Operational issues in high-speed curtain coating of paper, Part 2: Curtain coating of lightweight coated paper

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ABSTRACT: Curtain coating—a new coating process for specialty papers—is emerging as a potential method for coating printing paper grades as well. In Part 1, we discussed the operational principles of the process. In Part 2, we present results from pilot-coater trials that demonstrate: (a) the operational window of the process and potential defects, and (b) a value proposition for coating lightweight coated (LWC) papers. By removing the air layer traveling with the web (moving faster than 400 m/min), we have been able to coat LWC at web speeds as high as 1500 m/min. Coating at high speeds requires low air void volume in the coating color and viscosity control. The most challenging issue has been removal of air bubbles from the coating color that might break up the curtain at the slot die exit or create coating layer defects. Macrovoids created from large air bubbles are easily managed. Microvoids of a few 10ths of a millimeter, however, are more difficult to remove and can induce fine coating layer defects. Careful choice of coating formulations and deaeration has made high-speed curtain coating possible. We show that curtain coating can achieve low coat weights (5.8 g/m²) on LWC, with high coverage (85%), even at low coating solids (54%) to avoid detrimental bubbles in the coating. At a constant coat weight of 5-6 g/m², we saw nearly a 40% advantage in coating coverage using the curtain coating process instead of a metered size press.

Application: Pilot coater trials are showing the potential of the high-speed curtain coating process to produce superior LWC coating coverage at low coat weight.

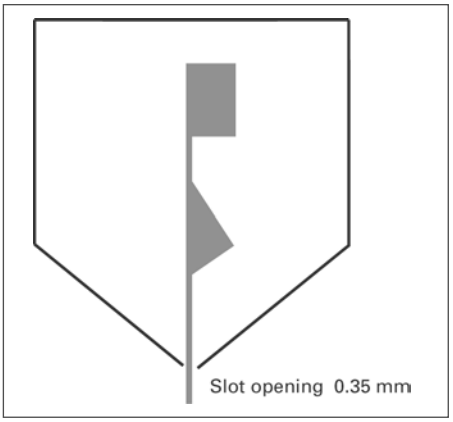
Precision, contactless coating methods, such as curtain coating, pose the interesting possibility of reducing, if not eliminating, paper web breaks. Curtain coating is also a contour coating method that provides the opportunity to reduce coat weight without compromising coated paper properties. In Part 1, we discussed the basics of curtain coating and its stability parameters [see *TAPPI JOURNAL*, 3(11): 6(2004)]. In Part 2, we present results from pilot coater trials with high-solids pigmented coatings applied to lightweight coated (LWC) paper at high speeds. Although commercial curtain coating applications exist for making carbonless, thermal, NCR, and inkjet grades of papers, research is now focused on applying the technology to manufacturing printing papers. In the latter, coating solids and application speeds are high; eventual application to practice requires forming a very wide curtain.

Several recent pilot coater trials have evaluated the curtain coating process using highly pigmented coatings for commodity paper grades [1-5]. These works have explored the limits of the process at high operational speeds (i.e., faster than 1000 m/min), and they have sought to optimize coating solids and rheology. Effective deaeration is recognized as a critical operational issue. Advances in slot-die designs provide a wide window of flow rates (and corresponding coat weights), from 2-50 L/min/m deckle width [2].

In Germany, the "High Speed/Solids Pigment Curtain Coating" consortium has conducted pilot coater trials for offset printing papers and paperboard [3]. Coating requirements identified by the consortium include high solids-low viscosity coatings, low surface tension, high coating elasticity and "stretchability," and low air bubble content. Successful applications included all-carbonate, carbonate/kaolin, and carbonate/kaolin/TiO_2 pigments in all-synthetic thickener coatings at about 50%-55% solids. Applications included LWC and woodfree paper coating at 1000 m/min and paperboard coating.

Voss and Tadjbach [5] demonstrated that, by increasing the stretchability of a coating, an improved LWC quality could be achieved with curtain coating. Pilot coating was possible for a 42 g/m² LWC base paper at machine speeds from 1200-1600 m/min, for a coat weight target of 12 g/m² with 61% solids coatings using different thickeners. An increase in extensional viscosity led to a reduction in coating surface defects under the selected pilot coater conditions. Focusing on coating rheology, the authors discussed the influence of the *Trouton ratio,* which compares the shear and extensional viscosities. The latter were measured with a uniaxial extensional viscometer [5]. For Newtonian fluids, the ratio is 3. For non-Newtonian paper coatings with limited efficiency thickeners, the values were 3-6. The ratio was about 10 for coatings that corresponded to defect-free curtain coater runnability. A selected polyacrylate coating thickener displayed improved curtain stability and coated paper quality, especially at high concentrations. However, an extensional viscosity limit would exist, corresponding to a certain coater speed. If a paper coating exceeds that limit, tension on the curtain and extensional forces could become too high, causing curtain break-up or splitting, and interfering with curtain impingement.

For specialty paper grades, commercial applications of slot-die curtain coating have been successful for speeds up to 1600 m/min [6]. Typical solids are between 30% and 40%, much lower than anticipated for coating printing type



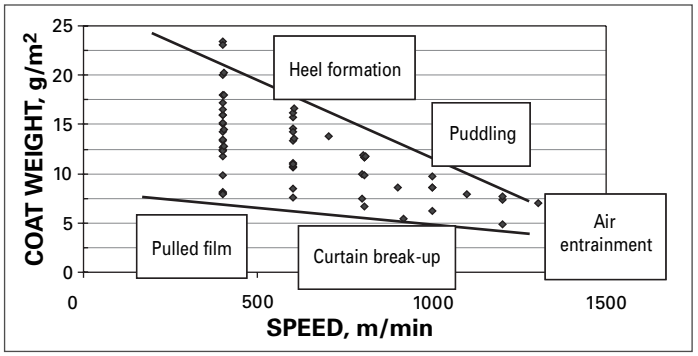
1. Slot-fed type curtain die used in pilot coating trial.

Component	Type	Trade name	Curtain	MSP
Pigments	Clay	Suprawhite® 95	20	20
	$CaCO_3$	Carbital® 95	80	80
Binder	All-purpose SB latex	—	20	12
Thickener	CMC	FF-30	—	0.4
	PVOH	Elvanol® 71-30	2	—
Surfactant		Surfynol® SE-F	0.3	—
Optical brightening agent		Tinopal®	1	1
Solids content, %			54	64
Brookfield viscosity (100 rpm), mPa•s			120	1440
Static surface tension, mN/m			34	—

I. Coating color formulations listed in order of addition of the individual ingredients. Amounts of pigments represent percent, all other amounts are in parts per hundred.

Properties	Values
Basis weight, g/m²	40.2
Thickness, mm	69
Density, kg/cm³	600
Bendtsen smoothness, mL/min	230 (top side) 290 (bottom side)
Bendtsen permeability, mL/min	278
Cobb-Unger oil absorption (CU10), g/m²	18.2 (top side) 19.1 (bottom side)

II. Base paper properties.



2. Influence of web speed (U) on the coat weight development. At a constant speed, the coat weight varied by changing the flow rate (Q). The data were collected from pilot coater trials with the curtain coating color shown in Table I.

grades. However, curtain heel stability, avoidance of heel fluttering, and coating levelling require viscosity to be below 300 mPa•s, preferably below 200 mPa•s. Additionally, surface active agents have been commonly added to coatings to reduce surface tension for curtain stability and ease of spreading. Nevertheless, it is low viscosity and high surface tension that assist levelling of the coating film after its deposition onto paper.

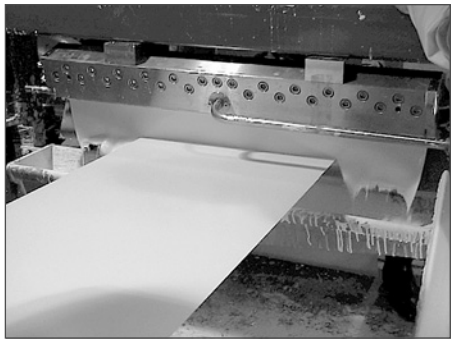
Although previous studies presented isolated formulation and operational aspects of curtain coating, there is no systematic presentation of the operational window and potential defects of high-speed curtain coating onto paper. At the pilot coater trials presented here, the focus was on (a) showing the operational window of the curtain coating process, its potential defects, and the operational conditions causing them, and (b) defining a potential value of the curtain coating process for LWC. Trials were executed on the pilot coater at the Metso Paper Technology Center in Järvenpää, Finland, using the single slot-fed die shown schematically in **Fig. 1**. Results were compared with the same LWC paper coated in a metered size press (MSP) pilot coater.

PILOT COATER SETUP AND TRIAL CONDITIONS

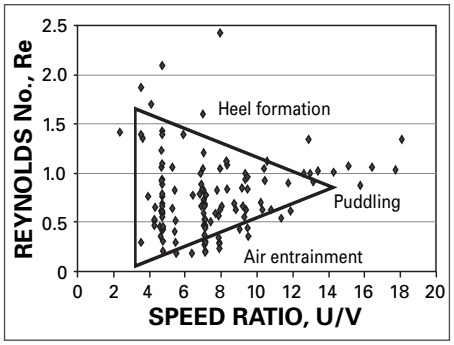
Multiple trials were run with the curtain pilot coater and compared to trials with MSP using the coating colors described in **Table I**. Attempts for curtain coating were also made with all-carbonate and all-kaolin coatings. For reference, **Table II** lists the 40-g/m² LWC base paper properties. During the MSP trial runs, the unit was operated at a speed of 1500 m/min, with coat weights in the range of 5-10 g/m². The two-sides-simultaneously coating unit was equipped with 35 P&J hardness polyurethane covered applicator rolls and smooth 20 mm metering rods. The loading pressure in the transfer nip was controlled to 20 kN/m pressure. For the curtain coater trials, the unit was operated at speeds between 400 m/min and 1500 m/min in an attempt to define the operational window of the process (i.e., the combination of flow rate and curtain/web speeds for the minimum coat weight and a stable operation without catastrophic coating defects). Coat weights of 5-24 g/m² were possible, controlled by coatability, as shown in **Fig. 2**.

The coating color supply through the slot-die was equipped with a deaerator to remove air and bubbles that can break up the curtain or create coated surface defects. The geometry of the curtain slot-die, illustrated in Fig. 1, had a slot width of 0.35 mm, while the curtain height was kept constant at 100 mm. As expected from previous work [7], the curtain height did not influence stability. In our experiments, the curtain height was originally varied between 35 mm and 180 mm, but no influence was observed on stability. The height was then kept constant at 100 mm, which is typical for vertically mounted slot-die curtain coaters. Air entrapment in the coating was assessed by visual inspection of the curtain and the coated paper. To avoid disturbances by the boundary air layer at the impingement zone, a mechanical doctor was positioned closer than 20 mm ahead of the curtain impingement onto the moving paper web.

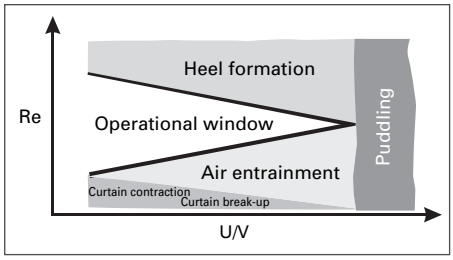
When trying to run a curtain coater at high speeds with high-solids coatings, air entrainment may occur at the heel of the curtain impingement onto the web and create defects. For stable



3. A stable curtain on the exit side at a web speed of 1400 m/min.



4. Operational window in trial series with the Reynolds number (Re) as a function of the speed ratio (U/V).



5. Principle of the operational window for curtain coating described with the Reynolds number (Re) as a function of the speed ratio (U/V).

and defect-free operation, the air boundary layer traveling with the incoming web needs to be broken or eliminated at the impingement zone. This problem has been well documented in stability analyses of pure liquids in curtain coating. It has also been observed previously when starch foam was applied on a 75 g/m² woodfree sheet with a size press [8]. In the latter application, a plate was attached on an air deflector pipe to achieve uniform coverage at speeds as fast as 1160 m/min for one-side coating. Under these conditions, the foam gave superior sheet coverage when compared to conventional sizing with a starch solution. In our case, a mechanical doctor plate removed the air boundary layer at speeds above 400 m/min. Additionally, air entrapment limited the effective solids content of the coating colors. Carbonate-based colors were restricted to maximum solids content between 50% and 60%, while all-kaolin colors run well between 40% and 50% solids. Macrovoid defects, created from air bubbles several millimeters in size, are easily managed through solids and formulation control, efficient deaeration, and the installation of a mechanical plate. Microvoids of a few 10ths of a millimeter are more difficult to remove and can induce fine coating layer defects. Further improving color deaeration can potentially allow raising the coating solids content.

Coat weight development with the curtain coating process depends on speed, as shown in the diagram of Fig. 2. Trials demonstrated that, for a constant die thickness, coat weight decreased with web speed (U), but also changed as a function of the slot-die flow rate (Q). The maximum coat weight limit was manifested by formation of a heel at the impingement zone and subsequent puddling at low speeds. At high speeds, air entrainment limits the maximum coat weight. As shown in the literature [7], the minimum flow rate for achieving a stable curtain determines the minimum coat weight with a certain coating color.

At high speeds, quite low coat weights could be achieved with curtain coating without processing defects, which is very different from other coating processes, such as MSP and blade coating. In MSP, solids content and rod loading limits determine the minimum coat weight. For defect-free blade coating, coat weight is limited by a maximum of coating solids and blade load. However, uniform coat weights lower than 8 g/m²/side are many times desirable for LWC grades. Pre-metering and precision of the curtain coater process provide the opportunity to uniformly apply low weights without having mechanical metering elements that make direct contact with the fast moving paper web. As we demonstrate next, curtain coating also gives an advantage in paper coverage quality at coat weights down to 5 g/m².

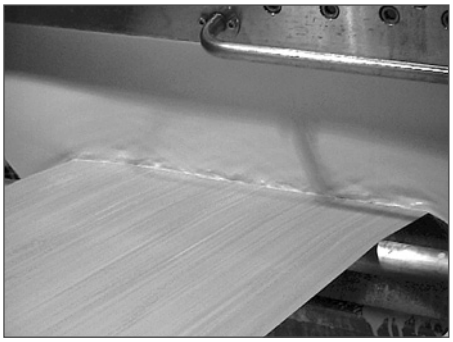
RESULTS AND DISCUSSION

Curtain stability

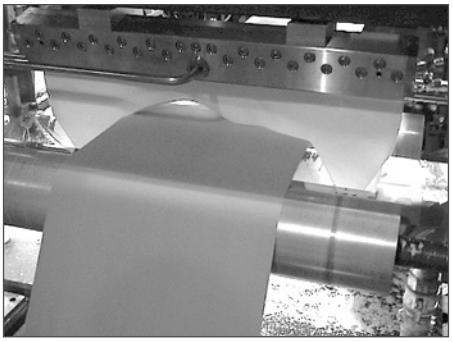
It is possible to form and retain a stable curtain film even at web speeds of 1500 m/min with high-solids pigmented coatings, while the air boundary layer is removed. **Figure 3** shows an example with a stable curtain at 1400 m/min. To succeed, it required balance of die pressure and slot opening to optimize the coating flow rate at a certain web speed, corresponding to a range of coat weights, while color formulation had been carefully selected for rheology and surface tension. As shown in Part 1, a combination of dimensionless numbers [speed ratio, Reynolds (Re), Weber (We), and Capillary (Ca)] determine the relative influence of governing parameters and the stability of curtain coating. A critical operational factor is coating viscosity at the prevailing shear rates. Viscosity influences both Re and We numbers and can be easily varied by orders of magnitude through changing coating solids or through the choice of coating thickener and its addition level. Although relatively high viscosity values reduce Re and stabilize the curtain, they also cause air entrainment at comparatively low speeds and make it more difficult to exclude the boundary layer.

Surface tension is another important variable that influences the Ca and We numbers. It nevertheless can only be changed within a narrow range, mainly through the choice or addition of formulation components with surface-active agents (i.e., surfactants, dispersants, and latex).

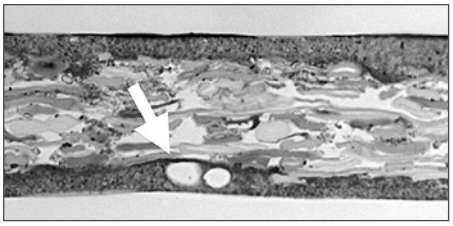
Determining the operational window is an important step toward optimum use of the curtain coating method. In its dimensionless form, the window established with our trials (**Fig. 4**) takes the well-known form presented schematically in **Fig. 5**. We verified that the operational window with pigmented paper coatings is similar to that of pure liquids. The key for a stable process lies in controlling flow parameters incorporated in Re and the speed ratio, U/V. This, in turn, allows stabilizing the curtain, precisely controlling the position of the dynamic contact angle at the impingement zone, and achieving the desirable coat weight. At very low Re and U/V, the curtain is pulled and starts to contract at the edges.



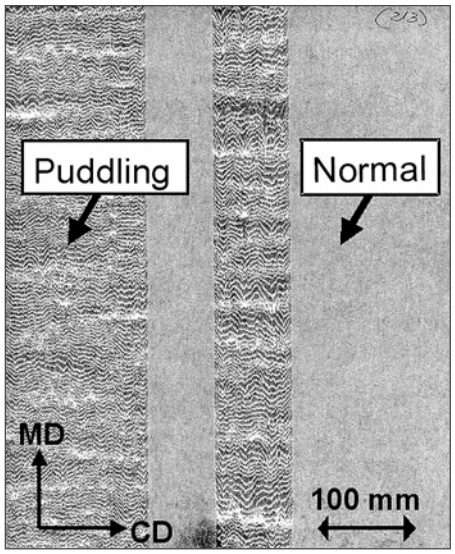
6. The curtain is disturbed by a heel formation at the impingement zone, which creates a ribbing pattern on the deposited coating layer.



7. The entering side of the curtain, where the curtain is disturbed (e.g. swinging) by the air boundary layer causing uncoated areas.



8. Air voids trapped in the coating layer, where the coating layer thickness is approximately 16 µm and the sheet thickness about 90 µm. Larger air voids act as pin-holes through the coating layer.



9. Puddling pattern created in the CD direction of the coated sheet as a combined result of heel formation and air-entrainment at a high-speed ratio (approximately at U/V more than 15).

The pulled film will finally break up at raised U/V. Low Re numbers allow air to be entrained at the impingement zone and the curtain breaks up. Very high Re numbers result in heel formation. The window gets narrower at high-speed ratios; hence the flow rate becomes more critical (Fig. 4). Beyond a certain speed ratio limit, heel formation and air entrainment cause puddling. When this occurs, CD-patterns appear on the coated surface. Examples of the different operational conditions and defects include the restrictive phenomena of heel formation, air-entrainment, puddling, and curtain contraction.



10. Contraction of a pulled curtain observed from the exiting side.

Heel formation

Curtain heel formation with paper coatings is favored at high flow rates and low coating speeds, as expected from theory and supported by finite-element models. The heel forms as a meniscus building up on the entering side of the curtain. When heel formation takes place, a ribbing pattern develops onto the deposited coating layer (**Fig. 6**).

Air entrainment

Air entrainment produces an unstable boundary layer at the curtain impingement zone and appears as air voids in the coating color. The boundary air layer is always present and needs to be removed to keep the curtain stable and uninterrupted (**Fig. 7**). Various physical means, such as deflectors or conventional doctoring, can be used to avoid air intrusion between the coating layer and paper. Removal of the boundary air layer closer than 50 mm to the impingement zone is always necessary at speeds over 400 m/min. The volumetric roughness of the base paper surface—in addition to hydrodynamic effects—influences the stability of the boundary air layer. A smooth surface (i.e., papers with Bendtsen smoothness less than 300 mL/min) reduced the risk for air intrusion. With effective air removal, it was possible to reach web speeds of 1500 m/min with a uniform coating.

Air bubbles in the coating color can also cause problems with curtain uniformity and coated paper quality. The bubbles generate air voids in the jet exiting the slot-die opening and may break the curtain film. Macrovoids, with a diameter larger than 0.3-0.4 mm, can be effectively removed with commercial deaerators. Microvoids, however, with a diameter less than 0.3-0.4 mm, are more critical (**Fig. 8**). These pass through the slot opening and cause pin-holes in the coating layer, deteriorating coated surface quality. Rheological properties of coatings are critical to avoid, or reduce, the presence of microvoids because they influence how easily air bubbles can be extracted from a coating color. Generally, it is difficult to remove air bubbles from coatings characterized by high yield stress or elasticity. With more effective deaerators, colors with comparatively high solids content could be used with a curtain coater.

Puddling

The puddling phenomenon is the combined effect of heel formation and air-entrainment at high speed ratios and relatively high Re numbers. Under these conditions, the heel becomes unstable and starts to entrain air, forming cross-directional patterns in the coated paper surface. In our study, a critical U/V above 15 created a puddling pattern. Regions with an unstable heel formed a patterned coating defect, while adjacent areas remained stable, as demonstrated in **Fig. 9**.

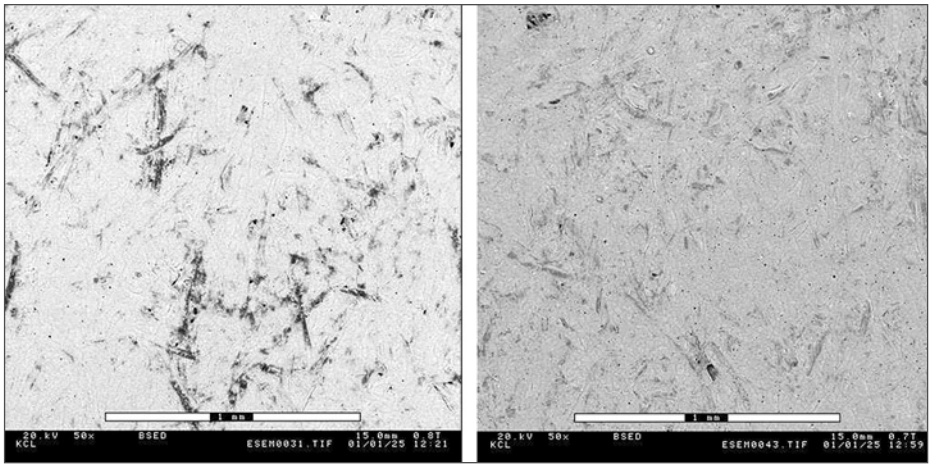
Curtain contraction

Contraction of the curtain film occurs when color flow rate is low or color elasticity is too high. If the flow rate is not raised, the curtain disintegrates. Coating color elasticity needs to be reduced at low web speeds and flow rates. This allows edge stability of the curtain to be maintained, without reducing the width at the impingement zone, compared to the die exit, as shown in **Fig. 10**.

Coating coverage

A previous study by Grön and Rautianen [9], compared differences in coating coverage between MSP and blade coating application techniques. The MSP coating process gives better coverage, compared to blade coating, because of its contour coverage of paper. In MSP, transfer of the coating onto paper takes place in a roll nip. In curtain coating, there is no mechanical element contacting the moving web—the coating is premetered and deposited with a curtain. Therefore, the strength of the base paper could be considerable lower than that required by any other coating method. Weak paper substrates are still processable in a curtain coater.

Curtain coating could also be used to achieve superior coverage, even with low coat weights, depending on the type of base paper or paperboard. **Figure 11** displays paper coverage differences between the MSP and the curtain coating methods in low magnification scanning electron microscope (SEM) micrographs. To demonstrate the difference, LWC base paper was coated in the pilot coater with coat weights between 5 g/m² and 10 g/m², using both coating methods. With the curtain technique, 85% coverage was achieved with a coat weight of 5.8 g/m², whereas the MSP technique required 8.5 g/m² to reach 87% coverage. This coverage advantage was achieved with the curtain method even though the coating solids content was 10 points low. At the same coat weight of 5-6 g/m², there was almost a 40% difference in coverage in favor of the curtain coating method (**Table III**). Coverage was determined with back scattering in an environmental scanning electron microscope. The settings were HiVAc mode, 15 mm working distance, 20 KeV, and 50x magnification. Image analysis was performed on the micrographs to determine the extent of surface coverage. Again, superior coverage, even at low solids content, demonstrated the advantage of curtain coating.



11. Coverage of papers coated with the metered size press unit (left) and the curtain unit (right). With the metered size press unit, the paper was coated to 8.5 g/m² at a solids content of 64%, which gave 87% coverage. The curtain unit produced 85% coverage already at a coat weight of 5.8 g/m² and a solids content of 54%.

Technology	Speed	Coat weight	Solids content	Coverage
Curtain	1200 m/min	5.8 g/m²	54%	85%
MSP		5.0 g/m²	63%	60%
		7.1 g/m²	64%	75%
		8.5 g/m²	64%	87%

III. Examples of achieved coating coverage in this study with the curtain and the MSP techniques.

CONCLUSIONS

Compared to traditional coating methods, such as MSP or blade coating, curtain coating gives superior coating coverage in LWC. Reaching high speeds during coating application is possible. Stability requirements for forming and maintaining a uniform curtain and defect-free coating include control of the boundary air layer and air bubbles in the color. In the trials presented, it was possible to reach web speeds of 1500 m/min, with removal of the boundary air layer before the impingement zone. To avoid problems with air bubbles in the color (i.e., air bubbles with diameters below 0.3-0.4 mm), the solids content was kept below 55%. Even at these comparatively low solids, paper coating coverage was good. With curtain coating, 85% coverage was achieved with a coat weight of 5.8 g/m², while the MSP technique required 8.5 g/m² to reach 87% coverage. At the same coat weight of 5-6 g/m², there was almost a 40% difference in coverage in favor of the curtain coating method. Because there is no pressure penetration in a curtain coater, low-solids coatings give a bulky coating structure and better coverage. In spite of the encouraging results, the curtain coating technology is new for high-speed paper coating. Further process and formulation studies are required before implementing it in practice. In particular, research needs to shed light on the conditions for maintaining high solids content, while applying thin curtains at high machine speeds and effectively deaerating the coating to keep a smooth and uniform coating layer. **TJ**

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INSIGHTS FROM THE AUTHORS

Looking with vision toward new paper coating processes to improve productivity and product quality, we studied the possibility of using curtain coating—a process used for coating specialty papers—in mass-produced publication grades, seeking to define a new value proposition. Extensive work has been done in curtain coating specialty grades of paper and paperboard, but little has been published on the potential value of such a process in mass-produced paper grades and the operational challenges of making that application work.

One of the biggest challenges we faced during the pilot coater testing turned out to be fine air bubble removal from high-solids coating colors. Our efforts to meet this challenge actually led to the development of a whole new degassing device.

A particularly rewarding finding was that the capability to obtain best-in-class coverage as curtain coating raises the possibility of applying low coat weight (5.8 g/m²) in LWC with high coverage (85 %), even at low coating solids (54 %); or, at a constant coat weight of 5-6 g/m², there is almost a 40 % advantage in coating coverage using the curtain coater instead of a metered size press.

This work can be beneficial to paper companies in two main ways: first, by defining a compelling value proposition to use curtain coating in LWC; second, by implementing startup and operation of the new curtain coating process.

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