OPTIMIZING SHEET EXTRUSION CONDITIONS TO MINIMIZE INTERNAL STRESSES IN THERMOFORMED SHEET

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INTRODUCTION

AS FLEXIBLE POLYVINYL chloride (FPVC) is processed and cooled in a typical plastic sheetline system, complex patterns of internal stresses are developed as the result of restraints which are characteristic of normal shrinkage. Such induced stresses are common in all areas of plastic processing and the ability to control or minimize the amount of these stresses makes it possible to determine the characteristics of processes performed on the sheet afterwards [1].

This study was performed on an alloyed FPVC sheet which was extruded under controlled conditions. Some of the conditions consisted of draw ratio, die temperature, melt temperature before the die, center chill roll temperature and bottom roll temperature on a three roll down-stack sheetline (Figure 1).

The FPVC alloy that was processed during this study was a compound that is used for the thermoformed skin of automobile dashboards. If the internal stresses are not reduced to the lowest level, the FPVC dashboard skin will be uncontrollable during the thermoform-

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CONDITION	LOW	HIGH
DRAW RATIO	1.1:1	2:1
DIE TEMPERATURE	171°C (340°F)	204°C (400°F)
MELT TEMPERATURE	177°C (350°F)	199°C (390°F)
CENTER ROLL TEMPERATURE	77°C (170°F)	110°C (230°F)
BOTTOM ROLL TEMPERATURE	10°C (50°F)	38°C (100°F)

Figure 1. Test parameters.

ing process. Also, after being exposed to extreme environmental temperatures over an extended amount of time, stresses can go undetected until cracking or curling of the dashboard skin becomes evident to the car owner. In some parts of the continental United States temperatures can range from 38°C (100°F) in the summertime to −32°C (−25°F) in the wintertime; interior temperatures can soar to 82°C (180°F) or higher.

BASIC THEORY

The die gap and draw ratio have a direct relationship to each other. During all of the tests 1 mm thick sheet was being made. The effect of different draw ratios was part of the control variables and was examined for the effect on inducing stresses. To be able to make 1 mm sheet with a 1.1:1 draw ratio the die gap was set at 1.1 mm; to check the high limit of 2:1 draw ratio the die gap was set at 2.0 mm. The drawing of the material between the die lip and roll nip can either cause increased stresses because of stretching or decreased stresses because the material is allowed to relax before it is cooled. In these tests, the lower draw ratio had better effects in all cases.

The size of the bank or the reservoir of material that rolls on the material at the nip of rolls can also have an effect on the stresses that are induced into the finished product. Whenever stresses are induced into the material before the nip and then come in contact with a chill roll of extremely low temperature, the induced stresses become fixed. But when the temperature of the nip is set just low enough to allow the material not to stick to the center roll, then the material is given time to cool at a uniform rate and time to relax before the stresses are set into the sheet.

Another condition that must be considered is the thermal equilibrium of the extruded material [2]. The polymer must be processed at a temperature which will allow any stresses that have been induced during plasticating to be relieved as much as possible before entering the die. Once the polymer has entered the die the temperatures need to be set so that the material will flow uniformly without introducing anymore heat into it; in effect, to allow the material to relax in the die and to stabilize.

DESCRIPTION OF EQUIPMENT (FIGURE 2)

Extruder

The extruder that was used for these tests was an 88.9 mm (3.5″) diameter by 32:1 L/D single screw extruder. The extruder was equipped with a 150 horsepower drive and motor, which has a 1150 rpm base speed and field weakened to 2000 rpm. The D.C. motor was directly coupled to a double reduction gearbox which had an 11.02:1 gear reduction. The bi-metallic barrel was heated with cast aluminum heaters and water cooled. The vent section of the extruder was allowed to vent to the atmosphere.

Screw

The screw that was used was made from SAE 4140 steel heat treated to hardness of Rockwell C 28 to 32 with the following flight configuration:

Feed: 6 dia. @ 11.43 mm deep (.450″)
Trans: 6.9 dia.

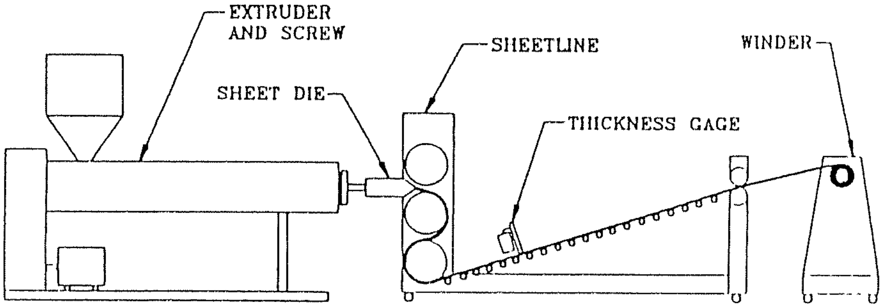

Figure 2. Schematic diagram of equipment used to make FPVC sheeting.

Meter: 4.9 dia. @ 4.57 mm deep (.180″)
Vent: 4.7 dia. @ 12.7 mm deep (.500″)
Trans: 4.5 dia. Plasti-screw section with .5 mm (.020″) barrier undercut
Pump: 5.5 dia. @ 6.73 mm deep (.265″)
Nose: Five flighted nose (1 dia.)

Sheet Die

The sheet die that was used throughout all of the tests was a 137 cm (54″) flexible lip die with an adjustable restriction bar. The die had five heat zones with individual temperature controllers.

Sheetline

A three roll sheetline with a down-stack configuration was used for these tests. Each of the rolls in the system was 40.6 cm (16″) diameter by 137.8 cm (54.25″) face width. These rolls were designed with the typical spiral baffle configuration to allow for maximum cooling efficiency. Downstream of the bottom chill roll was a 15 foot long cooling rack, which was located just before the rubber coated draw rolls.

Thickness Gauge

The equipment that was used throughout these tests to make sure that the plastic sheet was processed within the acceptable thickness tolerances was a gamma "back scatter" gauge.

Winder

A single spindle winder was used as the take-up mechanism for this system and the finished material was wound onto 15.2 cm (6″) diameter cardboard cores.

EXPERIMENTAL PROCEDURE

Based on an earlier test to determine the operating parameters which had the most effect on the controlling of the induced stresses of the FPVC material, the following variables were chosen for this test: die gap setting, draw ratio between die and roll nip, die temperature, melt temperature of the compound before the die, various temperature

TEST	DRAW RATIO	DIE TEMP.	MELT TEMP.	CENTER ROLL TEMP.	BOTTOM ROLL TEMP.
		°C (°F)	°C (°F)	°C (°F)	°C (°F)
1	1.1:1	171° (340°)	177° (350°)	77° (170°)	10° (50°)
2	1.1:1	171° (340°)	177° (350°)	110° (238°)	38° (100°)
3	1.1:1	171° (340°)	199° (390°)	77° (170°)	38° (100°)
4	1.1:1	171° (340°)	199° (390°)	110° (230°)	10° (50°)
5	1.1:1	204° (400°)	177° (350°)	77° (170°)	38° (100°)
6	1.1:1	204° (400°)	177° (350°)	110° (230°)	10° (50°)
7	1.1:1	204° (400°)	190° (390°)	77° (170°)	10° (50°)
8	1.1:1	204° (400°)	190° (390°)	110° (230°)	38° (100°)
9	2:1	171° (340°)	177° (350°)	77° (170°)	38° (100°)
10	2:1	171° (340°)	177° (350°)	110° (230°)	10° (50°)
11	2:1	171° (340°)	190° (390°)	77° (170°)	10° (50°)
12	2:1	171° (340°)	190° (390°)	110° (230°)	38° (100°)
13	2:1	204° (400°)	177° (350°)	77° (170°)	10° (50°)
14	2:1	204° (400°)	177° (350°)	110° (230°)	38° (100°)
15	2:1	204° (400°)	190° (390°)	77° (170°)	38° (100°)
16	2:1	204° (400°)	190° (390°)	110° (230°)	10° (50°)

Figure 3. Setup table for design test.

settings of the center roll, and the temperature settings of the bottom roll. The operating variables that were chosen are shown in Figure 3. The tests were not necessarily done in the sequence as shown in the table, but in a manner that allowed the most efficient use of time. For example, all of the tests with the same die gap setting were done as the first group. Then the group having the cooler die temperature settings was chosen due to the fact that the die could be heated up faster than cooled down. The remaining parameters were done with the hotter roll temperatures followed by the cooler roll temperatures because of the ability to cool rolls more rapidly than heat them up. All of the sheet that was produced was in the range of 1 mm plus or minus 5 percent.

To evaluate which operating conditions had the most effect on reducing the internal stresses induced during processing, the center 102 cm (40″) of material that was processed through the 137 cm (54″) die was cut into four 25 cm × 25 cm (10″ × 10″) samples and labeled "left outside", "left middle", "right middle", and "right outside", with the machine direction marked on each sample. The 10″ × 10″ dimensions were chosen so that each sample would represent 100 square inches or 100%. Then each was placed in an oven for one minute and thirty seconds at 171°C (340°F). This is the temperature and cycle time that the automaker used during the thermoforming operation. After all four samples from each of the sixteen tests were taken from the oven, they were allowed to cool to room temperature. Once the samples had cooled, they were physically measured for dimensional changes. The dimensions that were taken were the length of all four sides and the length of the longest diagonal. These dimensions were used to calculate the percentage of shrinkage and the uniformity of the shrinkage. Since most of the samples shrank into irregular forms, the following method was used to calculate the area of shrunken form. The shortest side and the shortest length were used to form a right triangle. The basic equation for the area of a right triangle was used:

$$A_R = .5\,(w \times h) \tag{1}$$

To find the remaining area of the irregular form, the longest side, the longest length, and the longest diagonal were used to solve for the area of an acute triangle:

$$A_A = (.5b)\sqrt{a^2 - \left(\frac{a^2 + b^2 - c^2}{2b}\right)^2} \tag{2}$$

The sum of these two triangles gives a very close approximation [3] of the irregular form:

$$A_T = A_R + A_A \tag{3}$$

Now by using the total area of the shrunken irregular form and dividing that by the pre-shrunken sample (100 sq. in.) and subtracting from unity, this gives the percent shrinkage (%S):

$$\%S = 1 - (A_T/100) \tag{4}$$

This method of calculating the total area of shrinkage for the shrunken form was checked by taking some random samples of the shrunken forms and laying them out by locating all four corners of the forms and then completely triangulating the entire form into right triangles; this method showed a variation of the area of 0.3%.

Another piece of information that was examined was the uniformity of shrinkage. This was defined as the amount of change between the original form and the shrunken form. It could be determined by assuming the original form had a value of units and subtracting from it the change in the shrunken form and averaging this value over the four samples retained from each of the tests. In our experimental procedure, however, the uniformity of shrinkage was determined by taking the worst condition observed in each sample. We divided the length of the shortest side by that of the longest and averaged this value over the four samples, expressing the result as a percentage:

$$U_n = \frac{\text{length of shortest side (in.)}}{\text{length of longest side (in.)}} \tag{5}$$

where $n = 1, 2, 3,$ and 4

$$U_T = \left(\frac{U_1 + U_2 + U_3 + U_4}{4}\right) \cdot 100\% \tag{6}$$

The final data that were collected were the observation notes after the samples were removed from the reheat cycle. The samples varied from flat square shrinks to samples that were rolled tightly from both ends towards the center. There were also tests where the outside samples shrank more than the inboard sample shrunk and vice versa. These observed notes had a direct correlation with the calculated findings.

The material that was produced during these tests was sent back to GM-Inland's plant in Dayton, Ohio, where they performed similar shrinkage tests. After collecting all of their data, they used the Taguchi Analysis and found the same results as were discovered in this method [4,5].

INTERPRETATION OF DATA

Once all of the data were collected from the sixteen different tests that were performed and all of the necessary calculations were compiled, two main items of interest were charted: percent shrinkage and uniformity of shrinkage (Figures 4 and 5). It can be seen from the tabulation of these two pieces of data that the amount of shrinkage has a direct relationship with the uniformity of the shrinkage. As the percent shrinkage increased, the uniformity of the shrinkage decreased.

It was observed that after the samples were exposed to the reheat process to simulate the thermoforming operation, the samples which shrank the most in the machine direction of extrusion had the largest increase in the transverse direction. Some had decreases in the machine direction as much as 40% and increases in the transverse direction as much as 5%. The remaining increases went to the thickness of the sheet. This increase in thickness threw the stock out of acceptable tolerance.

After all of the tests were completed and numbers tabulated the following operating conditions were followed to give the best overall results on this particular FPVC alloy:

1. Draw ratio: 1.1:1
2. Die temperature: 171°C (340°F)
3. Melt temperature: 199°C (390°F)
4. Center roll temperature: 110°C (230°F)
5. Bottom roll temperature: 10°C (50°F)

These were the conditions for test #4 which resulted in producing an end product which had a uniformity of shrinkage of 89.8% and a percent shrinkage of 9% (Figure 4).

CONCLUSIONS

Based on the tests performed it is very evident that proper operating conditions can and do have a dramatic effect on the amount of induced

TEST	SHRINKAGE (%)	UNIFORMITY OF SHRINKAGE (%)
1	16.8	76.7
2	18.3	75.5
3	12.3	85.3
4	9.3	89.8
5	15.8	74.0
6	13.3	75.2
7	16.5	73.5
8	13.0	82.5
9	31.0	60.7
10	28.1	60.0
11	33.7	58.0
12	15.7	77.3
13	25.4	62.6
14	20.8	68.4
15	18.5	66.7
16	22.7	67.5

Figure 4. Data on shrinkage and uniformity of shrinkage.

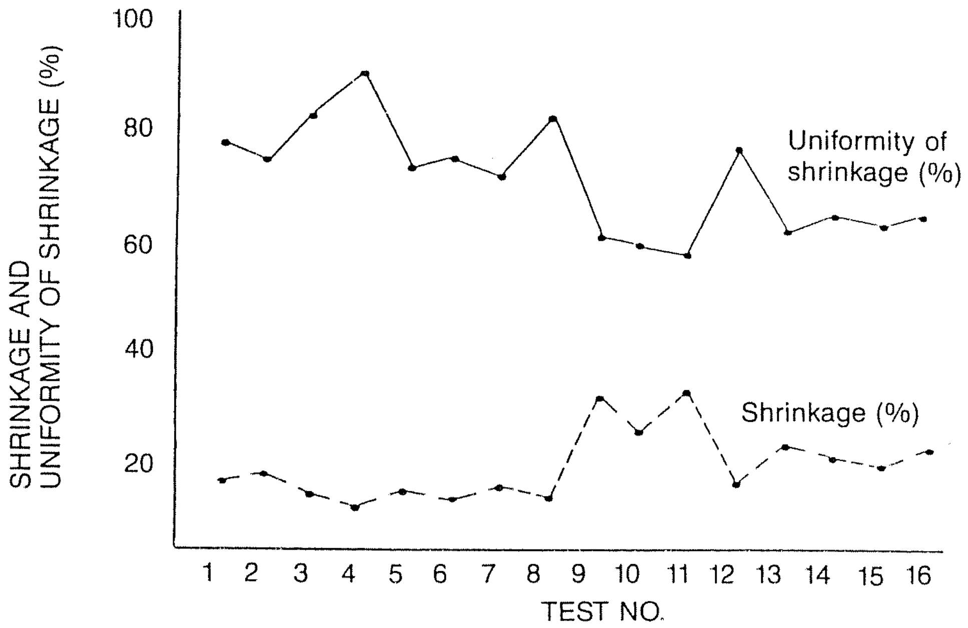

Figure 5. Comparison of shrinkage and uniformity of shrinkage for different conditions.

stresses that can or cannot be processed into flexible polyvinyl chloride sheet. Even though the product that has been produced may appear to be acceptable, once it is exposed to another thermal history any internal stresses that have been processed into the product become evident. These hidden stresses can be devastating problems to the next in-house operation or may create a very dissatisfied customer. Therefore, it is very important that great efforts are taken from the very start to make sure that all precautions are taken to alleviate unnecessary stresses.

NOMENCLATURE

A_R = Area of right triangle
w = Shortest side
h = Shortest length
A_A = Area of acute triangle
a = Longest side
b = Longest length
c = Longest diagonal
A_T = Total area
$\%S$ = Percent shrinkage
U_M = Uniformity of shrinkage for any sample
U_1 = Uniformity of shrinkage for left outside sample

U_2 = Uniformity of shrinkage for left middle sample
U_3 = Uniformity of shrinkage for right middle sample
U_4 = Uniformity of shrinkage for right outside sample
U_T = Total uniformity of shrinkage for each test

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