MD microstriations in paper: a two-sided shrinkage phenomenon?

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ABSTRACT *We observed extremely small striations or fissures, highly oriented in the machine direction, on one side of finished paper from various paper machines. Observations and measurements of this previously unreported roughening showed it to adversely affect coating and printing quality. The MD microstriations were always worse on the paper side that was pressed against the wet felts in the last nip or two, but there was no correlation between the striations in the paper and the felt contact pattern. The mechanism appears to be an interaction between pressing and drying that leads to a different rate of shrinkage on each side of the paper during drying, causing a microscopic buckling and delamination.*

KEYWORDS
Drying
Image analysis
Microstructure
Graininess
Print quality
Shrinkage
Smoothness
Surface properties
Wet pressing
Xrays

We have given the name "MD microstriations" to a paper defect resembling "graininess," except that it occurs all across the paper web. It is worse at the edges, and, curiously, it is much stronger on one side of the paper. These microstriations are tiny ridges and valleys in the paper surface, highly oriented in the machine direction. **Figure 1** shows MD microstriations observed under low-angle illumination. Note that they are much less prominent on the smooth roll side of the papers.

Even though they are quite small, MD microstriations can be important for certain paper grades because they give a visible roughening that can be detected in the final product. For example, **Fig.** 2A shows a special test print made from a coated, supercalendered paper having prominent MD microstriations in the basesheet. The white streaks correspond to the thicker coating, filling a microstriation valley. We think these result when the ink film split occurs within the colorless first ink down instead of within the pigmented second ink down. The trapping problem is thought either to be initiated by a large variation in absorbency between the thick coating streak and the adjacent thin coating *(1)* and/or by the variation in the film thickness between the high and low areas. (The white areas tend to lie several microns below the dark areas.)

The gloss image of the same test print (Fig. 2B) reveals another important problem caused by microstriations—that of angular variations in the coated surface. The dark MD-oriented lines correspond to the slightly depressed white streaks in the test print (Fig. 2A) and result from the lack of local gloss at that particular lighting angle. The eye is extremely sensitive to gloss variations, and the print is disturbed by both the gloss nonuniformity and the resultant loss of color saturation. Interestingly, the presence of MD microstriations is probably impossible to detect by conventional air-leak smoothness and gloss measurements *(2).* Their presence is much better detected by low-angle lighting, microscopy, and image analysis techniques such as those used in this work.

A literature search revealed some anecdotal experiences with shrinkage-related problems such as paper graininess, but we did not locate any systematic study of the exact mechanisms causing paper graininess, especially of a two-sided nature. We therefore undertook a limited examination of what we believe is a previously unreported problem. Our efforts were aimed at measuring and characterizing MD microstriations and at formulating some theories about their origin.

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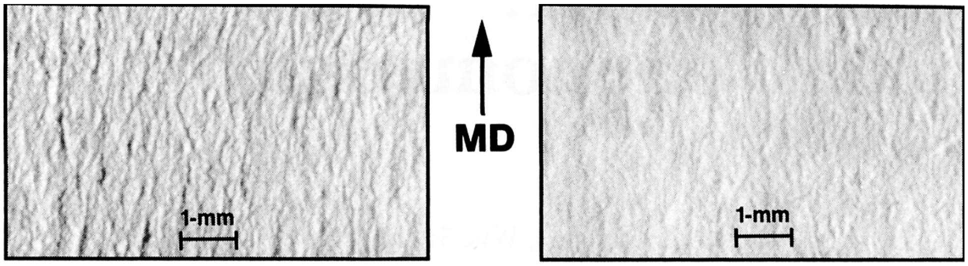
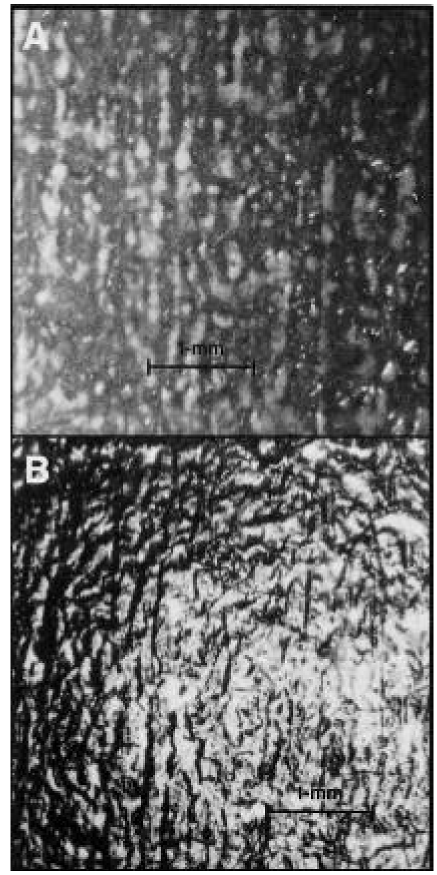
1. MD microstriations in dried paper on the side against the press felt in the last 2 nips (left). The smooth roll side is on the right



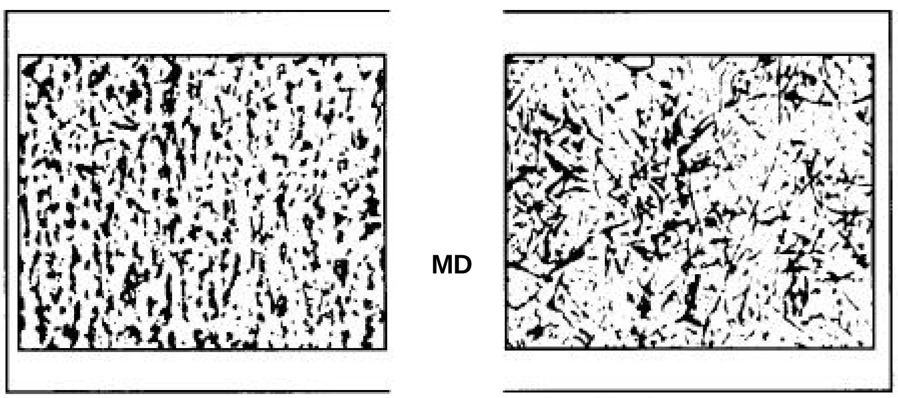
2. Special test print showing the effects of MD microstriations with normal overhead illumination (top) and a gloss image of same area (bottom). This paper has been coated and supercalendered.



I. Base sheet survey for microstriations

Machine No.	Prominence of microstriation	Paper side	Extent of wire mark	Press type	Uni-run?
1	None	. . .	Slight	Tri-nip	Yes
2	Some	Felt	Some	Trivent	Yes
3	None	. . .	Slight	T-Press	Yes
4	Severe	Wire	Severe	T-Press	Yes
5	None	. . .	Some to medium	Twinver	No
6	Some	Felt	None	Tri-nip	Yes
7	Medium	Felt	Some	Tri-nip	Yes
8	Medium	Felt	None	Tri-nip and smoother	Yes
9	Medium	Felt	Some	Tri-nip	Yes

3. Enhanced images of paper (left) and used felt (right) in contact with glass plate under pressure (200 psi for paper, 1200 psi for the felt) show no correlation.



I. CD surface roughness measurements

	Wire, microns	*Felt,* microns
Base paper	3.9 (14.3)	--- (8.0)
Coated, supercalendered	0.83	0.16
Coated, supercalendered, printed	1.57	1.94

Data in parentheses are based on microscopy measurements and are more accurate.

Field experience

MD microstriations were first brought to our attention while we were studying a particular lightweight coated paper that had a number of print quality problems *(1)*. We looked at paper from other machines to determine if the microstriation problem was unique to Paper Machine 4 in **Table 1.**

As the table shows, MD microstriations were not evident in every paper, and their presence did not seem to be influenced by the forming method or conditions. Also, serpentine dryer felting did not seem to be a factor. Although it is not shown in the table, some furnishes were associated with stronger MD microstriations. For example, Machines 3 and 4 had essentially the same configuration and. operations but different furnishes

Also, it seemed likely that the intensity of pressing was significant. Machine 7, with more intense pressing, consistently had more prominent microstriations than Machine 6. The two machines were otherwise identical, and the same furnish was used. The most striking observation, however, was that *whenever MD microstriations were present, they always appeared on the paper side that was against the felt in the last press nip or two.* Therefore, microstriations can occur on either the felt or wire side, depending on the press configuration.

Measurements of MD Microstriations

Various techniques were used in attempts to measure MD microstriations. These included the use of soft X rays, processing and analysis of surface images, surface profilimetry, microscopy, and image enhancement and analysis of cross sections.

Soft X ray

Beta rays are often used to measure mass variation in paper sheets, but problems of diffraction with beta particles can cause topographic variations to be erroneously registered as mass variations. Soft X rays (less than 10 keV) are preferable because they are sensitive to true mass variations and they can resolve objects with dimensions much smaller than paper fibers *(3).* Therefore, if the MD microstriations result from localized mass variations, one would expect them to appear in a soft X-ray photograph of the paper. Their absence, even after image enhancement, suggests that MD microstriations are probably variations of localized density or topography in the paper but that they are not a mass variation.

Although flocks are readily apparent to the naked eye, the wire mark in the soft X ray is invisible without computer enhancement. Therefore, the wire marks are possibly due as much to topographic, density, or filler variations as to mass variations. This hypothesis is contrary to conventional expectations *(4).*

Image analysis of surface views

Images of the microstriations and wet felt surfaces (under pressure) were enhanced with an image analyzer (5) to compare the dimensions and spacing of the microstriations with the patterns in the felt. As **Fig. 3** shows, there is no obvious correlation between the two images. Not only is there little MD orientation in the felt pattern, but the shapes of the pattern components are different.

We used another image analyzer to perform a two-dimensional Fast Fourier Transform analysis (FFT) of the MD microstriations shown in Fig. 1 *(6).* No periodic pattern was found in the MD microstriations, and the width and spacing randomly varied between 75 *mm* and 400 *mm.* The random spacing implies that the MD microstriations do not originate from either periodic variations in the paper machine clothing or from press roll surfaces.

Surface profilimetry

We used a profilimeter capable of measuring topographic variations less than 1 *mm* in height (at 1 mg of tracking force) to make surface measurements of both coated and uncoated paper (Table II). Tracings of the problem paper (Fig. 4) supported earlier conclusions drawn from the FFT analysis. The wire side tracings showed that the valleys were often rather deep (about 20 *mm)* compared to the average paper thickness (60 *mm).* These tracings also showed that these valleys were fairly narrow (50 *mm* - 125 *mm)* and that a relatively wide plateau (200 *mm* - 400 *mm)* often separated a ridge-valley combination.

The arithmetic roughness, R_m, of the paper side against the wet felt was about twice that of the smooth roll side. Finally, the base paper was smoothed by coating and supercalendering, but then roughened after printing (Table II).

Microscopy

Cross sections 1 *mm* thick were microtomed from the problem paper. **Fig.** 5 shows a typical cross-section taken across the microstriations in the CD. The characteristics of this cross-section are similar to those of the surface profile, except for an apparent compression of the peaks by the profilimeter stylus which occurred even under the 1 mg tracking force. These microtome cross sections reveal a large variation in sheet caliper ($2\sigma /x$ = 30%) and a greater variation on the paper side against the wet felt (R_m = 14 *mm* vs. 8 *mm).* Even more dramatically than the profilimetry data, the cross sections show that some of the ridges are quite sharp and have steep sides, that the depth of the valleys is 15*mm* - 20 *mm,* and that their occurrence is random.

Next, we examined the surfaces of the problem paper in the SEM. **Figure 6** shows that the side against the wet felt is strikingly more closed-up or densified than the side against the granite roll. This two-sided densification results from the "stratification phenomenon" caused by wet pressing *(7).* However, the microtomed cross sections in Fig. 5 did not make it obvious how deeply the dense felted-side layer penetrated into the sheet.

Image enhancement and analysis of cross sections

To try to answer this question of the layer depth, we enhanced the image of a single microtome cross section. This image showed a more or less continuous layer of fibers on the felted (WS) side of the paper (Fig. 7). By contrast, the smooth roll side (FS) was characterized by numerous discontinuities along the surface. A study of many cross sections showed the smooth roll side to have at least three times the discontinuities of the felted side of the paper. Furthermore, observations of both the surface and the cross section led us to believe that a dense "skin" (or a severe gradient in z-direction density) may be incorporated into the wire side of the sheet.

We noticed that the dense skin is not obvious when viewing the normal cross section, as shown in Fig. 5. The skin is only slightly more obvious in the enhanced image of Fig. 7. However, when we determined the percent fiber within each of ten layers and presented the data in the form of a histogram, a density gradient became immediately obvious (Fig. 8). These data, collected over several millimeters of paper, suggest that the bottom-most 20% of the problem paper is denser than the remaining 80%. Since the total paper thickness averages only 12-15 fiber layers, 20% represents only a few fiber layers!

We could find no reference to a dense "skin" like this in the relevant literature, but we think it is a manifestation of "interfacial-controlled pressing," first postulated by Chang *(8)* and discussed later by others *(7, 9).* In this process, the fiber layers adjacent to the press felt are rapidly densified by the intense pressing, which in turn causes an immediate buildup of flow resistance in these layers. This resistance results in even more densification of the surface, while the inner layers are prevented from becoming too dense by the buildup of fluid pressure inside the sheet.

We are not aware of this dense layer being reported in the literature, but it may be playing an important role in producing microstriations.

Possible causes

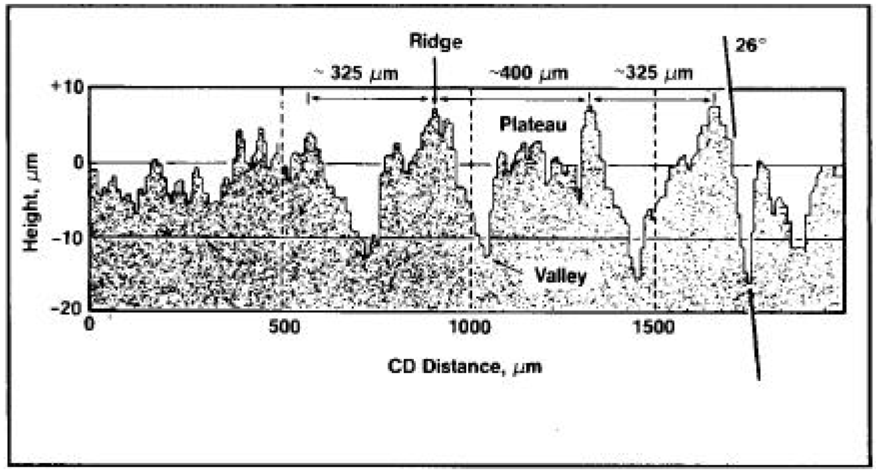
Some believe that MD microstriations are caused by embossing from the wet felt. However, our work casts doubt on that hypothesis as the true mechanism. Another mechanism suggested is that of microrivulets of water passing between the felt and the sheet during rapid pressing. If this were happening, however, there should be some evidence of surface fiber slippage and disruption.

Wet straining of the paper, particularly as it peels from the smooth press roll, has also been mentioned as a possible mechanism. However, we found no evidence of MD microstriations in samples of the freshly pressed and peeled problem paper. This observation supports the candidacy of a mechanism that occurs after the press.

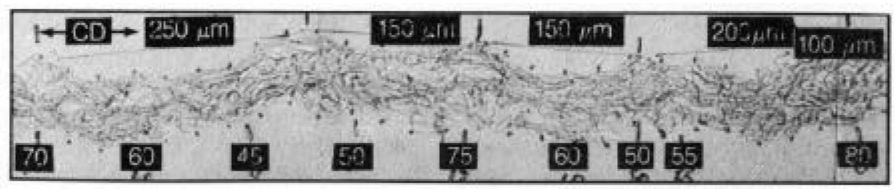
Although we do not yet have proof, we currently feel the most viable mechanism is that of two-sided shrinkage during evaporative drying. One idea is that the drier dense skin created during wet pressing dries and shrinks into position first. The remaining loosely densified layers, containing more water, dry later and shrink more *(10)*. Since the thin skin is bound to these layers, it delaminates and buckles. This buckling/delamination occurs mainly in the cross-machine direction because the paper is more strongly restrained in the machine direction than in the cross direction or the *z* direction. Both sides of the paper are roughened, but the smooth roll side is not roughened as much.

The buckling/delamination process must relieve much of the internal stress, since we never observed abnormal curl behavior in the lightweight coated basesheet we studied. However, this does not imply a total absence of internal stresses; for example, we observed a greater tendency for "destructuring" *(11)* on the striated side of the paper.

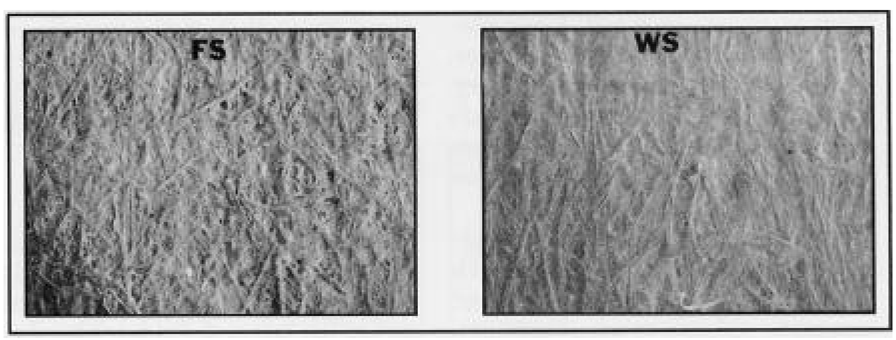
4. Surface profile of a lightweight coated basesheet showing several prominent MD microstriations



5. Cross section taken across the MD microstriations, where the numbers on the bottom indicate sheet thickness in µm

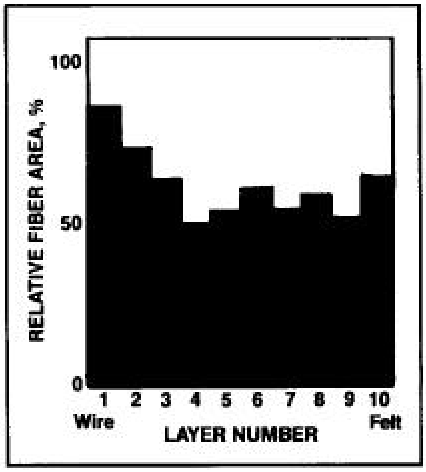


6. Surface views of dried paper with MD microstriations. Surface on left (WS) in contact with felt in last 2 nips. Surface on right (FS) was against smooth press roll.



7. CD section of a LWC basesheet used to determine z-direction density by image analysis.

8. The relative density distribution in the z direction of a LWC basesheet with MD microstriations (as determined by image analysis).



Implications and future work

If microstriations are originating from the dense skin created during wet pressing and drying, then changing the wet felt design should not make a significant improvement in this particular roughening unless the felt creates a more "gentle" nip. There may be other ways to reduce MD microstriations (and graininess in general). These may include

- More careful attention to water removal directions and rates in the press section to avoid creating sharp density gradients
- Production of fewer fines during refining
- Using a less shrinkage-prone furnish
- Greater CD restraint during drying (such as more tension on the dryer felt)
- Improved formation down to a microscopic level
- Improved drying strategies (for a reduced gradient in z-direction drying).

A dense skin is not always bad; it might even be desirable, since it contributes to coating holdout. There is an apparent dilemma, however, in that MD microstriations originating from the dense skin decrease the sheet smoothness and will consequently affect the uniformity of the coating mass distribution. This uniformity has previously been shown to affect print quality *(1)*.

Much of this theory is predicated On the existence of the thin dense skin and the mechanism which leads to micro-buckling and delamination. Through further work, we hope to determine whether the paper shows a less uniform topography on the denser side of the paper.

Summary

MD microstriations are quite small and are often masked by other defects, which probably accounts for them not being previously reported. However, the combination of increased wet pressing intensity and demands for better print qualify make microstriations more important today than in the past.

Intense pressing creates a nonuniform density gradient in the sheet. We believe this leads to a two-sided shrinkage during drying, causing the microstriations. If this hypothesis turns out to be true, then paper smoothness can be improved by reducing the density gradient by various means. Unfortunately, this could then lead to coating holdout problems for the washed-out wire side. This dilemma emphasizes the need to better understand the microstriation mechanisms.

This work has strengthened our conviction that nonuniform densification is important not only for the *z*-direction but also for the *x-y* plane. We think that areas of small-scale nonuniform density created during pressing and drying result in a rougher paper with nonuniform microcompressibility and absorptivity. In turn, this nonuniformity places demands on calendering, coating, and supercalendering which often cannot be met.

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