

Mechanism and prevention of coat weight nonuniformity due to high speed blade coating

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ABSTRACT: *Web speed, backing roll hardness, applicator gap height, premetering, and blade angle are the coating parameters which influence applicator roll coater streaking. Using a hard backing roll or operating in a low angle mode eliminated streaking in a production coater.*

KEYWORDS: *Blade coaters, coating weight, high velocity, homogeneity, reaction mechanisms, roll coaters, streaking, trouble shooting, variations*

Blade coating is the most common method for improving a paper surface for high-quality printing. The two main types of blade coaters in use today, applicator roll and short dwell, differ mainly in the method of applying excess coating to the base sheet. As shown in Fig. 1, the applicator roll coater applies the excess coating to the base sheet via a flooded nip, whereas the short dwell applies the excess coating in a confined pond before the blade.

When the short-dwell coater was introduced, it gained popularity due to its compactness, operational efficiency, and increased productivity. A major problem with the short-dwell coater, however, is that coat weight nonuniformities, referred to as "coating streaks," develop at high web speeds. These streaks range from 25 mm to 50 mm in width and extend various distances in the machine direction. In general, short-dwell coating streaks first appear at about 1000

m/min and worsen as speed increases. The "streaky" appearance of the sheet has been extensively studied and shown to correlate with hydrodynamic instabilities in the short-dwell pond (1-8). The physical mechanism by which these hydrodynamic instabilities cause streaking is currently not known.

Due to the absence of the type of hydrodynamic instability caused by the short-dwell pond, applicator roll blade coaters had been thought to be immune to this nonuniform coat weight defect. Recently, however, as coater speeds have increased, the applicator roll coater has been found to produce its own distinct pattern of nonuniform coat weight streaks. These streaks are narrower than those observed with short-dwell coaters and are the subject of this paper.

Theoretical models

Various theoretical models have been

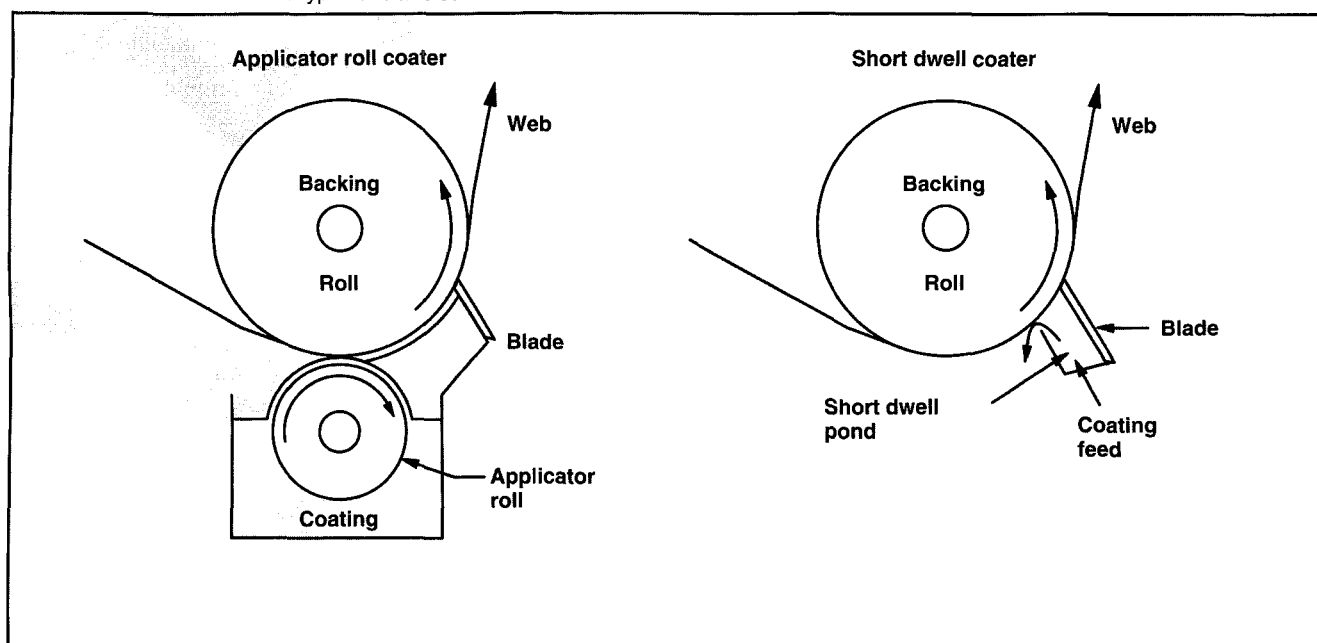
used to describe the blade coating process (9-15), but none were designed to explain the coat weight variations described in this paper. The theoretical model outlined by Eklund (9) indicated that the force exerted by the coating impact on the blade (impact force) was the dominant force acting on the blade in high-speed, rigid blade coating geometries. This impact force depends on web speed and coating mass arriving at the blade. Operational experience and experimental studies support this model by showing that these two variables greatly influence coat weight at high web speeds (10, 15).

The recent theoretical modeling of blade coating by Pranch and Scriven (14) is also relevant. They introduced elastohydrodynamic analysis encompassing Eklund's model for impact approximation. They used finite element analysis to calculate the machine direction pressure field on the substrate approaching and under the blade. They also included the concept of a deformable substrate, but they used thickness and elastic modulus values close to that of only the base paper. The wider range applicable to commercial paper/backing roll combinations was not covered.

Experimental results

The cross direction (CD) coat weight variation which produces the streak pattern in commercial applicator roll coaters at high speeds are visible as an opacity pattern in the unprinted paper. The opacity pattern can be seen by variations in transmitted light commonly called "show-through." If the

1. Schematic illustration of two types of blade coaters



basestock and coating fluorescence differ, streaks can be seen also by UV radiation (viewing the resulting fluorescence pattern of the surface). The "show-through" combines the effects of streaking from both sides of the sheet, whereas the UV light shows the coating streaks only on the illuminated side. Ashing of samples from high and low opacity areas confirmed that the streaks were caused by uneven coat weight distribution.

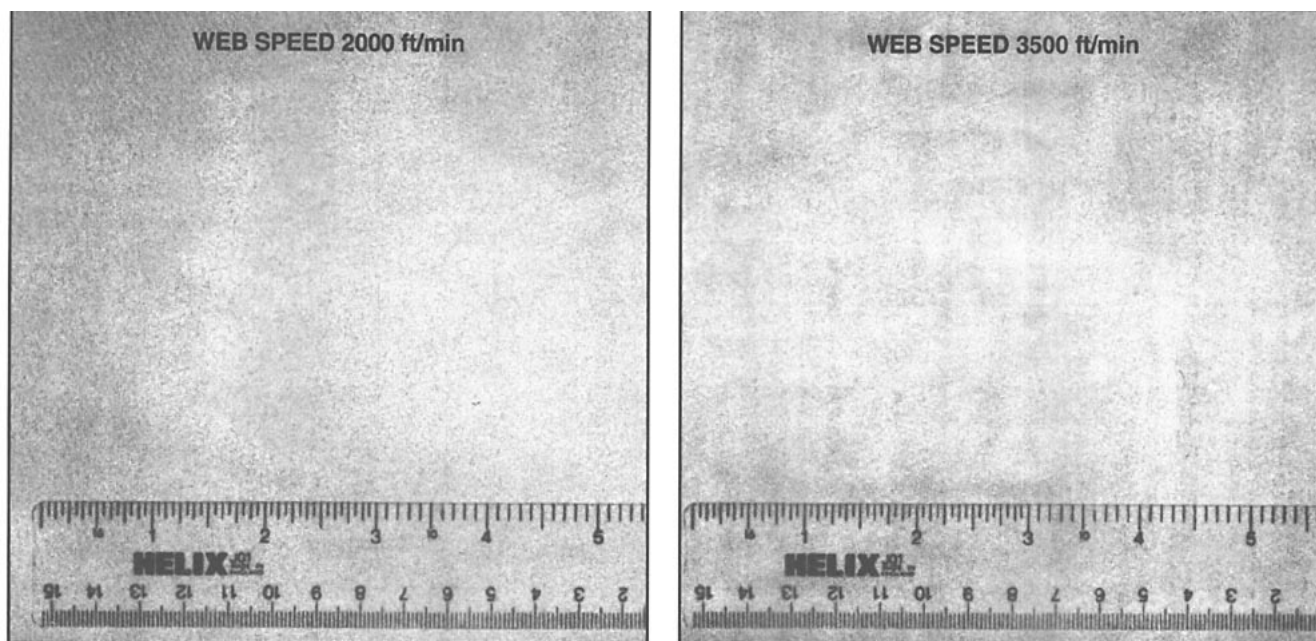
Production and pilot coating trials showed that streaking was influenced mainly by the operating conditions for the coater. Changes in basestock variables such as moisture, machine calender compression, filler level, wet-end sizing, amount of size press starch, level of refining, hardwood/softwood ratio, and wet press consolidation over normal operational ranges were not found to influence coating streaks significantly. In addition, variations in coating drying rate and changes in coating formulation such as solids, binder level, type, and amount of thickener, and pigment type had at most only a small influence on coating streaks.

Ten different coater parameters were studied. The effects of these parameters on coating streaks are listed in **Table I**. Of these ten parameters

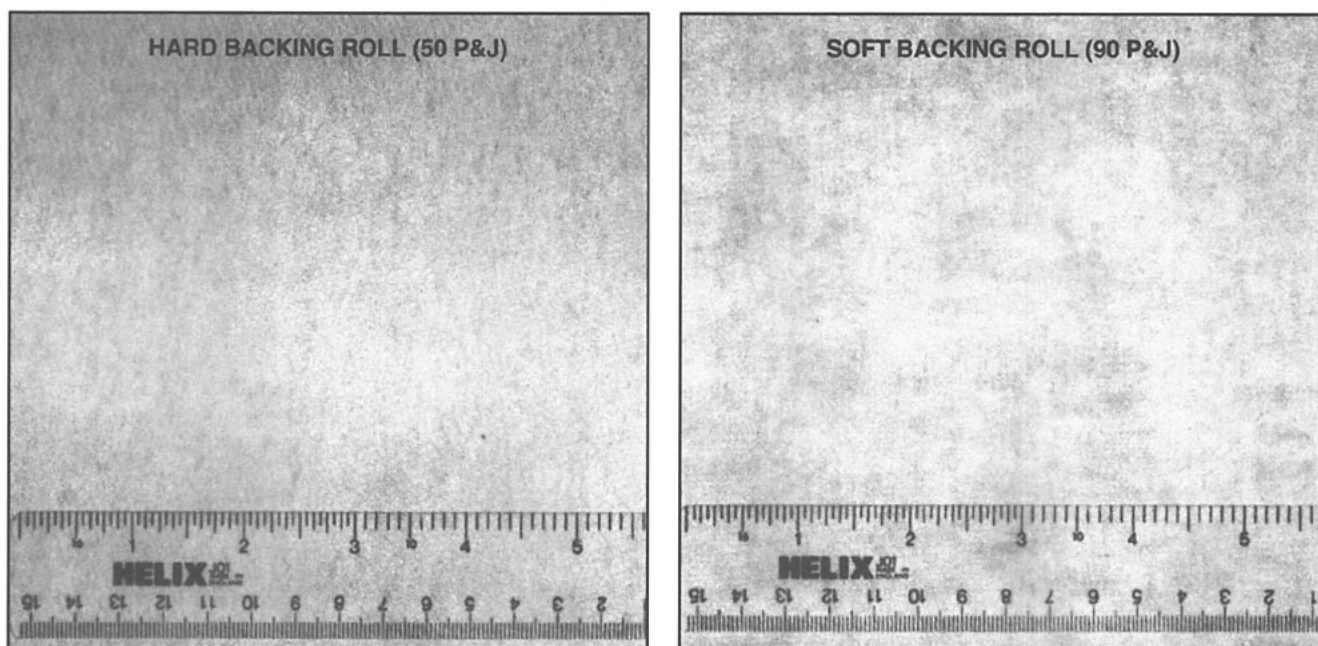
I. Effects of coater parameters on streaking

	Parameter	Streaking
(1)	Web speed Streaks are worse as web speed increases (Fig. 2)	Large
(2)	Backing roll hardness Streaks are worse with soft backing roll (Fig. 3)	Large
(3)	Applicator Streaks are wider and less frequent as gap increases	Large
(4)	Premetering Streaks are worse without premetering (Fig. 5)	Large
(5)	Blade angle Streaks are worse at higher blade angle (Fig. 6)	Large
(6)	Side coated first Streaks are generally worse on first coater head	Very minor
(7)	Web tension Streaks can be worse with more web tension. This effect was only observed on one pilot coater.	Very minor
(8)	Applicator roll speed Varying applicator roll speed 15–30% of backing roll speed did not affect streaking	None
(9)	Blade extension Streaks were not affected by changing blade extension from 14 mm to 18 mm.	None
(10)	Roll wrap Backing roll wrapped before entering applicator/backing roll nip did not affect streaking	None

2. Transmitted light showing the effect of web speed on streaking



3. Transmitted light showing the effect of backing roll hardness on streaking



only the following five had a significant influence on coating streaks: web speed, backing roll hardness, applicator gap, premetering, and blade angle. All the other parameters listed had either a minor effect or no effect on coating streaks.

Web speed

Figure 2 shows coating streaks produced on a production coater (75 P&J backing roll hardness) at two speeds: 2000 ft/min and 3500 ft/min. As can be seen from these "show-through" photographs, streaking is much worse at the higher web speed. Similar speed dependence of streaking was also ob-

served on two high-speed pilot coaters. The minimum speed at which streaking occurred depended on the specific coater.

Backing roll hardness

Coating streaks appeared at lower speed and became more intense when a softer backing roll was used. In **Fig.**

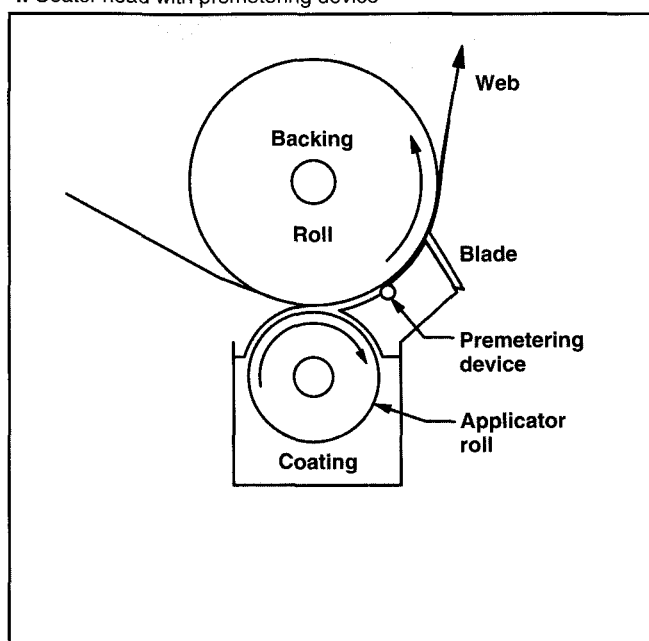
II. Streak variation with gap thickness

Gap (mm)	Streaks/cm	Streak width (cm)
0.4	3 ± 0.3	0.3 ± 0.1
0.8	2 ± 0.3	0.5 ± 0.1

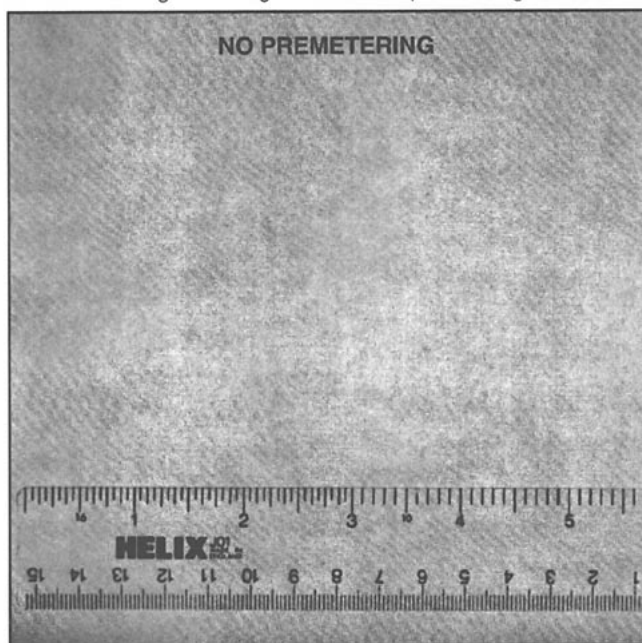
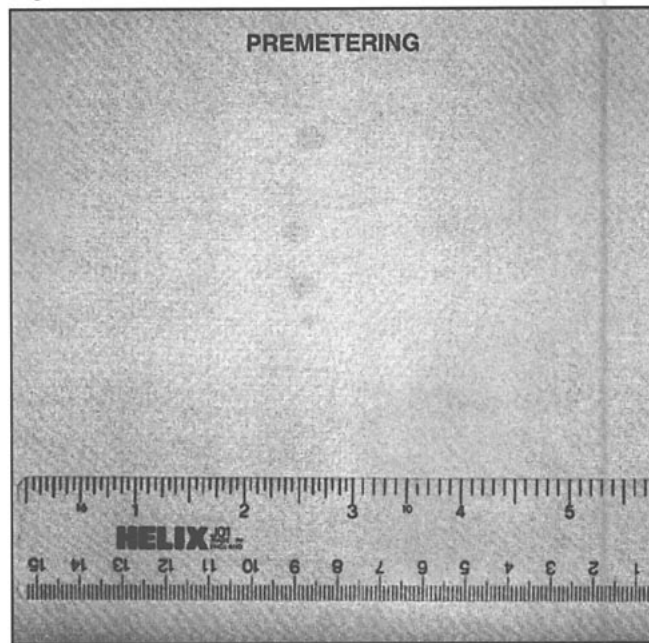
III. Comparison of calculated and observed values

Calculated			Observed	
Gap height, mm	Ribs/cm	Rib spacing, cm/rib	Streaks/cm	Streak width, cm
0.4	3.2	0.31	$3 \pm .03$	0.3 ± 1
0.8	1.8	0.56	2 ± 0.3	0.5 ± 1

4. Coater head with premetering device



5. Transmitted light showing the effect of a premetering device on streaking



3, photographs are shown of paper coated at 4260 ft/min with backing rolls of two different degrees of hardness. The soft backing roll (90 P&J) produced severe streaking, while the hard backing roll (50 P&J) gave no streaking. Similar results were observed in two high-speed pilot trials and on a production coater.

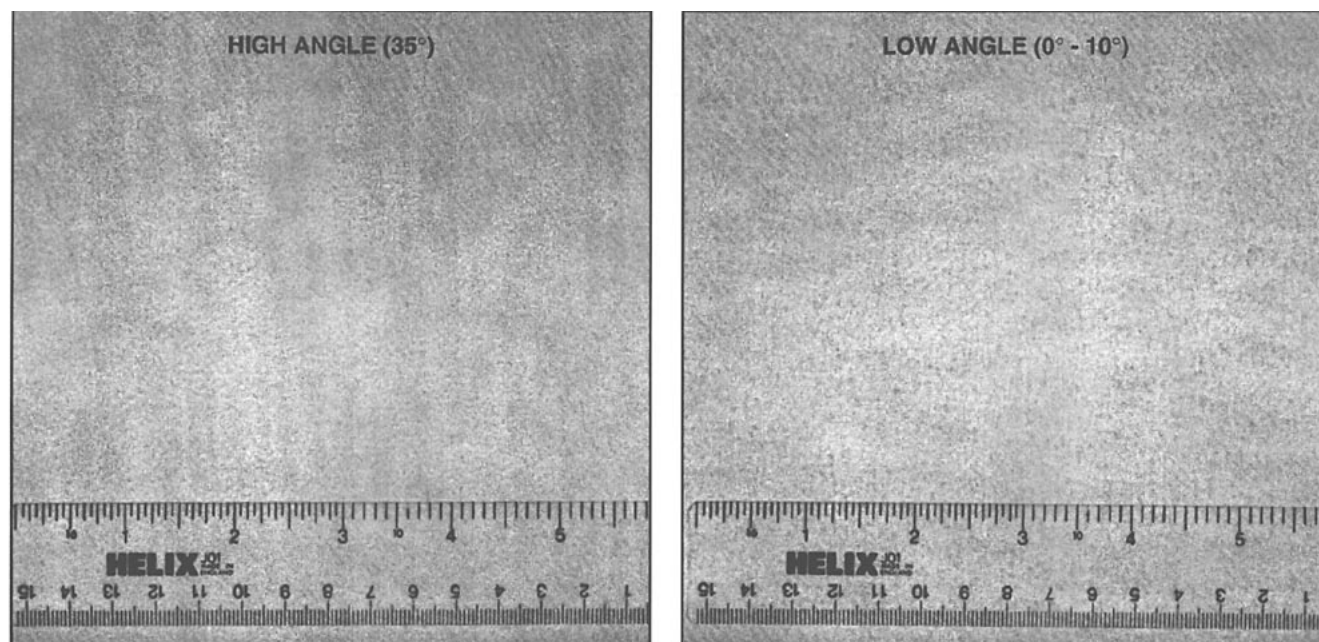
Applicator gap height

The streaking pattern on the coated paper appeared visually similar to the rib pattern in the coating film on the exit side of the applicator roll nip. When the applicator gap of a high-speed coater was decreased from 0.8 mm to 0.4 mm, the ribs on the applicator roll narrowed in width and increased in

CD frequency. A smaller gap also narrowed the width and increased the CD frequency of coating streaks observed on paper, as shown in **Table II**.

Premetering

A premetering device placed between the applicator roll/backing roll nip and the blade metered off 50–80% of the coating. A diagram of the premetering



device used on a high-speed pilot coater is shown in Fig. 4. The metering rod rotated at about 100 rpm in the reverse direction of the web. With this device, the amount of coating arriving at the blade is reduced greatly and the rib pattern produced at the applicator roll/backing roll nip is reduced or eliminated. This was confirmed by visually observing the coating film as it passed the premetering device. When the coater was run at 4500 ft/min, the premetering device greatly reduced the streaks even when a soft backing roll (90 P&J) was used. Figure 5 shows a comparison of paper coated with and without the premetering device on a soft backing roll. In addition, the premetering device significantly reduced the blade pressure needed for target coat weight.

Blade angle

A low angle (0–10°) and a high angle (35°) blade geometry were compared. The change to low angle resulted in coating streaks being completely eliminated regardless of backing roll hardness or coater speed or both factors. Figure 6 shows a comparison of paper coated with low angle and high angle geometries at 3500 ft/min. These results were confirmed on several pilot

coaters.

Coating streak mechanism

As previously discussed, five of the coating variables studied had a significant effect on streaking. Based on these, the most plausible origin for streaking is the rib pattern produced at the applicator roll/backing roll nip divergence. The CD variations in coating mass are believed to produce CD variations in pressure in the vicinity of the blade tip. These produce CD variations in backing roll deformation and consequently coat weight variations. This hypothesis is supported by the experimental results discussed below.

Web speed

The higher the web speed, the greater the momentum of a unit mass of coating coming into contact with the blade. At a high web speed, the CD variation in momentum due to the rib pattern in coating approaching the blade is proposed to cause CD variations in the pressure field. These in turn are believed to cause variations in backing roll deformation which allow local excesses of coating to pass underneath the blade. Coating streaks increased with increases in web speed.

Backing roll hardness

A hard backing roll will be less responsive than a soft backing roll to CD variations in the pressure field near the blade. Streaking was reduced when a harder roll was used.

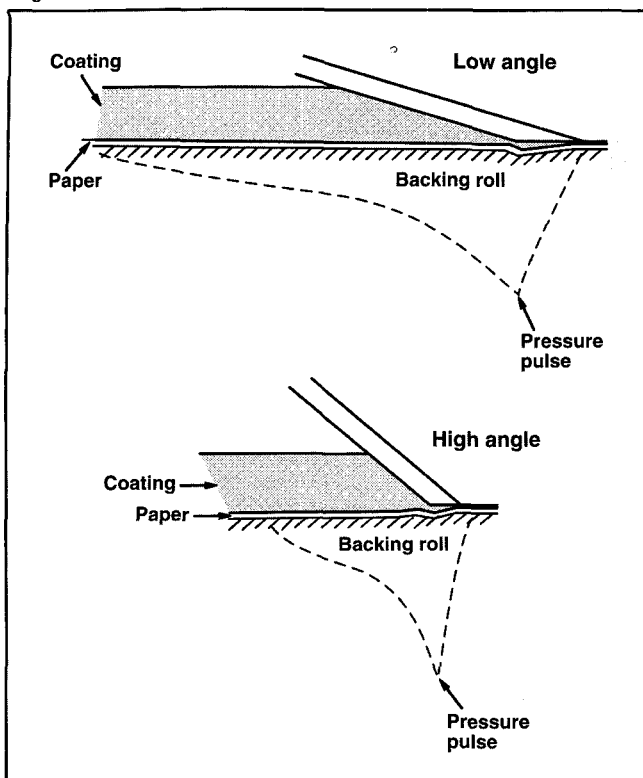
Applicator gap height

At standard coater operating speeds and coating viscosities, rib frequency and size are strongly dependent on applicator gap. Therefore, if ribbing is responsible for streaking, reducing the applicator gap should increase the frequency and reduce the width of the streaks. When the applicator gap was varied, the streaking frequency and width also varied in accordance with the hypothesis that ribbing is a source of streaking.

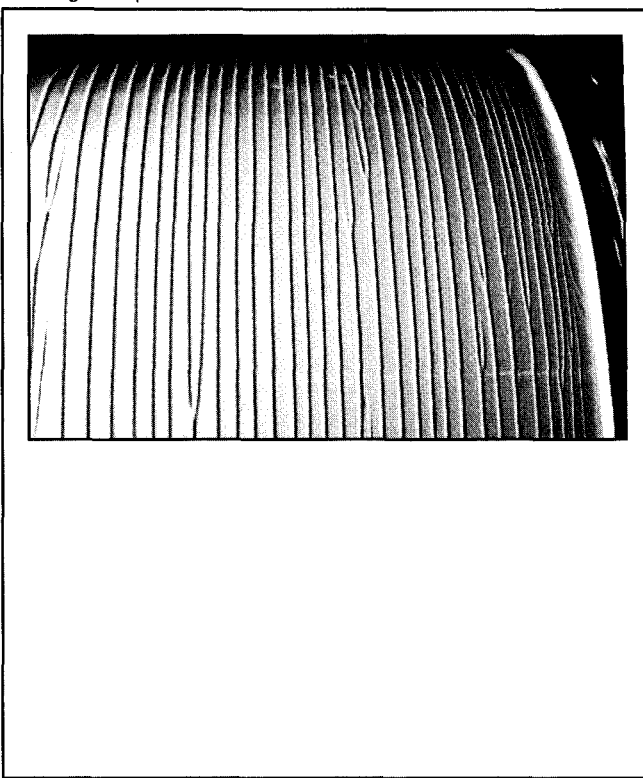
Premetering

One function of a premetering device is to eliminate or reduce greatly the rib pattern on the web before the coating is metered at the blade. If this pattern is responsible for streaking, the premetering device should eliminate or reduce streaking on the sheet in proportion to changes in the rib pattern. Coating streaks were greatly reduced when a premetering device

7. Comparison of pressure pulses generated with high and low blade angle



8. Ribbing intensity occurring at the divergence of the applicator/backing roll nip



was used even at high web speeds and with a soft backing roll.

Blade angle

Figure 7 compares qualitatively the pressure pulses that build up in the high and low blade angle modes. With the low blade angle, the pressure pulse is very long and the rib pattern strikes the blade well in advance of the metering point. This is proposed to allow time for the effect of the uneven coating mass to disperse and the CD pressure field to become more uniform before metering takes place at the tip of the blade.

A high blade angle, on the other hand, allows closer approach of the rib pattern to the blade tip before the uneven coating mass has an impact on the blade. This gives less distance and time for the rib pattern and pressure differences to disperse and even out. In the high angle blade configuration, the uneven CD pressure field is believed to unevenly deform the paper and backing roll where metering takes

place, thereby resulting in streaks.

Ribbing

To understand the proposed mechanism for coating streaks, the origin of the ribbing and effects of coating rib impact on the blade and backing roll deformation at high speed need to be described.

When a coating is applied to a paper web by an applicator roll, the film on the web prior to blade metering is not a uniform film but one with a wavy surface pattern transverse to the direction of coating. This behavior is called ribbing and is illustrated in **Fig. 8**. As previously discussed, this ribbing pattern is visually similar to the streaking pattern on the paper.

The formation of ribs in a fluid has been described in the literature and shown to be a general hydrodynamic property of fluids at the diverging nip of two counter-rotating rolls. Thus the excess coating applied to the basestock in applicator roll coaters is nonuni-

form before metering occurs at the blade. With Newtonian fluids, the rib frequency depends only on the applicator roll gap at high coating speeds, when the capillary number calculated from theoretical equations as shown by Coyle *et al.* (16) exceeds 2.4. The capillary number, N_{Ca} , is defined as $V\mu/s$, where V is velocity, μ is viscosity and s is surface tension.

Although coating colors are two-phase and not Newtonian, this approach was used for a first-order approximation. For typical coating conditions, the capillary number is above 300, which is well above the capillary number required for the gap to dominate the rib pattern. The rib frequency in a coating operation, therefore, will depend to first order only on the gap and can be quantified by a regression derived from a plot calculated from Eq. 1 (17).

$$y = 0.84/x^{0.84} \quad (1)$$

where

IV. Elastic modulus of substrates

Substrate	Measurement method	Elastic modulus
53 P&J rubber button	mechanical (1/2 in. rod)	2,500 psi
72 P&J rubber button	mechanical (1/2 in. rod)	1,850 psi
70 lb Basestock	Ultrasonic (z-direction)	33,000 psi
70 lb Basestock	Ultrasonic (z-direction)	24,000 psi

y = ribs/cm

x = gap/2 in mm.

This regression combines measurements of several independent authors. For the two applicator gap settings studied in this report, 0.4 and 0.8 mm, the calculated values are shown in **Table III**. These calculated frequencies are in good agreement with the spacing of streaks on commercial papers, as previously discussed.

As the centrifugal force generated on the rotating backing roll increases, the liquid ribs grow in height while the valleys decrease. This increases the nonuniformity of the coating film on the paper prior to blade metering. At high speeds, the centrifugal force can become great enough to cause the rib peaks to be flung off the web, thereby increasing the uniformity of the coating film. These competing phenomena make it hard to quantify the uniformity of the coating film approaching the blade and consequently the degree of streaking.

Backing rolls

The rubber covers of backing rolls are usually characterized by an elastic modulus or a P&J hardness number. The lower the P&J number, the harder the roll, i.e., the more resistant it is to deformation. A compressibility instrument was constructed and used to measure the elastic modulus of two 10-mm-thick backing roll buttons. In addition, two production basestocks differing in calendering and refining were sent to the Institute of Paper Science and Technology to have the z-direction modulus measured by an ultrasonic technique. The results of these

measurements are given in **Table IV**.

These results show that the z-direction elastic modulus of paper conditioned at 50% RH is higher than that of even a hard backing roll. The paper will be partially wetted during the coating process. Even if the elastic modulus decreased by a factor of 10 due to wetting, however, the fact that paper caliper is well below 1% of the backing roll rubber thickness indicates that the rubber will deform far more than the paper.

Coat weight variations of 20–50% would require a deformation difference of only 0.005–0.01 mm. A one-inch-thick rubber sleeve would only need to deform 0.02–0.04% of its thickness, while paper would be required to deform 5–10% of its thickness to allow the observed coat weight variations. The fact that paper does not deform significantly, when compared to the rubber backing roll, is also supported by the experimental findings of Sommer (18). The compressibility of the backing roll, however, has not been thoroughly treated in previous theoretical models. Pranckh and Scriven (14), for example, described the compressibility of a substrate. In their model, they used values for thickness and compressibility much closer to that of base paper conditioned at 50% RH than to the backing roll rubber cover.

The elastic modulus and P&J measurements above were made under static conditions and therefore provide no information on the dynamic responses of the rubber rolls. Materials such as rubber exhibit time-dependent, stress/strain behavior. These materials are described as being vis-

coelastic (19). Again the published theoretical treatments to date do not take into account time-dependent backing roll response to stress under the blade.

Blade Coating

To model the blade coating process, both the deformation behavior of the rubber roll and the coating pressure field that acts on the roll need to be known as functions of speed. These two factors are discussed in the following section.

Blade flexibility has been discussed previously by Pranckh and Scriven (14). These authors show that the blade is far too rigid to deform nonuniformly over the small distances required to cause streaking. Therefore, this discussion will concentrate on the effect of the coating forces acting on the paper and backing roll. At web speeds of 1000 ft/min and above, it has been shown both experimentally (10, 15) and theoretically (9, 14) that the dominant force acting on the blade is the force due to coating impact on the side of the blade. This force is commonly called the impact force and is given in Eq. 2.

$$F_i = \frac{mV(1 + \cos w)}{\sin w} \quad (2)$$

where

F_i = impact force

m = mass flow rate

V = coating speed

w = blade angle.

Since the mass flow rate is the product of the density (ρ) times the cross sectional area of the coating film approaching the blade (A) times the coating speed (V), this can be rewritten as Eq. 3.

$$F_i = \frac{A\rho V^2(1 + \cos w)}{\sin w} \quad (3)$$

As shown in Eq. 3, the coating variables affecting the impact force at a given blade angle are the amount of

coating having an impact on the blade and coater velocity. Increasing coating thickness or density increases the impact force linearly while coating velocity increases the impact force to the second power. The square dependence on velocity comes from the product of coater speed and coating mass per time hitting the side of the blade.

At typical web speeds of 1000–3000 ft/min, the coating forces are believed to be insufficient to deform the backing roll. The hypothesis that the rubber backing roll does not significantly deform at these speeds is supported by an experimental study by Kahila *et al.* (20). In this study, the coat weight and paper properties were compared for paper coated at three speeds (1200, 1800, and 2400 ft/min) on three backing rolls (steel, 60 and 125 P&J). Coat weight was equivalent for the three backing rolls indicating that all rolls acted as if they were noncompressible. Moreover Kahila's results showed no significant difference in any paper or print properties for paper coated with these three rolls.

It should be noted that this is the speed region where most experimental and theoretical studies have been conducted. Therefore the fact that the rubber backing roll has not been explicitly described in theoretical models and in experimental studies probably has not mattered. The impact force in this speed range may be insufficient to cause significant deformation of the backing roll.

At high speeds, however, variations in the impact force will become increasingly significant due to the square dependence on velocity. Finite elemental analysis by Prancek and Scriven (14) shows how this impact force is transferred to the backing roll. Their analysis indicates that the pressure exerted on the substrate (paper and backing roll) increases as the coating approaches the blade, reaches a maximum right at the heel of the blade, and falls to zero near the toe of the blade. The stress applied to the substrate increases in magnitude as the web speed increases. Therefore both the web speed and the properties of the

backing roll will determine how much the backing roll deforms.

Prancek and Scriven's theoretical calculations did not take into account the effect of a variable coating height in CD. One can speculate about the effect of CD coating variations on this pressure field. If one assumes that the variable coating mass colliding with the blade causes a corresponding variable pressure field against the backing roll at the metering location, the resulting variable deformation of the backing roll would explain streaks. The soft roll would produce streaks more readily than the hard roll because it is more responsive to variations in pressure.

Mechanism

The mechanism by which a variable pressure field causes variable backing roll deformation is not known. At least two possibilities can be envisioned. First, a purely elastic model ignoring edge and skin effects would describe deformation as directly proportional and immediately and completely responsive to local pressure at the blade metering point. This type of model is sufficient when the process changes are slow in comparison to the time constant of the deformable material. Second, a viscoelastic model would invoke the time period over which the pressure pulse is applied as well as the pressure magnitude at each instant. In this latter case, the backing roll would be presumed not to reach equilibrium deformation during the rapid growth and decay of the pressure pulse. A longer pressure pulse would cause more deformation than a shorter pulse of the same peak amplitude. To distinguish among these possibilities, an understanding of the viscoelastic properties of the backing roll materials would need to be developed.

These models differ in estimating how much pressure must be present to deform the backing roll and cause the observed streaks. The pressure variations need to cause differences in backing roll deformation of only about 0.005 mm. Assuming the backing roll

is completely elastic so that equilibrium deformation is attained instantly (first model), pressure differences of less than 0.5 psi would be required to generate coating streaks with a 60 P&J backing roll. If the backing roll is viscoelastic (second model) so that less than equilibrium deformation is attained during the brief period of pressure application, higher pressure differences would be required to cause the same amount of backing roll deformation and the same coating streaks.

In summary, roll deformation at high coater speed is proposed to depend on the height of the incoming coating layer. This hypothesis is supported by the fact that the rib pattern on the web described earlier corresponds to the nonuniform coat weight streaks and by the observation that a premetering device eliminates streaking. Since the blade is too rigid to bend over these small distances, deformation of the backing roll is a likely explanation for the streaking. The fact that a hard backing roll does not produce streaks at high web speeds further supports this conclusion.

Short-dwell coater streaking

Short-dwell coater streaks and applicator roll streaks are similar in that both appear at high web speeds and become worse as speed increases. In both cases, the streaking is characterized by coat weight nonuniformities in the CD. One main difference between the streaking observed in the two coating methods is the width of the streaks. In applicator roll coaters, they are 0.2–0.5 cm wide, while in short-dwell coaters they are 2–5 cm wide.

Previous work by others (1–8) has documented that the wide streaks in short-dwell coaters relate to the size and onset of hydrodynamic instabilities in the short-dwell coater pond. The mechanism by which these vortex instabilities cause coat weight variations, however, is not well understood.

The present mechanism describing applicator roll streaks, i.e., variation in the CD pressure field deforming a

rubber backing roll, should be evaluated as an explanation for short-dwell streaking. With this mechanism, it is hypothesized that the hydrodynamic vortices in the short-dwell pond create a CD pressure variation. Visualizations suggest that vortices in the short-dwell coater head extend for some distance in the machine direction so the time for backing roll deformation to occur is much greater than for applicator roll ribs to cause streaks. The pressure field experienced in a short-dwell coater extends about 50 mm in the machine direction (the width of the short-dwell pond) compared to an estimated 0.5 mm impact zone for the applicator roll coater. Because machine direction distance translates into time and the backing roll's response is probably time-dependent, the response to a given pressure will be greater with short-dwell coaters. This also may explain why streaking is observed at a lower speed with short-dwell coaters than with applicator roll coaters.

Triantafillopoulos and Aidun (8) concluded that "the onset of instabilities constitutes a sufficient, but not always necessary, requirement for the appearance of streaks." To date, the effect of backing roll hardness on coating streaks in short-dwell coaters has not been reported. This approach combined with available information about short-dwell coaters should be evaluated.

Conclusions

Coat weight streaks on high-speed blade coaters have been investigated. Major coater parameters affecting streaking have been identified. At high coating speeds, the backing roll hardness has been shown to have a much greater effect on the blade coating uniformity than had been previously recognized. A mechanism that causes streaking in applicator roll coaters has been proposed. Streaking appears to be related to the rib pattern originating at the divergence of the applicator/backing roll nip. The ribbed coating flow is proposed to cause an irregular

pressure field with CD variations in the vicinity of the blade. When the pressure field variations are great enough to nonuniformly deform the backing roll, nonuniform coat weights pass underneath the blade producing a streaky coating.

Streaking can be eliminated by reducing CD variations in the coating approaching the blade or by reducing the deformability of the backing roll. The irregularity of the pressure field immediately before the blade can be reduced by using a premetering device before the blade or by operating in a low angle mode. The deformability of the backing roll can be reduced by increasing the elastic modulus of the rubber roll. Varying applicator gap changes the width and frequency of streaking but does not eliminate streaking. Paper compressibility, because of its relatively high elastic modulus and low thickness, has been shown to have less effect on coating nonuniformities than the backing roll. **■**

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