BASESTOCK COATABILITY

Effect of basestock surface structure and chemistry on coating holdout and coated paper properties

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ABSTRACT

Water absorption by the basestock during coating affects coating pickup and coating mass distribution and, thus, the properties of the coated paper. This work presents results of experiments that were designed to separate the effects of two important factors that determine sheet absorbency: hydrophobic sizing and porosity. Bleached kraft handsheets with a broad range of pore size, void fraction, and roughness were sized to different levels with a solution of alkyl ketene dimer (AKD) in non-swelling hexane. A lightweight coated (LWC) basestock was treated similarly. Coating was performed at 762 m/min on a cylindrical laboratory coater. The effect of hydrophobic sizing on coating pickup depended greatly on sheet porosity and roughness. On dense–smooth sheets, sizing resulted in lower coating pickup. On rough sheets, including LWC basestock, the effect of sizing on pickup was concealed by the overwhelming effect of roughness on the metering action. Coating uniformity and holdout were very good on the dense–smooth sheets (although sizing gave a slight reduction) and poor on the porous rough sheets and LWC basestock (sizing had little effect). The results suggest that coating holdout and uniformity are determined mainly by sheet surface structure (porosity and roughness) and not by sizing.

Application:

A study to separate the effects of sizing and sheet porosity on coating uniformity and holdout. The results suggest that sheet porosity and surface roughness have a greater effect than sizing.

IN THE PAPER COATING PROCESS, A water-based pigmented coating is applied to the base paper to enhance the optical and topographical properties of the printing surface. It is generally believed that basestock absorbency and its spatial variation across the sheet are very important, since these might affect the coat weight pickup and its spatial distribution, as well as the structure and uniformity of the coating layer. Coat weight variation is an important problem because recent research shows that it is related to print nonuniformity *(1–4)*.

During coating, some of the water contained in the coating (35–50% of the wet coating volume) is absorbed by the hydrophilic cellulosic fibers, changing the base paper structure and properties (roughness, compressibility, etc.). It is also possible that the coating pigment penetrates the sheet, which would defeat the goal of surface treatment. However, there is not much experimental data available in the literature about these effects.

This paper discusses the meaning of absorbency and its implications in the context of paper coating.The work also attempts to clarify the influence of substrate absorbency on coating pickup, coat weight distribution, and coated paper properties.

BACKGROUND

Coating absorption into the interfiber pore system

The coating slurry can be absorbed as a continuum into the bulk of the sheet. The ill-defined term "holdout" is often used to indicate the base paper's resistance to coating penetration. This type of penetration presupposes that the base sheet pores are large enough to allow the coating suspension, including pigment, to flow inside the sheet beyond the surface pores. The driving force is the pressure at the applicator roll or under the blade. Coating penetration is a function of application or, more exactly, the difference between the application solids and the "immobilization" solids *(5)*, since this difference determines the amount of water that must be removed before all motion stops.

It is also possible that only the aqueous phase (water, soluble binder and additives, and perhaps very small particles) is absorbed, leaving a pigment cake on the surface *(6)*. The driving force for dewatering can be external pressure (applicator roll or blade), capillary pressure developing in interfiber capillaries, vapor diffusion in these capillaries, or intrafiber osmotic effects, which cause molecular diffusion of water into the fiber wall.

Previous investigators examined the mechanisms for water absorption by paper and concluded that penetration under capillary pressure (interfiber penetration) and molecular diffusion (intrafiber penetration) are the two predominant processes *(7–9)*.

Penetration into the interfiber capillaries is often described using the Lucas–Washburn (L-W) approach *(10)*. In the L–W analysis, contact angle, pore radius, and sheet void fraction are controlling parameters. If the sheet void fraction is large, if interfiber pores are large, or if contact angle is low, the solids from the coating suspension might penetrate into the sheet internal pore system.

Samples	Pore size, μm	Void fraction	Pulp freeness, mL CSF	Wet-pressing pressure, kPa	PPS roughness (S10), μm	Air permeability (Gurley), s	Sizing (AKD) level, g/L	WATER DROP TIME, s		CONTACT ANGLES, °	
								Unsized	Sized	Unsized	Sized
Porous handsheets	6.2	0.52	600	345	4.9	6	0.025	8.6	infinity	21	38
							0.25	8.6	infinity	21	119
							2.5	8.6	infinity	21	159
Dense handsheets											
Smooth	2.1	0.29	300	2778	3.1	440	0.025	220	infinity	11	76
							0.25	220	infinity	11	118
							2.5	220	infinity	11	155
Rough[a]	2.1	0.29	300	2778	6.5	510	2.5	220	infinity	11	155
LWC basestock	4.5	0.52	N.A.	N.A.	5.1	58	2.5	>10 min[b]	infinity	69	137
							heated[c]	>10 min	infinity	69	128

[a] Handsheets prepared by wet pressing against 1000-grit sandpaper
[b] The water drop spreads very slowly
[c] Self sized by heating for 2 hours at 100°C

I. Base-sheet properties

The coating would "sink" into the sheet, giving poor coating holdout and thus poor coated paper properties.

The notion that coatings penetrate into the base sheet internal pores is widely held, although there is no evidence to support this, even for a very bulky sheet *(11–13)*. Poor coating holdout is usually inferred from the properties of the coated paper and not directly measured by, for example, microscopic observation of cross sections *(14)*.

Molecular diffusion of water into the fiber cell wall

Cellulose and especially hemicelluloses are water-sorbing polymers, and water molecules diffuse into the cell wall when a concentration gradient is established. Diffusion of water into cellulose, contrary to conventional thinking, can be very fast. A 10 μm film of water can be absorbed by cellophane in less than one second *(9)*.

As water diffuses from the coating layer, the solids concentration increases and forms a pigment cake without the need for any filtration process. The diffusion of water into cellulosic materials increases sharply with increasing water content *(15)* and is slowed down by barriers such as a film of starch. Hydrophobic sizing experiments should therefore avoid the formation of a barrier. For this reason, hydrophobic sizing in this work was done with a dilute solution.

EXPERIMENTAL TECHNIQUES

It follows from the previous discussion on capillary absorption that base sheet absorbency has two components: hydrophobicity on the one hand and pore size and total pore volume on the other hand. A change in basestock absorbency is often accompanied by other changes in basestock properties. This work attempts to clearly demonstrate the separate effects of hydrophobic sizing and sheet density on coating pickup, coated paper gloss, roughness, and coat weight distribution.

Basestocks

Table I lists the properties of the base sheets used in this work. Handsheets were prepared from a 50/50 blend of bleached hardwood and softwood pulp according to TAPPI T 205, except that different refining levels and wet-pressing pressure were used.

Open–porous sheets were produced from unbeaten pulp and wet pressed under 345 kPa (50 psi). They had a porosity similar to that of a basestock of lightweight coated (LWC) paper.

Dense–smooth sheets were made from pulp beaten with a PFI mill and wet-pressed using the same sequence as described in TAPPI T 205, except that wet-pressing pressure was 2778 kPa (400 psi). Refining and wet pressing have the side effect of decreasing handsheet roughness as well as sheet porosity.

To separate the effect of absorbency from that of roughness, a set of dense-but-rough sheets was made by wet pressing the wire side of the handsheet against sandpaper (grit number 1000) instead of the metal plate at high pressure. The wire side of the handsheets was coated in all cases.

One sample of commercial LWC basestock was also used. Sheet properties are given in Table I. The air-permeability test, which measures rate of air flow through the paper, is an indirect measure of the pore size of paper in this particular context. Actual pore size was determined by mercury porosimetry.

Components Parts	Type and manufacturer	
No. 1 clay	Lustra, Engelhard	80
$CaCO_3$	Hydrocarb 60, OMYA	20
Poly(styrene/butadiene) latex	Dow 620, Dow	10
Water-retention aid	Alcogum L-35, Alco	0.2
Polyacrylate dispersant	Dispex N40, Allied Colloids	0.03

II. Coating formulation (application solids = 60%)

Property	Method
Contact angle	Sigma 70 tensiometer; water drop
Pore size	Hg porosimeter, air permeability
75° gloss	Hunter gloss meter
Roughness	Parker print–surf (S10)
Average coat weight	O_2 ash tester
Coat weight distribution	Image analysis of burnouts, ESEM on cross sections

III. Paper properties and the characterization test methods

Sizing

A clear assessment of the effect of hydrophobic sizing is difficult with conventional wet end sizing methods, since the sizing process can affect the sheet structure. The approach used here was to size with a hexane solution of alkyl ketene dimer (AKD). Hexane does not swell cellulosic fibers, so it is assumed that the paper structure remained unaffected.

The handsheets were cut into 11 cm × 11 cm squares, then cut in half. One half was dipped into a 2.5 g/L hexane solution of AKD (Aquapel 364, Hercules), followed by air drying and curing in the oven over a water tray at 100°C *(16)*. The other half of the same handsheet went through the same treatment but without sizing. Different AKD concentrations were used to produce different levels of AKD coverage and, thus, different water contact angles (Table I). Sheets of commercial LWC basestock were sized with AKD solution or self-sized by heating in the oven at 100°C for 2 hours.

Coating

The size of the pores relative to that of the pigment particles presumably plays a role in determining whole-coating penetration. To maximize the possibility of penetration, the pigment system used was a blend of fine clay and ground $CaCO_3$, with average equivalent spherical diameter of 0.5 µm, much smaller than the 6.2 µm pore size of the coarsest sheet (Table I). A latex binder was used for the same reason. The level of application solids was held constant at 60% throughout the study.

Basestock		CONTACT ANGLE, ° Unsized	Self sized	AKD sized	COAT WEIGHT*, g/m² Unsized	Self sized	AKD sized
Smooth	Dense	11	…	155	5.1	…	4.1
					6.0	…	5.1
					6.4	…	5.7
					7.6	…	6.9
					8.0	…	7.1
		11	…	118	7.7	…	7.0
		11	…	76	7.7	…	6.3
Rough	Dense	11	…	155	6.7	…	7.0
					7.1	…	6.6
					8.7	…	7.3
					9.1	…	8.5
	Porous	21	…	159	6.7	…	6.6
					8.3	…	8.1
					9.1	…	8.7
		21	…	119	7.7	…	7.0
					8.6	…	8.7
					9.0	…	8.7
		21	…	38	7.6	…	7.4
					8.7	…	8.3
					11.1	…	10.6
LWC		69	128	137	8.1	8.2	8.4
					8.5	8.1	8.5
					9.2	9.4	9.1
					11.1	11.4	10.8

*:Standard deviation of coat weight = 2%

IV. Effect of sizing on coating pickup

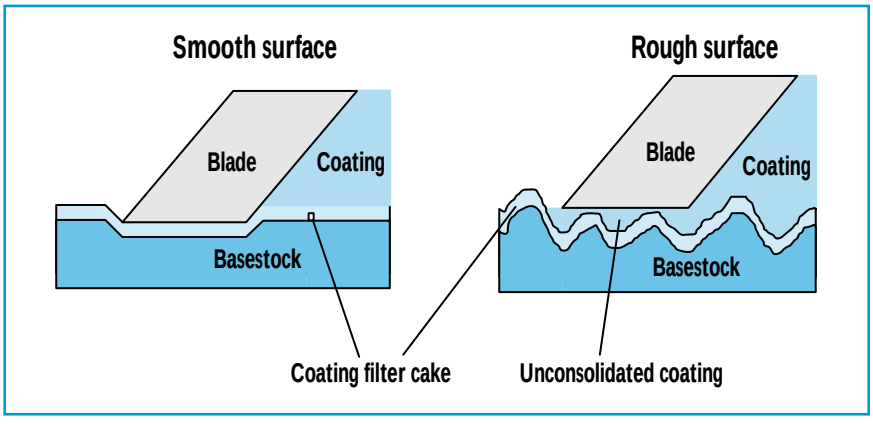
The first critical concentration, or immobilization point—determined using a method described by Stanislawska *(17)*—was 80% by weight. **Table II** shows the coating formulation. The Brookfield viscosity of the coating was 1000 ± 50 cP at 20 rpm.

Coating was performed at 762 m/min on a short-dwell-type beveled-blade pilot coater—a cylindrical laboratory coater (CLC). The

Basestock	Diffusion rate,* $1/s^{0.5}$
Porous	
Unsized	0.32
Sized	0.30
Dense	
Unsized	0.26
Sized	0.26

*The slope of water pickup vs. square root time

V. Diffusion rate of different basestocks



1. Base-sheet roughness hinders removal of unconsolidated coating.

sized and unsized halves of the same handsheet (or patches of LWC basestock) were taped side by side on LWC basestock backing paper and coated simultaneously. Coat weight was varied by changing the blade loading. Coated sheets were dried by IR lamps.

Characterization

All measurements were made on uncalendered sheets, since it was assumed that calendering would diminish the differences in surface properties. **Table III** summarizes the characterization techniques that were used to measure paper properties.

The contact angle of base paper was measured with a Sigma 70 tensiometer. The "advancing contact angle" was recorded. A higher contact angle indicates higher hydrophobicity or lower absorbency. The time required for a drop of water (0.03 mL) to disappear on the paper was also used as an indication of sheet absorbency.

Average coat weight was measured with an oxygen ash tester. The 75° angle coated gloss was measured with a Hunter glossmeter. Roughness was measured with the Parker print–surf roughness tester at a clamp pressure of 1 MPa (S10) with soft rubber backing.

One gloss–roughness measurement was done on each coated handsheet or LWC patch. Three to four coated sheets were available for each condition/coat weight, and averages were calculated. The coefficient of variation for the roughness measurements was approximately 0.03 for LWC and porous sheets and 0.07 for dense sheets.

Coat weight distribution was measured with an image analyzer on the burnouts of coated samples. Burnouts were prepared with NH_4Cl *(18)*. On a burnout, white coating stands out from the black base sheet background. For the coat weight range used in this work (5–12 g/m^2), it was assumed that gray level was proportional to coat weight, as described in previous work *(3)*. Though not strictly rigorous, the variance of gray level was used as a measure of the coating weight distribution.

Ten gray-level profiles from the digital image of the burnout were filtered using one dimensional FFT (fast Fourier transforms). From a reading distance for a given contrast, the human eye is most sensitive to the wavelength range of 1–10 mm *(12)*. This was the range selected for the calculation of the overall coating uniformity. The range 0.5–1 mm was also considered to examine the small wavelength variations. The variances of gray level of each of the ten filtered profiles were calculated for ten profiles, and the average was used to indicate the coating unevenness *(19)*. The higher the variance, the worse is the coat weight uniformity. Standard deviation of the variance was approximately 15%. The distribution of coating on coated paper cross sections was also observed with an environmental electronic scanning microscope (EESM).

RESULTS AND DISCUSSION

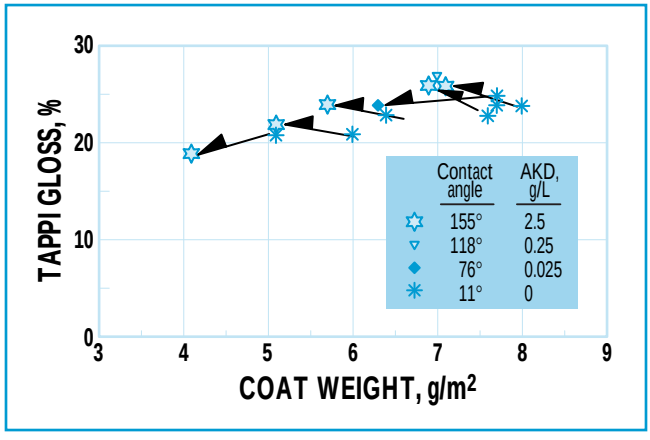
The following results show the effect of sizing and sheet porosity on coating pickup, gloss, and roughness.

Coating pickup

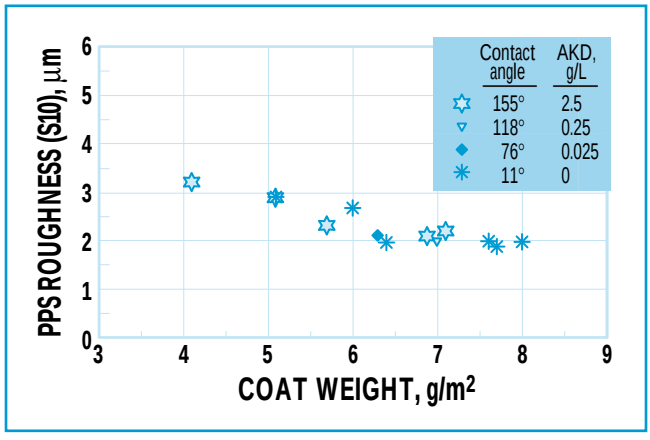
The sized half sheet almost always picked up less coating, as seen in **Table IV**. The difference in coating pickup for the dense–smooth sheets was about 1 g/m^2, independent of coat weight. This effect was less obvious with the rough handsheets (whether dense or porous) and the LWC basestock.

The results appear to concur with expectations. The higher absorbency of the unsized sheets would lead to faster dewatering and produce a thicker filter cake of coating. Since the blade meters mostly nonimmobilized coating *(20)*, the consequence would be a higher coating pickup on the unsized sheets. However, it is difficult, on the basis of the L–W equation, to explain the smaller effect of sizing observed on the porous sheets and on the LWC basestock than on the dense sheets. Calculations showed that the difference in penetration of the aqueous phase because of sizing would be much larger with the porous sheets than with the dense sheets. This should have made the difference in coating pickup between unsized and sized sheets larger for the porous sheets than for the dense sheets, opposite to what occurred (Table IV).

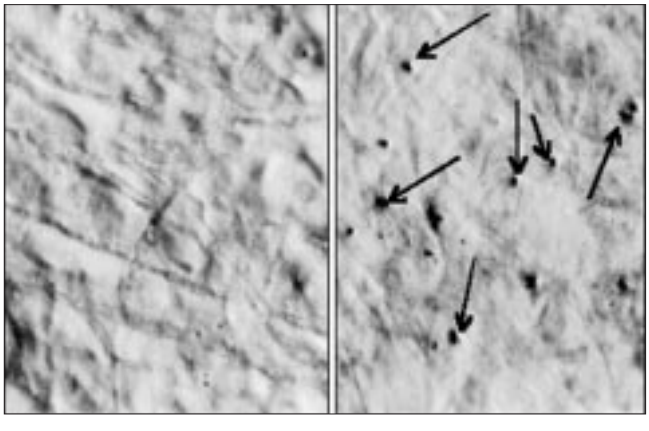
One possible explanation is that molecular diffusion, not capillary penetration, of water into the fibers is the predominant mechanism in the case of the dense sheets, and perhaps sizing slowed down diffusion. Diffusion rate was measured with an



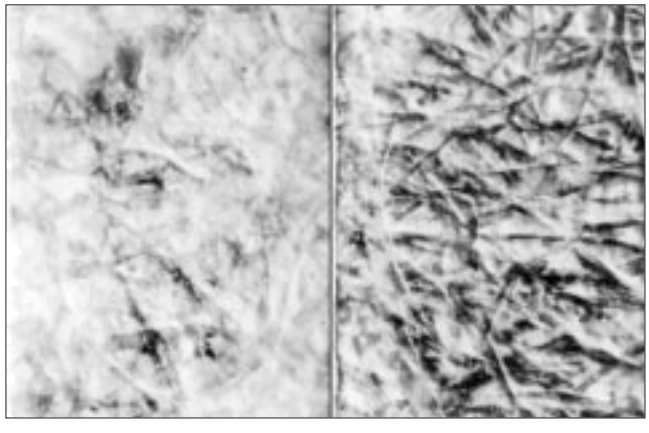
2. Gloss vs. coat weight at different sizing levels for dense–smooth handsheets (air permeability = 440 Gurley s). The arrows connect the gloss values of the unsized and sized halves of the same sheet.



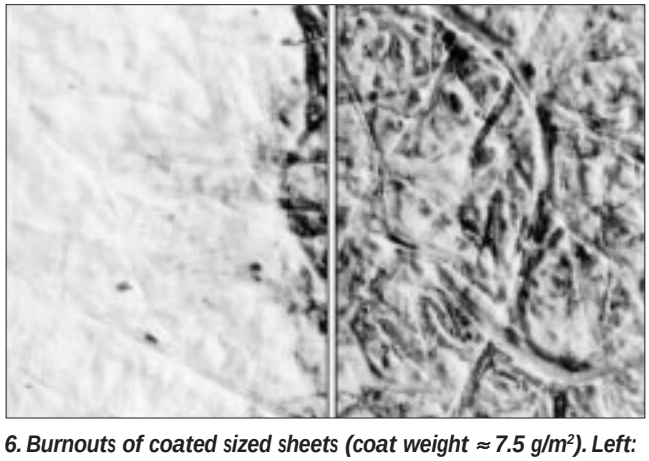
3. Coated roughness vs. coat weight at different sizing levels for dense–smooth sheets (air permeability = 440 Gurley s)



4. Burnouts of coated dense sheets (coat weight ≈ 8.2 g/m²). The arrows on the right point to the pinholes. Left: Unsized, Right: Sized



5. Burnouts of coated unsized sheets (coat weight ≈ 8.0 g/m²). Left: Dense, Right: Porous



6. Burnouts of coated sized sheets (coat weight ≈ 7.5 g/m²). Left: Dense, Right: Porous

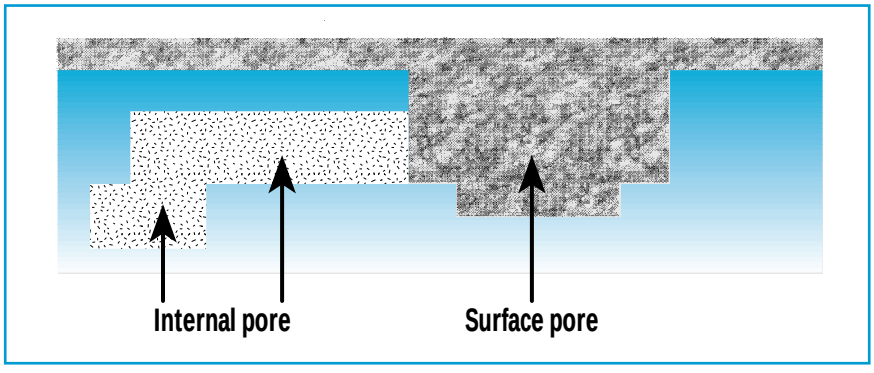
experimental sorption device *(21)*. However, the results in **Table V** show that sizing—in the way it was performed for these tests—did not affect diffusion rate.

Therefore, we propose that, with smooth paper, capillary absorption, leading to filter cake buildup from either external pressure or under capillary pressure, controls coat weight. The blade removes the layer of unconsolidated coating. The data show that the very short contact time before doctoring (16 ms) was still enough to build up a 1 g/m² filter cake. With rough papers, whether dense or porous, removal of the unconsolidated coating is hindered by the remaining basestock roughness under the blade, and the effect of capillary absorption is thus masked, as seen in **Fig. 1**.

Note, however, that the experimental results were obtained with a short-dwell-type coater, i.e., a CLC. Other coating application methods, such as a roll applicator, could give somewhat different results.

Coated gloss and roughness

Gloss generally increased slightly with increasing coat weight, as



7. Depiction of internal pore and surface pore

expected. **Figure 2** shows that the gloss of the sized, dense sheets was generally slightly higher than the unsized half at the same coat weight. It is speculated that a slower water absorption in the sized sheets would give more time for orientation of the clay plates before the immobilization point, thus giving a slightly higher gloss *(22)*. In the case of the porous handsheets and LWC basestock, sizing had almost *no* effect on gloss. We suspect that roughness partially masked it. A recent report, however, confirms that sizing did raise the gloss of wood-containing papers slightly *(23)*.

With regard to coated paper roughness, a similar trend was observed. Coated roughness decreased slightly with increasing coat weight, as expected. But comparison between the two halves of the same sheets showed *no* effect of sizing on coated roughness, irrespective of base sheet porosity, sizing level, or roughness. **Figure 3** shows the results for dense–smooth sheets.

Effect of sizing and sheet porosity on coating mass distribution, coating holdout, and penetration

KEYWORDS
Absorption, absorptivity, bibliographies, coated papers, coatings, holdout, paper grades, paper stock, physical properties, pore size distribution, sorption, water absorption, water sorption.

Coat mass distribution and coating holdout. **Table VI** shows the variances of gray levels over wavelength ranges of 0.5–1 mm (graininess) and 1–10 mm (cloudiness). High variance means poor coat mass uniformity. The chosen samples all had similar coat weight (7–8 g/m^2).

The reflectance of the burnouts was used to evaluate coating holdout. The assumption is that, if the coating remains at the surface of the sheet, its contribution to sheet brightness is enhanced. Therefore, our definition of holdout is the degree to which the coating contributes to surface brightness. As shown later, this definition is used also to distinguish between "surface" pores and "internal" pores.

The dense unsized sheets had better coat mass distribution than the sized sheets, regardless of roughness. This is believed to be due to poor spreading of the coating on the sized sheets, where coating has a tendency to bead up or to form pinholes, as seen in **Fig. 4**. The effect of sizing became less obvious with the porous sheets, both handsheets and LWC basestock, as seen in Table VI.

The dense sheets had better coating uniformity and higher reflectance than the porous sheets, also shown in Table VI. Again, a higher reflectance is interpreted here as an indication that the coating is located at the surface of the basestock, providing better coating holdout. The micrographs of porous and dense sheets in **Fig. 5** (unsized sheets) and **Fig. 6** (sized sheets) confirm the reflectance data in Table VI. The differences in coating uniformity and reflectance caused by sizing are not nearly as large as that caused by densification. Therefore, densification, rather than sizing, improved coating holdout and coating uniformity. Note that coating holdout and coating uniformity are not independent of each other. Better holdout (higher reflectance) gives better coating uniformity (less gray level variance).

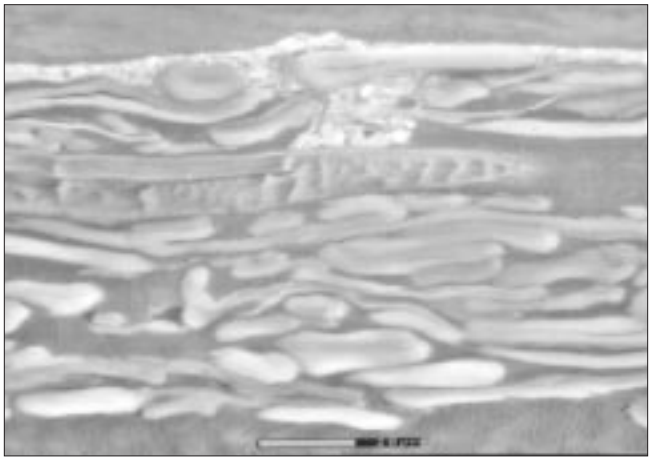
Bulk penetration vs. surface penetration of coating. At similar coat weight, the burnouts of the dense sheets had a much brighter appearance (better coating holdout) than the porous handsheets and LWC. Under the microscope, the burnouts of the dense sheets showed fewer uncovered fibers, in agreement with the higher reflectance. On the porous sheets, much of the coating seemed to have disappeared into the sheets.

There are two possible destinations for the "disappeared" coatings:

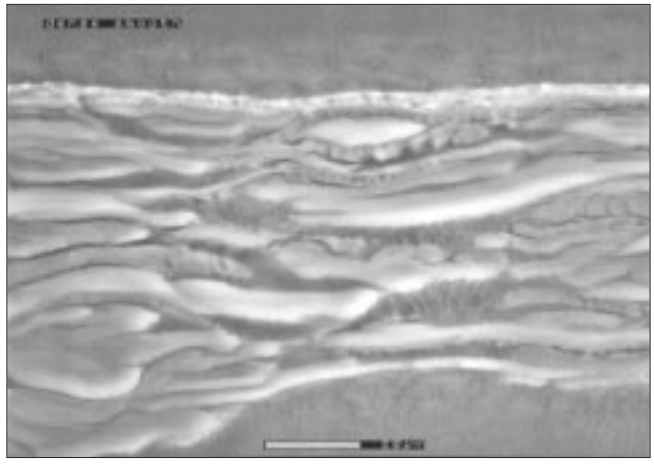
1. Into the surface pores—the porous sheets have higher surface roughness
2. Beyond the surface pores into the bulk or internal pores.

When coating penetrates beneath some of the top fibers, it contributes less to the brightness of the coated paper, causing lower coated paper reflectance. We define the pores with at least one layer of fiber on top of them as "internal pores." **Figure 7** is a graphic depiction of internal and surface pores.

Figures 8 and 9 are cross sections of porous and dense coated sheets, respectively, with similar coat weights (7–8 g/m^2). On the dense sheets, the coating stays at the surface all along the cross section. On the porous sheets, however, coating



8. Micrograph of cross section of porous sheet (×825)



9. Micrograph of cross section of dense sheet (×825)

distribution is more uneven. Although there are parts of the cross section where coating stays on the surface, there are also areas where coating penetrates into the bulk of the sheets (Fig. 7). The penetration of coating was normally not deeper than 15–20 μm (two fibers' thickness).

This observation appears to contradict the results of earlier work on LWC, where it was concluded that there was no bulk penetration even for porous sheets *(13)*. However, close reexamination of their micrographs does reveal shallow (within one or two fiber layers) penetration of the coating. The conclusions of the referenced work were based on the unexpected absence of extensive inroads by the coating into these very bulky base sheets.

Basestock			Coat weight, g/m²	VARIANCES OF GRAY LEVEL 0.5–1 mm (graininess)	1–10 mm (cloudiness)	Reflectance,* %
Smooth	Dense	Unsized	8.3	10.1	31.5	44.2
		Sized	8.1	17.3	48.7	39.4
Rough	Porous	Unsized	7.6	26.3	56.2	27.5
		Sized	6.9	26.9	62.3	25.6
Rough	LWC	Unsized	8.1	25.7	59.6	29.6
	LWC	Self-sized	8.2	22.0	48.1	33.0
	LWC	AKD sized	8.4	23.4	56.0	32.8

*Measured with Brightmeter from Technidyne Co.

VI. Effect of absorbency and roughness on coating uniformity and holdout—burnouts of coated samples

CONCLUSIONS

The effect of base sheet absorbency on coating pickup, mass distribution, and sheet properties was investigated. Results show that two important contributors to base sheet absorbency—hydrophobic sizing and sheet density/porosity—had very different effects.

On dense–smooth papers, hydrophobic sizing led to lower coating pickup. This was attributed to a reduced filter cake buildup under the capillary pressure from the base-sheet pores prior to metering by the blade. On rough papers, the lack of influence of sizing was explained by the overwhelming effect of roughness on the metering action.

Overall, hydrophobic sizing improved coated gloss slightly, particularly on dense base sheets, but it had no effect on coated roughness, regardless of base sheet density.

Coating holdout and coating mass distribution—as judged from image analysis, reflectance of the burnouts, and by microscopic examination—were significantly poorer on all porous sheets. This is attributed to the surface topography causing a variation in coat weight and some penetration of the coating underneath the surface fibers, where it is shielded from the light.

It is concluded that—for a blade coating process—sizing does not determine coating holdout and uniformity. Rather, base sheet surface structure, namely its density and roughness, governs coating holdout and uniformity. TJ

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