Submillimeter gloss variations in coated paper

Part 2: Studying "orange peel" gloss effects in a lightweight coated paper

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ABSTRACT *The methods presented in Part 1 were used in an exploratory study of "orange peel," a pattern of submillimeter gloss variations. In viewing the* <u>*un*</u>*calendered lightweight coated paper sample with transmitted light, we noticed a small-scale grainy pattern which we attributed to the coating mass distribution. This grainy pattern did not correspond well with the basesheet look-through formation. Instead, when we added the two gloss images together and compared this sum to the grainy pattern, we found quite good agreement. In comparing the gloss patterns of the two sides, we found better agreement than we had anticipated. Still, there were enough high-gloss areas lying over places of low apparent coating weight and enough apparently heavy areas where the gloss was low, that we feel the relationship between the coating mass distribution and the gloss distribution is not a simple one. Instead, we wonder whether there is a more fundamental relationship between the surface coverage distribution and the gloss distribution.*

KEYWORDS
Coatings
Formation
Gloss
Image analysis
Optical properties

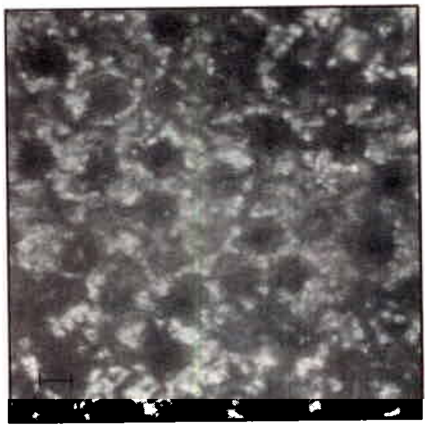
In Part 1, we discussed the equipment and techniques for obtaining highly detailed gloss images of coated paper (*1*). These digitized images provide the basis for various approaches to characterizing submillimeter gloss variations. We introduced the registered image stack concept and the feature correlation technique as a way of facilitating the direct measurement and spatial correlation of numerous small features in paper. The techniques can be used to indicate how well the submillimeter features of different images match each other, and even features such as individual paper fibers can be followed through several stages of manufacturing.

Here, in Part 2, we will look at a problem of interest to manufacturers of lightweight coated and other coated grades. This problem is the appearance of small-scale gloss patterns, often called "orange peel" because it resembles the skin of an orange.

The problem

The high-gloss areas in a paper with orange peel are numerous and are strong enough to give satisfactory

A gloss image of an orange skin.



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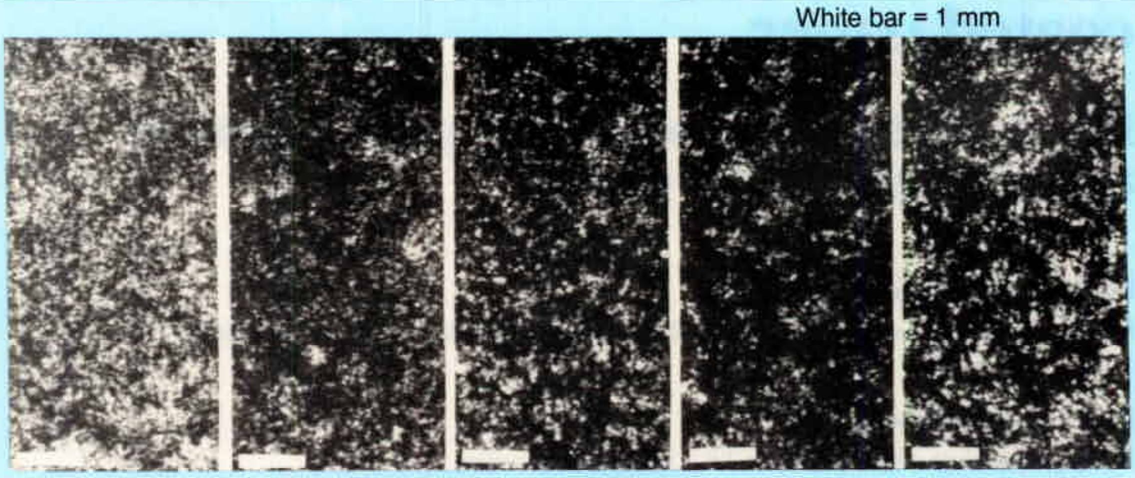
1. Gloss images from one manufacturer's ranking system for orange peel



Ranking	No. 1	No. 2	No. 3	No. 4	No. 5
Mean gray level	158	123	115	101	127
75° Gloss	78	64	56	56	68

average gloss. For this reason, paper with orange peel can often meet gloss specifications though there are still problems with print quality. Orange peel appears to varying degrees. Although it seems more prevalent for lightweight coated paper coated with a short dwell coater, the fundamental causes have not been elucidated.

One paper manufacturer has devised a ranking standard to visually rate the degree of orange peel in his production. **Figure 1** shows the printed gloss images of these ranking standards obtained with our gloss imaging equipment.

To understand the orange peel effect better, we examined samples of commercial supercalendered paper having prominent orange peel. We noticed that this same paper in its uncalendered state exhibited tiny dark spots when viewed in transmitted light, giving it a "grainy" appearance. Besides wondering exactly what caused this grainy appearance, we wished to discover whether it had any direct connection with the orange peel gloss patterns observed in the supercalendered paper.

Results of imaging and feature comparisons

For the lightweight coated paper used, the image measurements are based on techniques presented in Part 1, as well as visual comparisons between images from various registered image stacks. These image stacks allow us to compare a single feature at a time among the various images.

On the basis of the Kubelka-Munk theory, we consider that the optical density distribution of the small dark spots seen with light transmitted through the uncalendered sheet coated on both sides (**Fig. 2**, Frame D) indicates the distribution pattern of the combined coating mass. At submillimeter dimensions, the basesheet contributes little to the optical density variations seen in the transmitted-light image. This hypothesis may be verified later using the image correlation techniques presented in Part 1, combined with new sensing techniques still under development.

Transmitted light, soft X-ray, and beta-ray images

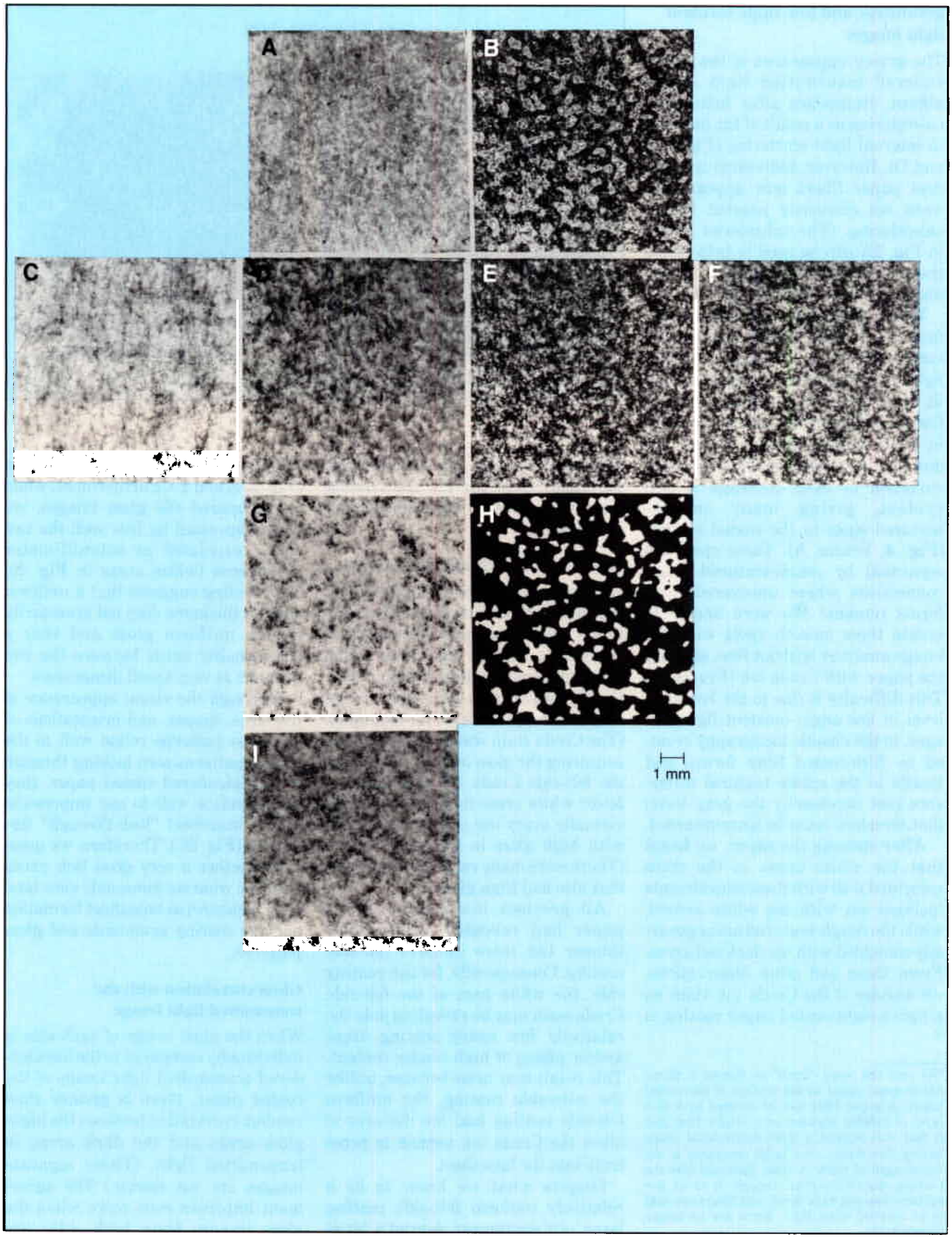
These images (Fig. 2, Frames D, G, and I) result from the combined effect of two coatings and some contribution from the basesheet. All images generally agree with one another except for differences in character.

There are some places where there is definite disagreement, perhaps as a result of differences in scattering and absorption between the three methods. An example is the dark area (indicating heavy coating) at the upper right in the soft X-ray radiograph, which shows faintly dark in the beta-ray radiograph and almost not at all in transmitted light.

The soft X-ray radiograph reveals distinct spots in the calendered paper that are difficult to detect in the beta-ray radiograph image and are not even present in the calendered or uncalendered transmitted light image. These can be seen as the tiny 75 to 100 μm-diameter black spots in Fig. 2G. Because of its higher resolution and greater sensitivity to coating pigment, we wonder if the soft X-ray radiograph is better able to detect small places where the coating pigment has penetrated deeply into the basesheet—perhaps even thin coating "bleed-through" points. Microscopy of cross sections taken from the reference area might confirm that the tiny dark spots are indeed places of high coating pigment penetration.

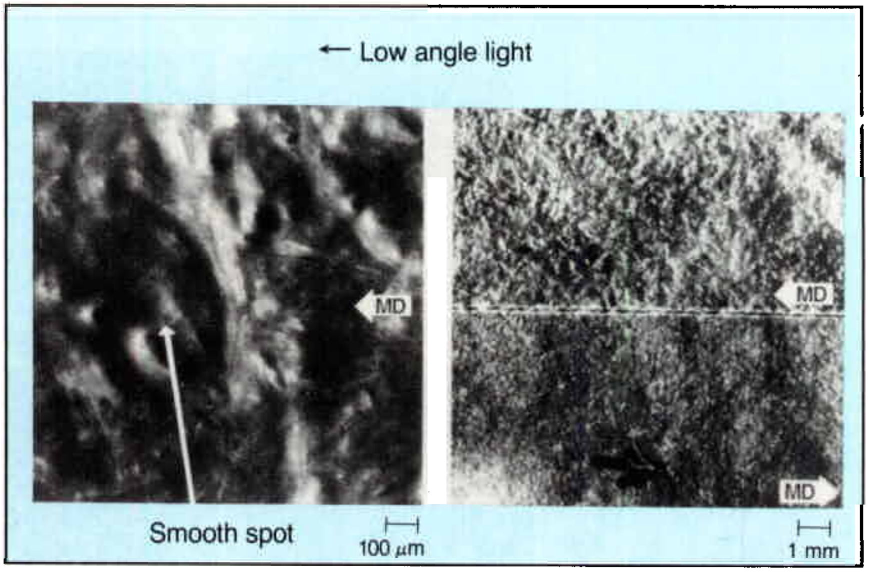
Compared to the beta-ray radiograph image, the soft X-ray radiograph image seems more similar to the uncalendered transmitted light image, again possibly because of the differences in absorption, scattering, and resolution. More work with our direct comparison methods, together with microscopy, would be useful in distinguishing the subtle differences

2. Registered image stack of commercial LWC having coated graininess and orange peel. (A) Transmitted light image, after calendering, of the paper coated on both sides. (B) Felt-side gloss image with high-gloss areas marked. (C) Transmitted light image of typical coating basestock for this paper (not from the reference area). (D) Transmitted light image of uncalendered paper coated on both sides, showing grainy spots. (E) Felt-side gloss gray image. (F) Wire-side gloss gray image. (G) Soft X-ray mass image (dark = heavy). (H) Feature-extracted binary image of felt-side gloss image (the high-gloss areas of Image E). (I) Beta-ray mass image of reference area (dark = heavy).



between the various mass-sensing methods [including the electron beam technique discussed by Tomimasu (*2*)].

3. Coating directionality in the machine direction in a supercalendered lightweight coated paper. The small coating spot (arrow) fills in the upstream side of the CD-oriented fiber bundle: top and bottom are from the same paper cut in half and turned 180°. Perception of greater roughness comes from light being reflected upwards from the poorly-covered downstream sides of fibers still raised out of the coated surface even after supercalendering.



Transmitted light, coating graininess, and low-angle incident light images

The grainy appearance of the uncalendered transmitted light image almost disappears after laboratory calendering as a result of the increase in internal light scattering (Figs. 2A and D). However, individual translucent paper fibers now appear that were not obviously present before calendering. (The calendered image in Fig. 2A can be used to help locate these fibers nearly hidden in the uncalendered image in Fig. 2D.)

When viewing the calendered surface of a blade-coated lightweight coated paper in low-angle incident light, a coating directionality is readily apparent: the upstream sides of fibers and high areas are more filled in with coating pigment than the downstream sides (**Fig. 3**). A localized variation in fiber coverage is also evident, giving many smooth-textured spots in the coated surface (**Fig. 4**, Frame A). These spots are separated by rough-textured interconnections where uncovered fiber forms remain.[2] We were unable to isolate these smooth spots with the image analyzer without first staining the paper with Croda ink (Frame B). This difficulty is due to the low light level in low-angle incident light images, to the chaotic topography created by film-coated fiber forms, and finally to the subtle textural difference (not necessarily the gray level) that somehow must be discriminated.

After staining the paper, we found that the white areas in the stain coincided well with these smooth spots (pointed out with the white arrow), while the rough-textured areas generally coincided with the dark red areas. From these and other observations, we wonder if the Croda ink stain on a lightweight coated paper coating is affected more by coating coverage variations than merely the coating mass variations or local binder content patterns (*3*, *4*).

Gloss and Croda image correlation

In addition to the good correlation of the smooth spots with the white areas in the Croda stain, our gloss imaging equipment showed that these same spots had a nearly perfect match with the high-gloss areas in the gloss image (Fig. 4, Frames B vs. F, for example). (The Croda stain was performed *after* acquiring the gloss images.) Although the felt-side Croda image had many fewer white areas than the wire side, virtually every one of them coincided with high gloss in the gloss image. (There were many red areas, however, that also had high gloss.)

All previous microscopy of this paper had revealed a somewhat thinner but more uniform felt-side coating. Consequently, for this coating side, the white part of the felt-side Croda stain may be revealing only the relatively few heavy coating areas and/or places of high binder content. This result may arise because, unlike the wire-side coating, the uniform felt-side coating had few fissures to allow the Croda ink vehicle to penetrate into the basesheet.

Despite what we knew to be a relatively uniform felt-side coating layer, our equipment showed a large variation in gloss for both coatings (Fig. 2, E and F). Furthermore, when we compared the gloss images, we were impressed by how well the two sides correlated at submillimeter dimensions (white areas in **Fig. 5**). This finding suggests that a uniform coating thickness does not necessarily ensure uniform gloss and that a commonality exists between the two coatings at very small dimensions.

Although the visual appearance of the sizes, shapes, and orientations of the gloss patterns relate well to the grainy patterns seen looking through the uncalendered coated paper, they do not relate well to our impression of the basesheet "look-through" formation (Fig. 2C). Therefore, we question whether a very good link exists between what we commonly view (and even measure) as basesheet formation and the coating graininess and gloss patterns.

Gloss correlation with the transmitted light image

When the gloss image of each side is individually compared to the uncalendered transmitted light image of the coated paper, there is greater than random correlation between the high-gloss areas and the dark areas in transmitted light. (These separate images are not shown.) The agreement improves even more when the gloss images from both sides are

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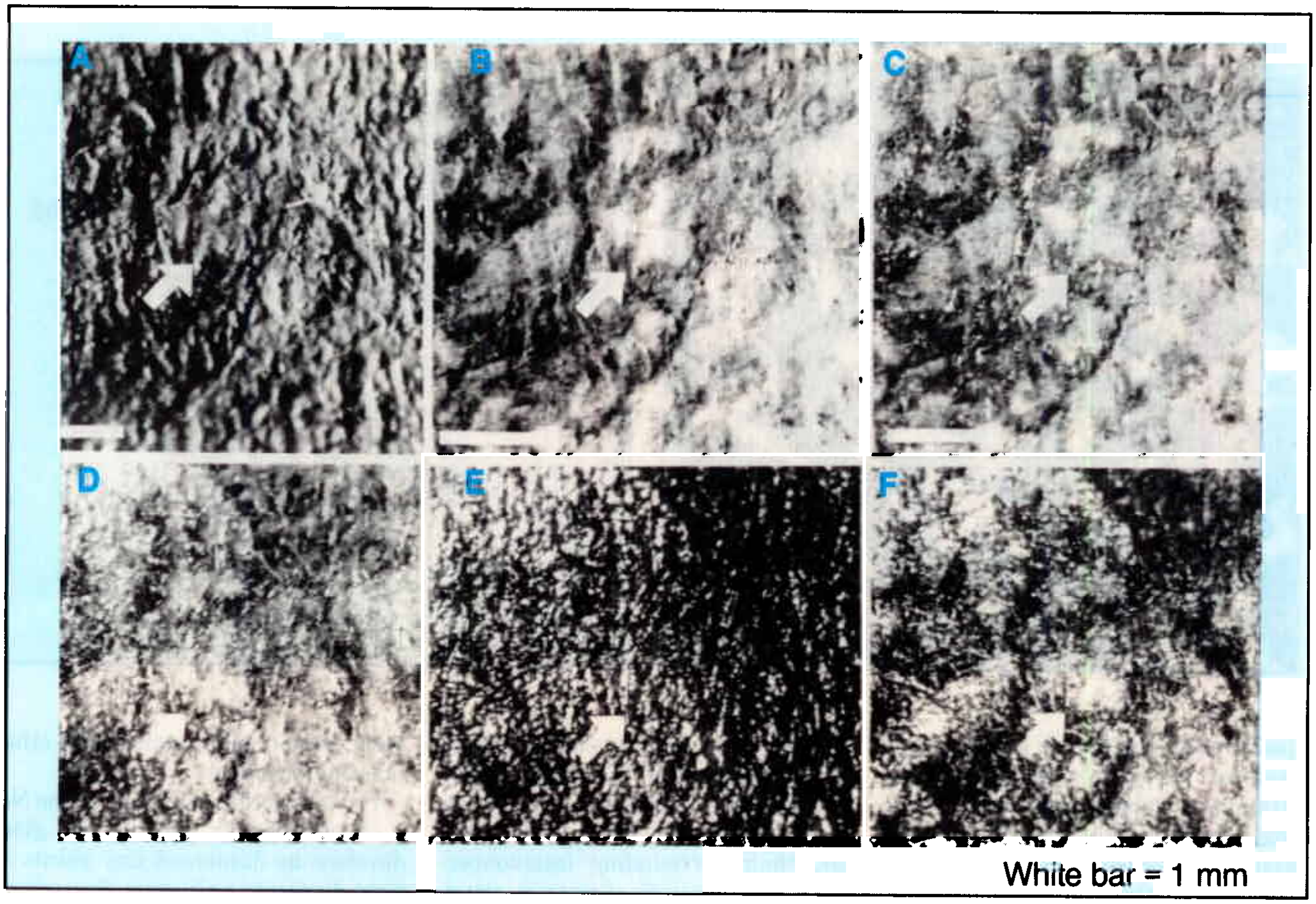
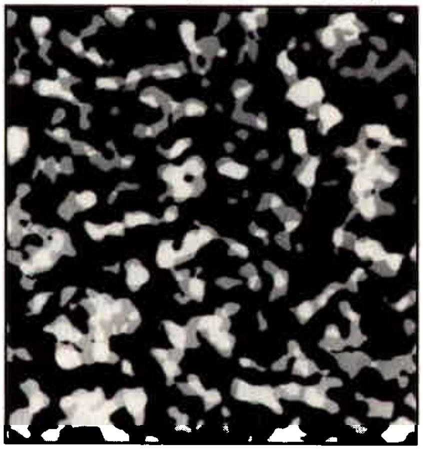
[2] We use the word "form" to denote a three-dimensional object at the surface of the coated paper. A paper fiber can be covered by a thin layer of coating pigment or a binder film, but it may still present a three-dimensional shape having dimensions very large compared to the wavelength of light. A fiber flattened into the coating pigment—even though it is at the surface-does not have form, and fibers are said to be covered when their forms are no longer recognizable.

4. A registered image stack for a supercalendered, commercial, lightweight coated paper having orange peel finish (wire side). In each image, the white arrow marks the same smooth coating spot. (A) Low-angle incident light. (B) Low-angle incident light+ overhead illumination. (C) Low-angle incident light+ overhead illumination+ partial gloss illumination. (D) Transition point: low-angle incident light+ overhead illumination+ more partial gloss illumination. (E) Partial gloss illumination only at transition point. (F) Full gloss.



5. Image comparing high-gloss features on the wire and felt sides (White = high-gloss features in common; area = 11.4%. Gray = high-gloss features not in common; area = 25.5%. Black = areas of low or no gloss; area = 63.1%.)



added together and this combined image is compared to the graininess seen in the transmitted light image (denoted by the white areas in **Fig. 6**).

This correlation implies a fairly strong association between the mass distribution of the combined coatings and the gloss variation. This finding is consistent with the belief that higher gloss develops during calendering in places where the coating is heavier.

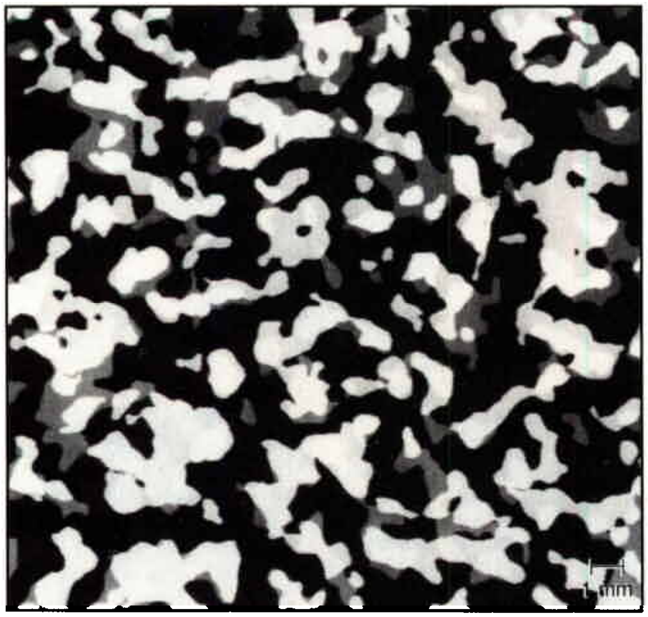
However, this belief does not explain why there are still so many high-gloss areas that do not match those on the opposite side (denoted by the light gray areas in Fig. 5). It also does not explain why so many dark areas in the transmitted light image lack gloss on one or both sides (denoted by the light and dark gray areas in Fig. 6). Much of the gloss variation is undoubtedly caused by the localized pressure distribution resulting from the superposition of both coating mass distributions. However, our observations about the unexplained gloss raise the intriguing possibility that, during the calendering operation, the resulting gloss variation for each of the coatings may also be influenced by the fiber coverage in that coating. These thoughts are explained more fully elsewhere (*7*).

Gloss response to varying illumination

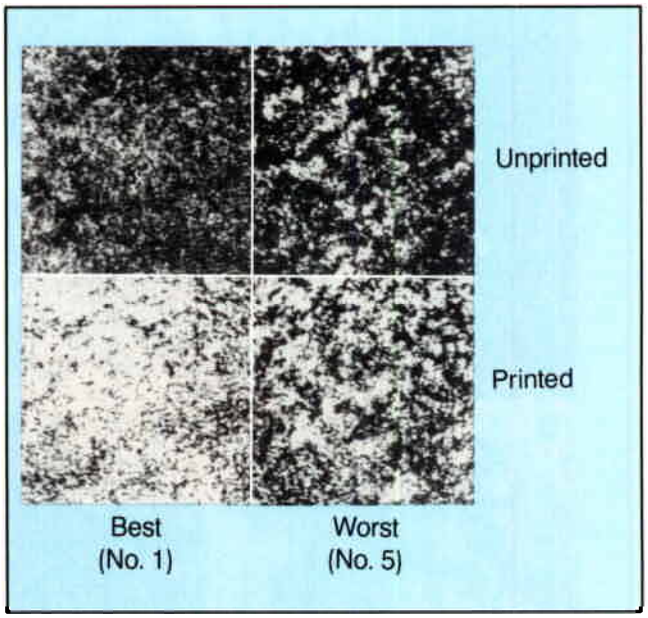
Many observations using the gloss imaging equipment convince us that the way the paper surface responds to varied forms of illumination could be an important distinguishing characteristic. If this is so, the equipment offers the potential for quantifying this characteristic, which is not feasible by other means to our knowledge. To help demonstrate this, Fig. 4 shows a registered image stack for the wire side of a commercial supercalendered lightweight coated paper having pronounced orange peel (No. 5 from Fig. 1).

As the gloss illumination lamp is swung from the diffuse lighting

6. Image showing high-gloss areas in common with dark transmitted-light features (White = combined wire-side and felt-side high-gloss features that are common to dark transmitted light features; area = 19.6%. Light gray = wire-side and felt-side high-gloss features added together and *not* in common with transmitted light; area = 36.9%. Dark gray = dark transmitted light features not in common with either gloss; area = 13.7%. Black = areas of low or no gloss; area = 29.8%.)



7. Printed vs. unprinted gloss images (laboratory solid test prints of commercially manufactured lightweight coated paper)



position into the partial gloss position (see Part 1, Fig. 1 for definitions), the first places to begin reflecting are the tiny facets of film-coated fiber sides and tops in the rough interconnections between coating smooth spots (Fig. 4C). Even over a large range of lighting or viewing angles, the paper with bad orange peel always has some facets in these interconnections that produce specular reflection. As the gloss lamp is moved, the reflections from these facets die away, and new ones take their place. The spots that lack gloss at this time are actually the smooth coating spots because they face outside the specular angle. These spots can also be observed as the white Croda regions in Fig. 4C.

As the lamp is moved nearer the specular position, there is a point where the gloss in the smooth areas rapidly increases and then approximately equals that in the rough areas. At this transition point, the gloss image variation is lowest, and the paper exhibits almost no orange peel pattern (Figs. 4D and E). As the lamp continues past the transition point to the full specular position, the gloss in the smooth areas suddenly increases to its maximum, while the gloss in the rough areas remains relatively unchanged. The orange peel pattern is therefore strongest when the lamp is at or near the full specular position (Fig. 4F). The large difference in gloss response between the smooth spots and their surrounding interconnections, just hundreds of microns apart, is responsible for the flashing or glaring effect seen when looking at paper with an orange peel finish.

Compared to a smooth paper, the rough interconnections in the paper with bad orange peel probably cannot be covered by normal ink film thicknesses (**Fig.** 7, Frame B). Although the varnished fiber forms in these areas are individually reflective, they form a facet assembly that has less total reflection at the specular viewing angle but has more specular reflection at almost all other viewing angles. These random reflections give the print a "grayish" cast over a wide range of viewing conditions, thus degrading the color saturation in the print (*5*). The printer may attempt to alleviate this gray look by covering the surface with heavy ink films, but even if this facet assembly could be completely covered by varnish, the subsurface roughness would still produce scattered reflections (*6*). In any case, heavy ink films are not a viable cure for an optically rough surface because heavy ink can lead to trapping problems, loss of color balance, and other printing problems.

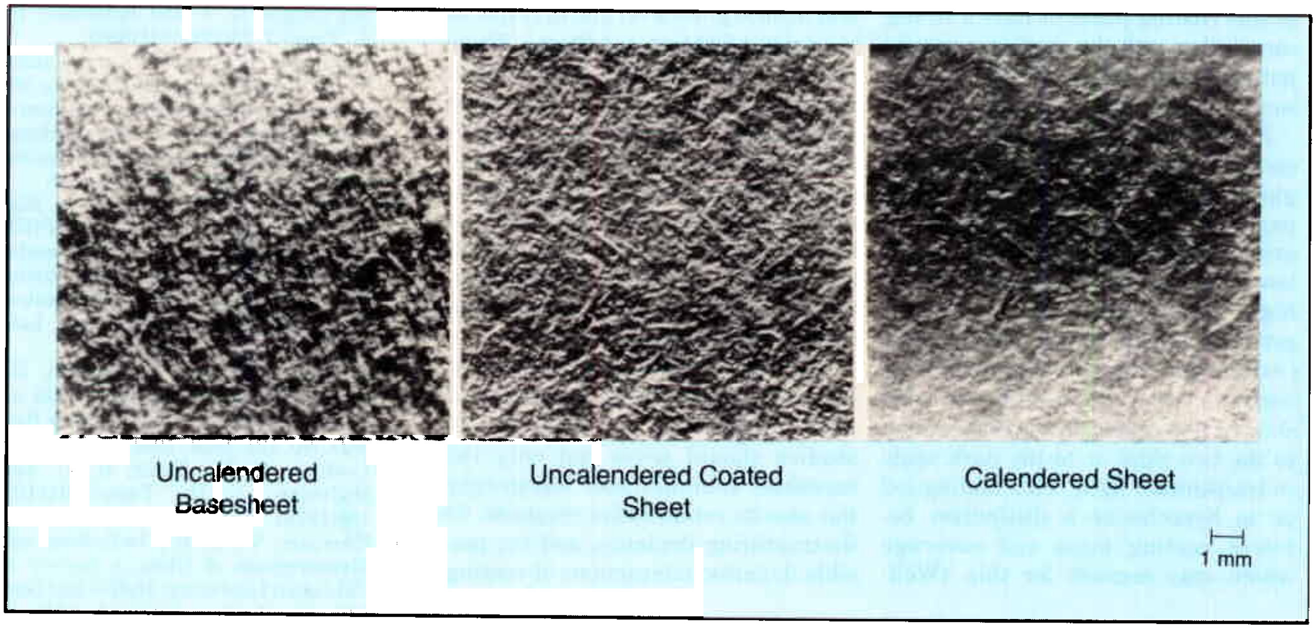
For a smooth paper (such as the No. 1 orange peel in Fig. 1), the gloss develops as numerous tiny points of light dispersed uniformly throughout the image. Although these points grow in size, they do not merge into strong patterns as the gloss illumination lamp is moved to the full specular position. When a smooth surface like this is printed, the average gloss improves greatly (Fig. 7, Frame A) because normal ink films are thick enough to cover the tiny surface imperfections with a more optically flat varnish film.

Our thoughts on the causes of "orange peel"

We have developed a generalized visualization of the commercial blade coating process for lightweight coated paper that is consistent with the observations reported here.

The attributes and causes of orange peel are complex, and the example detailed here deals with paper from only one commercial paper machine. We found that most of the gloss patterns in this lightweight coated paper seemed to be strongly associated with submillimeter coating cover-

8. Commercial lightweight coated uncalendered vs. laboratory-calendered coated paper in low-angle incident light, showing the basesheet after the breaker stack, the coated sheet after the finishing stack, and the same sheet after lab calendering



age and mass variations from causes that are still unclear. These variations can then lead to large localized differences in both the gloss level and the response to varying lighting conditions, especially in the dark solid tones of a print (*5*). Our work also confirms the importance and difficulty of achieving good fiber coverage when the coating thickness has dimensions similar to, or even much smaller than, the imperfections in the basesheet (*8*).

There is considerable commonality between the gloss images of the two sides, which we think may be due to small heavy areas of inelastic coating that could lead to high localized pressures during calendering. It is not known how much of the commonality is caused by coating bleed-through, by coating filling in both sides of a thin spot in the basesheet, or by the localized pressure distribution from superimposing one coating mass distribution over another during the calendering operation. We can offer one explanation to account for the gloss not common to both sides—that of differences in coating coverage (*7*)—but we do not know exactly how these coverage differences arise. Our coating coverage hypothesis implies that high gloss develops more easily in places where the fiber is well covered, even though the local coating mass and the local calendering pressure need not be high.

What about the characteristics of the orange peel gloss images we have observed in numerous supercalendered lightweight coated papers? The high-gloss areas are often slightly elongated in the cross-machine direction, are typically 1 mm or less in size (Figs. 1 and 2F), and are surrounded by rough interconnections having lower gloss. Neither the orange peel gloss patterns nor the grainy coating patterns seen in transmitted light bear much resemblance to the basesheet formation as perceived by traditional look-through. Instead, the patterns seem more compatible with the basesheet microtopography as revealed in low-angle light (**Fig. 8**). Although our gloss imaging equipment gives extremely fine detail, it has yet to reveal a periodicity to the gloss patterns as might result from a wire mark pattern in the coating distribution—even for base papers known to have a strong wire mark (*9*). More work is needed to understand the exact reasons for this.

All our results suggest that, rather than pursuing higher formation ratings, it may be more productive to develop methods of submillimeter imaging of certain basesheet properties [such as localized topography, compressibility, "destructuring" (*10*)] which might be helping to determine the coating distribution patterns. In this work, the dynamic aspects of the blade coating process must also be considered.

Summary

The creative use of image analysis is a potentially powerful tool for helping to understand problems that occur in the submillimeter dimension. Although we made an effort to develop objective techniques in this work, our subjective evaluations of registered image-pairs made us appreciate that there are aspects of the human perception that cannot be quantified. We have come away with the feeling that one of the most potent uses of image analysis for us lies not so much in producing numbers but in permitting these exceedingly complex human evaluations to be made more easily.

Even though the techniques presented here have certain limitations, our explorations into the causes of "orange peel" in commercial lightweight coated paper were encouraging. Here, we could demonstrate for one lightweight coated paper that much of the grainy coating pattern seen when looking through the uncalendered paper was transformed during calendering to the gloss patterns known as "orange peel." We could also show by direct comparison that the grainy coating patterns have a strong correlation with the coating coverage patterns seen on the calendered paper surface in low-angle incident light.

Furthermore, we could show a certain degree of match between the gloss patterns on both sides of the paper. We suspect that the high-gloss areas could correspond to the thin or low areas in the basesheet where a high total coating mass and local pressure exists during calendering. (Additional microscopy work can confirm this.) However, we also showed that much gloss is not common to the two sides or to the dark spots in transmitted light. This finding led us to hypothesize a distinction between coating mass and coverage which may account for this. (Well-covered places also develop high gloss even though the coating mass and pressure may not be high.)

Finally, we could demonstrate that the ultimate result of coating coverage and mass variations is a large variation in local gloss level and in response to varying lighting conditions. These easily visible gloss patterns occur at dimensions that coincide with print components to produce a noticeable disruption in the print quality. Besides creating poor gloss uniformity, uncontrolled specular reflections from a poorly covered paper surface also impart a grayish cast to the print, taking away print depth and robbing colors of their saturation.

Although we did not yet discover the origin of the coating coverage and mass variations, we think future studies should cover not only the basesheet submillimeter topography but also its compression response, its destructuring tendency, and the possible dynamic interactions of coating with the basesheet. In these studies, we hope that some of our methods will be helpful.□

Literature cited

1. MacGregor, M. A. and Johansson, P.-Å., Tappi J. 73(12): 161(1990).
2. Tomimasu, H., Luner, P., and Hanna, R. B., BPBIF Transactions of the 9th Fundamental Research Symposium—The Fundamentals of Papermaking, Mechanical Engineering Publications Ltd., London, 1989, Vol. 1, p. 159.
3. Engstrom, G., Johansson, P.-Å., Rigdahl, M., and Norrdahl, P., BPBIF Transactions of the 9th Fundamental Research Symposium—The Fundamentals of Papermaking, Mechanical Engineering Publications Ltd., London, 1989, Vol. 2, p. 921.
4. Bristow, J. A. and Bergenblad, H., Interpretations of ink-stain tests on coated papers, STFI-meddelande Serie D, No. 121, Sept. 1981.
5. Leekley, R. M., Tyler, R. F., and Hultman, J. D., Tappi 61(10): 108(1978).
6. Harrison, V. G. W., Definition and Measurement of Gloss: a Survey of Published Literature, Heffer and Sons Ltd., Cambridge, England, 1945, p. 145.
7. MacGregor, M. A., and Johansson, P.-Å., 1990 Coating Conference Proceedings, TAPPI PRESS, Atlanta, p. 125.
8. Kartovaara, I., Paperi Puu 71(9): 1033(1989).
9. MacGregor, M. A. and Conners, T. E., Tappi J. 70(9): 95(1987).
10. Lepoutre, P., Bichard, W., and Skowronski, J., Tappi J. 69(12): 66(1986).

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