held under continuous restraint (both XY and Z) throughout the entire evaporative drying process. This assures the highest bonding and strength possible.

The Condebelt process [37, 38], now commercialized [39], probably offers similar consolidation to Press Drying. Both these processes, especially the Condebelt, have relatively low intensity.

Impulse Drying [40], the most intense web consolidation process known, still remains, after more than 20 years, in the fundamental research stage. This process also potentially allows reasonable consolidation possibilities but *only if flashing of superheated water is prevented (or its effects overcome).* Long before the large-scale event researchers have termed delamination occurs [41], flashing prevents in local areas on the hot roll side the development of sustained capillary pressures and subsequent bonding on the molecular scale needed for structural order and integrity.

Concluding remarks

The commercial paper making system is multivariate, highly nonlinear, and, therefore, highly complex. Due to its combined deterministic and chaotic behavior what we learn by studying separately its parts doesn’t necessarily translate to the whole. This creates surprises, some of them unpleasant. In general, when we ask paper to undergo more within a shorter time frame (as invariably we do), the paper structure is hurt—it becomes more disordered and it may be unable to perform the way intended. This is acceptable only if we either lower our expectations or redefine what is *really* required to accomplish the goals. Some of the examples discussed here from the commercial practice like fiber orientation streaking, fiber tilt, the skin, MDMs, cockle, and flashing, clearly call for further fundamental study. However, in these times of globalization, consolidation, and restructuring occurring within all industries, it is unclear who will undertake this. Still, it should be heartening to researchers and technologists that at least we have a relevant TO DO list to work on.

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Figures and Captions

Figure 1 . Fiber orientation streaks in a Linerboard wire side. These SEMs show how remarkably lined-up the wire side fibers are by fluid shear forces inside the distributor roll headbox. As for any machine-made paper, the non-streaked area (top) exhibits some MD orientation but the streaked area (bottom), adjacent by only a few cm, is almost perfectly lined up (at least at the surface).

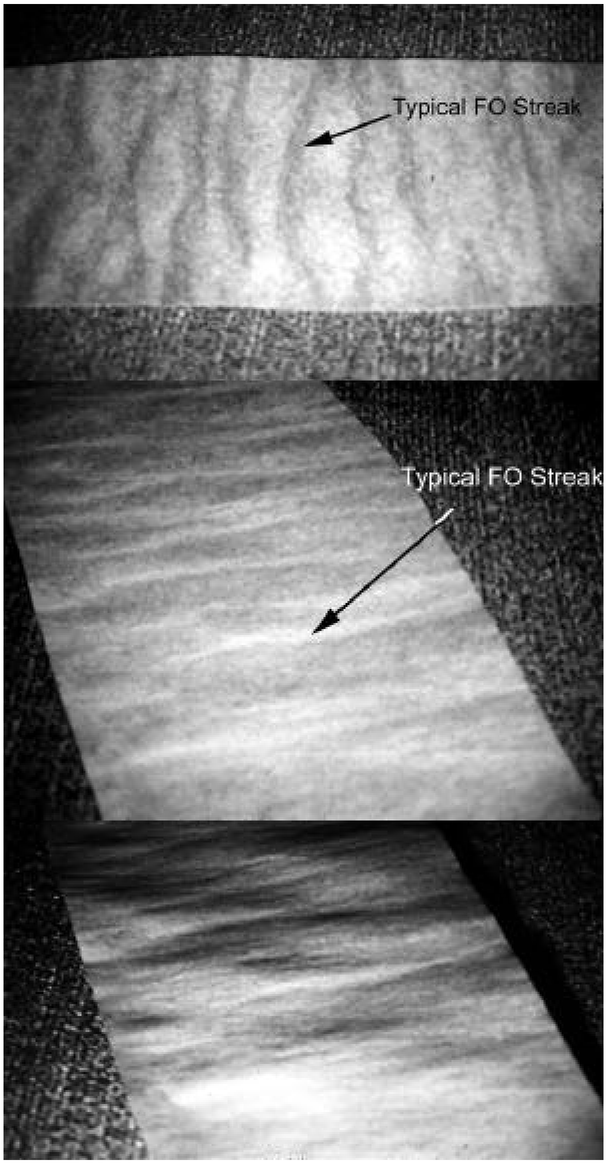


Figure 2 . Image showing how light reflects differently from the streaked area. Viewing down the streak (upper) makes it appear darker; viewing across the streak (middle) makes it appear lighter; low angle CD lighting (bottom) shows the extreme out-of-plane-ness associated with the streaks. The variation in paper properties from fiber orientation streaking is very bad for converting and end-use.

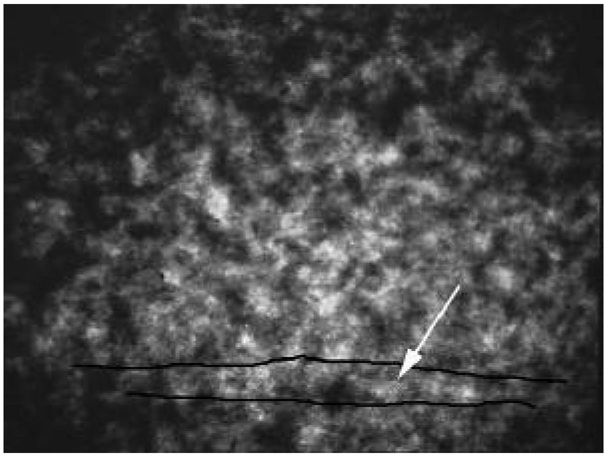


Figure 3 . Transmitted light image in the streaked area. The streak (arrow) is not associated with a basis weight streak as verified light transmission and also by independent local basis weight measurements.

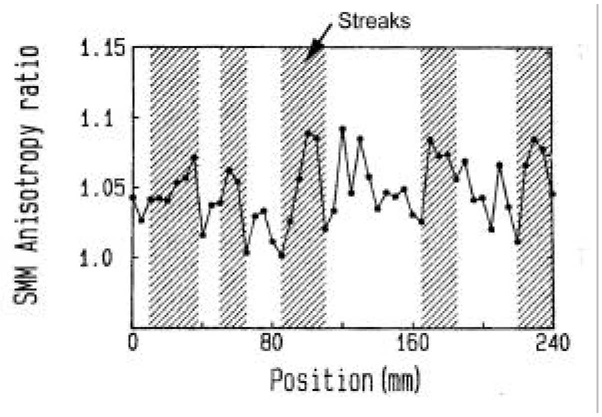


Figure 4 . IR-Anisotropy profile across the streaks [7]. Higher ratio corresponds to more MD alignment. In the places where the visible streaks are located (crosshatching) the IR-A profile shows a much higher fiber orientation. The IR-A senses only 10 to 20 mm into the paper [7]. Fiber orientation streaks usually do not extend through the entire sheet thickness and, therefore, other sensing methods that measure the entire sheet thickness are not as sensitive for detecting them.

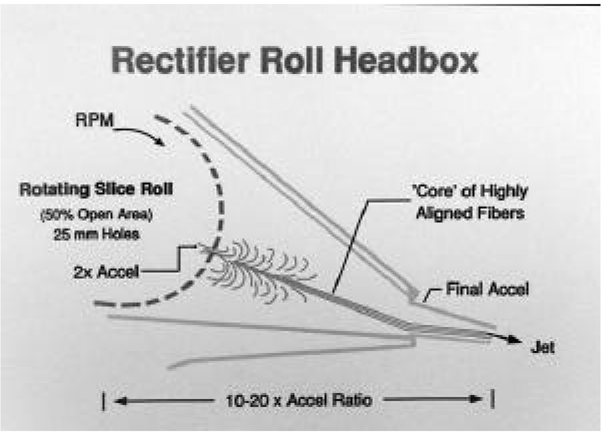
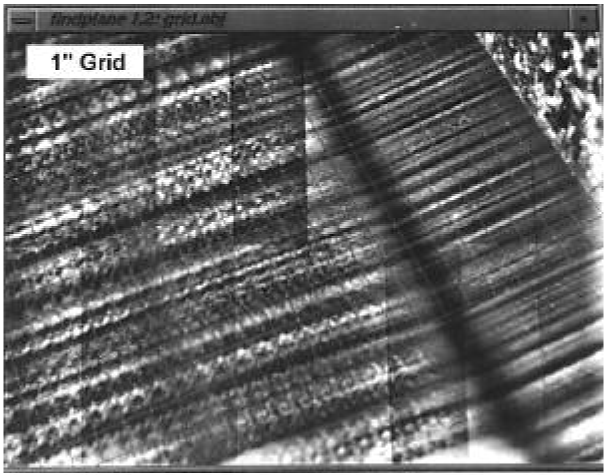


Figure 5. Sketch of an air-padded headbox illustrating that the distributor roll holes are the origin of fiber orientation streaks



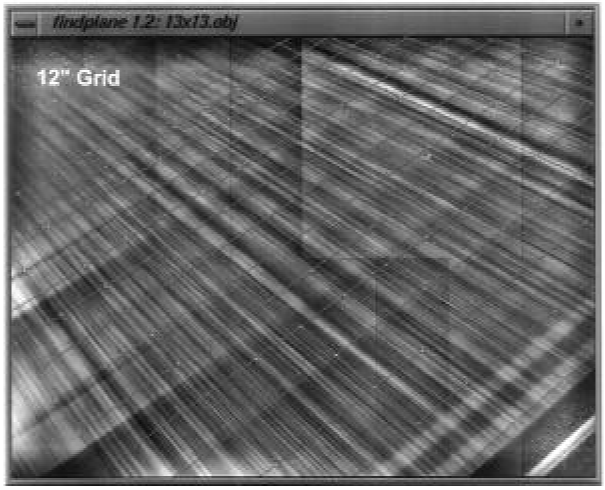


Figure 6 . High-speed digital images of streaks from a hydraulic headbox impinging on the forming board (upper) and then on the table (lower). These are deterministic streaks because the random noise has been removed by averaging at least 100 images. Note also the very interesting deterministic high spatial frequency MD variation over the forming board (upper image). The suspension can be thought of as a spring-mass-damper system. Imaging by Aidun [11].

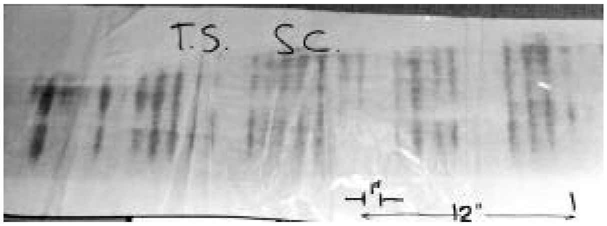


Figure 7. Carbon rubbings after the supercalender showing finger ridging on a medium-weight coated publication grade. The carbon streaks are generally about 25 mm apart. The peak to valley height differences at the outside of the reel (1.5 m radius) are only about 1000 μm.

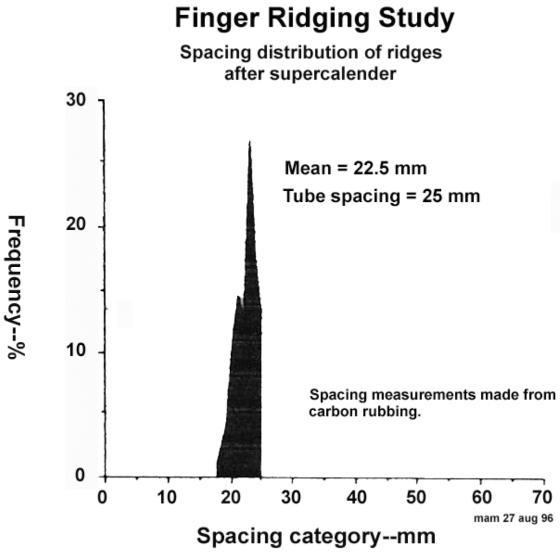


Figure 8. The finger ridging spacing obtained from manual spacing measurements made on carbon rubbings from ONE reel of paper. The dominant frequency does NOT have to agree exactly with the tube bundle spacing to still be associated with the tubes [5]. Other frequency distributions are more broad-shouldered than this, more like that shown in Figure 9.

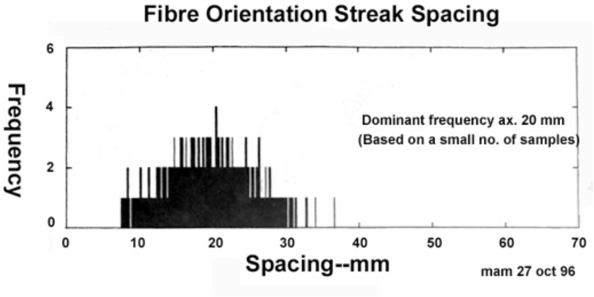


Figure 9. The FO Streak spacing distribution (obtained from the IR-A mapping, Figure 10) is rather broad-banded (possibly due to insufficient data) but the dominant frequency is in the same region as the finger ridging (Figure 8) and also the tube bundle spacing.

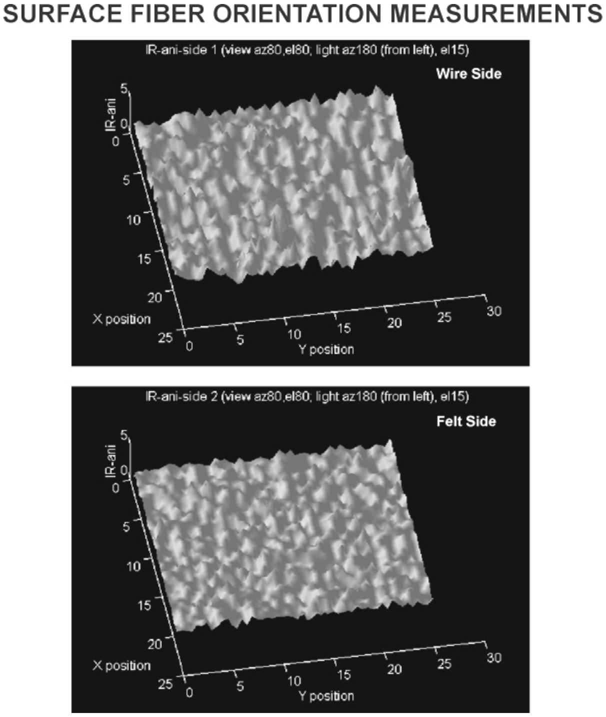


Figure 10 . Surface fiber orientation mapping for a coating basestock. The IR-Anisotropy is measured to a depth of 10 to 20 µm into the sheet. Along the ridgeline of these streaks the IR-A is about 6.0 while

the overall mean is about 2.0. Data obtained with an Infra-Red sub millimeter laser sensor [7].

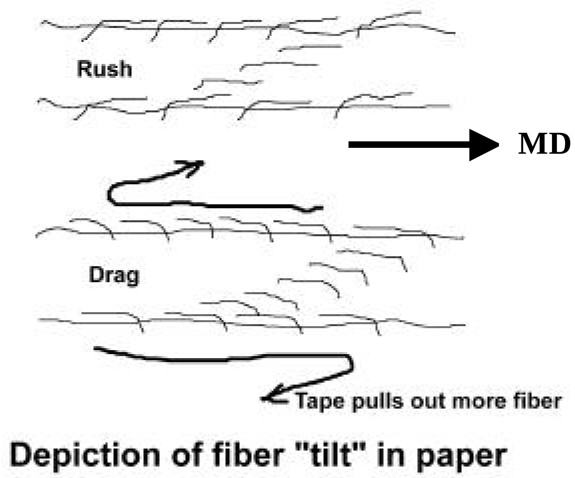
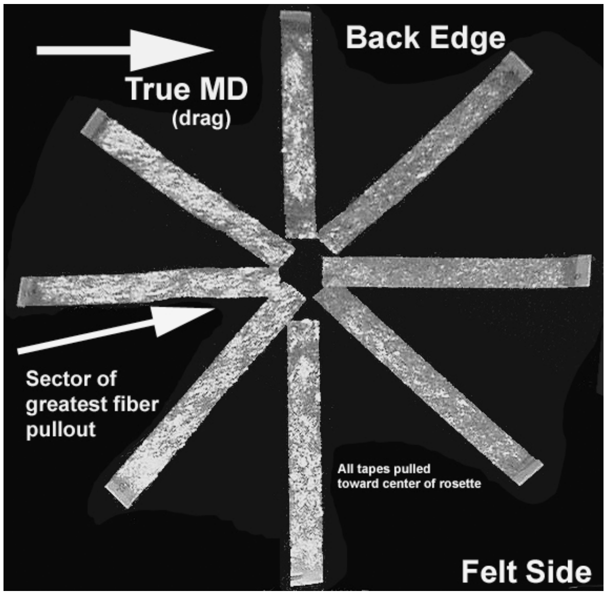


Figure 11. Schematic depicting how the tape peel indicates fiber tilt for a Fourdrinier sheet. The true MD is toward the right. For the Drag mode, greater fiber pullout occurs on the wire side when pulling backwards towards the headbox (anti-machine-direction). Everything is opposite for the Rush mode. For twin-wire sheets both sides are usually in the Drag mode, due to the converging forming gap, so more pullout occurs in the anti-machine-direction.



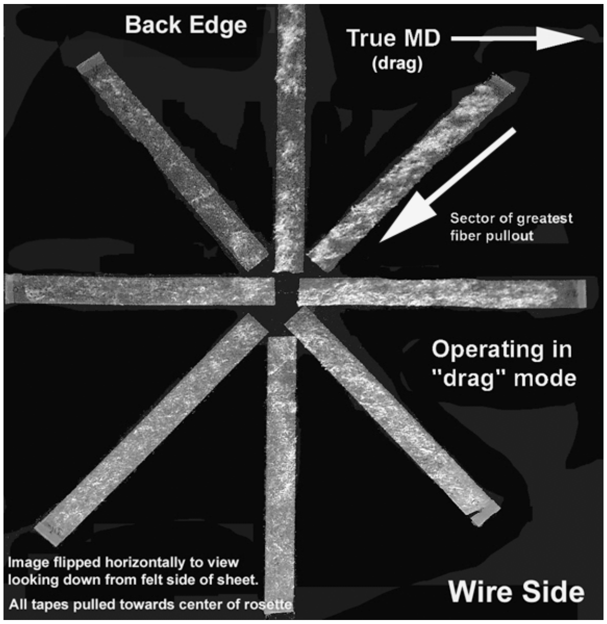


Figure 12. Tape peel rosette (viewing from above) for the Drive Side edge of a Fourdrinier sheet operating at 15 m/min drag. The Wire Side image has been inverted to allow direct comparison with the Felt Side image. For a Fourdrinier the direction of greatest fiber pullout occurs in the tilt direction on the wire side (toward the headbox) and against it on the felt side. Wire side fibers (bottom image) have their leading ends nearer the surface and the trailing ends deeper within the sheet (Figure 11.). The trailing end is also directed more towards the center of the machine due to CD crossflow from the headbox pinched slice (fibers tilted backwards and toward center of machine). Fiber orientation measurements therefore show an outward (negative) angle (Figure 13). The Felt Side fibers (top image) have their trailing ends nearer the surface but are not as affected by headbox crossflow and there isn't quite as much difference between MD and anti-MD.

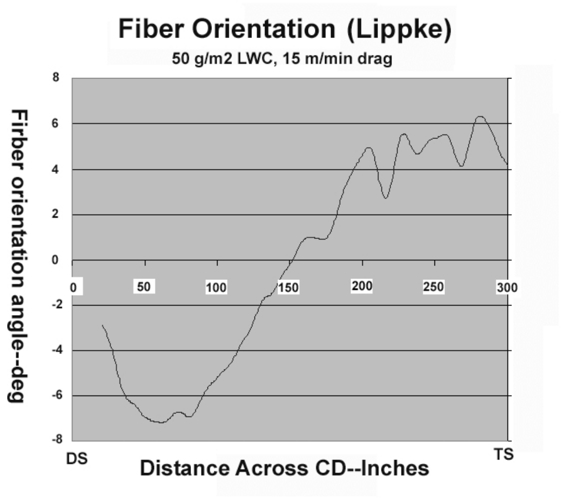


Figure 13. Fiber orientation (Lippke) for the LWC paper shown in Figure 14. The negative (outward) FO angle on the Drive Side agrees with the results of the tape peel rosette in Figure 12.

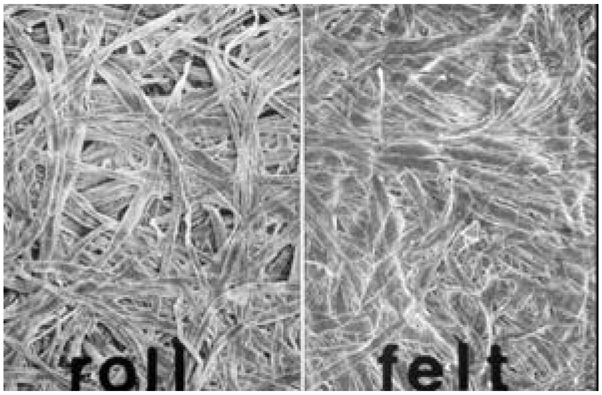


Figure 14. A comparison of the sheet surface density due to press section water removal. The side through which the water is removed (right-hand image) is always much denser than the smooth roll side (left-hand image). This example is typical for all paper and board from Bible paper to Market Pulp.

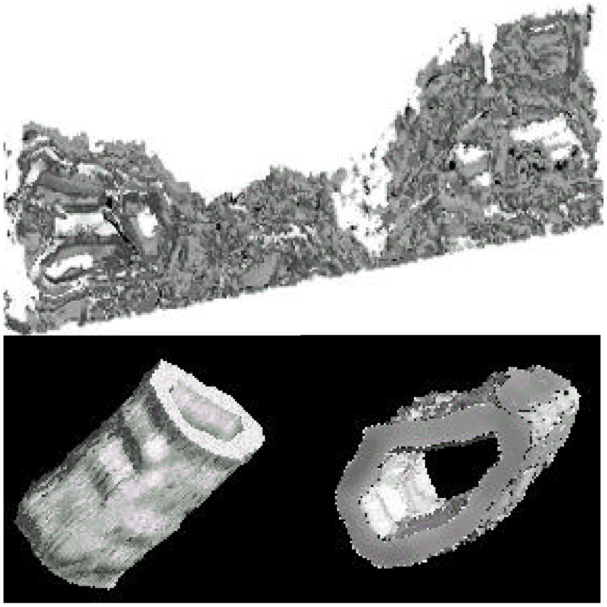
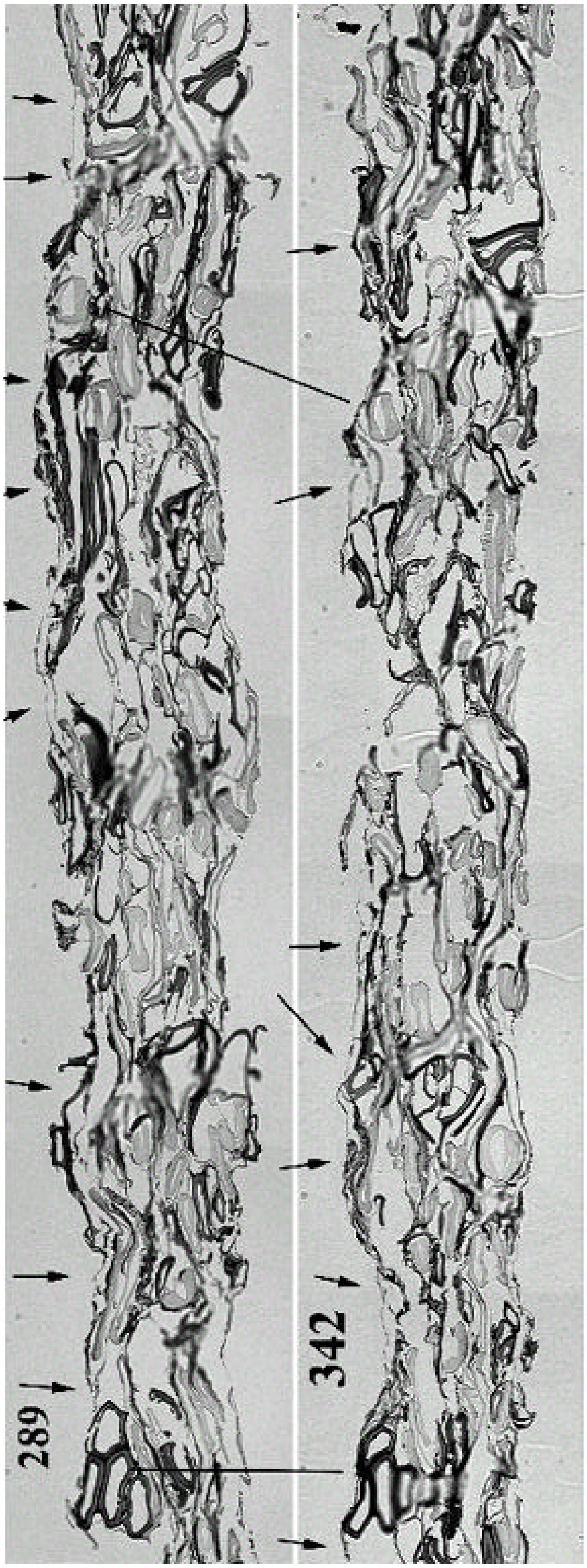


Figure 15 . 3D reconstruction of a LWC paper (upper). The inability of maintaining pixel registration between the serial cross sections (Figure 16) makes the resulting rendering very “noisy.” This cannot be mathematically corrected due to the complexity of the image and also to the large errors from artifacts introduced during cross sectioning. Two volume renderings (lower) of a prominent feature (fiber shive) extracted from the left-hand area of the serial cross sections (Figure 16). The images were manually adjusted into register using an image editing program and thus introducing some subjectivity.



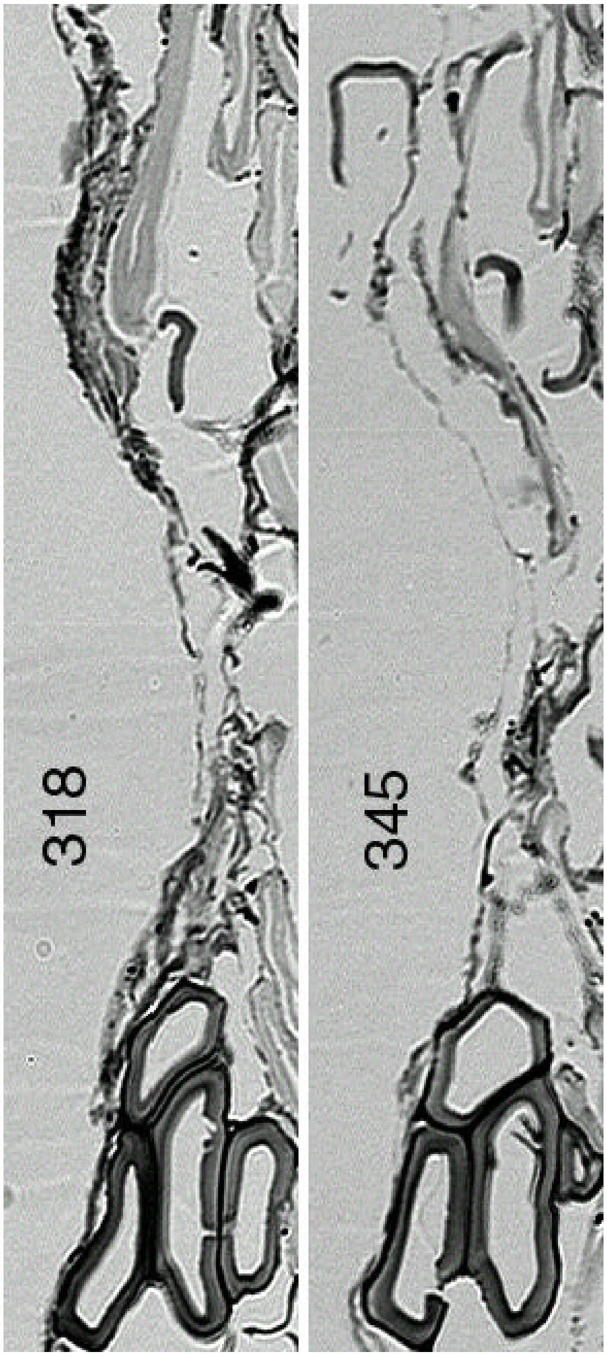


Figure 16. Typical cross section from the 3D-reconstruction project showing the very thin membrane or "skin" on the paper surface (arrows). This skin appears in dozens or even hundreds of consecutive 1-micron-thick cross sections (sections 289, 318, 342, & 345). The 2nd image pair shows a close-up view of the skin. Also seen here is the cross section of the wood shive seen in 3D reconstruction of Figure 15 (lower). This is a 50 g/m^2 basesheet with a stone-groundwood, 60% aspen, 40% kraft

furnish, pressing and drying both occurred toward the top.

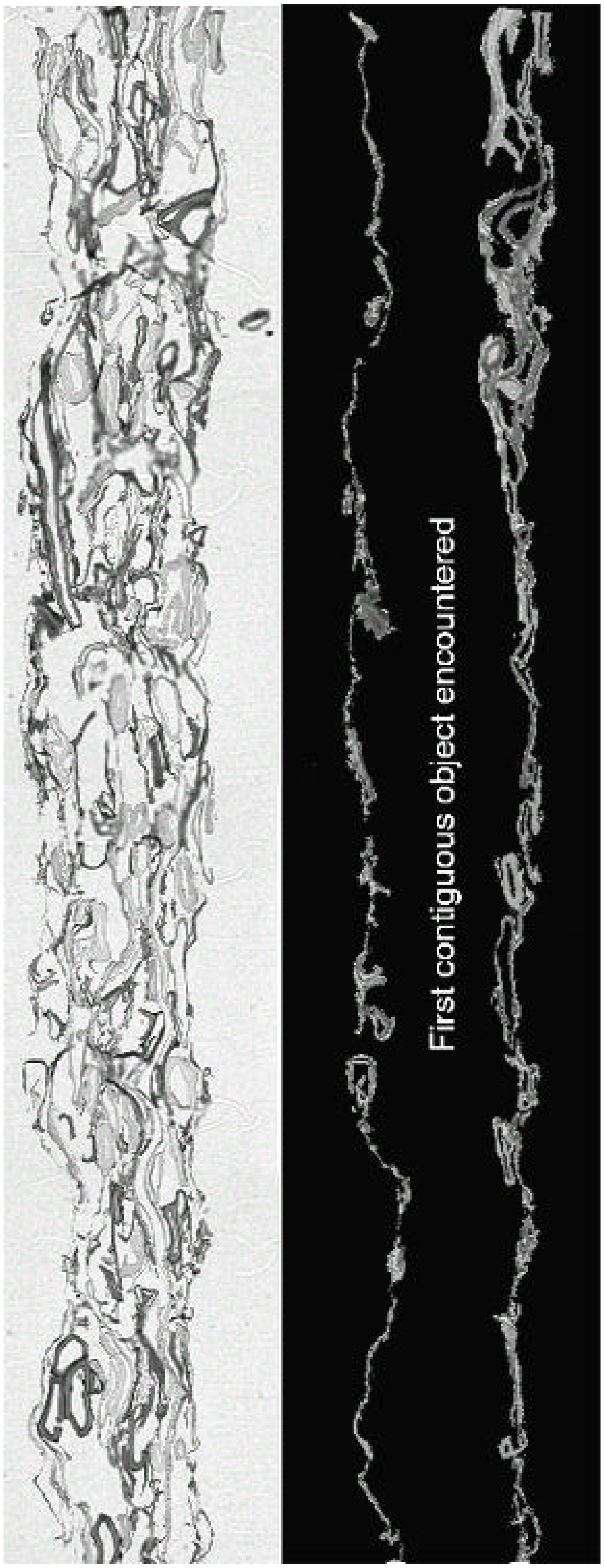


Figure 17. The 1st contiguous object encountered. The original cross section (left) and the interior pixels removed for clarity (right). The top side is almost completely solid (sealed up), whereas the fibers on the bottom are not totally collapsed and there are many openings into the interior.

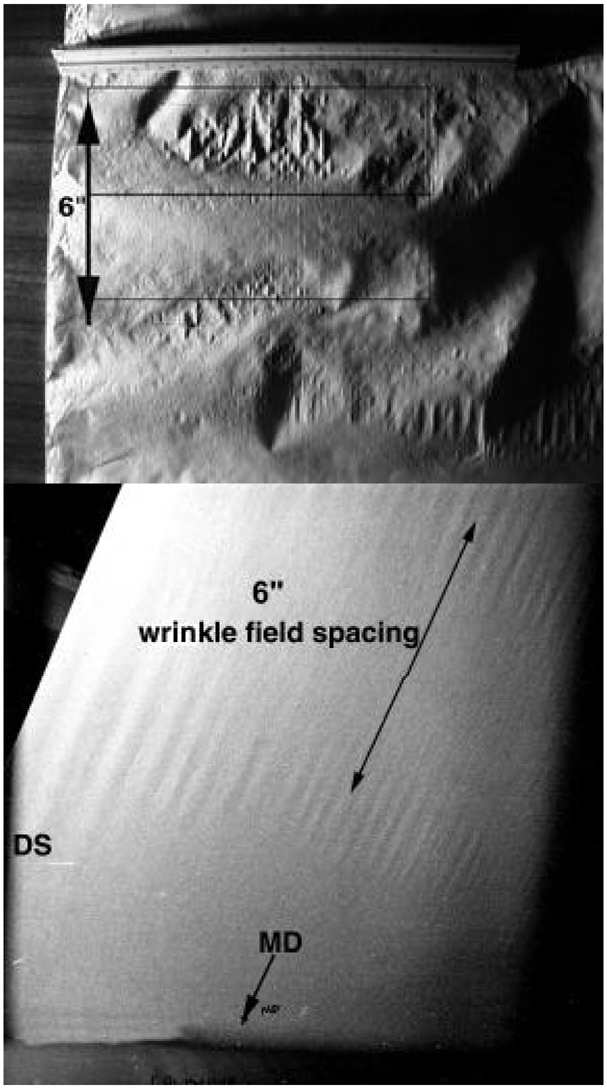


Figure 18. Cockle fields and wrinkle fields on the edge of two machines. These are spaced about 4 to 8 inches apart. For the machine speed of 2750 ft/min, this corresponds to a frequency of about 85 Hz. The cockled and wrinkled areas are lighter basis weight by only several percent than the non-cockled areas.

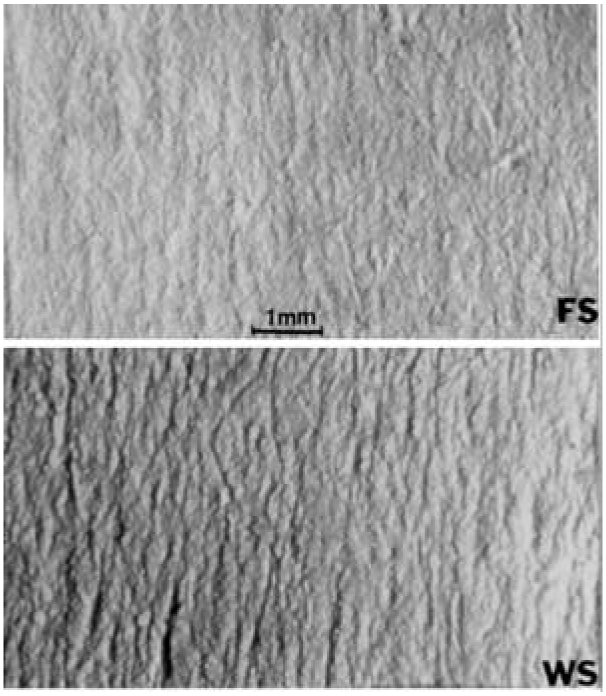


Figure 19. MD Microstriations seen on the wire side (bottom image) of an LWC basesheet in low angle lighting. The wire side against the press felt is denser due to water removal out that side and this leads to the MD-oriented surface fissures (microstriations) seen here. It hardly seems believable that this rough side is only about 60 microns away from the much smoother felt side (above).

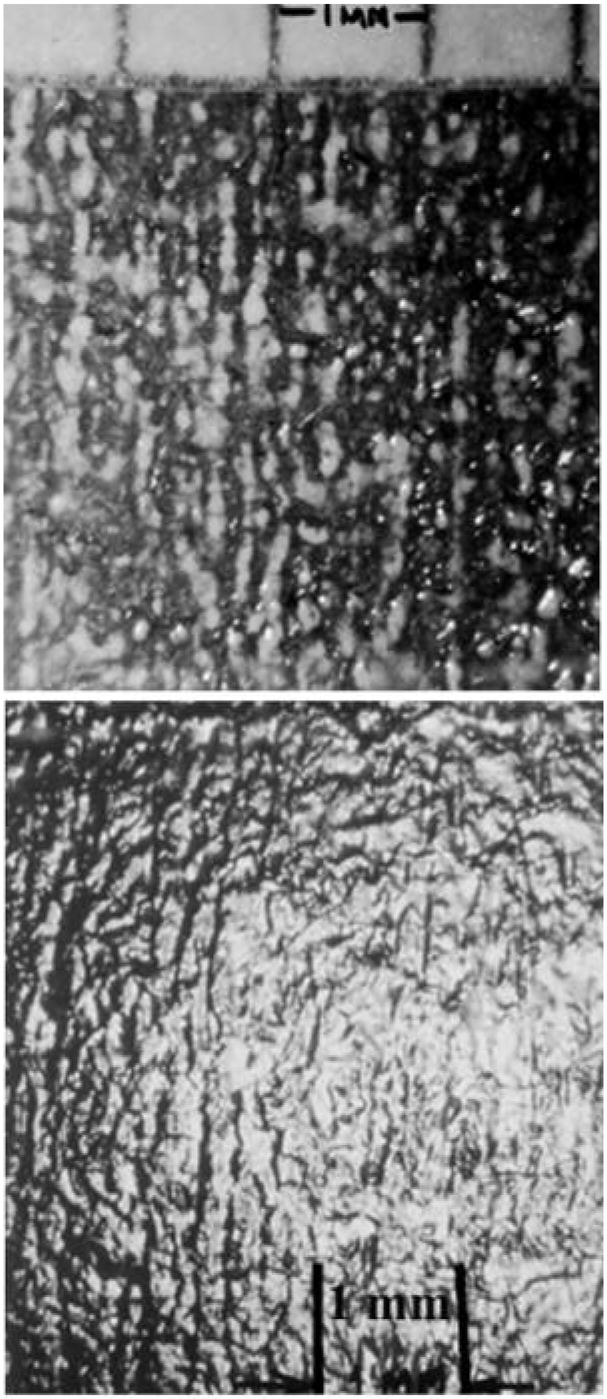


Figure 20. Effect of MDMs on printing. The MDMs survive even the coating and supercalendering processes. Nonuniform ink density distribution from poor trapping (upper) and nonuniform gloss distribution from poor topography (lower).

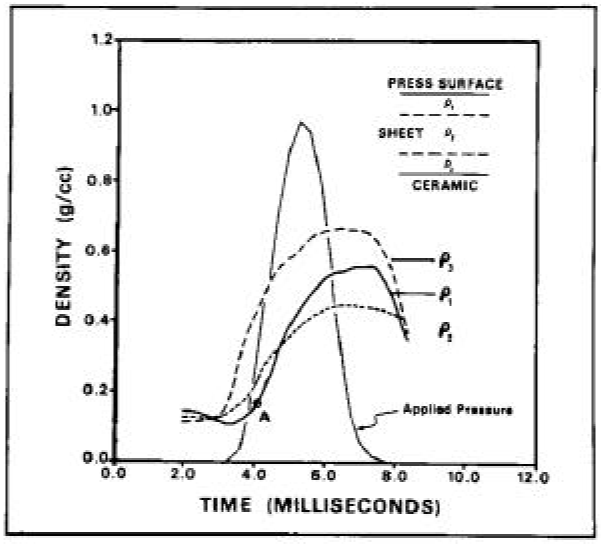


Figure 21. Burton's data on z-direction density development during a wet press event.[31]. Note how the mid-nip gradient is completely lost near the nip exit as the pressure approaches zero.

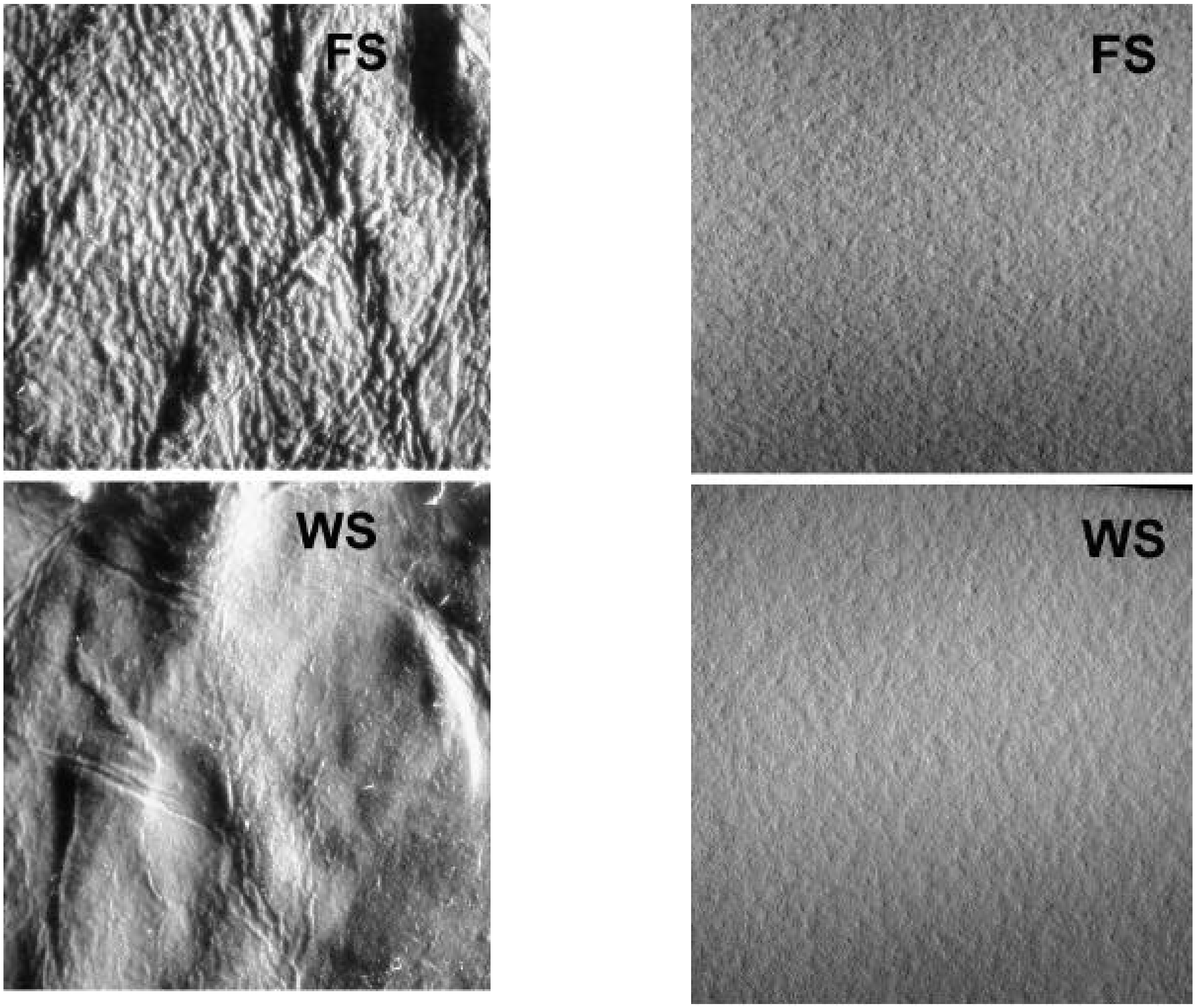


Figure 22. Surface texture on the basesheet of a coated food board. The top side texture originates in the forming process (1st image pair) and survives two dandy rolls, a lumpbreaker, the wet presses, a smoothing press, main dryer, 3 coaters, the wet and dry stacks, and the gloss calender. The top side texture migrates to the bottom (coated) side in the main dryer section (2nd image pair). Amazingly, this bottom side was extremely flat leaving the forming section (bottom image in 1st pair).