

Parameter design on the Cylindrical Laboratory Coater

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ABSTRACT *Parameter design, a technique developed by Genichi Taguchi, was used to determine the effects of speed, blade thickness, blade extension, and infrared drying conditions on the properties of the coated paper produced by the Cylindrical Laboratory Coater. These effects are small, especially for the wide changes in parameters studied here. The two levels of backing roll speed were 700 and 1400 m/min, for example. The largest effect on gloss was about 1.5 points, and the largest effect on opacity was 0.13. These small effects are shown to be significant, however, because of the low error variation of the coatings obtained with the CLC®. Three of these parameters—speed, blade thickness, and blade extension—are shown to be significant sources of error variation. Three-dimensional bar charts of Taguchi's signal-to-noise ratios are used to show the variability at different coat weights. The knowledge gained may be used to reduce or even eliminate these sources of variability for the many users of the CLC.*

KEYWORDS

Blade coaters
Coated papers
Coaters
Cylinder machines
Design
Gloss
Opacity
Parameters
Variability
Variables

For those paper coating laboratories that do not have pilot coaters available, the Cylindrical Laboratory Coater (CLC®) has proven to be an effective simulator of machine coating. It held out the promise of high-speed blade coating at more than 1800 m/min, great flexibility in operation, and coated sample sizes large enough for calendering and testing. All of these advantages can be obtained safely with minimal consumption of personnel time, coating raw materials, and rawstock. The features of the machine have been described in detail elsewhere (1). In brief, the machine was built with the ability to vary the speed of the backing roll, the coating dwell time before doctoring, the blade stiffness and extension, and the infrared preheat and drying conditions.

However, once the system design was established, it became the responsibility of the user to further tune the CLC for his or her own work. This

second phase is referred to as "parameter design" by Genichi Taguchi, the engineer whose ideas on quality have recently caused waves in the statistical community. As he said, "...the next step is to ascertain the optimal levels for the parameters of each element in the system so that the functional deviations of the product are minimized" (2).

The product in this case is a 16-m-long spiral strip of coated paper that is obtained from one pass of the coater head. Our purpose was to determine the effects that speed, the blade dimensions, and infrared drying conditions have on the coated paper produced on the Cylindrical Laboratory Coater. This knowledge can be used to reduce the variability of the coated paper produced, enabling us to make more accurate assessments of the performance of our products.

Parameter design

Inner and outer arrays

Montgomery described and thoroughly analyzed the Taguchi approach to parameter design (3). In Taguchi's methodology, one design is selected for controllable factors, and another is selected for noise or uncontrollable (conditioning) factors. In this complete layout of parameter design, the array containing controllable factors is called the "inner" array, while the array containing the noise factors is called the "outer" array.

In the example described by Taguchi, each of the nine runs from the inner array is tested across the eight runs from the outer array, for a total sample size of 72 runs. A criticism leveled at the Taguchi approach to parameter design is that the scheme for inner and outer arrays usually leads to a very large experiment. In the testing of electronic components, a large experiment in which only one

I. Taguchi "L₈" orthogonal design matrix

Run	Speed, m/min	Thick- ness, mm	Exten- sion, mm	Dummy	Pond dwell, cm	Pre- coat dry, %/s	Post- coat dry, %/s
1	-1	-1	-1	-1	-1	-1	-1
2	-1	-1	-1	1	1	1	1
3	-1	1	1	-1	-1	1	1
4	-1	1	1	1	1	-1	-1
5	1	-1	1	-1	1	-1	1
6	1	-1	1	1	-1	1	-1
7	1	1	-1	-1	1	1	-1
8	1	1	-1	1	-1	-1	1
Lower (-1)	700	0.38	15.24		3.66	15/5	40/40
Upper (+1)	1400	0.64	10.16		6.20	80/15	80/20

response is measured may be quite practical. In the case of paper coating on the CLC, with a dozen or more responses, it is not.

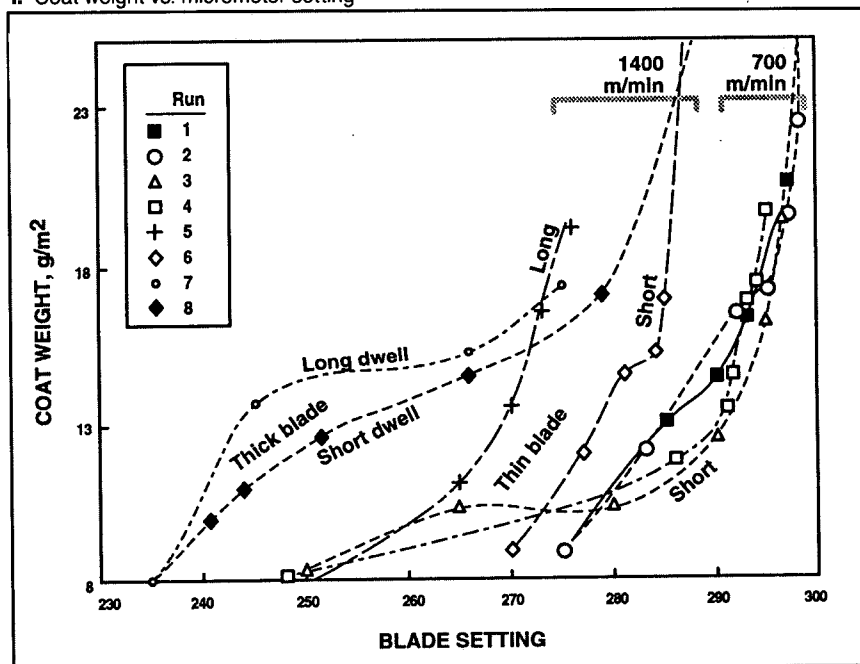
Thus, for the purpose of these experiments, the original parameter design has been modified. The outer array, which contains the uncontrollable variables, was not used. Such variables as temperature and humidity variations and human error during calendering and testing are minimized to the greatest possible extent and are dealt with in the final analysis.

The independent variables

For our parameter design study, we selected an L₈ orthogonal array for the study of the controllable factors. This array is shown in Table I. The -1s and +1s represent the two levels of the independent variable indicated in each column. Actual lower and upper levels of these variables are shown in the two rows at the bottom of the table. Taking the speed column as an example, each -1 would be replaced with 700 m/min in practice, and each 1 would be replaced by 1400 m/min.

The speed levels were set at 700 and 1400 m/min (2295 and 4590 ft/min). The blade thickness was either 0.381 or 0.635 mm (0.015 or 0.025 in.). The -1 for blade extension from the clamp represents 15.24 mm (0.6 in.), and the +1 represents 10.16 mm (0.4 in.). The pond dwell was set at 3.66 and 6.20 cm (1.441 and 2.441 in.). The lower level of rawstock precoat drying was set at 15% power for 5 s, and the upper level for this factor was set at 80%

1. Coat weight vs. micrometer setting



power for 15 s. Finally, the post-coating dry levels were set at 40% power for 40 s and 80% for 20 s, as shown.

Other practitioners have suggested that at least two of the columns should not be assigned to an independent variable, to give some measure of error variation. Taguchi always recommends running a saturated design, one in which every column represents a variable. Note that the middle column in Table I was not assigned to a factor. We did this to show that the spreadsheet used for this analysis can handle dummy

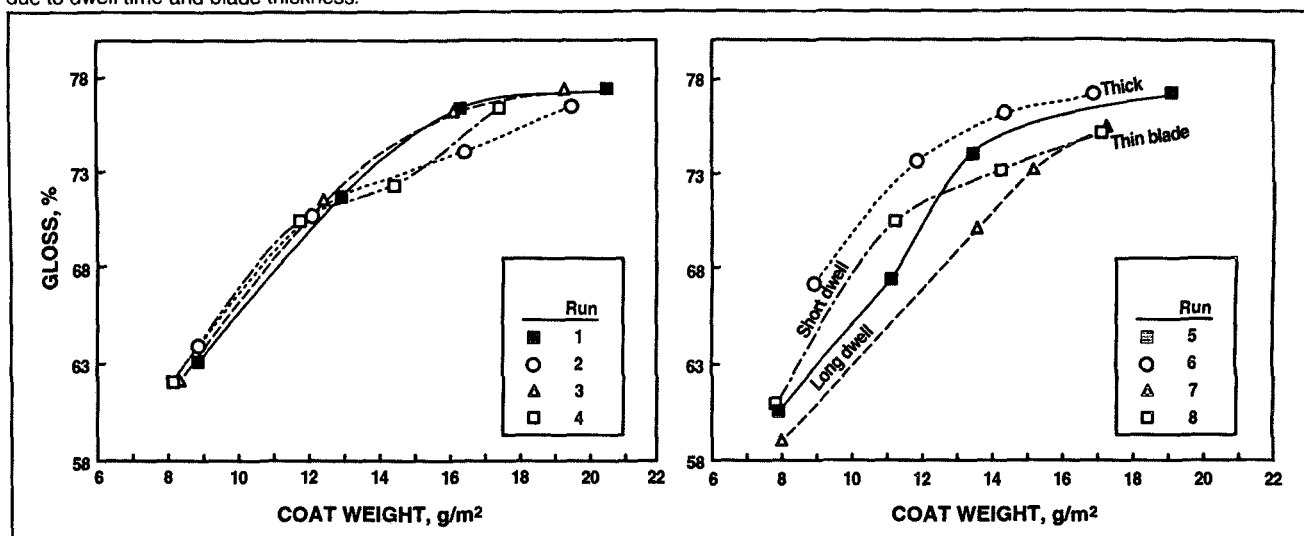
variables selected either before or after the experiment. In this case, an independent variable which has an effect smaller than the dummy is assigned this status to obtain an adequate measure of variability.

Experimental procedures and results

Procedures

The coating color was prepared with 50 dry parts each of a high-brightness No. 1 coating clay and a fine-ground calcium carbonate. An additional 0.1

2. At 700 m/min, the differences in gloss by coat weight are caused mainly by differences in dwell time. At 1400 m/min, the effects are due to dwell time and blade thickness.



II. Interpolated values of physical properties in response to a coat weight of 10 lb/3300 ft²

Property	Run number							
	1	2	3	4	5	6	7	8
Gloss, %	74.7	73.0	74.8	72.7	75.3	76.2	72.4	73.5
Brightness, %	78.4	78.4	78.5	78.9	78.4	78.2	78.2	78.4
Opacity, %	95.1	95.1	95.2	95.1	95.0	95.0	95.0	95.1
Print gloss	88.7	87.7	87.4	88.1	89.4	87.8	85.9	86.5
Roughness, μm	0.930	0.960	0.925	0.918	0.975	1.000	0.900	0.955
Porosity, s	5.30	4.40	3.00	5.25	4.43	5.93	4.60	5.30
Density	1.834	1.826	1.822	1.831	1.838	1.831	1.823	1.828
K&N brightness, %	65.0	66.3	66.2	63.5	64.6	65.8	64.8	64.0
IGT speed	120	124	113	100	126	106	110	106
Wet pick	0.54	0.54	0.48	0.63	0.57	0.62	0.59	0.44

pph of a polyacrylate dispersant was added to the pigment dispersion. Fifteen dry parts of a styrene-butadiene latex, designed for blister-resistant performance on web offset printing grades, were used. In addition, 0.4 pph of a calcium stearate lubricant was used.

The total solids content of this color was 64%, and the viscosity was adjusted to 1000 cp (Brookfield, Model RV, No. 5 spindle at 100 rpm) with medium-viscosity CMC (carboxymethyl cellulose). The pH was adjusted to 8.5 with sodium hydroxide. Target

coat weights for the runs on the CLC were 9, 12, 15, and 18 g/m² (6.0, 8.1, 10.1, and 12.2 lb/3300 ft²).

A specified coat weight was obtained through an iterative process. The micrometer, which controls the blade loading to the sheet during coating, had to be changed for each condition within our parameter design.

The setting had to be changed to adjust for each set of machine conditions in the design. At 700 m/min, it was easier to predict which setting would give the desired coat weight, since its response to the micrometer

setting was about the same for Runs 1-4 (Fig. 1). At 1400 m/min, it took quite a few trials to determine the exact micrometer setting to get a specific coat weight, since the influences of blade thickness and pond dwell were more pronounced at the higher speed. For Runs 5-8, using the thin blade, the micrometer setting had to be 12-22 points lower (higher blade loading) at 1400 m/min than its setting at 700 m/min to get a specified coating weight of 12 g/m². When the thicker blade was used, because it applied less force per unit area to the

sheet, the micrometer setting had to be 26–30 points lower at 1400 m/min than at 700 m/min. The blade loading required to obtain a specific coat weight at a specific speed was also affected by the dwell of the coating before doctoring. Longer dwell required more blade loading to obtain the same coat weight.

Since it would take quite a few trials to obtain the exact micrometer setting to obtain a specific coat weight, we used the following procedure. When a coat weight within about 1 g/m² of the target coat weight was obtained, the iterative process was stopped, and that weight was accepted. The trials for the next coat weight then began. After a flaw-free sheet (free of streaks and spatter) was made at each coat weight for each parameter setting, the experiment was complete. The actual coat weights measured ranged from 7.8 to 20.5 g/m².

The coated area of the sheet was trimmed and cut into pieces 12.7 cm wide by about 40 cm long. Samples were conditioned at 23 ± 1°C and 50% ± 2% RH for 12 days before testing began. The pieces were calendered in three nips of steel over Supertex® at 118°C, 50 ft/min, and 1000 psi through the Beloit Wheeler Laboratory Calender. Ten readings were taken of gloss, brightness, opacity, Sheffield porosity, and Parker Print Surf roughness of the coated, calendered paper.

Ten readings were taken of gloss, brightness, opacity, and Sheffield porosity. Ten readings of Parker Print Surf roughness were taken for the coated, calendered paper, and ten readings each of gloss and optical density were taken for the printed paper. Prints were made with 0.3 mL of Suntec 1300 web offset heat-set cyan (21725) ink applied on the Prufbau Multipurpose Printability Tester at 1000 N and 1 m/s. Ten readings were taken of the gloss and optical density of the prints. In the more elaborate, time-consuming tests, fewer tests were done. The IGT pick velocity was replicated four times, the K&N brightness was run three times, and the Prufbau wet pick and oven blister tests were run twice.

Results

The actual gloss readings for Runs 1–4 at 700 m/min are shown in the graph on the left in Fig. 2. Notice that

III. Effects of independent variables on responses at a coating weight of 10 lb/3300 ft²

Variable	Dummy	Effect	Student's t test	Probability, %
<u>Gloss</u>				
Speed		0.55	1.997	85.7
Thickness		-1.45	5.265	99.6
Extension		1.35	4.902	99.4
Dummy		-0.45	1.634	79.1
Dwell		-1.45	5.265	99.6
Dummy	*	0.05	0.182	13.7
Dummy	*	0.15	0.545	38.2
<u>Brightness</u>				
Speed		-0.213	3.422	94.2
Thickness		0.188	3.019	91.8
Extension		0.138	2.214	84.1
Dummy		0.088	1.409	68.9
Dwell		0.108	1.731	76.2
Pre-dry		-0.193	3.100	92.4
Dummy	*	0.008	0.121	9.5
<u>Opacity</u>				
Speed		-0.128	51.000	100.0
Thickness		0.053	21.000	100.0
Dummy	*	-0.003	1.000	56.4
Dummy		0.003	1.000	56.4
Dwell		-0.043	17.000	100.0
Pre-dry		-0.003	1.000	56.4
Post-dry		0.013	5.000	98.4
<u>Print gloss</u>				
Speed		-0.58	2.335	85.6
Thickness		-1.42	5.787	99.2
Extension		0.98	3.960	96.3
Dummy		-0.32	1.320	66.6
Dwell		0.18	0.711	44.6
Pre-dry		-0.98	3.960	96.3
Dummy	*	0.12	0.508	34.4

the lines are superimposed at low coat weights. This figure shows that Run 2 yielded lower gloss than Run 1 at coat weights above 13 g/m². This result is definitely not the effect of speed, blade thickness, or blade extension, because these parameters were the same for Runs 1 and 2. This effect was due to the dwell, since pre-dry or post-dry conditions were negligible, as we will see later. Similarly, Run 4 gave lower gloss than Run 3 at higher coat weights, with the same conclusion.

When you examine the Runs 5–8 in the graph on the right, the influences of blade thickness and dwell are clear. At 10 g/m², the gloss for short dwell is five points higher than for long dwell, whether the blade is thick or

thin. By comparison, the thick blade yielded only 2.5 points higher gloss than the thin blade. At higher coat weights, the difference between short and long dwell diminishes at 17 g/m²: the thicker blade gave 2.5 points higher gloss than the thin blade.

These data were used to prepare plots of each response against coat weight. This was done with the "spline fit" option in the graphics software called Energraphics® (Version 2.2). The spline fit option generates a smooth curve that is constrained to pass through every point. The scales were expanded so that an accurate interpolation could be obtained. The value of each response at 8, 12, 14.8 (10 lb/3300 ft²), and 17 g/m² was

IV. Summary of the significant effects of independent variables on means of physical properties at 90% probability

Property	Speed	Thickness	Extension	Dwell	Pre-dry	Post-dry
Gloss		-1.45	1.35	-1.45	Dummy	Dummy
Brightness	-0.21	0.19			-0.19	Dummy
Opacity	-0.13	0.05	Dummy	-0.04		0.01
Print gloss		-1.4	1.0		-1.0	Dummy
Roughness			-0.04		Dummy	Dummy
Porosity			Dummy	Dummy		
Density	0.0018	-0.0063	0.0028	Dummy	-0.0073	
K&N brightness		-0.8	Dummy		1.5	
IGT speed	Dummy	-12		Dummy	Dummy	
Wet pick	Dummy	-0.033	0.048	0.063		-0.088

V. Summary of the significant effects of independent variables on signal-to-noise ratios at 95% probability

Property	Speed	Thickness	Extension	Dwell	Pre-dry	Post-dry
Gloss		Dummy				
Brightness	Dummy					
Opacity	-7.1	5.6		Dummy	Dummy	
Print gloss	-2.7	5.3	-4.1		-2.3	Dummy
Roughness						Dummy
Porosity			-5.1	Dummy		Dummy
Density		3.1	-2.3	Dummy	Dummy	
K&N brightness		6.4	Dummy	Dummy		
IGT pick speed			5.2	Dummy		Dummy

obtained in this way. The interpolated responses are shown in Table II.

Analysis of the experimental design

The design was analyzed with a Lotus 1-2-3® spreadsheet template that is an improved version of the template described earlier (4). With the new template, dummies can be assigned either before the experiment or after it is completed. In this experiment, the middle variable in the design was already defined as a dummy. After the experiment, a second or even a third independent variable that had a small effect was assigned this status.

The Student's *t* values in Table III

are ratios of effects to a measure of error variance. Student's *t* values indicate the significance of the effects. The probabilities are calculated from these values.

Significant effects

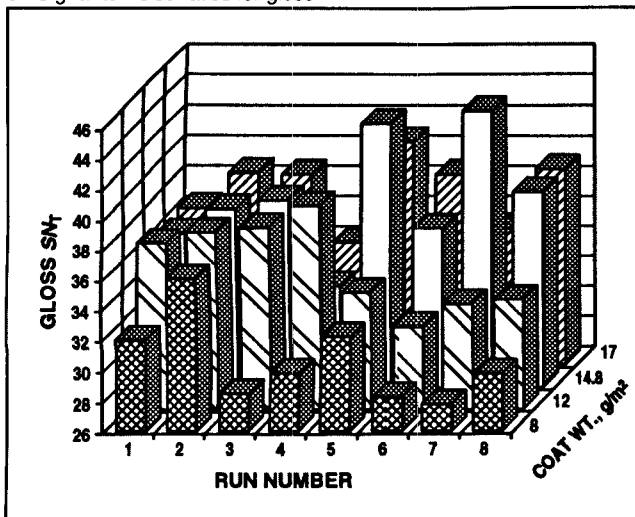
Table III shows the effects of the six independent variables on four of the optical properties at 14.8 g/m². Significant effects on gloss, brightness, opacity, and print gloss were observed even though the paper was coated with the same coating color.

In the case of gloss, blade thickness and pond dwell both gave a 1.45-point decrease, while the shorter extension gave 1.35 points higher gloss. While the magnitudes of these effects might

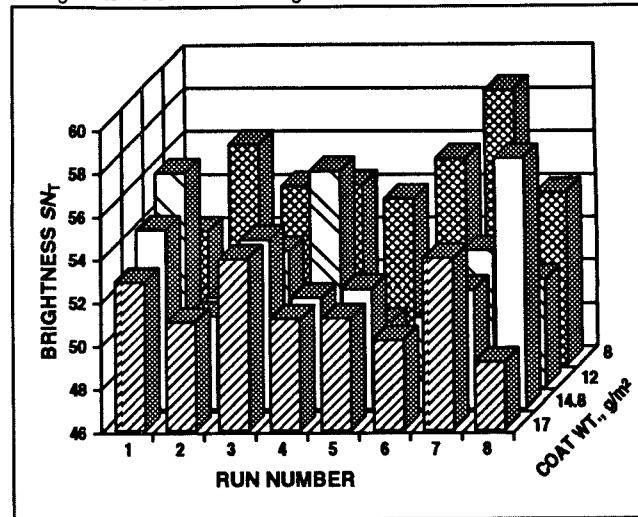
not be considered significant in a less-controlled experiment, the analysis of variance shows that there is more than a 99% probability that these effects on the means are significant. The two drying variables, pre-dry and post-dry, had such a small effect on gloss that they were marked as dummies with an asterisk in the table.

For brightness, machine speed, blade thickness and pre-dry conditions each had a significant effect (90% probability). Opacity was influenced strongly (100% probability) by machine speed, blade thickness, and pond dwell. The higher machine speed gave a 0.128-point decrease in opacity, while the thicker blade yielded a 0.053-point increase in opacity. This

3. Signal-to-noise ratios for gloss



4. Signal-to-noise ratios for brightness



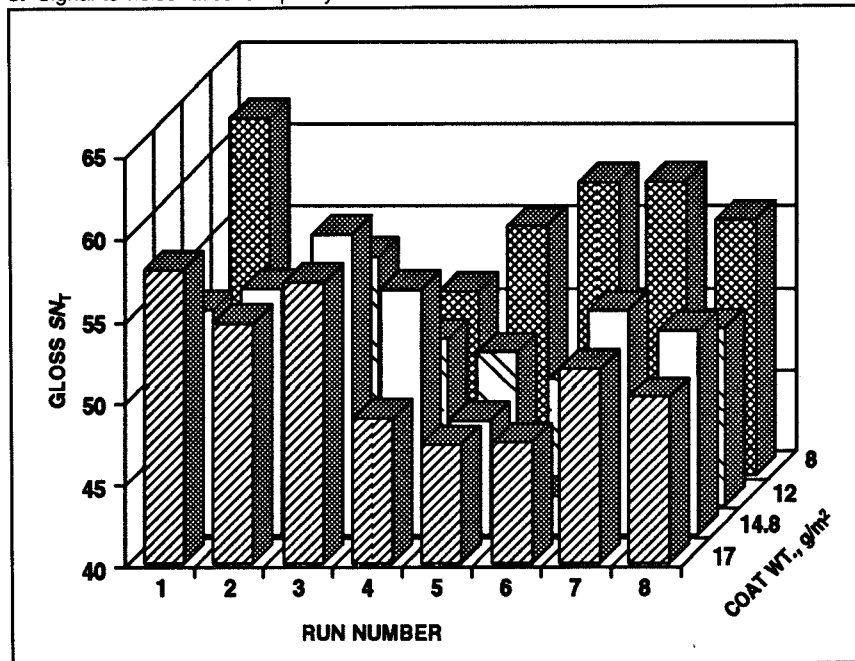
result can be attributed to the very small variability seen with the dummies (-0.003). Print gloss was affected by blade thickness (a 1.4-point decrease), extension (a 1-point increase), and pre-dry (a 1-point decrease). The magnitudes of the significant effects of machine parameters on brightness and opacity may not be too surprising, considering the reproducibility of these tests. However, it might be surprising that the significant effects of some parameters on the two means of the gloss measurements are of the order of one point. Tables similar to Table III are generated for all of the properties by the Lotus 1-2-3 template.

A brief summary of the significant effects of the machine parameters examined in this study is shown in Table IV at 90% probability. Blade thickness had a significant effect on almost every property except porosity and roughness. A shorter blade extension had a positive effect on gloss, print gloss, optical density of the print, and wet pick. Higher pre-dry conditions decreased brightness and optical density. Higher machine speed yielded lower brightness and opacity at this coat weight but yielded significantly increased optical density of the print. Even post-dry conditions had a strong effect on opacity (+0.01) and wet pick (-0.088).

Variability

In the case of the optical measurements, which were replicated ten times, the standard deviations are generally lower than one, even for the

5. Signal-to-noise ratios for opacity



two gloss determinations. Taguchi suggests that the variation be analyzed using an appropriate signal-to-noise ratio (SN). Since the goal here is reproducibility, the "nominal best" ratio was selected:

$$SN_T = 10 \log (\bar{y}^2 / S^2) \quad (1)$$

where

$\bar{y}$ = mean of the given property

S^2 = variance

T = subscript denoting nominal best.

Table V shows the significant effects of the independent variables on the signal-to-noise ratio of each property at 95% probability. The objective here is for us to maximize the value of SN_T .

The higher speed decreased the SN_T for opacity (-7.1) and print gloss (-2.7). The thicker blade gave much more reproducible results—that is, it increased the SN_T for opacity, print gloss, print density, and K&N ink brightness. On the other hand, the shorter blade extension produced coatings with more variable print gloss and porosity. It reduced their

respective SN_T s. Pre-dry and post-dry conditions had few significant effects on the signal-to-noise ratios, and pond dwell time had no effect at all.

These signal-to-noise ratios, derived from Taguchi's quadratic loss function (3), are a convenient way of displaying the variability of the data obtained with the Cylindrical Laboratory Coater. In Fig. 3, the SN_T s for the gloss measurements are plotted against run numbers and coat weights. The taller bars in these plots represent the lower variances, since the means are relatively invariant. The SN_T for gloss is lower for each run at the lower coat weight. The greater variability of the gloss at 8 g/m² is due to show-through of the basestock. Ten gloss readings on this basestock gave a mean gloss of 6.5, with an S_{n-1} of 0.4. The SN_T s are highest above 12 g/m², at the highest machine speeds (white bars).

As Fig. 4 shows, brightness SN_T s are the highest at the 8-g/m² coat weight. (In this figure, for visibility purposes, the order of coat weights is reversed in comparison to Fig. 3.) The reduced variability of brightness at lower coat weights reflects the increased contribution of the base

paper. The mean and standard deviation for ten brightness readings on the 59-lb basestock were 77.28 and 0.04, respectively. The variance here is only 0.0016. The statistical situation was similar for opacity (Fig. 5) and K&N brightness (not shown).

Conclusions

Our purpose was to demonstrate the use of parameter design to analyze the effects of CLC variables on coated paper properties. The power of this tool is evident in that, with only eight experiments, we were able to draw conclusions on the effects of as many as seven variables. Furthermore, the precision of this experiment was such that levels of absolute difference that might otherwise have been thought to be insignificant were proven to be significant in the analysis.

On the whole, the number of variables tested on the CLC in this experiment were not overwhelming. Parameter design may be used in other multivariate experiments to extract the maximum number of conclusions for a limited amount of experimental time. □

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Thanks to Louis Bertrand of Reichhold's Dover laboratory for completing the 2592 individual measurements required for this study.

The Cylindrical Laboratory Coater 6000 was manufactured by Sensor & Simulation Products, a division of Weyerhaeuser Company, Tacoma, Wash. 98477. CLC is a registered trademark of Sensors and Simulation Products.

Energraphics is available from Enertronics Research, Inc., 1910 Pine Street, St. Louis, MO 63103.

A copy of the Lotus 1-2-3. experimental design template used in this study is available from the authors. Please include a formatted high-density disk of any size.

Received Nov. 11, 1991.

Accepted Dec. 10, 1991.

Presented at the TAPPI 1992 Coating Conference

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