Preferred citation: P.A.C. Gane and J.J. Hooper. An evaluation of interactions between coating colour and base paper by coating profile analysis. In **Fundamentals of Papermaking**, *Trans. of the IXth Fund. Res. Symp. Cambridge, 1989*, (C.F. Baker & V. Punton, eds), pp 871–893, FRC, Manchester, 2018. DOI: 10.15376/frc.1989.2.871.

AN EVALUATION OF INTERACTIONS BETWEEN COATING COLOUR AND BASE PAPER BY COATING PROFILE ANALYSIS

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ABSTRACT

Using techniques of coating thickness analysis and frequency transform procedures developed in the ECCI laboratories it has been possible to describe the basesheet surface profile changes caused by the coating application. Relaxation of the fibre network has been observed and found to depend not only on the base stock furnish, formation etc., but to a large extent on the coating pigment type, size distribution, coating colour rheology and most importantly the dewatering interactions between the coating colour and the base. Factors determining the dewatering characteristics of a coating colour will include the base absorbency, pigment particle packing and suspension fluid viscosity.

1. INTRODUCTION

Lightweight paper coating makes demands on coating colour and machine runnability under conditions of high speed often associated with high blade pressures. Basesheet substances of 35-40 gm^{-2} increase the problems of consistency of formation, surface roughness and absorbency.

High levels of basesheet surface roughness result in a proportion of pigmented coating penetrating the surface voids contributing to poor fibre coverage and poor coat weight control at the coating blade. Basesheet roughness reduces the quality of the coated sheet and the control of formation and processing is essential to minimise the degree of roughness of the uncoated surface.

Application of a water-based suspension of pigment particles to the paper surface leads to a number of dynamic interactions between the components of the coating colour formulation and the basesheet fibre structure. These interactions can be effective chemically and structurally.

Roughening of the underlying basesheet during coating can be caused mechanically by blade pressure forces and rheological effects under the blade nip. Lightweight coating is, naturally, more prone to these mechanical and dynamical effects on the base surface profile as blade pressures and speed increase and runnability factors become increasingly important.

The role of fluid imbibition by the basesheet as an initiator of fibre relaxation and fibre-fibre debonding during coating colour dewatering has been extensively investigated by optical and electron microscopy[1,2,3] and has been shown to contribute markedly to the final coated sheet properties. The rate of imbibition is controlled by the basesheet fibre network dimensions, the degree of hydrophobicity and the dewatering rate of the coating colour. These contributions to the immobilisation of the coating colour define the coating thickness distribution during and after application of the colour.

2. DISTRIBUTION OF COATING THICKNESS

The quality of a coated sheet and the design requirements of lightweight coating applications are determined by the distribution of coating over the paper surface, the structure within the coating layer and the surface or roughness profile of the coating on both a micro and macroscale[4].

The distinction between micro and macroroughness is inherent to the system under investigation. Firstly, the macroroughness is primarily associated with initial basesheet roughness, surface voidage, fibre compaction etc.. This macroprofile is in the important region related to coating coverage. The macroprofile of the basesheet has been shown to change significantly during wetting[5] and can result, in extreme cases, in rupture of the surface coating.

Secondly, the microprofile is related to the structural packing of the pigmented coating layer and is determined by the pigment size and shape distributions and the interactions between the coating colour and basesheet. Anisometric particles, such as the platey kaolinites, micas etc., can pack together in different conformations or orientations depending on the dewatering and drying conditions applied and the coating dynamics experienced under the blade[6]. The structure of the coating layer also influences the macroroughness by the effective coating holdout and coverage associated with coating bulk and void bridging.

2.1. Profilometric Analysis

Figure 1 is a schematic of a cross-section taken from a coated paper as might be viewed in an electron microscope. Typically, the surface profile of the coating is smoother than the coating/base interface profile. The macroroughness of the finished sheet is determined by the underlying base profile and the coverage properties of the coating.

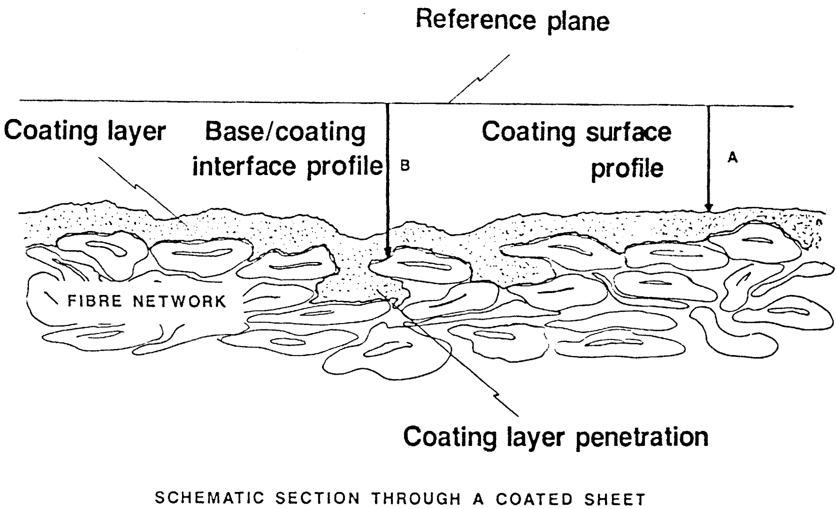

Figure 1. Microscopic cross-section of a coated sheet.

A coating layer modifies the surface macroprofile of the base by filling the voids between the fibres or retains the profile by forming a contoured layer of constant thickness over the fibre structure as illustrated in Figure 2.

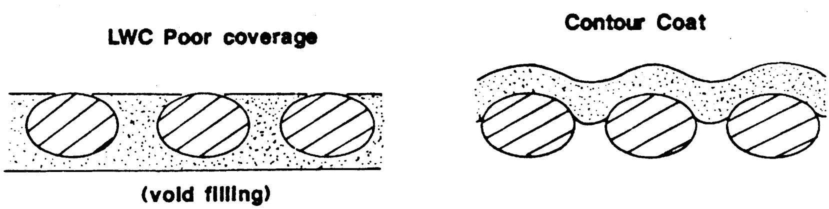

Figure 2. Modification of sheet profile by the application of coating.

In practice an ideal coating will form a structure consisting of a combination of surface smoothing by void filling and enhanced coverage by displaying a tendency to contour coat at low coat weights. To analyse the mechanisms by which various coating pigments modify the basesheet profile it is necessary to quantify the distribution of coating thickness and to express the coating profile in terms of the contributions made to the surface contour by the micro and macroroughness. Figure 3 displays some typical processed images of the coating layer collected from the microscope, in which the coating thickness is magnified relative to the paper plane by use of a computer imaging system. Of particular interest is the effect that pigment application has on the basesheet roughness, i.e. base surface features, typically ≤ 200 µm, which are distributed spatially over the surface.

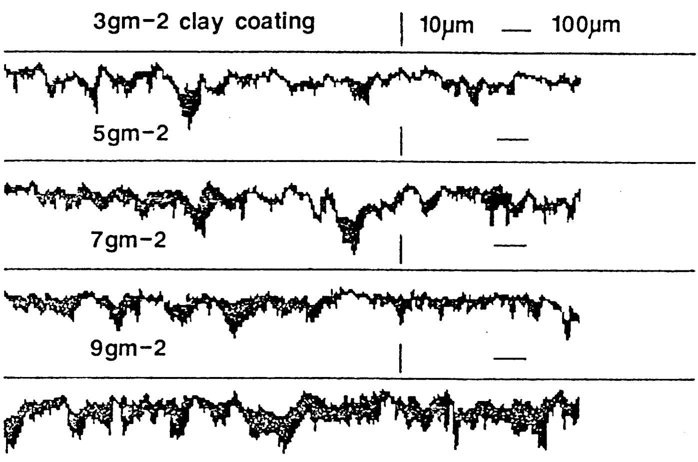

Figure 3. Computer images of the coating layer.

2.2. "Fingerprinting" the Profile by the Wave Transform Technique

Spatial frequency transforms can be used to resolve the peaks and troughs which make up the surface profile into a series of component waveforms and to describe the roughness profile in terms of a distribution of wavelengths and amplitudes, which when recombined, would reconstitute the characteristics of the original surface. The most common such transform is the Fourier Transform which breaks down the profile into its constituent sinusoidal functions. Other transforms exist which are more suitable to apply in certain circumstances. For example, the digitised data acquired during our analysis of the profile variations across the paper surface is more adaptable to the set of square wave functions defined by Walsh(6). Furthermore the stochastic nature of interlocking networks can be described more readily using a truncated Walsh function set rather than the continuously varying sine functions of the Fourier Transform. Using conventional spectral analysis the roughness of a surface is resolved into 15 component Walsh waveforms of decreasing wavelength and the amplitude of each roughness wavelength can then be computed [the basis set of 15 Walsh functions is shown ir Figure 4.] The amplitude spectrum defined in this way can be averaged over many transform lengths or span lengths and a statistical frequency "fingerprint" of the profile can be constructed from the averaged phaseless amplitudes.

The spectra obtained from different basesheets show some distinct features peculiar to each base formation. Comparisons of profiles measured in cross-section can be made readily by comparing the "fingerprint" spectra. In this way, the modification of a basesheet profile by the application of a coating can be monitored and the resultant effect on the surface contour of the finished paper can be quantified.

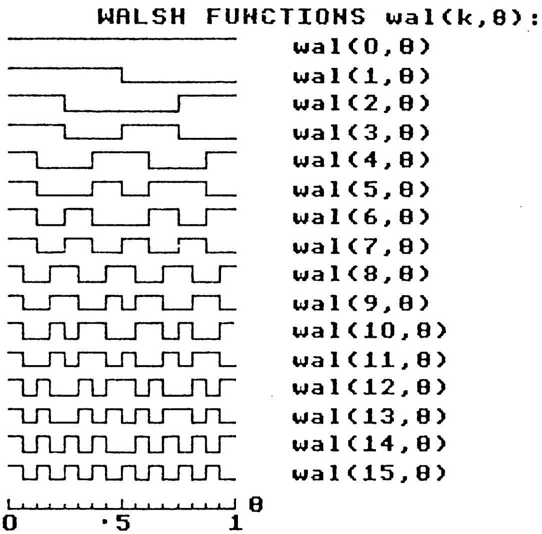

Figure 4. The basis set of 15 Walsh functions used to transform a span length of θ.

The concept of profile comparison by the transform technique is illustrated in Figure 5. The background large amplitude spectrum describes the base contour whereas the foreground spectrum is that of the profile on the surface of the coating. Idealised spectra from (i) a contour coat and (ii) a coating with poor fibre coverage at low coat weight are displayed in the foreground. The contour-following property of the coating is clearly seen in case (i), in which the relative spectral amplitudes are similar when comparing the underlying basesheet profile and the coating surface profile - the "shapes" of the spectra are similar indicating that the basesheet "fingerprint" is retained through the coating layer. In case (ii) the coating has a significantly different relative spectral content to that of the underlying base and the difference is a measure of the void filling, fibre relaxation and mechanical deformation of the basesheet during and after coating.

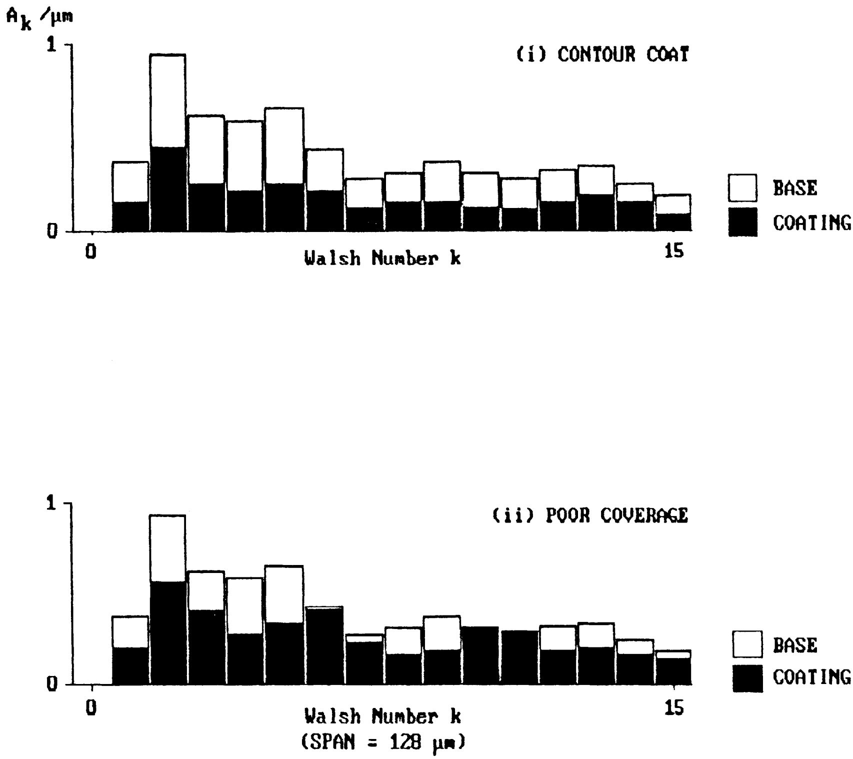

Figure 5. Comparison of coating surface and basesheet "fingerprints".

3. THE EFFECTS OF DWELL TIME AND PIGMENT DEWATERING RATE ON THE BASESHEET PROFILE

Application of a wet coating colour onto an interactive dynamically unstable basesheet results in severe restrictions on machine runnability. The need for water retention aids to prevent catastrophic rises in colour solids within critical regions of high shear is a direct consequence of the capillary network within the fibrous basesheet. The base fibres, however, do not constitute a static interlocking network but introduce dynamic and chemical interactions, particularly with the fluid component of the coating colour. These phenomena collectively control the overall absorbency of the basesheet, which in conjunction with the dewatering rate of the coating colour, determines the coverage, coating holdout and roughness of the coated sheet for a given pigment system.

Water absorption is related to the rate of diffusion of the vapour phase and the rate of capillary imbibition of the bulk fluid. The vapour phase precedes the fluid meniscus and initiates the process of fibre swelling and debonding which can lead to a significant roughening of the sheet. The rate of diffusion of water vapour into the fibre wall has been shown to be very rapid resulting in a swelling pressure after $\leq$ 1s[5,10].

The effective dwell time of the wet coating colour on the basesheet depends on the application system used and the rate of drying of the sheet after the metering blade[8]. In the case of the short dwell time applicator, wetting of the basesheet before the blade is minimised and most fibre stress relaxation effects take place after the blade before and during the drying process. For constant machine drying temperature profiles the wetting time of the basesheet depends on both the solids content of the coating colour and the coat weight applied. The lower the solids content or the higher the coat weight, the longer will be the drying time.

The Walsh function transform spectrum provides a measure of the roughness of the coating/basesheet interface profile, characterised within a fixed wavelength range. Roughness can be defined by the "moments" of the spectrum. A characteristic roughness is defined by the second moment

$$\mu_2 = \sum_{k=1}^{15} k^2 A_k^{\,2}, \tag{1}$$

where k is the order of the Walsh component (or "frequency") and A_k the amplitude of the kth component.

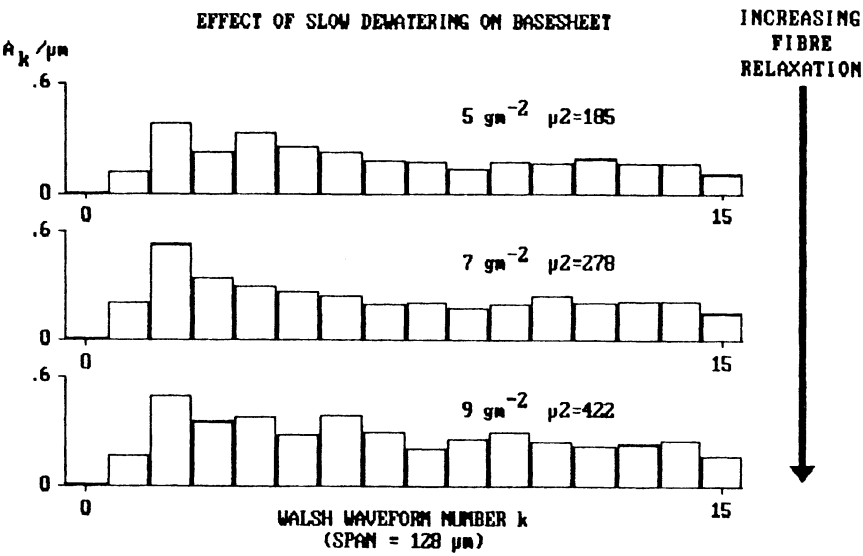

Figure 6(a). Changes in basesheet profile during slow colour dewatering.

Figure 6(a) compares the Walsh spectra of three coated papers of increasing coat weight, calculated from microscopic profilometry of the coating/base interface. The coating pigment is a fine clay (80 wt.% <2 µm), with relatively slow dewatering, applied at increasing coat weights of 5, 7 and 9 gm^{-2} using a short dwell system under constant temperature drying conditions. As the coat weight increases, the drying time and the effective post-blade wetting time increase. It can be seen that the underlying basesheet becomes rougher as the contact time with the wet coating layer increases.

The particle size of the coating pigment affects both the dewatering and drying rates such that the rate of immobilisation of a fine pigment is generally slower than that of a coarse pigment when applied in the same formulation to a given base. Figure 6(b) shows the Walsh amplitude spectra of

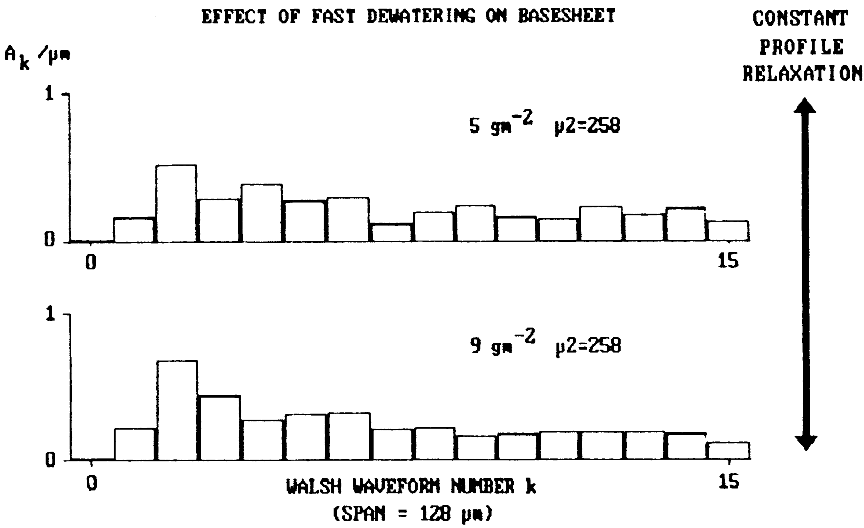

Figure 6(b). Changes in basesheet profile during fast colour dewatering.

the underlying profiles at increasing coat weight of a relatively coarse pigment (65 wt.% <2 µm) applied to the same base sheet profile as before. Figures 7(a) and (b) may be compared - the plots display the underlying base roughness induced by (a) the slow dewatering fine pigment, (calculated from the spectra in Figure 6(a)), and (b) the base profile roughness under the coating formulation containing the coarser, fast dewatering clay, (calculated from data included in Figure 6(b)). In the case of the fine clay, the μ_2 roughness values increase with increasing coat weight due to the prolonged wetting time. The coarser pigment, however, initially dewaters more rapidly into the base resulting in a significant roughening of the base sheet profile under the lightweight (5 gm^{-2}) coating. Immobilisation of the coating

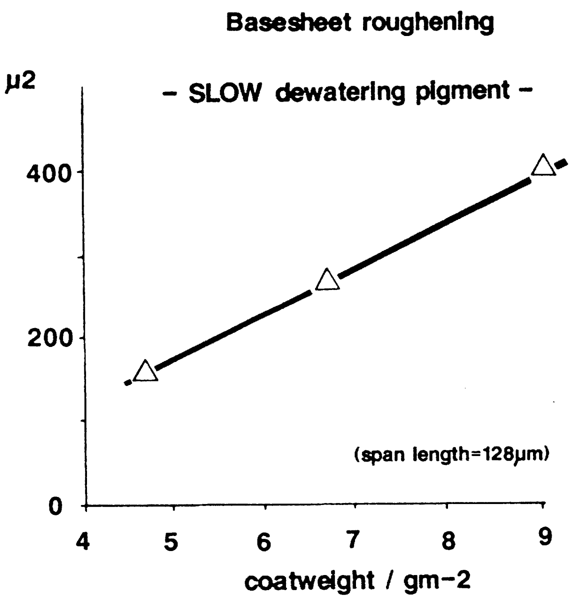

Figure 7(a). Unconstrained basesheet roughening - proportional to LWC coating weight.

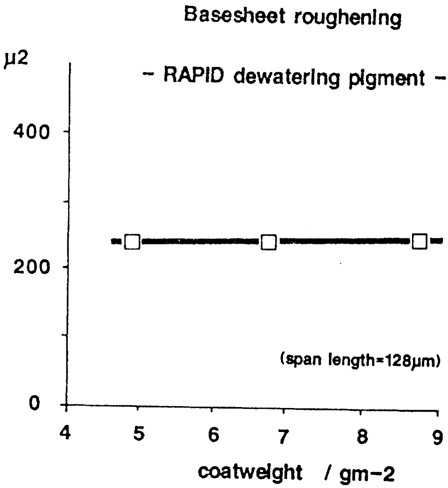

Figure 7(b). Constrained basesheet roughening - independent of coat weight.

colour in contact with the basesheet is also reached more rapidly and is virtually independent of surface drying conditions such that the effects of any further surface fibre relaxation are reduced even at higher coat weight. Micropore imbibition of the fluid phase raises the solids level of the colour in contact with the sheet, as illustrated in Figure 8. A fast dewatering pigment immobilises quickly and any further fibre swelling is constrained. This may be visualised in Figures 9(a) and (b).

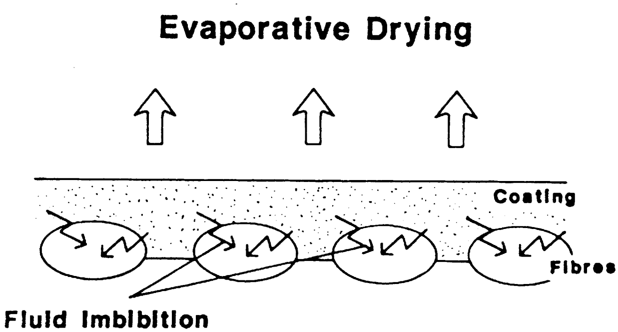

Figure 8. Coating colour immobilisation.

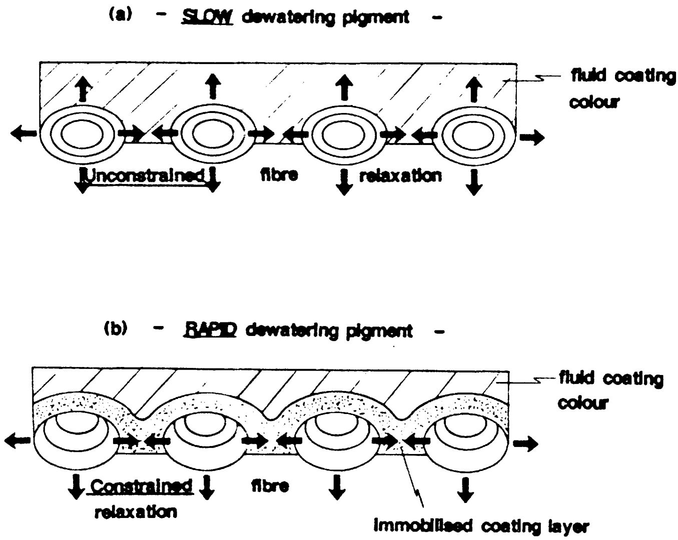

Figure 9. The constraining effect of rapid colour immobilisation.

The effective wetting time is further extended in the case of a roll applicator (LDTA) system due to the longer dwell time of the fluid coating colour on the basesheet prior to the metering blade. The resultant base fibre roughening is greater than the equivalent low coat weight applications using the Short Dwell Time Applicator (SDTA). Fibre roughening prior to the blade is particularly pronounced under conditions of slow dewatering. Figure 10 illustrates the difference in base fibre roughness between the LDTA and SDTA in the case of the fine slow dewatering pigment: the increased fibre roughness of the LDTA is measured as the difference between the μ_2 values calculated from Walsh spectra of the base profile. The fine pigment particles remain mobile on the paper surface between the roll applicator and the doctor blade and the delayed drying of the coating results in unconstrained base profile relaxation. Under given drying conditions, the difference between LDTA and SDTA will be coat weight dependent. The curve in Figure 10 illustrates this - at low coat weights (<4 gm^{-2}) the water available to induce profile roughening is limited in both cases and at higher coat weights (>10 gm^{-2}) fibre swelling is complete before the coating is fully dried in either system.

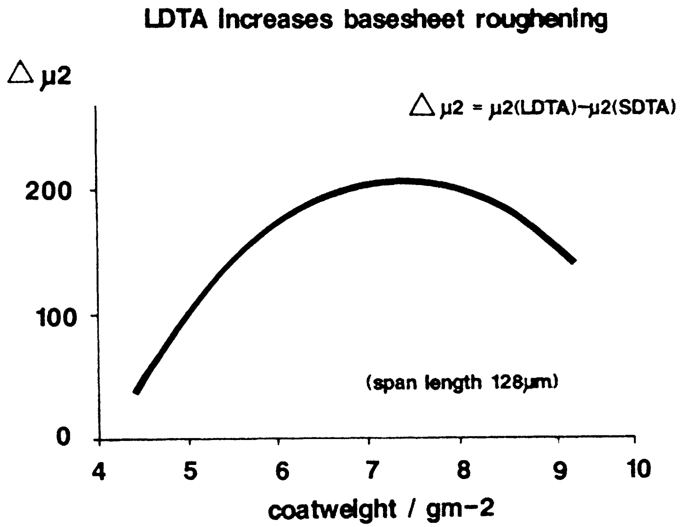

Figure 10. Effects of coater dwell time on basesheet roughening.

Dewatering rates, therefore, determine the time taken for the coating colour to reach the immobilisation solids at the fibre surface. Rapid immobilisation is normally advantageous for good coating holdout. However, at low coat weights, the susceptibility of the base sheet to fibre roughening is increased the more rapidly the colour dewaters prior to surface drying. Referring to Figure 8, at the lowest coat weights, the base roughness under the fast dewatering pigment is dried quickly from the coating surface at low coat weight before the fluid phase imbibition by the fibres is complete.

3.1. Pulse Dewatering at the Coating Blade

It has been shown that the choice of blade geometry and solids content can have profound effects on the coating structure[6]. Coatweight control and the forces imparted to the coating colour will differ as the blade geometry is changed. Naturally, forces applied to the coating colour are transmitted to the colour/basepaper interface due to their intimate contact. The effect of blade geometry on coating penetration[11] and dewatering is illustrated in Figure 11. High impulse forces result in penetration of the surface voids and induce pulse dewatering of the colour which in turn causes surface fibre roughening due to swelling and relaxation phenomena. It has been shown that penetration is most marked in the case of "free flowing" colours containing pigments of low aspect ratio.

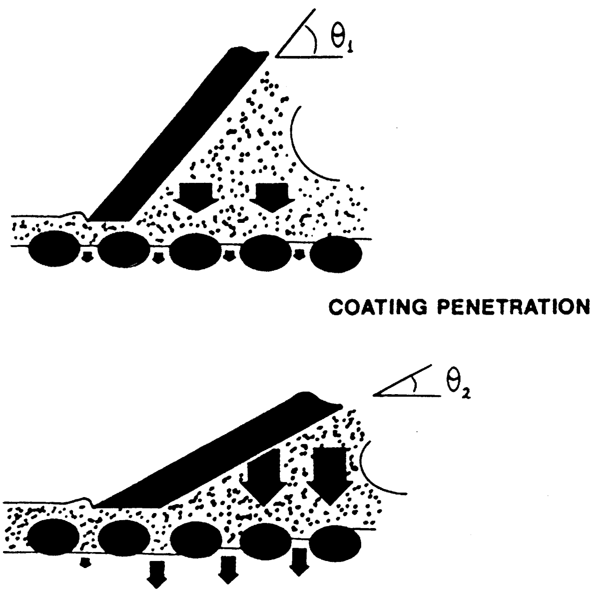

Figure 11. Low angle stiff blade increases pressure dewatering.

Figure 12 compares plots of the Walsh spectra of a rough basesheet underlying two 4.5 gm^{-2} offset coatings of a fine rapidly dewatering clay (92 wt.% <2 μm), using a latex formulation and a low level of water retention (0.5 p.p.h. CMC). One coating (a) was made at a blade clamp angle of 45° and the other (b) at a lower blade clamp angle of 30° in a stiff blade configuration using a Short Dwell Time Applicator (SDTA). The basesheet has evidently undergone a greater roughening during application at low angle - consistent with the penetration model illustrated in Figure 11. The coating surface after calendering retains evidence of the underlying base profile with the result that the surface of the coating is also rougher at low blade clamp angle, μ_2 = 23.2, compared with high clamp angle, μ_2 = 11.6

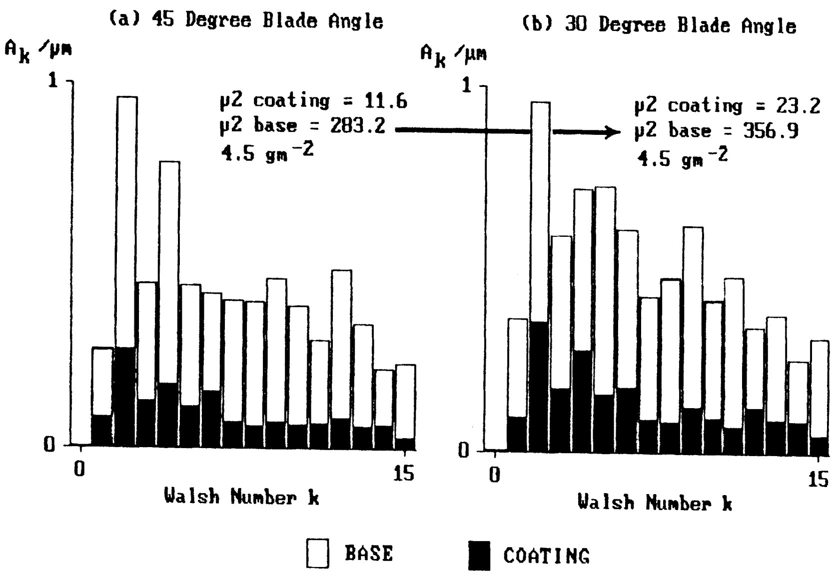

Figure 12. Basesheet roughening due to pressure dewatering.

Effects of pulse dewatering and penetration, such as have been described, are also applicable during any water-based surface treatments, for example, at a size press or at the nip of a roll applicator and can lead to significant increases in microscopic surface roughness.

4. FIBRE STRESS RELAXATION

For reasons of runnability in lightweight coating applications, which may be as low as 2-3 gm^{-2}, it is essential that the surface of the basesheet is macrosmooth. Pre-calendering of the base before coating can provide a means of reducing the macroroughness and facilitates the application of lightweight coatings at reduced blade pressure and at increased solids content.

The benefits obtained by coating a pre-calendered base, however, have proved to be variable in practice. On occasions the finished paper sheet gloss, for example, has increased only slightly over that of the coated uncalendered base.

A comparison of the distributions of coating thickness of an offset formulation, applied at 3 gm^{-2} to a machine calendered and uncalendered base, respectively, is made in Figure 13. The base stock is identical in each case, apart from the reduced macroroughness of the pre-calendered sample. The data illustrate the improved coverage achieved by coating the smoother base. Comparing the percentage occurrence of coating thickness in the thin 0-1 µm interval it is clear that the rougher base has a greater proportion of uncovered surface fibre in the finished sheet. However, the gloss of the two samples is similar.

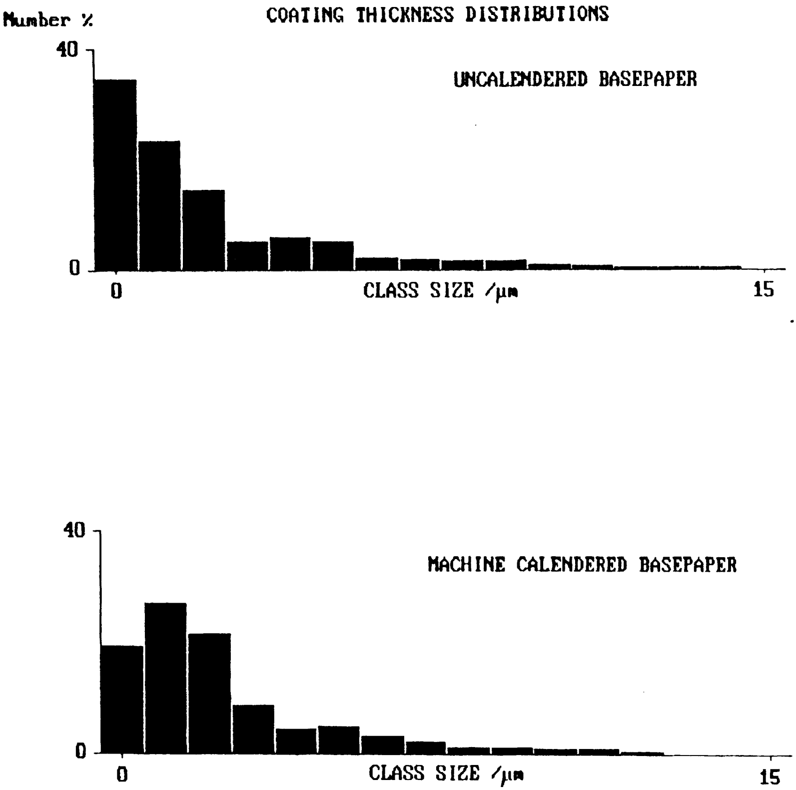

Figure 13. Precalendering the base results in improved coating coverage.

Using the techniques outlined above it has been possible to isolate the adverse effects of changes in the macro-profile of the precalendered basesheet underlying the coating layer. The Walsh Transform spectra of the surface of the uncoated base sheets in Figure 14 clearly show the effect of

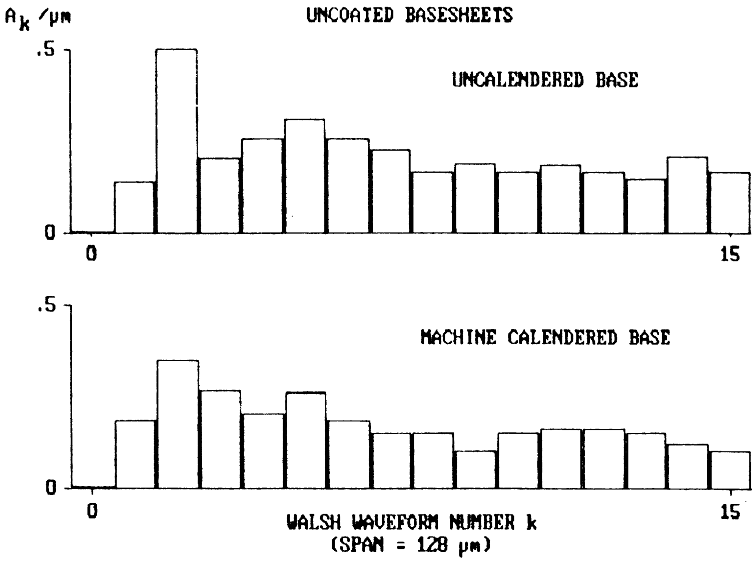

Figure 14. Comparison of the uncoated basesheet profiles.

pre-calendering. The calendered sheet is smoother and has a different distribution of roughness over the surface. For example, the relative amplitudes of peaks k = 2, 3, 4 and 5, and k = 13, 14 and 15 are distinctly different. Subsequent analysis of the profile of the precalendered sheet as viewed in cross-section under the coating reveals that the profile after coating has generated many of the features present in the uncalendered base (see Figure 15 in which the two coating/basesheet interface spectra are compared). In this example, the smoothing effects of calendering have not been retained during coating and the regeneration of the original base profile by a mechanism of relaxation of the fibre network has resulted in a coated sheet which does not achieve the gloss advantage that might have been expected from the improved coverage shown in Figure 13. If, however, the smoothness achieved by precalendering the base could be maintained in the coated sheet, perhaps by changing the calendering conditions, then the excellent coverage properties exhibited by the coating should result in a significant improvement in the sheet properties, i.e. the macro-profile of the base must remain stable.

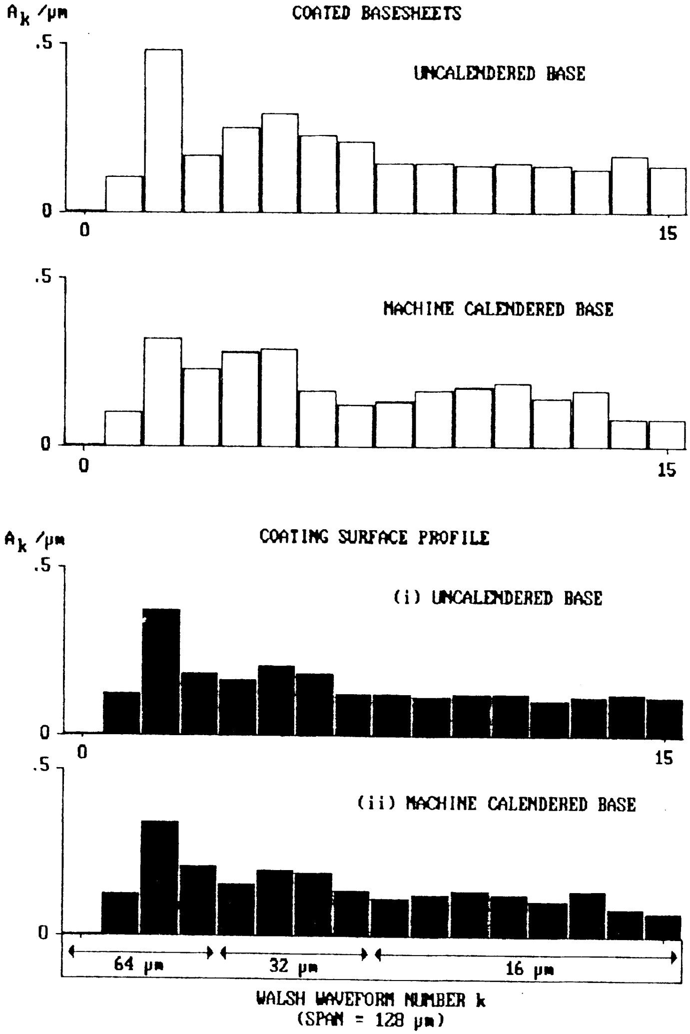

Figure 15. Relaxation of the precalendered base profile.

5. SUMMARY AND CONCLUSIONS

Microscopic sectioning techniques linked to spatial transform analysis enables the effects of basesheet profile changes to be monitored.

Roughening of the base due to wetting by the coating colour relates to fibre swelling, debonding and stress relaxation of the paper surface. The runnability of lightweight coating applications is greatly influenced by the macroprofile of the underlying fibre network. It is therefore important to minimise the base roughness both for ease of coat weight control and fibre coverage. However, optimisation of the coated sheet properties is dependent on any base macroprofile changes which occur <u>during and after coating</u>. Relaxation of fibre stress, created during base formation and any subsequent surface treatment such as calendering, is induced by dewatering of the pigment layer either by base sheet water sorption or pressure / pulse dewatering during application. A rapidly dewatering, loosely packed pigment immobilises rapidly and limits the extent of surface relaxation of the base such that any induced fibre roughening is virtually independent of coat weight and hence the rate of surface drying. A fine slow dewatering, closely packed pigment induces a varied amount of fibre roughening. At high coat weight, the effect is greatest, but at low coat weight, under conditions of rapid drying, macroprofile relaxation is minimised.

The short dwell applicator offers the most scope for controlling base sheet profile changes since any changes take place after the blade and can be minimised by pigment choice, drying conditions, etc.. A roll applicator system extends the wetting time of the base and the only control of fibre roughening offered by pigment choice is to maximise the immobilisation rate of the coating colour such that any further base roughening is reduced. An absorbent base will also have the effect of increasing the rate of immobilisation of the coating colour and offers advantages in a roll applicator system provided the solids content of the colour at the blade does not increase sufficiently to impinge upon runnability.

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Transcription of Discussion

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Dr. P. A. C. Gane and J. J. Hooper

Dr. J.E. Luce, International Paper Co.

Have you had an opportunity to apply this interesting and obviously very powerful technique to the examination of coated papers after they have been moistened in the printing process?

Dr. P.A.C. Gane ECCI England

Not as yet. Obviously, this is another interesting area. One of the initial areas of interest is to build up a data bank of the behaviour of different furnishes throughout the coating process. Certainly the end use is always of great importance, and I agree that this work has to be done sometime.

Dr. D.J. Priest, UMIST

I just wondered if surface sizing of base papers was another area for your interesting studies? Do you have any information on the influence of surface sizing on some of your effects?

Dr. P.A.C. Gane

The variation in static absorbency, due to surface sizing, can be negated under those circumstances where pressure pulses are applied, particularly in terms of roll applicator systems, etc. To make the association between sizing and resistance to sheet relaxation is not valid. Depending on the application system, coating formulation, etc., it has some or no effect.

Dr. B.D. Jordan, PAPRICAN

A question about your Walsh transforms. Whereas I would agree that if we accept the idea that surfaces look like a pile of popsicle sticks that are nice and square, then you have a binary situation, and in this case, a square basis set by Walsh or Hadamard would be more appropriate than Fourier. If we look at Figure 15 (page 915) in the next paper in the Session, there is a nice void there which could be more accurately compared to cooked pasta. There is a lot of variation and rounded edges, etc., and if we then look at your own traces in Figure 3 (page 875), they look rather rounded as well. I would wonder whether we have as binary a situation as we need and if you have tried comparing the same number of basis functions in Fourier, but find that the Walsh equation gives you a better fit?

Dr. P.A.C. Gane

The point comes in when one chooses the scale of spatial distribution that one is looking at. When I say that it is made up of a number of obstacle boxes, what I was illustrating there is that when one extracts the interface profile, as I was doing there using image analysis, one can see the underlying square wave form. If one was looking over the complete span length range to satisfy the complete profile variation, one would need to go to an infinite set of basis functions. It is possible to reduce the problem of a step function by choosing the span length that one wishes to use to incorporate the roughness to be studied. Before moving to the Walsh function set, we did consider Fourier analysis, and the conclusion was that one could not truncate satisfactorily the basis set.

I.K. Kartovaara, The Finnish Pulp & Paper Research Institute

We have used a stylus instrument quite extensively to measure the base paper and blade coated paper. We always get the result that the smoothing effect is very poor with very narrow voids. Your results indicate that there is a considerable smoothing at higher frequencies. Have you ever measured the same sample both with a stylus instrument and this technique?

Dr. P.A.C. Gane

Yes we have for direct comparison. What one finds is that firstly the amplitude of roughness in the area of interest which I am discussing is somewhat reduced in the case of the stylus profilometer, so there is an artificial reduction in the high frequency component. This may be due either to tip pressure of the stylus or the size of the stylus tip, which produces some kind of convolution between the actual profile and that of the machine function. To get the complete information on the sort of scale and detail I was talking about in cross section, one would have to understand the machine function of the stylus particularly well.

A. Ibrahim, PAPYRUS

I would like to put forward some concepts in flow dynamics and see if it makes sense to you. We measure the conveyance of flow in conduits and channels by the hydraulic radius, which is simply the area divided by the perimeter. Higher hydraulic radius will give high flow, so in other words, a square will give more flow resistance than a circular conduit, and a half full conduit will give less flow than when it is completely full. Does this fit with your studies, and if I understood correctly, this is an addition to Dr. Jordan's comment?

Dr. P.A.C. Gane

To answer your question, we would have to look at this in terms of the interactive de-watering that I described between the particular pigment particle packing, which is associated not only with size but shape and indeed orientation of those shapes, and that in relation with the fibre network, whether under pressure or not. In juncture with your comments, then I would have to step back a little from the interactive process I described and become a little more unrealistic for the purposes of understanding it to study both components in separation.

Dr. K. Ebeling, James River Corporation

Have you had a chance to study the role of flocculation and flocs in relaxation? Are the effects that you are seeing mainly due to the relaxation of individual surface fibres? Can you comment if the underlying flocs and density differences between the flocs are causing the phenomena you observe?

Dr. P.A.C. Gane

This is a very good point. You would have to go back to the original spectra to study them more closely to see exactly what space range one is talking about and whether it is associated with flocs or not. What I can say is that transferring the floc argument from the base paper to the coating, then flocculation of the coating particles necessarily leads to a very different de-watering regime with different base sheet swelling. I have not related to the actual floc in the base sheet.