



## **Abstract**

This study explores variation in the dimensional parameters of tire tread extrusions. The methodology was based on measurement of width and thickness values of treads at two points in the manufacturing process. The first point was just after exiting the die, where the rubber is hot. The second point was at the end of the extrusion line, where the rubber is cold and has undergone shrinkage. The study evaluated the test data to answer several questions:

- What is the magnitude of the shrinkage from the hot to cold points?
- How uniformly is the rubber distributed in the cross-profile direction?
- How uniformly is the rubber distributed in the direction of travel?
- How do these changes compare between the hot and cold points?



### Test Methods

Measurements were conducted with the Starrett-Bytewise On-Line Profilometer (OLP); one at each point. The OLP is an on-line, real-time measurement system for continuously monitoring key profile dimensions in complex tread and sidewall extrusions. OLP employs CrossCheck™ line laser sensors manufactured by Starrett-Bytewise. The OLP is shown in Figure 1.



Figure 1 - OLP

Any measurement study is incomplete without an assessment of the associated measurement uncertainty. Measurement accuracy and repeatability were checked on both units. Thickness accuracy was within the allowable 60  $\mu\text{m}$  specification. Thickness repeatability ( $3\sigma$ ) was within the allowable 20  $\mu\text{m}$  specification. Width accuracy was within the allowable 250  $\mu\text{m}$  specification. Width repeatability ( $3\sigma$ ) was within the allowable 120  $\mu\text{m}$  specification. The measurement capability was verified by checking a metrology-lab certified gauge block at multiple points across the system's field of view. Error-of-Measure was calculated as the average bias plus 3 standard deviations for a test series at multiple points in the field-of-view (FOV).

The test method was designed to minimize any external sources of variation. All tests were run on the same extruder with the same die. All runs utilized the same compound produced on the same mixer, although in some cases mixed in different runs.

The measurement scheme was configured to acquire 10 channels of thickness and one channel of width across the tread profile. Figure 2 illustrates a similar measurement scheme.

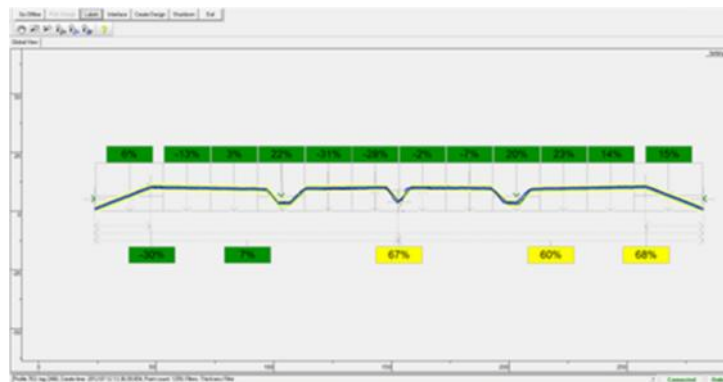


Figure 2 – This is an example of the measurement configuration employed. In this case the profile is divided into 10 equal-width channels across the central profile, plus two end channels whose widths align with the tapered wing profile. This includes an overall width channel plus shoulder widths and half-profile widths.



One tread profile was selected as representative of the typical production. It was run each day for 8 consecutive days. Measurements were taken on 10 minute intervals during each day's run. The longest run produced 8 measurement sets. Three days produced 3 sets each, 2 days produced 4 sets each, and 2 days produced 5 sets each. There were 43 measurement sets produced in total for each point.



### **Data Treatment**

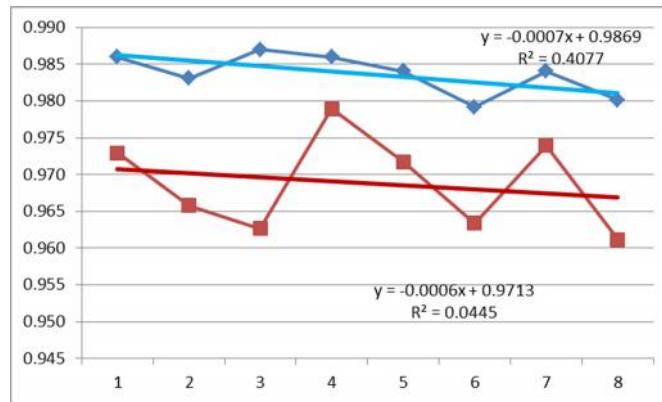
The data acquired consisted of 22 values per profile measurement – 10 thicknesses and one width for each of the two points. Data was rendered to three significant digits expressed in thousandths of a millimeter.

In order to make the data easier to interpret the measurements were reported as the difference between the measured value and the specification value. This is essentially the deviation of the measurement from the norm. This was converted to a dimensionless parameter expressing the error as a percent of the allowable tolerance. This normalization of the measurements allows us to compute standard deviations without unfairly weighting larger and smaller parameters.



**What is the magnitude of the shrinkage from the hot to cold points?**

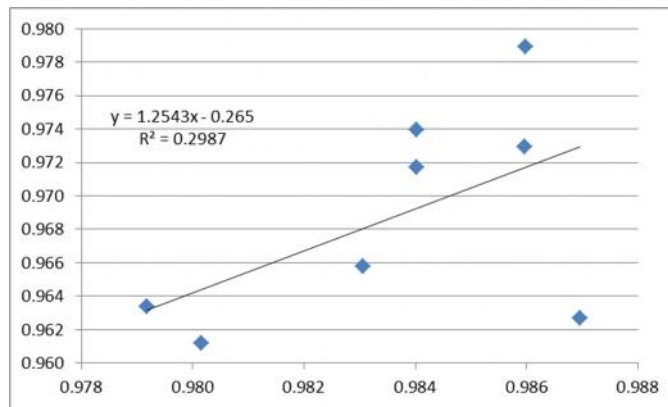
The longest run was selected to study shrinkage. Shrinkage was calculated in two axes – width and thickness. The thickness shrinkage was assessed by subtracting the average overall thickness of the cold measurement set from that of the hot set and expressing it as a percent of the hot value. This produced a plot of the overall average thickness for each profile measurement for each of the 8 cases. Width shrinkage was assessed based on the overall width measurements.



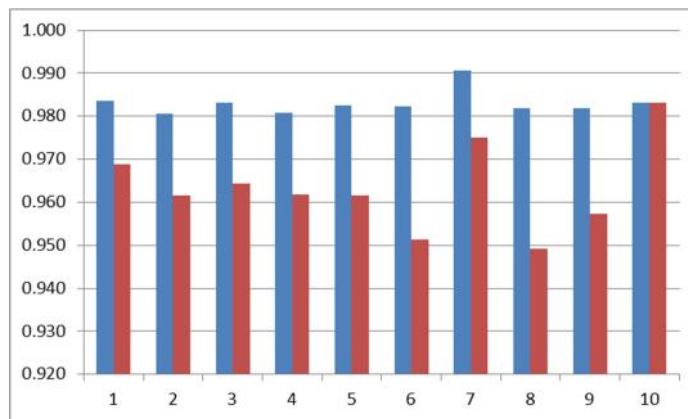
**Figure 3 – Width shrinkage is shown blue and thickness shrinkage is shown in red for a time series, 8 samples in a single run.**

As shown in Figure 3, the Width Shrinkage mean was 1.6%, with a standard deviation of 0.3%. The values ranged from a minimum of 1.3% to a maximum of 2.1%. The linear regression indicated a slight increase in shrinkage during the run, as shown in the regression line above. The data showed a moderate deviation from the regression line, with an  $R^2$  of 41%.

The Thickness Shrinkage mean was 3.1%, with a standard deviation of 0.6%. The values ranged from a minimum of 2.1% to a maximum of 3.9%. The linear regression indicated a slight increase in shrinkage during the run, as shown in the regression above. The data showed a large deviation from the regression line, with an  $R^2$  of 4%.



**Figure 4 – This scatter plot illustrates weak linearity in the relationship between width (horizontal axis) and thickness (vertical axis) shrinkage.**



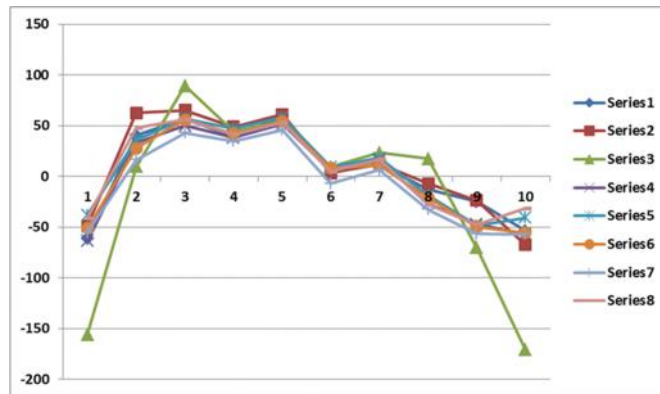
**Figure 5 – This column chart compares the Thickness Shrinkage (red) and the Width Shrinkage (blue) for the ten cases.**

The mean thickness shrinkage was 1.9 times the mean width shrinkage. Figure 4 shows a scatter plot of the width and thickness shrinkage values. The linear regression line confirms the positive relationship, although there is considerable deviation due to variation in the thickness parameters.

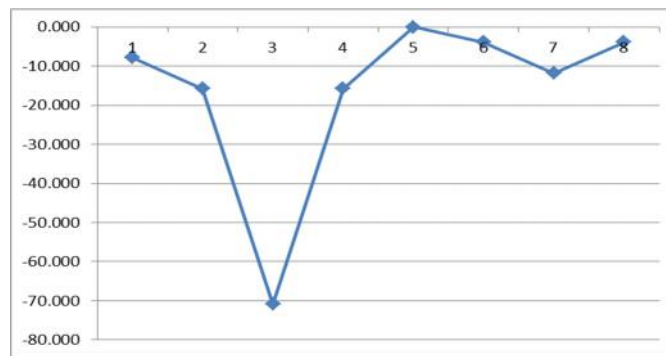


**How uniformly is the rubber distributed in the cross-profile direction?**

The longest run was selected to study the within-run variation. This data set was comprised of 11 measurements per profile for each of 8 profiles for each point.



**Figure 6 – This shows 10 channels of thickness across the tread for 8 measurements taken 10 minutes apart at the hot point. Series 1 is the first measurement and series 8 is the last measurement. The vertical axis on the left is the average thickness of each channel, expressed as a percent of the allowable tolerance.**

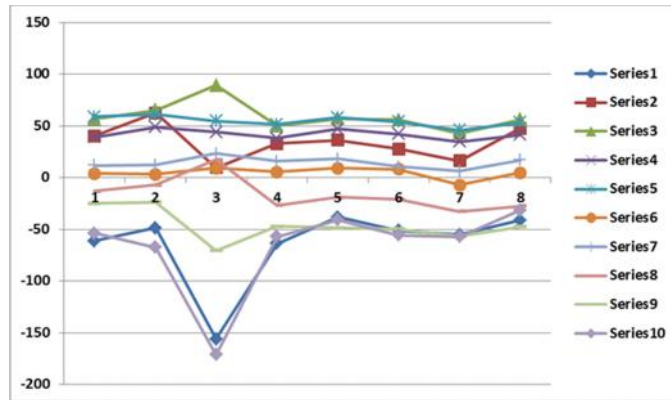


**Figure 7 - This shows 1 channel of width across the tread for 8 measurements taken 10 minutes apart. The vertical axis on the left is the average thickness of each channel, expressed as a percent of the allowable tolerance.**

We observed that the width was smaller than the specification by less than 20% of the tolerance in all but one case. The third series, the green line in Figure 6 and the third point in Figure 7, shows significant deviation from the other series. The width was undersized by 70% of tolerance in that case. This occurred 30 minutes into the run. We believe that this smaller width at 30 minutes accounts for the smaller average thickness measurements in the leftmost and rightmost channels.



How uniformly is the rubber distributed in the direction of travel?



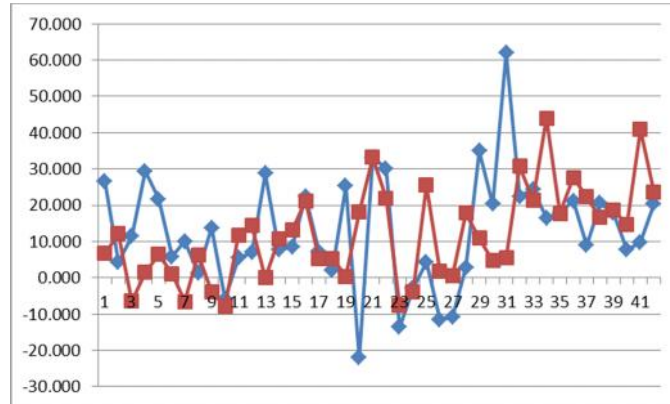
**Figure 8 – This is a time series of the 8 thickness channels. Column 1 is the first in the time series and column 8 is the last. The legend on the right indicates the thickness channel, with series 1 being the leftmost channel and series 10 being the rightmost channel.**

If we look at the third measurement, the one with a sharply reduced width, we see the sharpest reduction in the average thickness in channels 1 and 10, the leftmost and rightmost channels. Note that even though the width deviation was acceptable at 70% of tolerance (from figure 7), the resulting thicknesses for the two end channels were unacceptable, at better than 150% of tolerance (figures 6 and 8).

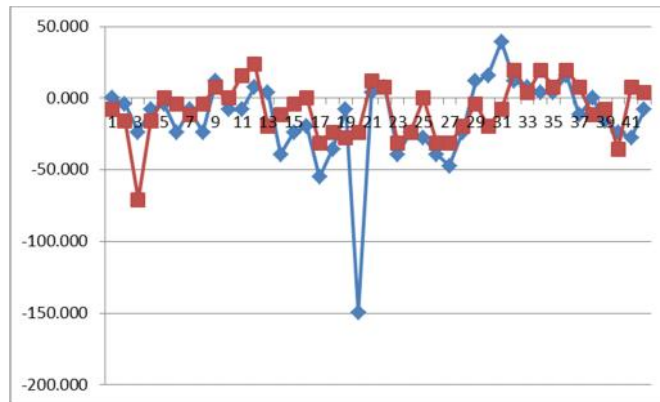




How do these changes compare between the hot and cold points?



**Figure 9 - This shows the average overall thickness for the 43-profile time series for both hot and cold points (hot is in red).**



**Figure 10 - This shows the overall width for the 43-profile time series for both hot and cold points (hot is in red).**

We observed that for both thickness and width the hot data sets exhibited less variation than the cold data sets. For the width parameter the standard deviation of the hot set was 15.3 compared to 12.9 for the cold set; a 16% smaller variation. For the thickness parameter the standard deviation of the hot set was 19.0 compared to 29.1 for the cold set, a 35% smaller variation.



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## **Conclusions**

- Thickness shrinkage value for one compound varied from roughly 2% to 4% over the 8 day period. If one were to tune a die based on the sample mean of 3% one would expect a process variation at the cold end of plus or minus 1% attributable to shrinkage alone. Since many tire makers seek to control their process to better than 1% this strongly justifies a nested feedback control scheme that monitors the shrinkage and adjusts the hot set-points periodically for drawdown control (see Appendix 1).
- The same conclusion applies to the width measurement, although less so, where the minimum shrinkage was 1.3% and the maximum was 2.1%.
- Distribution of rubber across the profile was generally within plus and minus 50% of the allowable tolerance. The greatest variations occurred in the rightmost and leftmost channels where the thickness was influenced by the width parameter.
- Distribution of rubber in the direction of travel was generally within plus and minus 50% of the allowable tolerance. The greatest variations occurred at the time when the width parameter went out of tolerance.
- Distribution of rubber was compared between the hot and cold points. For the cold point the thickness variation was 35% greater than at the hot point. The width variation was 19% greater at the cold point than at the hot point. This suggests that the cooling process adds significant variation to the hot extruded dimension.

## **Looking Forward**

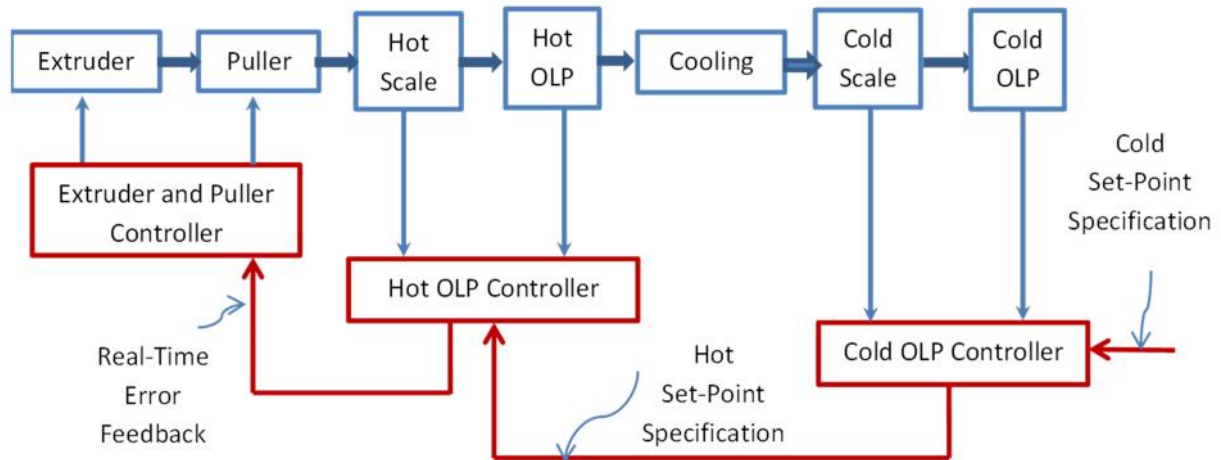
The sampling strategy utilized one measurement every 10 minutes. We recommend the next test series be done at a one-second frequency. We are concerned that sampling in the direction of travel would lead to higher certainty in the time-based analysis. This data could also be used to establish the process capability. Other studies have been done on tread rubber at measurement frequencies of 1 measure per second that suggest a stable extrusion process has a standard deviation in the range of 0.036  $\mu\text{m}$  thickness, and 0.39 in width, as related in Appendix 2.

This test would benefit from the addition of rheological data for each run as changes in the viscous modulus, elastic modulus, and tangent delta (factors that predict die swell) may relate in part to the shrinkage factors.

The addition of weigh scale measurement data would be recommended to determine the correlation between weight and dimensions.



APPENDIX 1 – Nested Feedback Control Scheme



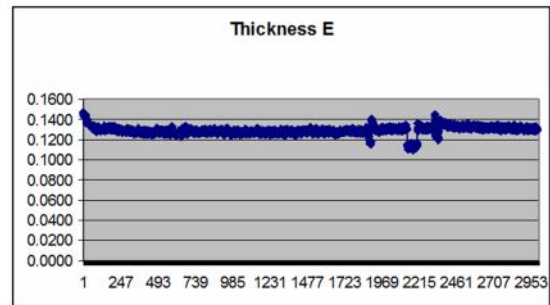
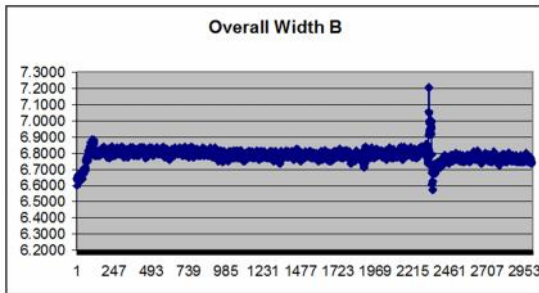
The *Hot OLP Controller* takes the real-time weigh scale and OLP measurements near the die and after the puller, compares them to the Hot Set-Point Specifications, and continuously outputs the error to the Puller Conveyor Controller so it can adjust the puller speed to minimize the combined hot weight and dimensional errors.

The *Cold OLP Controller* takes the final weigh scale and OLP measurements, compares them to the Cold Set-Point Specifications, and changes the Hot Set-Point Specifications in order to minimize final weight and dimensional error.



**APPENDIX 2 - Standard Deviation in Tread Extrusion under Stead-State Conditions**

This is an excerpt from a larger study. In this study various thickness and width parameters were sampled at a frequency of one measure per second for a 50 minute run. The figures below show one width and one thickness channel. Note that the width measurement ramps upward during start-up whereas the thickness ramps downward. Process interruptions are evident later in the run, and are likely due to die-flow interruption. One of the most powerful benefits of the OLP is the ability to recognize these interruptions and alarm the operator to intervene.



The data was filtered to remove the effects of start-up and the process upsets in order to characterize the steady-state process stability. Results are tabulated below.

Parameter	Width	Thickness
Mean	172.476	3.490
Standard Deviation	0.391	0.036
Variance	0.23%	1.02%



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