Stalagmite formation during blade coating—the effects of process conditions

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ABSTRACT *In pilot coater trials, the formation of stalagmites on the blade tip was studied with respect to the effects caused by coating conditions and coating color formation. Stalagmite formation increases when the high shear viscosity of the coating color, the machine speed, or the free blade length are increased; stalagmite formation decreases when the blade angle is increased. A model based on Navier-Stokes equations suggests that the angle of the inlet to the channel developed between the blade and the base paper is a factor controlling the stalagmite formation. This angle should be kept high.*

KEYWORDS
Coating
Blade coating
Fluid dynamics

The formation of stalagmites of wet or dry coating color on the blade tip (*1–6*) can cause runnability problems at high machine speeds or at high solids contents. These stalagmites are called "whiskers," and the process is called "bleeding."

The stalagmites trail on the wet coating layer. If they come loose and fall forwards, they adhere to the wet coating layer and fasten there. Stalagmites in the coated sheet may adversely affect both the printability and the print quality. For instance, when the sheet is printed on an offset press, stalagmites in the coating surface may be lifted away and accumulate on the rubber blanket in the press. Where there is a stalagmite on the blanket, no ink will be transferred to the sheet, and this will give a spotted print. Stalagmites falling backwards are not collected by the wet coating layer and are considered not to cause any problems.

Based on observations made in a pilot coater, a model is derived describing the formation of stalagmites in blade coating. The extent to which these observations and the difference between the flooded nip coater and the SDTA coater with regard to stalagmite formation is discussed in the following paragraphs.

Experimental methods

The experimental material on which this paper is based originates from two pilot coater trials. In the first trial, where the effects of machine speed and blade geometry were studied, a base paper for a lightweight coated grade (LWC) with basis weight 38 g/m² was coated with a flooded nip blade coater. The coating formulation was 100 parts U.S. No. 2 clay, 6 parts low viscosity grade (LV) starch, and 6 parts styrene-butadiene latex. The solids content of the color was 63.9%, and 11 g/m² (dry) was applied to the paper.

In the second trial, a wood-free sized base paper, 90 g/m², was coated at 400 m/min in the same blade coater with 35° blade angle and a free blade length of 20 mm. The coating colors used were based on English Kaolin, U.S. No. 2 clay or ground calcium carbonate. The binder system was 0.6 parts Lv CMC and 10 parts styrene–butadiene latex. The solids content of the color was varied during the trial, and 11 g/m² was applied to the base paper.

The effects of coating conditions and coating formulation

The stalagmite formation on the blade tip depends strongly on the conditions in the coater. **Table I** shows this relationship for the effects of the machine speed, the blade angle, and the free blade length. The formation increased with increasing machine speed, and it decreased with increasing blade angle and decreasing free blade length.

The color based on English Kaolin was runnable up to a solids content of 61.5%, and the color based on U.S. No. 2 clay was runnable up to 64.3% without any problems with stalagmite formation on the blade tip. With the color based on ground calcium carbonate, no runnability problems whatsoever were observed, even at its highest solids content of 67.8%.

A model describing stalagmite formation on the blade tip

In an operating situation where stalagmite formation on the blade is extremely heavy, which can easily be achieved on the pilot coater if it is run both at a high machine speed and with a coating color of high solids content, a reversed flow can readily be observed in the coating surface immediately after the blade. The coating color is flowing against the machine direction and up onto the blade tip where the stalagmites are formed, either in the wet or dry form. In the bulk and bottom of the coating layer, the flow is in the machine direction.

This occurrence implies that there is a certain velocity profile of the flow under the blade tip. **Figure 1** shows two velocity profiles. The profile to the left, with a reversed flow in the coating surface, illustrates a flow situation in which stalagmite formation may occur. The profile to the right, with a flow only in the machine direction, illustrates a case in which stalagmite formation may not occur. **Figure 2** is an illustration of the geometry of the channel between the blade and the base paper, explaining the notations of the velocity profiles.

Flow profiles of this kind can be described with Navier-Stokes equations and a suitable constitutive equation (*1, 7–9*). Turai (*8*) has derived an expression for the flow profile, satisfying the boundary conditions that exist in the vicinity of the blade tip:

$$U(y) = (U/h)y - (dp/dx)\,[(hy - y^2)/2\eta] \quad (1)$$

where

$U(y)$ = velocity in position y

U = machine speed

y = position coordinate

dp/dx = pressure gradient

η = viscosity of the coating color

h = width of the channel between the blade and the base paper.

According to Turai's derivation (*8*), a condition for reversed flow to occur is given by:

$$(U/h)y < (dp/dx)\,[(hy - y^2)/2\eta] \quad (2)$$

This expression may be used to describe the stalagmite formation on the blade tip (*1*) under conditions in which the observations made regarding stalagmite formation are applicable.

I. Effects of coating conditions on stalagmite formation

Machine speed, m/min	*Blade angle, degrees*	*Free blade length, mm*	*Stalagmite formation*
400	35	20	Heavy
800	35	20	Very heavy
400	45	20	Little
400	35	10	None

The process variable in Eqs. 1 and 2 that determines the onset of reversed flow and stalagmite formation on the blade is $(dp/dx) \cdot (1/\eta)$, or the pressure drop over the blade tip divided by the coating color viscosity. This factor should be kept as small as possible to minimize the risk of stalagmites forming on the blade tip.

The pressure drop over the blade tip may be assumed to be determined by the hydrodynamic pressure developed at the inlet of the channel between the base paper and the blade. This hydrodynamic pressure is directly proportional to the product of the machine speed, the coating color viscosity, and a geometry factor, as shown in Eq. 3 (*7, 10, 11*).

$$dp/dx \sim H = [U\eta/(\tan^2\alpha)] \cdot C \quad (3)$$

This equation may be rearranged to:

$$(dp/dx) \cdot (1/\eta) \sim [U/(\tan^2\alpha)] \cdot C \quad (4)$$

where

H = hydrodynamic pressure

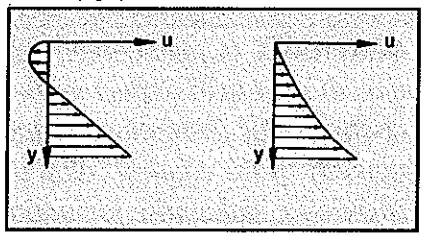
α = angle between the blade and base paper

C = geometry factor (dependent on coating weight).

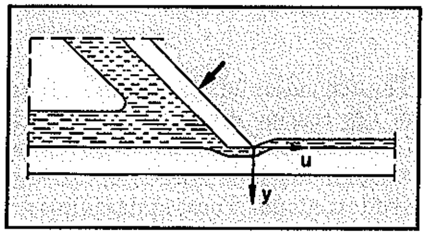
Since $(dp/dx) \cdot (1/\eta)$ is affected by changes in α, the shape of the inlet of the channel between the blade and the base paper is important. The shape might be a factor controlling the reversed flow observed in the coating surface immediately after the blade tip when stalagmites are formed.

The angle α is not the blade angle itself but the angle of the inlet of the channel between the blade and the base paper. This angle is determined by the blade angle θ, the curvature of the blade, and the compression of the base paper caused by the load from the blade tip.

1. Velocity profiles of the flow under the blade tip when stalagmites are formed (left) and not formed (right)



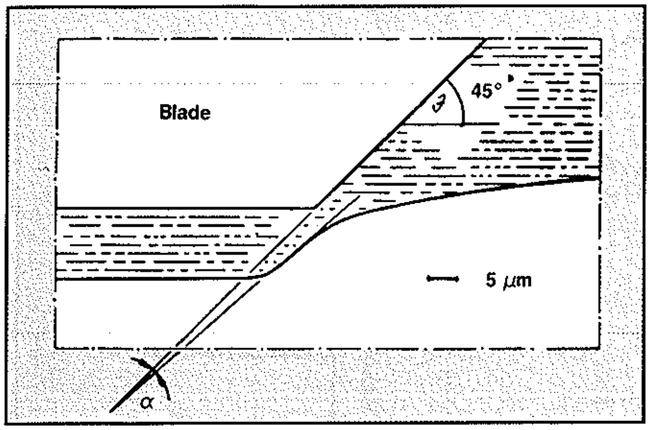
2. The channel between the blade and the base paper



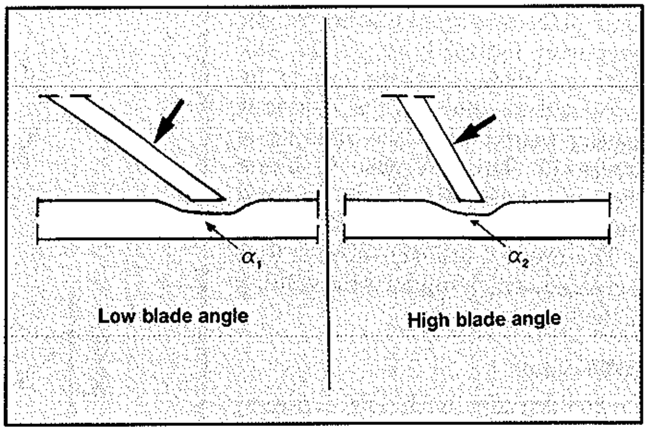
The shape of the impression caused by the compression of the base paper under the blade tip has been estimated in a static experiment where a sheet of the base paper was fastened on the backing roll in the pilot coater and loaded by the blade for 20 h. The shape of the track, shown in **Fig. 3**, was recorded using a profiler instrument to make a comparison between the blade angle θ and the tip angle α. A blade at an angle of 45° is also shown in the figure. The angle α is much less than the blade angle θ. Small changes in θ will consequently have a great impact on α and especially on $1/\tan^2 \alpha$.

The expression $(dp/dx) \cdot (1/\eta)$ decreases when α increases. Consequent-

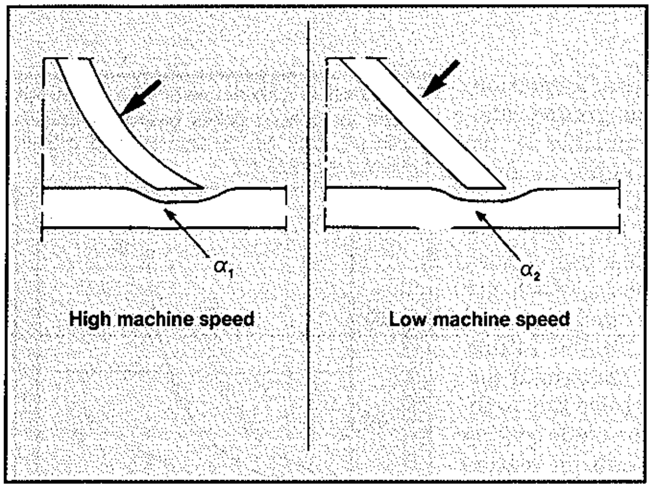
3. The shape of the channel is affected when the base paper is compressed. Also, the inlet angle α is much smaller than the blade angle θ.



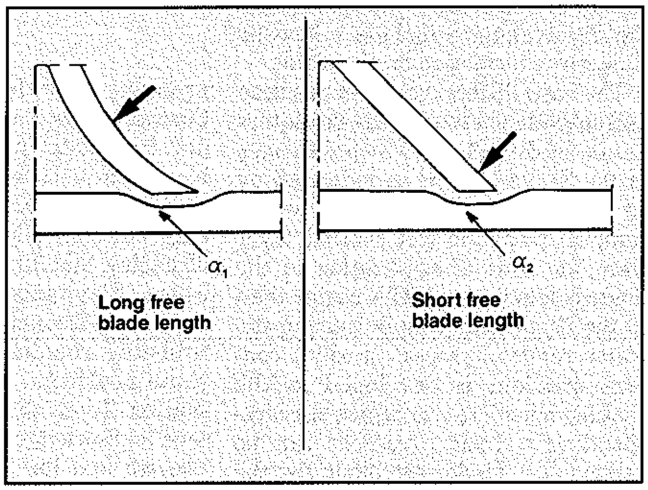
4. The inlet angle α increases when the blade angle is increased.



5. The inlet angle α increases when the machine speed is increased.



6. The inlet angle α increases when the free blade length is increased.



ly a high angle α should reduce the risk for reversed flow in the coating surface and thus for stalagmite formation on the blade.

Confirmation of the model

Blade angle

Table I showed that the stalagmite formation decreased when the blade angle θ was increased. However, the angle α increases simultaneously, as **Fig. 4** shows. Consequently, $(dp/dx) \cdot (1/\eta)$ decreases, and the effect of the blade angle on the stalagmite formation confirms the proposed model.

Machine speed

Also observed in Table I was that stalagmite formation increased with increasing machine speed.

When the machine speed is increased, both $(dp/dx) \cdot (1/\eta)$ and the term $(U/h) \cdot (y)$ increase at the same rate, so the conditions for a reversed flow in the coating surface will not be affected. Hence, high machine speed as such is not, according to this model, a factor causing reversed flow and stalagmite formation.

However, when the machine speed is increased, the blade pressure must be increased simultaneously to maintain a constant coating weight. Hence, the blade will be more bent. This makes the inlet of the channel between the blade and the base paper more acute, as shown in **Fig. 5**. Consequently, α decreases and $(dp/dx) \cdot (1/\eta)$ increases, and the effect of the machine speed is in accordance with the model.

Free blade length

As mentioned, a short free blade length gives less stalagmite formation on the blade tip than a long-free blade length. If the free blade length is increased, then the blade becomes more bent, as illustrated in **Fig. 6**, and $(dp/dx) \cdot (1/\eta)$ consequently increases. This effect is in accordance with the model.

Effect of coating color viscosity

In **Fig.** 7, the viscosity at a shear rate of 10^5 s^{-1} is plotted against the solids content of the coating colors based on English Kaolin, U.S. No. 2 clay, and ground calcium carbonate. The viscosities of the two clay colors were identical at their respective maximum runnable solids contents which gave no stalagmite formation. The color based on ground calcium carbonate had a lower viscosity than the clay colors throughout the range of solids contents studied.

The viscosity of the coating color may not control the reversed flow, since the relationship expressed in Eq. 4 is not affected by the viscosity. If the viscosity is considered to be a factor determining the coating weight directly or indirectly (*9, 11, 12, 13*), then the blade pressure has to be increased to maintain a constant coating weight when the viscosity is increased. This increase in blade pressure causes the blade to bend more and results in a smaller angle α. The product $(dp/dx) \cdot (1/\eta)$ is thus increased, which supports the validity of the model.

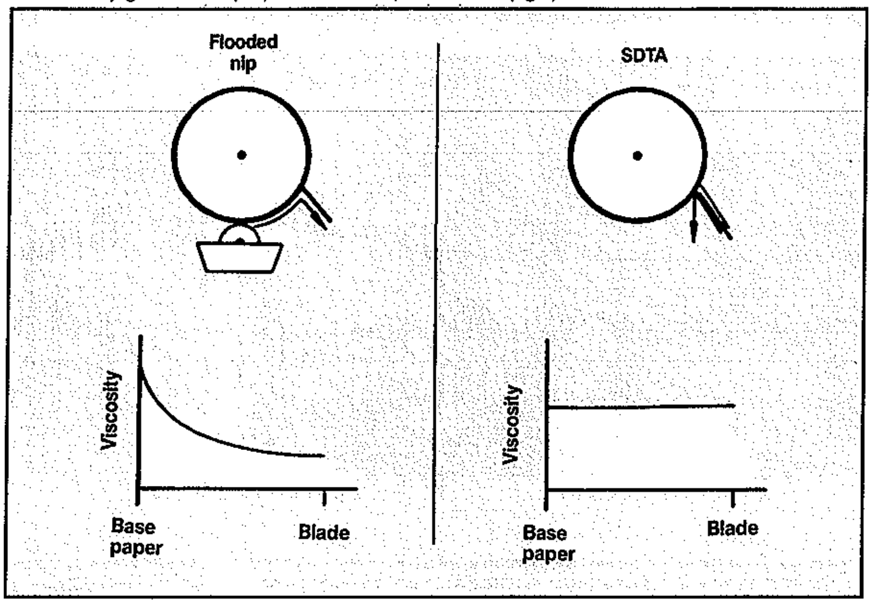
SDTA coater

In comparison with the ordinary flooded nip coater, the SDTA coater (short dwell time applicator) exhibits both advantages and disadvantages. The advantages include a lower frequency of web breaks at the blade, and the disadvantages include a heavier stalagmite formation on the blade.

The basic difference in construction and operation between the two coaters lies in the dwell time, which is shorter in the SDTA coater, as indicated by its trade name. Consequently, water removal from the wet coating layer from the time of application to the blade is less in the SDTA coater than in the flooded nip coater. During the water removal process, a solids content gradient is developed in the coating layer (*14*), to which a corresponding viscosity gradient can be related (*15*). Under the blade tip, the viscosity gradient is less pronounced in the SDTA coater than in the flooded nip coater as a result of the difference in dwell time, as **Fig.** 8 shows.

The derivation of Eqs. 1 and 2 by Turai does not include the consideration of a viscosity gradient in the coating layer under the blade tip. If such a gradient is considered, an expression is obtained which shows that the equivalent to $(dp/dx) \cdot (1/\eta)$ decreases with increasing viscosity gradient. The risk for reversed flow and for stalagmite formation on the blade should therefore be greater in the SDTA coater than in the flooded nip coater, as a result of the less developed viscosity gradient under the blade tip. This circumstance is in agreement with reality and supports the validity of the proposed model.

8. Viscosity gradients in (left) the flooded nip coater and (right) the SDTA coater

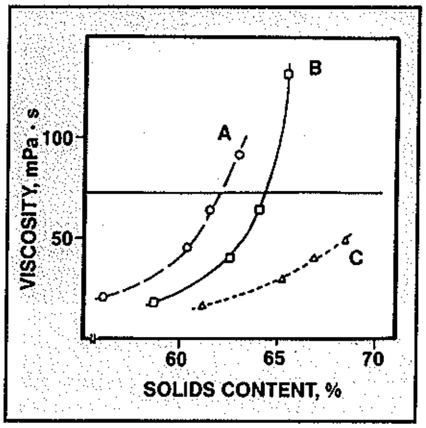


Final remarks

There are no simple solutions to the problem of stalagmite formation. Coating colors based on ground calcium carbonate are runnable in the blade coater both at higher machine speeds and higher solids contents than clay coating colors, but there are obstacles that limit the use of such colors. Clay-based colors, which are the most frequently used and will probably remain so in the future, cause problems with stalagmite formation. To be able to solve this problem, a knowledge of the blade coating process and its demands on coating color and base paper is necessary.

Stalagmite formation on the blade tip can be explained in a simple and elementary manner with the help of a model based on Navier-Stokes equations. This model suggests that the shape of the inlet of the channel formed between the blade and the base paper is important. Its shape is determined not only by the blade geometry but also by the compression of the base paper under the blade tip.□

7. Viscosity at a shear rate of 10^5 s^{-1} vs. solids content for coating colors based on English Kaolin (A), U.S. No. 2 clay (B), and ground calcium carbonate (C)



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