Requirements for CD measurement and control of coating weight

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ABSTRACT *Two technologies used in the on-line measurement of coating weight are based on (a) oven-dry weight and (b) ash content. These two technologies are beta absorption using the beta particle emitter Kr^{85} and photon absorption using the low-energy X-ray emitter Fe^{55}. The beta method determines coat weight from the mass difference between the coated and uncoated sheet and is equally sensitive to fiber, coating, and other constituents. The low-energy photons of the "ash" method are more highly absorbed by inorganic materials such as clay, calcium carbonate, and titanium dioxide. The absorption is dependant on the type of additive and concentration, so the correct recipe for the coating must be known. Each method can accurately determine the average coating weight, although the ash method offers a more precise measurement of cross-direction variations. Both can be improved by using scanner synchronization. Experimental data indicate that the measurement of coating weight can be improved by combining the two methods.*

KEYWORDS
Ash
Beta gauges
Blade coaters
Coating weight
Control systems
Cross direction
Equations
Mathematical analysis
Measurement
Moisture content
On-line measurement
Weight

The on-line measurement of coating weight must satisfy a number of general requirements to be useful in commercial production. The measurement must be highly precise in short sampling periods for meaningful cross-machine profiles and precise detection of areas of high coating weight (streaks). The condition of high precision in short sampling periods assures that precise scan averages will be obtained. The sensing technique should be highly sensitive to the coating, with the least possible sensitivity to other constituents, including the basesheet and moisture. The composition of the coating should not affect the accuracy of the measurement method.

Here, we review two methods:

1. Beta absorption using the beta particle emitter Kr^{85}
2. Photon absorption using the low-energy X-ray emitter Fe^{55}.

Here, we refer to the beta particle emission technology as simply "beta." We use the term "ash" for photon absorption because the measurement sensors are essentially the same as those used to measure the inorganic material in a paper sheet. Results from this measurement of ash content can be correlated to those of laboratory tests like the TAPPI percent ash test (TAPPI T 413).

Two techniques: beta and X-ray absorption

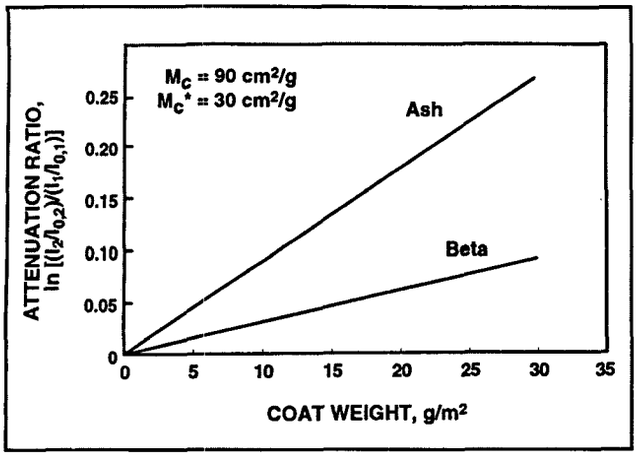
Several reviews have been published on techniques for determining coating weight (*1–5*). The two most suitable techniques for on-line measurement are beta absorption ("beta") and X-ray absorption ("ash").

Beta absorption method

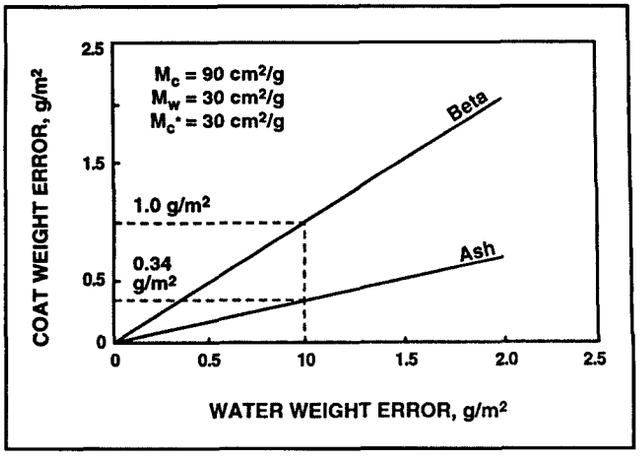
In the differential beta technique, the total mass of the material in the sheet is measured before and after coating is applied. This method is commonly used in measuring the coat basis weight, and it has low sensitivity to sheet composition.

The beta technique evaluates each constituent in the sheet according to its mass per unit area, without greater or less sensitivity to any particular one

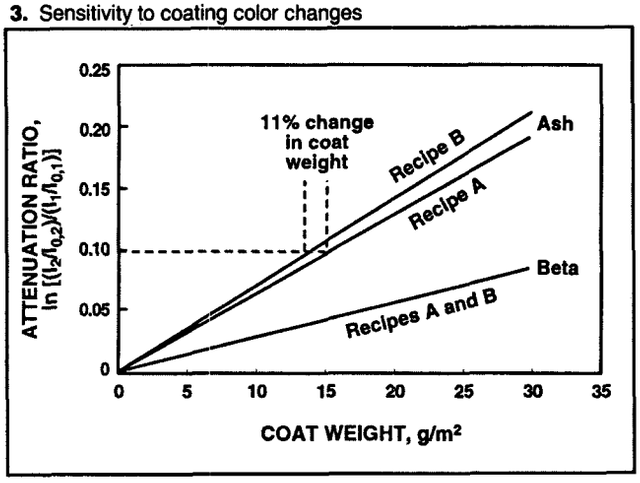
1. The sensitivity of the two techniques to coating



2. The effect of moisture sensitivity for each of the two techniques



3. Sensitivity to coating color changes



II. Recipes for Coatings A and B

	Coating recipe	
	A	B
M_c, cm²/g	65.2	72.5
Calculated coat wt.,* g/m²	15.3	13.8
Content, %		
Clay	38.4	37.1
Hardener	34.8	33.6
TiO_2	6.8	9.9
Starch	0.4	0.4
Latex	13.6	13.2
Residual	6.0	5.8

M_c β = 30.

*Fig. 3.

of the sheet components. Thus, the mass sensor is equally sensitive to fiber, coating, water, and other constituents. The coat weight is determined from the mass difference between the coated and uncoated sheet. The calculations are corrected for any difference in moisture, as determined by two moisture gauges, to yield the correct dry weight of the coating.

The beta method may be summarized using Eq. 1:

$$C = (T_2 - T_1) - (W_2 - W_1) \qquad (1)$$

where:

C = coat weight

T = total weight

W = water weight.

The subscript "1" designates conditions before coating is applied, and the subscript "2" designates conditions after the coating station.

Ash method

The ash method uses the attenuation of low-energy X-ray radiation before and after coating to determine the coat weight. This technique commonly uses photons of 5.9 keV from an Fe^{55} radioisotope. The attenuation of these photons in fiber is similar in magnitude to that of the beta particles from Kr^{85}. The low-energy photons are more highly absorbed in the inorganic materials used in coatings. These materials include clay (kaolin), calcium carbonate ($CaCO_3$), and titanium dioxide (TiO_2).

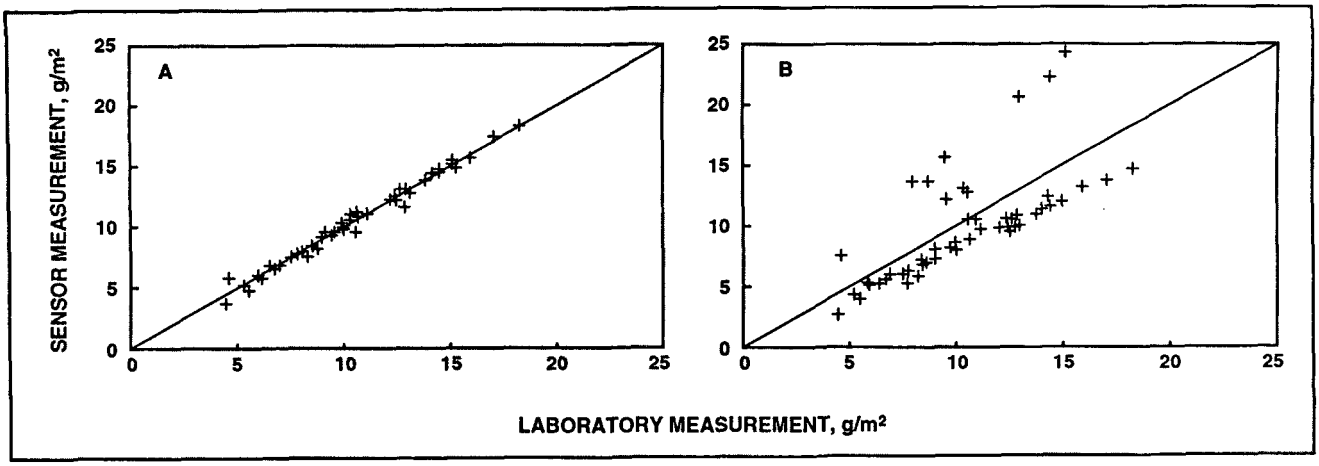
The radiation-absorbing properties of the material may be compared through mass absorption coefficient values, using the Lambert-Beer equation for photons and using it to approximate for beta particles. **Table I** is a partial list of experimental absorption coefficient values for paper and coating constituents.

I. Mass absorption coefficients for various coating constituents

	Coefficient	
Constituent	Beta,[a] cm²/g	Ash,[b] cm²/g
Kaolin 1	30	75
Kaolin 2	30	86
Talc	30	75
$CaCO_3$	30	165
TiO_2	30	290
$CaSO_4$	30	150
Latex	30	11
Starch	30	31
Residual	30	11
Hardener	30	41
Fiber	30	24
Water	30	30

[a] Approximate (Kr^{85}).
[b] Low-energy photons, 5.9 keV.

4. Ash coat weight correlations. A: correlation for ash measurement using static sampling. B: ash correlation using fixed calibrator



The measurement of coat weight by the ash technique may be summarized by Eq. 2:

$$C = (-1/M_c) \ln [(I_2/I_{0,2}) / (I_1/I_{0,1})] - (M_w/M_c)(W_2 - W_1) \quad (2)$$

where

C = coat weight

M_c = mass absorption coefficient for coating

M_w = mass absorption coefficient for water

I = radiation intensity with sample

I_0 = radiation intensity without sample

W = water weight.

The calibration parameter M_c is dependent on the coating composition. For accurate measurement, the correct recipe of the coating must be known. Because of the mono-energetic nature of the radiation, the factor M_c may be calculated by adding the constituent mass absorption coefficients weighted by their percentages in the coating.

The ash method may also be used with X-ray tube sensors. The emission spectrum of the sensor may be tuned to provide equal sensitivity to not more than three components (*2, 3*). Because typical coatings contain from two to eight components, this variation on the technique is also likely to require an accurate knowledge of the coating formulation.

Coat weight measurement

The need to calibrate four sensors is sometimes put forward as a disadvantage of the beta method (*4*). (Four sensors are involved because a moisture gauge is used with each beta sensor, one located before the coating station and one located after it.) The ash method requires the calibration of three separate functional devices for accurate measurement. These devices are two moisture sensors and the combined attenuation ratio of the two separate ash gauges. If a Lambert-Beer approximation is used for beta particle radiation, the differential beta measurement also reduces to the calibration of three functional devices:

$$C = (-1/M_c^*) \ln [(I_2/I_{0,2}) / (I_1/I_{0,1})] - (W_2 - W_1) \quad (3)$$

where

M_c^* = mass absorption coefficient of the coating for beta particle radiation.

Our previous experience in measuring coatings with the Betameter®[1] sensor indicates no sensitivity to coating constituents. In Eq. 3, the fact that the absorption coefficients of water and coating are essentially the same is evident from the term for correcting for moisture difference. The coat weight measurements derived using Eqs. 2 and 3 may be used to compare the two methods.

[1] Betameter is a registered trademark for the Valmet Automation sensor for basis weight.

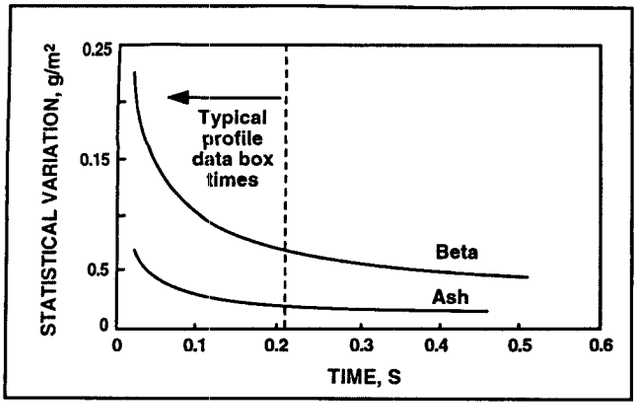
The sensitivities of the two techniques for a typical coating formula are compared in **Fig. 1**. The ash measurement shows higher sensitivity to the coating because of the higher photon absorption in the coating material. Depending on the coating composition, the sensitivity is three or more times higher than the sensitivity of the beta method.

Figure 2 shows the effect of an uncorrected moisture difference between the measurement locations. The coat weight error for the ash method is about one-third that for the beta method. For maximum accuracy, both methods require moisture measurement and correction.

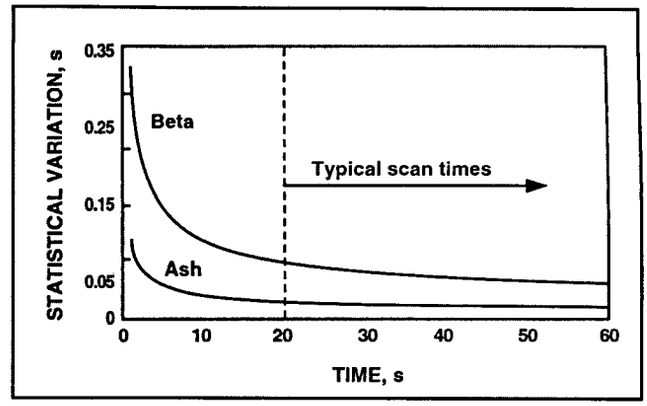
Although the ash method offers some measurement advantages, the coating absorption coefficient can change considerably with coating formulation. **Figure 3** shows the calculated coat weights using the two recipes given in **Table II** for the same radiation measurement from the ash sensors. As the figure shows, an 11.0% change in coating measurement results from an increase of 3.1 points in the percentage of titanium dioxide (from 6.8% to 9.9% TiO_2). The coating mass absorption coefficient can be calculated if the formulation and the mass absorption coefficients of the constituents are known.

The first graph in **Fig. 4** shows a correlation of an ash measurement system for static sampling (rather than on-line measurement). For this correlation, the coating type was entered, and the coating mass absorption coefficient was automatically calculated from stored data. These data were obtained from the analysis

5. Statistical precision of coat weight measurements over short measurement times



7. Statistical precision for scan averages over long measurement times



of samples with known color formulas, using de-convolution to determine the values for the coating components. The de-convolution procedure requires the measurement of many samples in the sensors and a detailed analysis of the coating absorption coefficients to determine the calibration for individual coating constituents.

The sample set shown in Fig. 4A includes 58 individual samples, with 24 different coating formulations. The constituents of the coatings include those shown in Table I. The overall standard deviation of 0.4 g/m² for the correlation is consistent with static sampling errors and laboratory uncertainties.

The importance of accurate values for the coating mass absorption coefficient is shown in Fig. 4B, where the average mass absorption coefficient for the coating sample set was used. Clearly, large deviations can occur if an incorrect value is used for the coating formula. This occurrence is particularly likely for coatings containing the more absorbing compounds, titanium dioxide or calcium carbonate. This complication is not a factor in the beta measurement, which is a major difference between the two methods. The beta difference method provides an absolute coat weight independent of the coating composition.

On-line measurements

For on-line measurement, there are two important requirements. The first is an accurate value of the coating applied. The second is a precise estimate of the variation of the applied coating over short distances and short times for cross-machine (CD) streak measurement and for machine-direction (MD) variation analysis.

6. On-line profiles of coat weight measured simultaneously by the beta and ash methods

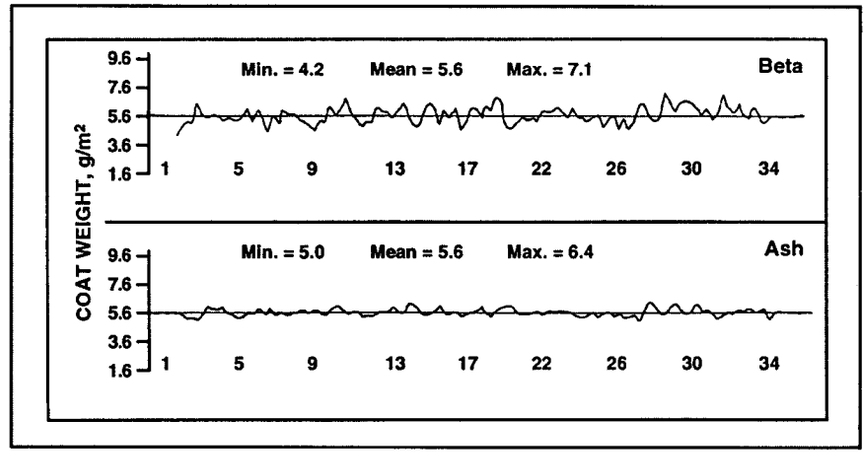


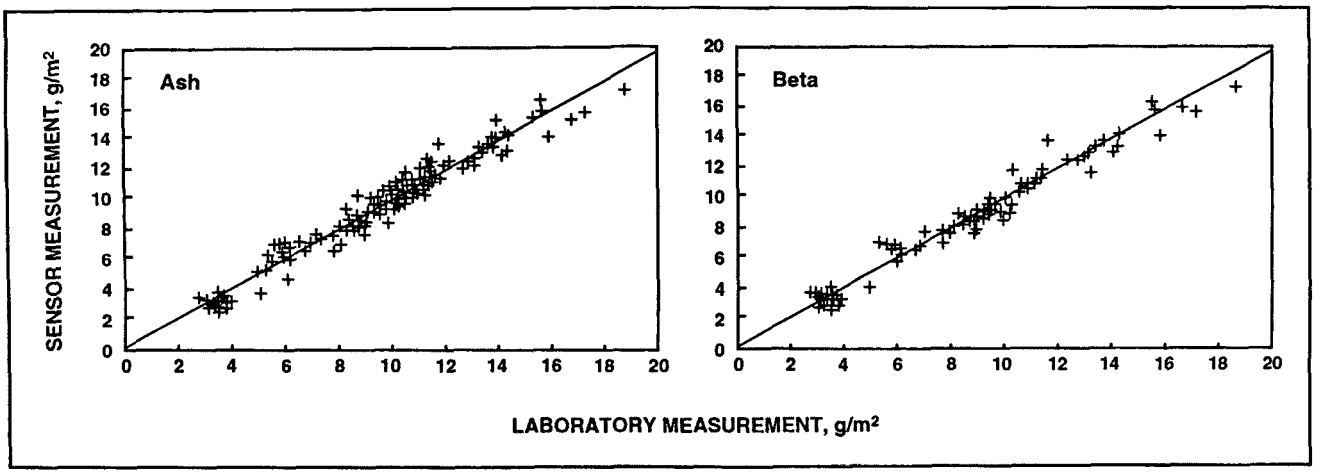
Figure 5 compares the static variation of the coat weight measurement by beta difference and ash difference. This variation results from the random nature of radioactive decay and the statistical propagation through the coat weight analysis. This variation is the contribution of the nuclear sensors to the overall uncertainty in the measurement.

For this calculation, signal-to-noise ratios were assumed to be equivalent for the beta and ash raw signals. The example is for a 100-g/m² basesheet coated to 20 g/m² with a coating absorption coefficient of 93.7 cm²/g. Of particular interest in this figure are points below 0.2 s, which would be typical of measurement times for a profile data box. (A data box is the distance scanned for each CD profile segment measurement.) Depending on the sensor and system characteristics, the data box time can be as low as 10-40 ms.

As the measurement time decreases, the uncertainty of the measurements increases with the beta method. At low measurement times, the uncertainty can be over 2 g/m² in the beta method, while the uncertainty in the ash method is less than 1 g/m². Thus, the differential ash method has advantages for CD streak detection and for MD variation measurement if fixed point data are taken.

Figure 6 illustrates this point using simultaneous profiles from the beta and ash coat weight measurements of lightly coated board. The CD variation for the ash method is a factor of two times less than that for the beta method. This difference results because of the higher precision of the ash method and the lower sensitivity to any variations in the basesheet weight and moisture.

8. Dynamic correlation results for ash and beta coat weight measurements



9. Consistency of the laboratory results

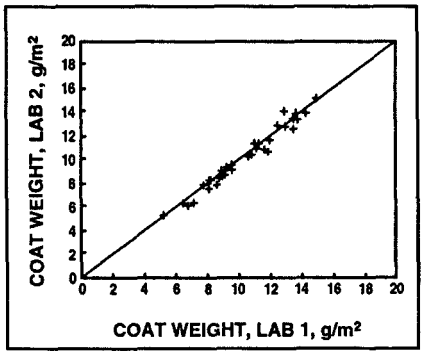


Figure 7 shows the statistical variation for longer measurement times. Of particular interest are times longer than 20 s, which corresponds to the time it takes to traverse the paper web. For these longer periods, the precision of both methods is better than 0.1 g/m², with a slight absolute advantage for the ash method. This level of uncertainty is slight compared with other sources of variability in the dynamic correlation, including process variation and laboratory testing error. When all sources of uncertainty are included, the correlation results are the same for the beta and ash methods.

Figure 8 shows dynamic correlation results for ash and beta coat weight measurements on a Valmet pilot coater running customer trials. The on-line data were obtained by placing the sensors at the same cross-machine position (fixed point) and averaging the collected data over 30 s. The ash correlation includes 161 points, with a standard deviation of 0.7 g/m² and a correlation coefficient of 0.98. The beta method correlation has 91 points with a standard deviation of 0.7 g/m² and a correlation coefficient of 0.98. More than 40 different formulas are represented in these correlations from actual trials. The ash data contain all of the tests shown in the beta correlation plus those from additional trials. In the beta sensor calibration, no knowledge of the coating formula was used.

The agreement between the two correlations supports the conditions shown in Fig. 7. Some of the variation on the ash difference correlation may result from variation of the coating mixture within a given recipe. This variation, combined with the ash statistical variation, yields a total measurement uncertainty equivalent to the beta method. When these sensor parameters are combined with the laboratory testing uncertainty and process variability, the final observed dynamic correlation is the same for both methods.

For these correlation tests, the laboratory uncertainty is a major contribution to the observed variation. **Figure 9** shows the consistency of the laboratory results. Here, the analysis of duplicate samples is plotted for comparison. The standard deviation of the correlation is 0.46 g/m², with a correlation coefficient of 0.99. The sensor-laboratory correlation also includes contributions from MD variations. The responses of the beta and ash sensors are the same, resulting in similar variations in both methods.

The fixed point testing simulates almost perfectly synchronized scanning on a production coater because both sensors "see" the same spot on the paper in the cross-machine direction. The ash method has been shown to be less sensitive to variations in moisture and basestock weight (*1,3*). This relative insensitivity is an advantage for nonsynchronized scanning because of the accumulation of errors in the beta method.

In synchronization, the two sets of sensors traverse the web in a coordinated fashion, monitoring along the same diagonal paths as each in turn moves across the web and the paper moves forward. When synchronization is used, the uncertainty of the beta method is reduced considerably. Only the normal variation of the sensor readings needs to be included, so no large errors result from the measurement of different positions on the sheet.

Synchronization is likely to result in equivalent scanning performance of the two methods for coated fine paper products. For heavier products, like paperboard with low coating, the ash method will show an advantage, particularly in streak profile definition, as Fig. 6 indicates.

Synchronization between the measurements improves both methods (*4*). Synchronized scanning is a feature of the system we used in this work.

Measurement applications

The choice of measurement technique depends on the application. For measurements of a single or few coating types with little moisture variation, two ash sensors may be sufficient. If moisture variations are common, it may be necessary to include moisture

measurements for both scanners.

For a wide range of products with many coating types, the use of the correct coating recipe is critical for the ash measurement of coat weight. Also, the coating mixture must be consistent over long periods of time with the original calibration. A combination of the beta and ash methods may be necessary to avoid large coat weight errors resulting from variations in coating color.

Errors can occur for a number of reasons, including entry of the wrong coating type and inaccurate calibration of coating constituents. Errors can also occur because of variations in raw materials and mixing processes. A combination of the beta difference and ash difference methods using Eqs. 2 and 3 can yield the ratio of the mass absorption coefficients for the ash and beta methods. Because the beta absorption coefficient is essentially constant, the coating absorption coefficient for the ash difference can be calculated. This calculation may be done over one scan or several scans because the coating formulation changes are likely to occur slowly over time. If the calculation is done over longer periods of time, the uncertainty in the calculated absorption coefficient will be minimized.

With this approach of combined beta and ash techniques, the absolute nature of the differential basis weight method can be used to limit systematic errors in the coating weight. The ash difference method can be used to provide high quality profile information because of the higher statistical precision and lower influence of basesheet and moisture variations.

In our on-line trials, we have used differential ash, differential beta, and the two combined for process optimization, measurement, and control of average coat weight and for CD coating control trials. For this work, it is important to have an accurate knowledge of the coating weight and high precision for the profile data boxes.

Control

We have been studying the use of microadjusters, known from headbox controls, on a blade coating station on the coater. Because of blade wear, the use of profiling screws on production coaters has been limited to direct manual operation, which leads to considerable settling times after a control action. A control action is effected by a change in blade angle; a change in the loading profile occurs simultaneously with a change in blade angle.

Coat weight is affected by a number of process parameters, the most important of which are coating color viscosity, base paper quality (roughness, moisture), machine speed, blade loading, and blade thickness. All these factors are at work when local coat weight changes are made using microadjusters. Additionally, when coating blades that are wearing are used, the history of control actions must be considered.

The response of a microadjuster profiling system to a control action depends on the geometry of the blade support system and the mechanical connection between the microadjuster rods and the blade support. The behavior of the response over time depends on the coat weight level, the paper quality, and the blade characteristics.

The use of ceramically coated blades has been limited by permanent quality problems, one of which has been a modest coat weight profile. A profiling system with a sufficiently narrow actuator spacing is a way to make the economic benefits of these blades available to papermakers without serious compromises in quality. Quality variations over a narrower extent than the actuator spacing must be mastered by other means.

Conclusions

Both the beta and ash coat weight measurement techniques can provide average scan values with high precision. The accuracy of each can be improved through the use of scan synchronization. Synchronization is especially important for accurate profile information and for the beta measurement.

The ash difference method offers advantages because of high sensitivity to coating and less influence of basesheet and moisture variations. This allows a more precise definition of coating variations, giving higher quality cross-machine profile information for the short time periods used to generate the profile data box values.

The ash sensor absolute measurement calibration is dependent on a knowledge of the coating color. Systematic coat weight errors can result from the use of improper recipes. This can occur through incorrect data entry, improper constituent calibration, and variations in raw materials or coating mixing. For applications with many coating types, a considerable calibration effort is required.

The best overall performance for coat weight measurement may be obtained by combining the best characteristics of the two methods. Beta difference is an absolute determination that can be used to calculate the average coat weight without the coating recipe information. The ash technique is essentially a relative measurement with high precision. The difficulty of systematic errors that can occur with the ash measurement can be limited by using a combination of the beta and ash methods to dynamically calculate the coating absorption coefficient for the ash difference. The combination of the two techniques gives an accurate absolute coat weight with better definition of coating variation.

An accurate absolute coat weight measurement with precise profile data box information is important for process optimization either through manual or automatic control. This is particularly true of automated CD control in which many parameters, including the history of control actions and blade wear, must be taken into account in the control algorithm.□

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