

Curl in a five-layer coextruded film

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ABSTRACT *A saturated fractional factorial experimental design was used to determine the cause of curl in a five-layer, coextruded, blown-film structure. The effects of seven processing and film-structure parameters on curl were evaluated. The causes of the curl were identified using a parsimonious experimental design that required only eight experimental runs.*

KEYWORDS

Coextrusion
Defects
Film (plastic)
Film formers
Statistical
analysis

Design of experiments (DOE) procedures have been around for many years. They are an English invention used in the 1930s and 1940s in agriculture and biological sciences. In the 1960s and 1970s, the Japanese used this method of testing extensively to improve their technical understanding, improve product quality, and develop manufacturing processes. The original methodology was modified for industrial applications at this time by Genichi Taguchi and others. In the late 1970s and early 1980s, the Japanese successes broadened the interest of American manufacturers in DOE techniques. Much of American industry now recognizes the utility and power of the DOE technique for analyzing and improving manufacturing processes and products.

This report discusses the application of DOE techniques to analyze and study curl in a five-layer coextrusion film process. The primary objective is to show that the DOE technique is easily applied to the blown-film process.

Curl

The curl problem occurred during the product-development phase of a coextruded film. Quick-fix attempts based on experience, theory, or "first prin-

ciples" were unsuccessful. A designed experiment was chosen as the next course of action.

When a piece of coextruded film is placed on a flat surface, the edges and sides of the film can either lie flat against the surface or they can curl away from or toward the surface. In extreme cases, a film with curl can actually roll up like a window shade around its core.

In some film products, curl is objectionable because of aesthetic considerations. Excessive curl also can cause problems when the coextruded film is processed downstream.

Curl is a common phenomenon in coextruded films. Processing conditions, equipment design, and a material's processing characteristics and thermal-expansion characteristics can contribute to curl. During the blown-film process, the polymeric materials solidify from a melt and shrink into a solid as they near the frost line. The amount of shrinkage varies with different materials, and differences in shrinkage can cause curl in a coextruded structure. These effects are also related to the crystalline structure formation in crystalline polymers. Process-related variables such as melt temperature, output rate, shear in the die, drawdown, and shear rate also can affect curl.

The coextrusion structure itself

provides a different set of variables that can affect curl. The materials at the surfaces have a larger effect than the core materials. Sometimes curl can be balanced by judiciously layering different materials to counteract the effects of shrinkage. Changing relative layer thicknesses is another variable in the structure-balancing technique. The moduli of the various materials in the structure can be a major factor influencing curl.

Given this wide range of variables, it can be very difficult, if not impossible, to predict curl in complex coextruded film structures from first principles or knowledge of the process.

Designed experiments

One method of testing the effects of several variables is to run all combinations of variables at two test levels and analyze the resulting data. This is known as a full factorial experimental design. Studying seven test variables at two levels would involve 128 tests or samples. Performance of a full factorial experiment would reveal the effects of all the variables and all their interactions.

It is possible to reduce the number of tests and still obtain all the useful information generated by testing all possible sample combinations. Such

III. Experimental design for seven variables and eight samples

Sample No.	Variable A		Variable B	Variable C	Variable D		Variable E	Variable F	Variable G
	Output rate, kg/h (lb/h)		Melt temp. EVA (Layer V)*	Melt temp. HDPE (Layer Z)*	Thickness, μm (mils)		HDPE content (Layer Z), %	EVA content (Layer V), %	Frost-line height, cm
1	200	(435)	Low	Low	25 (1)		20	10	28
2	200	(435)	Low	Low	76 (3)		10	20	64
3	200	(435)	High	High	25 (1)		20	20	64
4	200	(435)	High	High	76 (3)		10	10	28
5	135	(295)	Low	High	25 (1)		10	10	64
6	135	(295)	Low	High	76 (3)		20	20	28
7	135	(295)	High	Low	25 (1)		10	20	28
8	135	(295)	High	Low	76 (3)		20	10	64

*See Table IV for temperature profiles

an approach is known as a fractional factorial experimental design. The purpose of a designed experiment is to extract the useful information using a minimum number of test runs. Information about experimental design methods is available in the literature (1-4).

What is lost by the shorter test series is the full analysis of all the possible interactions of the variables. An interaction occurs when the response of one variable depends on the value of a second factor. In such a case, the effect of one variable is determined by the operation of a second variable.

Most processes are controlled by single variables or the interaction of two variables. Under this assumption, it is possible to reduce the number of tests. This is what makes the designed-experiment technique such an effective testing tool.

The curl problem was analyzed using a screening design. Seven variables were studied using eight test samples. This is known as a "saturated factorial" because the number of factors is only one less than the number of test samples. Such an experimental design allows the highest number of variables to be tested while running the fewest samples.

Equipment

The tests were run on a five-layer coextrusion line with a 400-mm (16-in.) die. Table I shows the structure of the five-layer film. Three 90-mm (3.5-in.) extruders fed layers V (outside), X (center), and Z (inside). Two

I. Structure of five-layer film

Layer	Material ^a	Content, %
V (outer)	EVA	10
W	HDPE	20
X (core)	LDPE	50 ^b
Y	LDPE	
Z (inner)	HDPE	20

^aEVA = ethylene-vinyl acetate; HDPE = high-density polyethylene; LDPE = low-density polyethylene
^bThe 50% LDPE content applies to both Layer X and Layer Y

II. Seven variables used in study of five-layer film

A	Output rate, kg/h
B	EVA melt temperature (Layer V), °C
C	HDPE melt temperature (Layer Z), °C
D	Film thickness, μm
E	HDPE content (Layer Z), %
F	EVA content (Layer V), %
G	Frost-line height, cm

IV. Temperature profiles for Variable B (melt temperature of EVA in the outer surface layer V) and Variable C (melt temperature of HDPE in the inner surface layer Z)

Extruder zone	EVA melt temp., °C (°F)				HDPE melt temp., °C (°F)			
	Low		High		Low		High	
1	77	(170)	88	(190)	93	(200)	104	(220)
2	99	(210)	110	(230)	193	(380)	204	(400)
3	141	(285)	152	(305)	199	(390)	216	(420)
4	141	(285)	157	(315)	199	(390)	216	(420)
5	141	(285)	163	(325)	199	(390)	216	(420)

65-mm (2.5-in.) extruders fed the W and Y layers. The line's width was 1800 mm (70 in.). The film was wound using a surface/center winder. A dual-lip air ring was used to cool the bubble, and a bubble cage was used to further stabilize the bubble.

The extruder's control system made it easy to change the film structure and the extrusion process. Each extruder was fed and controlled by a gravimetric weight feeding system, while the average layer thicknesses

were monitored and controlled by a microprocessor. A printout of the main process variables was available for each of the eight samples. Thus the changes made during the testing were quick, repeatable, accurate, and easily documented.

Test configuration

Table II shows the seven variables selected for the study. The variables were chosen carefully after much in-

V. Curl rating (1-5) for the eight test samples

Sample No.	MD curl	TD curl	Overall curl
1	4	3	3
2	3	3	2
3	3	4	4
4	1	1	2
5	2	2	2
6	5	4	5
7	2	2	2
8	5	5	5

VI. ANOVA table for determining the contribution to curl for each of the seven tested variables

Variable	Degrees of freedom	Sum of squares	Mean square error	F-ratio	Percent contribution
A (output rate)	1	1.125	1.125	9.00	7.8
B (melt temp. EVA—Layer V)	...	0.125	0.125	...	...
C (melt temp. HDPE—Layer Z)	...	0.125	0.125	...	...
D (film thickness)	1	1.125	1.125	9.00	7.8
E (HDPE content—Layer Z)	1	10.125	10.125	81.00	77.6
F (EVA content—Layer V)	...	0.125	0.125	...	...
G (frost-line height)	...	0.125	0.125	...	...
Error term*	4	0.500	0.125	...	6.8
Total	7	12.875	1.839	...	100

*Error term — applies to pooled nonsignificant factors

house brainstorming and discussions with equipment suppliers and resin suppliers. The variables were selected to test as many theories as possible regarding the causes of curl. It was not necessary to understand all the scientific phenomena that affect curl to design the test. However, a knowledge of the process and an understanding of the possible reasons for curl was essential to assure that the correct variables were selected for testing. Inclusion of all the independent machine variables that had a major influence on curl was crucial to the success of the analysis.

Table III shows the experimental test design for the seven machine variables and the eight sample runs. Each variable was run at a high and a low setting. Table IV shows the extruder temperature profiles used for Variables B and C.

Randomization/equilibrium

Randomization of variables is important in designed experiments to assure good test results. However, on large production equipment, the amount of running time and material usage are cost factors that need to be considered in designing an experiment. In this experiment, the order of the samples was chosen to reduce line running time rather than for optimal randomization.

The possible detrimental effects of not randomizing the test order was considered by testing the curl as a function of time on the samples run. Testing showed that after 20 min of running at any given condition, fur-

ther changes in curl did not occur. Film at the desired test conditions was run for at least 30 min before saving the sample for evaluation of the curl.

Test results

Film samples measuring 15-cm × 15-cm were cut from around the bubble at each test condition. The samples were laid on a flat surface, and the amount of curl from each sample was observed. Since curl was uniform around the bubble, only one sample from each run condition was needed to determine a curl "number" for each test condition.

The film samples were rated for curl on a scale of 1-5. A rating of 1 meant no curl, while a rating of 5 represented the highest level of curl observed in the test samples. Table V shows the test data on curl for the eight samples run, using the 1-5 rating system for curl. Machine-direction (MD) and transverse-direction (TD) curl differed slightly for the samples compared. Thus, curl in each direction was rated separately. Since any curl in the film was objectionable, an overall curl-severity rating was also given to the samples. The overall curl rating was used for all data analysis.

One of the common means of data analysis for designed experiments is an analysis of variance (ANOVA) table (1, 4). Table VI shows the ANOVA table for the overall curl. Figure 1 illustrates the effects of the seven variables on curl.

Discussion of results

Significance of factors

From Table VI, the last column shows the relative percent contribution for all of the statistically significant factors affecting overall curl. This analysis was carried out using a commercial computer program (5). The relative effects of the test variables on curl are summarized below.

- 77.6% of the test variation was from factor E, the percentage of HDPE in the inner layer. The lower percentage produced less curl.
- 7.8% of the test variation was from factor A, the output rate. The higher output rate produced less curl.
- 7.8% of the test variation was from factor D, the film thickness. The lower thickness film produced less curl.

The other tested variables had no statistically significant effect on curl. The "error term" in the ANOVA table is the amount of variation that is not associated with the evaluated test variables. The "error" can be from experimental error, from unexplained test variations, or from pooling of the nonsignificant test factors. The error term for this experiment was 6.8%, a low level of error and acceptable for this analysis.

Regression equation for curl

From this analysis, using a computer program for analysis (6), the regression equation for curl was found to be:

$$CR = 0.955 - 0.0054 A + 0.375 D + 0.225 E$$

where

CR = curl rating

A = output, lb/h

D = film thickness, mils

E = HDPE in layer Z, %

This equation predicts 93.2% of the effects on curl, as measured in this analysis.

The combination of high output rate, low film thickness, and low percentage of HDPE in layer Z—the optimal combination of variables to minimize curl—was not run in this analysis. Eight of the 128 possible data combinations would have produced this combination. (Table III lists the combinations used in this experiment.) Using the regression equation, a curl rating of 1.25 can be calculated from this optimal combination of variables. Thus, the regression equation predicts changes will probably be needed beyond those used in this analysis to completely eliminate curl.

Elimination of curl

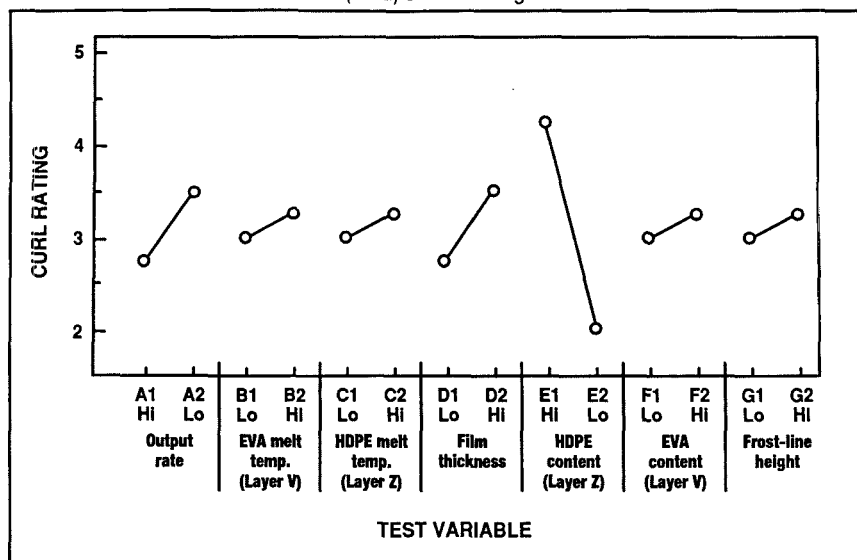
The final sample for customer evaluation was made thin (25 μ m, or 1 mil) at a high output rate (225 kg/h, or 500 lb/h). Fortuitous happenstance had the optimal setting of these two minor variables to control curl where they were most desirable from a production point of view. The percentage of HDPE was manipulated to obtain film with no curl. A percentage of 9% was finally used.

A roll of curl-free material was made for a future customer evaluation. Operating conditions of this run were recorded for use on future runs of this material.

Conclusion

A designed experimental technique proved to be an effective means of analyzing a film-extrusion process to correct a curl problem in a five-layer coextruded structure produced on a commercial blown-film line. The results showed that curl for this particular material was controlled by lowering the HDPE content in one of the surface layers, increasing the output rate, and reducing film thickness.

1. Influence of seven test variables (A-G) on curl rating



Efficiency of designed experiments

The utility and effectiveness of a structured designed experiment is clear from the results presented here. It was not necessary to understand all the theory and processing knowledge to make a film sample with no curl. It was only important to understand the process sufficiently to include the right variables in the testing. With eight samples, it was possible to determine three key variables and the direction of change that controlled curl for this particular extruded structure and the associated production equipment.

The tests consumed less than seven hours of time on the production line. This was less than the time that was initially spent trying to obtain a curl-free sample by manipulating production conditions. The designed experiment was a quick and effective way to analyze the causes of curl on a production-scale blown-film extrusion process.

It may be tempting to generalize and hypothesize about how the factors affect curl in a coextruded structure. The data presented here cannot be used for that purpose. The tests described here were specifically designed to eliminate curl on a particular coextruded structure. Had the intent been to analyze curl completely, the experiment would have been designed differently. □

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