PREDICTING THE FLUTING TENDENCY OF LIGHTWEIGHT COATED PAPER

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ABSTRACT: Fluting is a machine-direction waviness occurring in lightweight coated papers during a web heatset offset printing process. The web develops waves (or flutes) of about 1 cm wavelength due to the unsupported, high-temperature, moist web under tension in the dryer. The dried ink makes the waves permanent. Little was known of paper characteristics needed to prevent the fluting. Two printing trials were performed to generate printed paper samples, and a laser profilometer was utilized to measure fluting properties. Fluting correlated well with simple laboratory tests for ink absorption, thereby suggesting that coating formulation largely determines fluting tendency. Effects of grammage, calendering, and web width were also investigated.

INTRODUCTION

Fluting consists of transverse waves formed in lightweight coated (LWC) paper during the heatset offset printing process. The waves extend in the machine direction (MD) as shown in **Fig. 1.** These waves cause streaks of reflection or glare so readers may have to adjust the paper position with respect to the lighting to avoid them. There have been only occasional concerns for fluting in the North American paper industry because it is largely dismissed as a printing effect. Although there are a few in-depth studies *(1–5)* on this topic, they do not

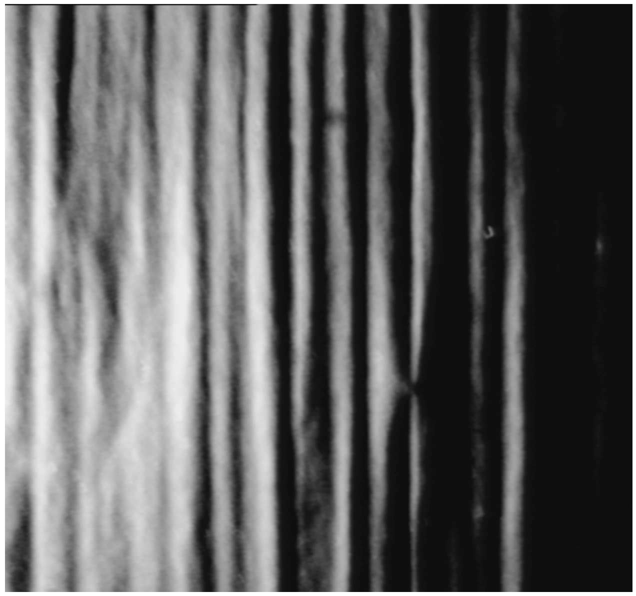

Fig. 1: Fluted printed paper. MD is in the vertical direction.

contain any experimentally proven conclusions as to the mechanism or control methods.

Almost all LWC papers flute under some conditions. However, the phenomenon is normally obvious only when there is a large area with a complete ink coverage on both sides of the paper. The bright glare is especially noticeable when contrasted with dark ink colors and when the print is glossy. A "four-color black" (four full layers of ink) on both sides of the paper usually shows the phenomenon well. After printing, the intensity of the fluting may decrease with time *(2B)* or storage while flat.

It is generally agreed that fluting occurs because the paper web is a hygro-thermal-sensitive viscoelastic material. For such a thin sheet, this material buckles in the cross-machine direction (CD) *(4)* when moisture, heat, and MD tension act on the unsupported web in heatset dryers.

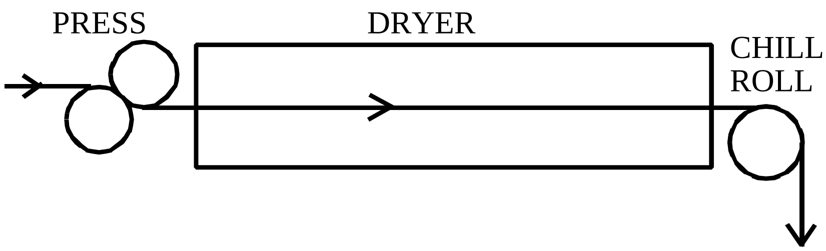

Fig. 2: Simplified diagram of the printing press dryer showing the unsupported web, last press, and a chill roll.

Referring to **Fig. 2,** our visual observations suggest that long-wavelength fluting in the unsupported web can change to shorter wavelength just before the web wraps the chill rolls that harden the ink. While moisture, heat, and tension cause waves, the dried ink seems to make the short-wavelength fluting persist after the printing process.

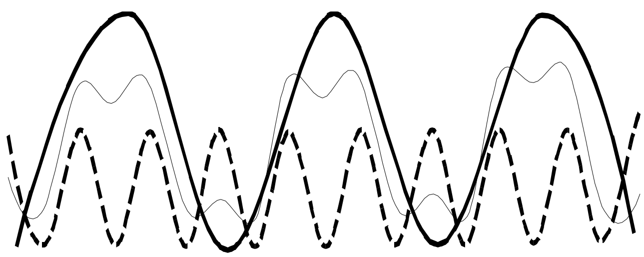

Fig. 3: A conceptual drawing of fluting across the web.

Fig. 3 illustrates these ideas. The vertical dimension is greatly exaggerated. The dashed line suggests the fluting at high tension or just before wrapping the chill roll. The wavelength of the fluting has decreased, in this case, by a factor of three.

PRINTING TRIALS

In order to determine what papermaking variables affect the fluting, two printing trials were carried out on the Harris M1000-B printing press at Rochester Institute of Technology (RIT). The printing conditions are listed in **Table I.** All prints included a 23 cm × 19 cm (9 in. × 7.5 in.) area four-color black (all four colors) solid on both sides.

Quantitative fluting data were obtained with a laser profilometer. Details of the method are presented in the appendix. The printed paper samples were scanned in the cross direction. These data was then filtered and analyzed to give a dominant wavelength, peak-to-peak values, and wave intensity. As illustrated in **Fig. 4,** the peak-to-peak value is the vertical distance between the highest peak and the lowest valley for a given scan. The wave intensity, our primary measure of the degree of fluting, was defined as

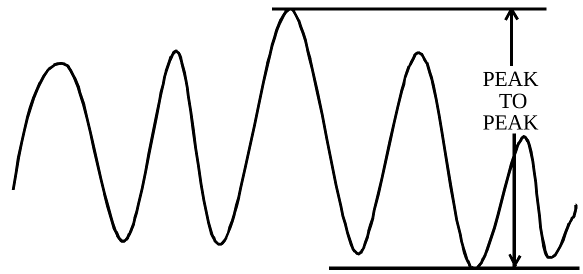

Fig. 4: Definition of peak to peak.

Table I. Printing conditions

Press speed	366 m/min (1200 ft/min)
Dryer exit temperature	130^0C (265^0F)
Ink levels	Kept constant after initial roll.
Colors	four--black, cyan, magenta, yellow

$$I=P/2\lambda \qquad \text{(Eq. 1)}$$

where *I* is the wave intensity, *P* represents peak-to-peak value, and λ is the dominant wavelength. High peak-to-peak values and short wavelengths, which result in many flutes per page, combine to give large wave intensities. Others have used similar parameters *(2A, 5).* The dominant wavelengths, peak-to-peak values, and wave intensities are given here in units of mm, microns, and microns/mm, respectively.

FIRST PRINTING TRIAL — WIDE WEB

The papers for the first trial were commercial European and American LWC rolls with widths near 89 cm. (35 in.). All of these had grammages near 60 g/m^2, except for one 80-g/m^2 paper. **Table II** includes pertinent TAPPI Test Method results for the paper used in the first print trial.

Table II. Data for papers used in the first print trial

ROLL NO.	GRAMMAGE g/m^2	CALIPER µm	DENSITY g/cm^3	BENDTSEN AIR PERM.	AVG. PEAK TO PEAK µm	AVG. DOMINANT WAVE-LENGTH mm	AVG. WAVE INTENSITY µm/mm	AVG. K & N % drop	AVG. LENETA TEST % drop	TENSILE STIFFNESS MN*m/kg MD	TENSILE STIFFNESS MN*m/kg CD	TENSILE RATIO	% ASH @ 482 ^0C
1	60.5	56.4	1.07	13.4	162	13.4	6.11	8.9	22.9	7.99	4.97	1.65	25.4
2	55.8	50.6	1.10	9.2	156	13.2	6.23	3.6	20.4	8.63	3.92	2.64	31.6
3	61.0	51.2	1.19	6.3	203	10.6	10.38	22.0	43.2	9.82	5.2 0	2.94	35.9
4	57.6	50.3	1.14	5.2	190	12.3	8.20	15.5	33.0	8.54	4.27	2.73	31.9
5	59.4	51.1	1.16	6.0	233	11.2	10.59	19.9	38.0	10.57	4.81	3.43	36.2
6	56.4	55.9	1.01	8.0	198	10.9	9.13	14.8	31.4	8.14	3.44	3.36	30.5
7	80.2	67.2	1.19	7.4	95	12.8	4.15	8.6	26.2	11.00	5.28	3.81	33.9
8	59.6	52.0	1.15	7.0	133	10.7	6.67	10.3	23.8	8.94	3.07	3.68	34.5

A continuous four-color press was utilized, and the web was printed in the order of black, cyan, magenta, and yellow. Three different web infeed tensions were applied in the trial, but it was visually obvious that these web tensions had no effect on fluting. Thus, only the medium-tension samples were selected for fluting evaluations. At the trial, the printing samples were ranked for fluting by three judges, and the results were averaged. Good correlation of this visual ranking and the later-measured wave intensities was found. **Fig. 5** shows this relationship.

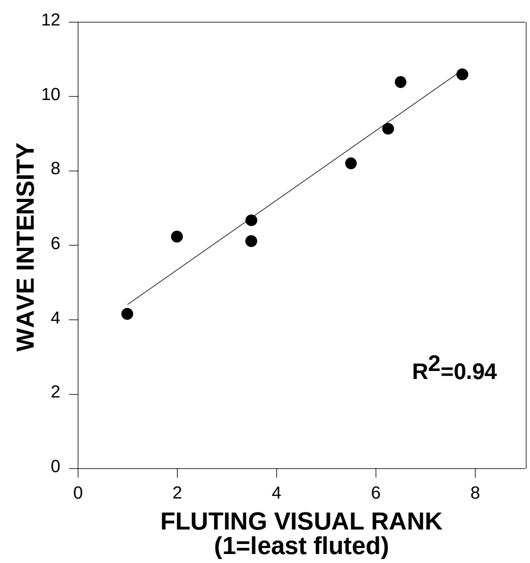

Fig. 5: Correlation of visual rank and measured wave intensity.

A large number of paper physical properties were measured. The correlations between these properties and the fluting evaluation results (both visual and measured) were studied. There were surprisingly poor correlations for almost all the cases, including those properties one might expect to influence fluting. This is probably because these paper physical properties were not measured at the high moisture and temperature presented in the dryers. However, there were good correlations of wave intensity with K & N ink absorption and with Leneta ink absorption. The percentage drop in brightness, averaged for the two paper sides, was measured after K&N ink had been smeared on the paper samples and left for 2 min. The K&N values are plotted against wave intensity in **Fig. 6.** Low-

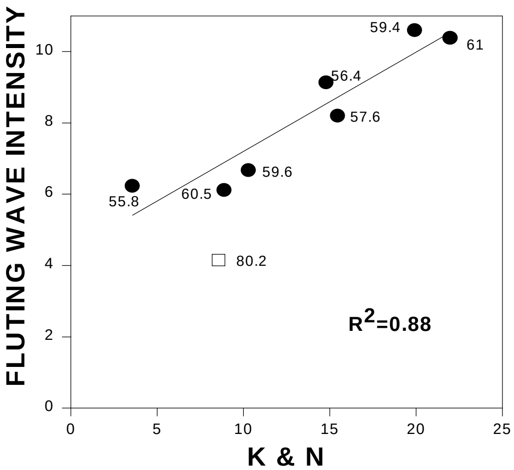

Fig. 6: Wave intensity correlates well with the K&N test. Grammages are given at points.

grammage sheets are above the curve fit line for 60 g/m^2, and high grammages are below the line.

Fig. 7 shows a similar graph for Leneta ink left on the paper for 0.5 min. These "inks" or stains have a longer time for being absorbed into the paper than ink on an offset press, but they are at lower temperature in the lab than on the press. They are oil based as are offset inks.

For papers of the same nominal grammage, the data of Fig. 7 almost fit the equation

$$I = k\,L \qquad \text{(Eq. 2)}$$

where I is fluting wave intensity, k is a constant, and L is the Leneta percentage drop in brightness. Since the Leneta graphs are nearly linear and the K&N were curved, this paper will only show the Leneta graphs, even though K&N data also correlated well. The K&N results can be found in the literature *(6).*

As shown in **Fig. 8,** one can also fit all the data points, regardless of grammage, to the

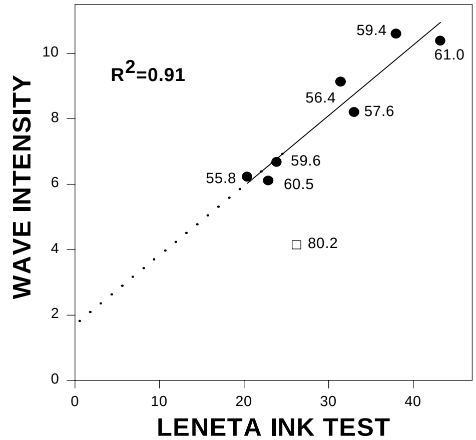

Fig. 7: Leneta ink test correlates with fluting intensity. Again, high-grammage points are below line fit.

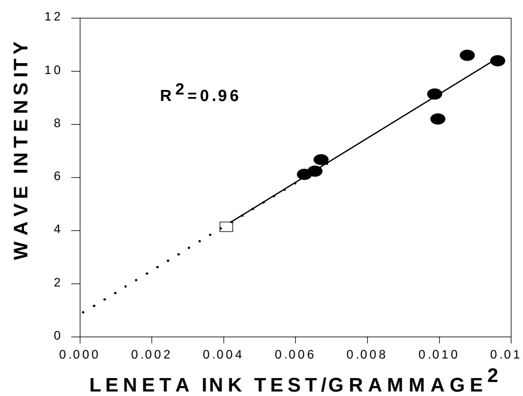

Fig. 8: The data can be corrected to compare papers with somewhat different grammages. The four points in the upper-right corner correspond to the papers with calcium in their coatings.

normalized form

$$I = k'\,L\,/\,G^2 \qquad \text{(Eq. 3)}$$

where G is the grammage and k' is a constant.

The K&N test is known to be sensitive to coating pigment shape and size distribution *(7)*. For this set of coated papers, **Fig. 9** shows that four of the coatings had high levels of calcium (from calcium carbonate) while others had mainly silicon and aluminum (clay). The four highest wave intensity values from Fig. 8 correspond to the four papers containing calcium. Coating clays are often plate-like particles that can lie flat to cover or eliminate pores in the coating layers. One might expect that the calcium carbonate type and the binders can affect K&N tests, Leneta tests, and fluting tests as well. Electron photomicrograph (SEM) pictures were taken of the coated paper surfaces. **Figures 10 and 11** show the SEM pictures comparing a low-intensity-fluting and a high-intensity-fluting paper surface. The surface of the high-intensity-fluting paper showed more and bigger pores.

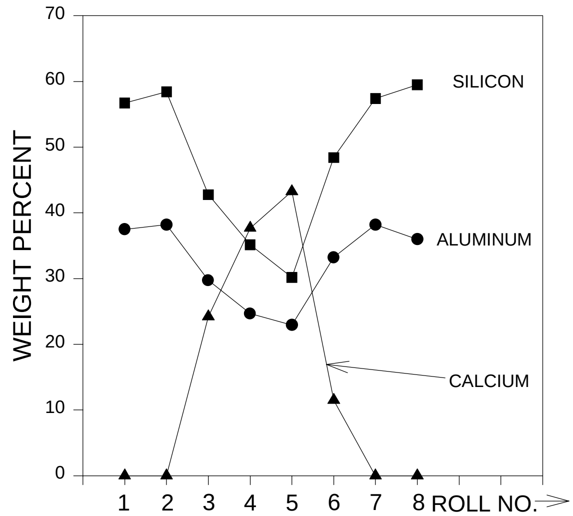

Fig. 9: Major components of the surfaces were aluminum and silicon (clay) and calcium (calcium carbonate). The composition affected fluting. Analysis was by Energy Dispersive Spectroscopy (X-ray analysis on a scanning electron microscope).

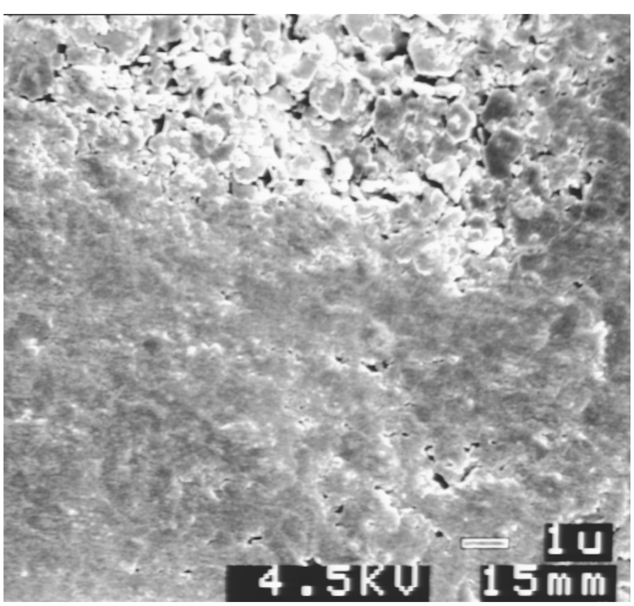

Fig. 10: SEM picture of a low-fluting-tendency coated paper surface

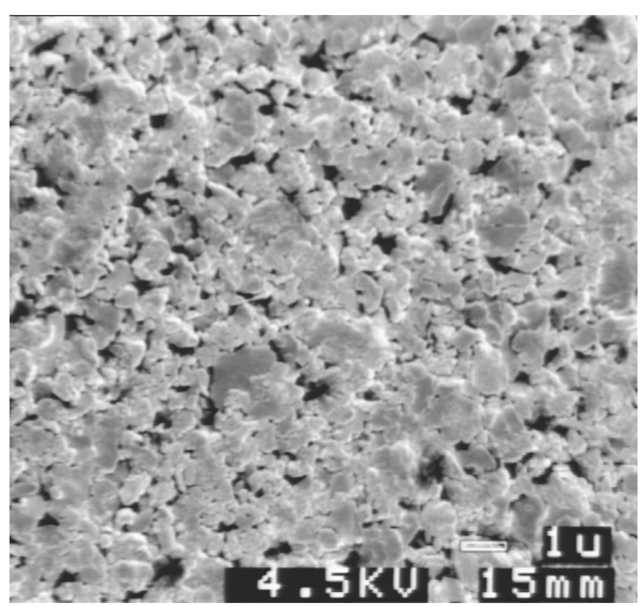

Fig. 11: SEM picture of a high-fluting-tendency coated paper surface

SECOND PRINTING TRIAL -- NARROW WEB

Due to the limited number of samples in the first trial, it was desirable to confirm some of the effects. **Table III** shows information on the second trial samples. To eliminate effects of the base sheet, the same commercial base sheet was used for all but one of the second trial samples. For most samples, the uncoated raw stock was flooded nip coated on a pilot coater. Many were pilot supercalendered. In addition, some rolls were coated in paper mills and calendered on the pilot calender. Some were uncalendered, some were highly calendered, and one was a normal commercial roll. Another commercial roll (K) from the first trial was included after slitting. All were 46-cm (18-in.)-wide rolls printed as half-width webs on the front side of the press. Various coatings were used, some of which included a calcium carbonate as the pigment and some that did not.

Again, the visual assessment of three evaluators correlated linearly with the measured wave intensity (**Fig. 12**). This time, several high-fluting samples had to be rated the same because no difference was obvious to the eye, and big differences in gloss made judging more difficult. As for the first trial, Leneta ink absorption correlated with fluting wave intensity. Refer to **Fig. 13,** but note that only the "normally" calendered samples are included. **Fig. 14,** including the uncalendered and heavily calendered samples, is more complicated.

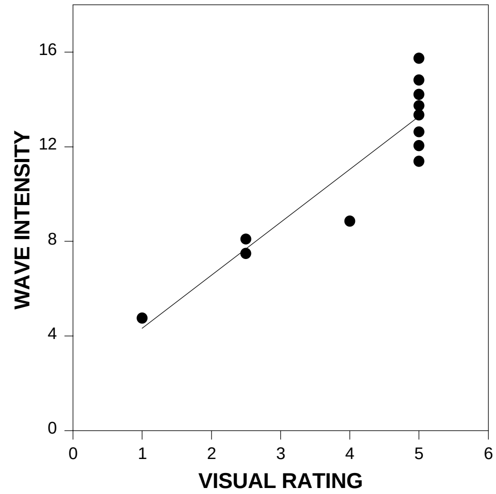

Fig. 12: Visual rating and wave intensity correlate.

Table III: Test data for second trial—narrow web

SAM-PLE ROLL	NOTES ON SAMPLE/ COATING	CALEN-DERED ?	K&N AVG. % DROP	LENETA AVG. % DROP	FLUTE RATING 1= LEAST	AVG. WAVE LGTH. mm	AVG. PEAK TO PEAK microns	AVG. WAVE INTENSITY :m/mm	GRAM-MAGE g/m^2	CAL-IPER microns	DEN-SITY g/cm^3
A	HIGH $CaCO_3$	YES	17.2	34.7	5	11.4	301	14.2	62.3	51.7	1.20
B	CLAY	YES	5.6	15.1	1	13.8	123	4.8	61.0	54.6	1.12
C	MAINLY CLAY	YES	7.4	23.4	4	14.0	224	8.8	57.8	51.2	1.13
D	HIGH $CaCO_3$	YES	16.6	33.0	5	10.2	273	13.7	59.4	52.0	1.14
E	CLAY	MUCH	2.0	9.9	2.5	12.9	181	7.5	59.9	48.6	1.23
F	HIGH $CaCO_3$	NO	28.1	43.7	5	13.6	297	12.0	62.9	71.1	0.88
G	10% $CaCO_3$	YES	13.8	27.9	5	10.8	267	12.6	61.9	53.6	1.15
H	10% $CaCO_3$	NO	23.1	34.9	5	11.7	249	11.4	62.8	71.2	0.88
I	UNCAL. COMM.	NO	27.7	41.5	5	13.0	336	13.3	61.6	71.2	0.87
J	BELOIT CAL.	MUCH	13.1	30.0	5	10.1	303	15.7	61.0	50.0	1.22
K	COMM.--FROM 1ST TRIAL	YES	9.6	23.0	2.5	11.1	173	8.1	61.5	51.3	1.20
L	COMMERCIAL	YES	21.1	33.8	5	10.1	291	14.8	60.8	51.1	1.19

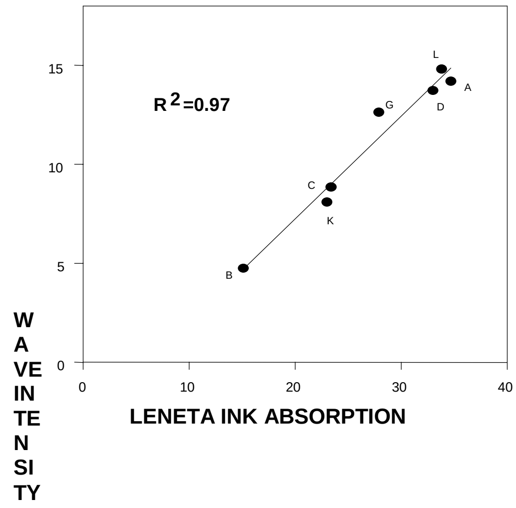

Fig. 13: Fluting correlated with the Leneta ink tests. Uncalendered and heavily calendered rolls are not included.

Dashed arrows show how samples, otherwise equivalent, change in fluting and Leneta values as calendering varies. Uncalendered samples are low in wave intensity, and highly calendered samples are high in spite of the lower ink absorption. The low caliper and presumably lower stiffness after heavy calendering can explain this. **Fig. 15** shows the same data as Fig. 14 but includes a density effect. Then the plot fits the empirical equation

$$I = k'' L\, d \qquad \text{(Eq. 4)}$$

where k'' is a constant for this set of sheets and d is density. If one combines this with Eq. 3, it suggests that, for a wide variety of LWC sheets printed under the same condition but having different Leneta ink absorptions, different densities, and different grammages

$$I = K\, L\, d\, /\, G^2 \qquad \text{(Eq. 5)}$$

K, otherwise constant, would vary with printing condition and web width.

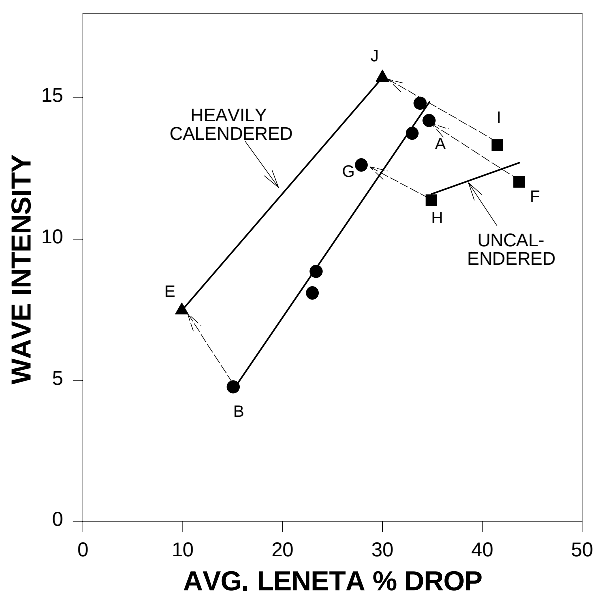

Fig. 14: Heavy calendering decreased the Leneta test, yet increased fluting. Square points represent uncalendered, and triangles show heavily calendered.

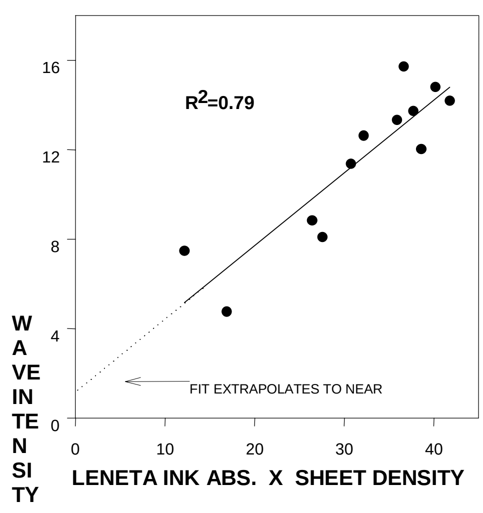

Fig. 15: All of the second-trial data fit on a linear plot that extrapolates to near (0,0). This suggests there is no fluting if there is no ink absorption or if the sheet is very high in caliper.

COMPARISON OF THE TWO TRIALS—WIDE AND NARROW WEB

Figure 16 shows that the two trials gave similar trends with ink absorption. However, the data do not overlay each other. There are several possible reasons: (a) conditions such as ink level may have been different for the two trials, (b) somewhat different printed areas were measured for the two sets of prints, and (c) the web widths were different. The narrower web probably caused the higher fluting for the second trial. Some lab experiments indicated that a reasonably large aspect ratio (free web length/web width) is necessary for getting fluting. This phenomenon is also suggested in some literature *(1C, 3).*

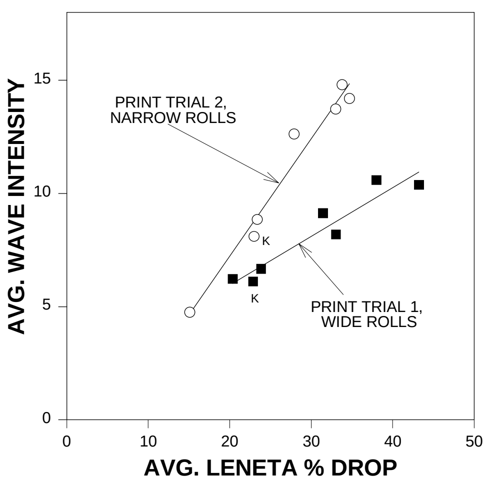

Fig. 16: Narrow rolls seem to flute more. Only "normal" calendered rolls of about 60 g/m^2 are included in this graph. Roll K was used for both trials, but at different widths.

DISCUSSION OF THE FLUTING MECHANISM

The printing trial results showed that the fluting tendency was largely determined by the ink absorption, which in turn is greatly influenced by the coating formulation. Brief speculations on a fluting mechanism based on these observations are in order. While many mechanisms were considered, two reasonable mechanisms are suggested here without specifying one as being more likely.

ELASTIC MODULUS EFFECT: A low elastic modulus of paper contributes to fluting according to a few analyses *(3, 4),* and the elastic modulus can be reduced by several absorption/porosity influences in the heatset dryer:

1.) Lab experiments suggest Leneta ink fills almost the whole coating surface of the paper; this suggests that the vehicle of the printing ink may do the same as well. The outer layers of paper, wetted by ink vehicle, may reduce their contribution to the average paper modulus.

2.) Water is known to reduce the average elastic modulus of the web *(1D).* The offset process water, applied in an ink emulsion, may enter the web, possibly as steam.

3.) Heat, possibly transported by steam, is also known to reduce the elastic modulus of the web *(1D).*

A lower web elastic modulus provides lower web flexural rigidity. A web with lower elastic modulus may be stretched beyond the elastic limit, a cause of plate buckling noted by others *(3).* The effective elastic modulus, defined beyond the elastic limit as the slope of the tangent line of the stress-strain curve, is lower than the elastic modulus. This will lower Habeger's *(4)* value of "critical buckling compression."

PERMANENT EXPANSION EFFECT: The wetting by ink and water may also expand the sheet printed area within the framework of the less-expanded area of the margins. (Ink in the offset process is known to carry much water with it. The non-image-printed areas may get less water wetted, and therefore be less expanded.)

For either mechanism, high absorption of ink into the pores of the web may stiffen the flutes and/or the expansion and make the expansion and the flutes permanent.

CONCLUSIONS

1.) Fluting wave intensity for LWC was found to be a function of the coating absorptivity. Less-absorbent coatings lead to less fluting. Any theory of fluting should take this observation into account.

2.) A Leneta test or a K&N test indicates fluting tendency for similarly calendered samples of similar grammage. Fluting is approximately proportional to the Leneta test.

3.) In spite of decreasing ink absorption, calendering slightly increases fluting tendency.

4.) One can predict the effects on fluting of small changes in grammage or sheet density using equations given in this paper.

5.) The observations about the fluting behaviors in this study might be explained by a mechanism of the ink vehicle and/or water being absorbed to the bottom of the coating layer and even beyond. This allows more fluting to form by either (a) buckling of the web with a lower elastic modulus or (b) sheet localized expansion. Cooling of the paper at the chill roll hardens the ink vehicle within the pores and stabilizes the undulations present at the chill roll.

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APPENDIX: Laser Profilometer Scans

Apparatus: Computer, XY scanning table, laser proximity sensor

Sheet size: Usually about 22 cm CD x 28 cm MD, but larger and smaller sizes can be run

No. of scans: 10; Distance between scans: 5 mm

Scan length: 187 mm (taking 181 points). Points spaced about 1 mm apart.

Filter: A band-pass digital filter is applied to the data of each scan to eliminate the effects of sheet curl, etc. The Butterworth filter has the parameters chosen as 3,15 where 3 is the order and 15 is the cutoff frequency. A cutoff frequency of 15 attenuates waves of wavelength greater than about 15 mm.

Ambient conditions: 50% relative humidity, 22°C

For dark black–printed samples, a dusting of TiO_2 is applied to the sample to reflect the laser light.

A one-dimensional FFT analysis of each scan gives intensities of different wavelengths, and the dominant wavelength is the one with the greatest intensity.

For the measurements of this paper, the averages from several different printed areas of different colors were used, and the areas were not the same for the two trials. The areas all had full coverage of at least one layer of ink.