SPECIAL REPORT Rubber Machinery

Rubber extrusion in an Industry 4.0 environment

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The term Industry 4.0 and its variants—Fourth Industrial Revolution, Internet of Things, Cyber-Physical Systems and Smart Manufacturing—have received a lot of attention recently. So what gives?

The Fourth Industrial Revolution is about computer-enabled interchange of data among machines and people to enhance product design, machine performance, inventory control and human decision making. It involves sensors and data on a large scale and figuring out what all that data means (analytics). The idea of turning data into information and

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information into knowledge is not new, now we just have a lot more data.

The rubber industry emerged near the end of the First Industrial Revolution (1760-1840) with Charles Goodyear's discovery of vulcanization, enabling factory production of durable rubber goods. Harvey Firestone, along with many others, drove the rubber industry into the Second Industrial Revolution (1870-1914) with assembly lines as steam power was replaced by electricity and petroleum.

Computers were the number-crunching machines enabling the Third Industrial Revolution, starting in the 1960s, of digital design software and automation.

So how is the rubber industry participating in this Fourth Industrial Revolution?

First consider that rubber product manufacturing, as with composites in general, the formation of the rubber compound(s) and the formation of the product occur simultaneously.[1] With rubber this occurs during the mixing, shaping, building and curing steps. In contrast, a metal part typically needs just shaping and assembly of already fabricated materials.

In rubber manufacturing there is additional benefit, but added complexity, in monitoring and controlling both changes in material properties and the constantly changing product shape for each production unit (for example, a tire), through the various stages of the production process. That cured or outdated rubber cannot be recycled directly is an added financial incentive.

The makers of tire building machines, test equipment, and their suppliers are increasing their ability to track tires through these process steps mostly with RFID tags,[2] but with some use of bar/QR codes. This traceability can start with incoming materials, be used to troubleshoot process problems upstream from final finish[3] and facilitate inventory control to the point of sale and on the road.

Michelin truck tires now report out tire status to fleet managers with RFID tags,[4] while Pirelli's high-end tires send reports to drivers' smart phones and onto tire dealers.[5]

However not much Industrial 4.0 level effort seems to have gone into the processes for preparing tire components—mixing, extrusion, and calendering—and for molding tires. One need is for the development of specific algorithms for monitoring, control, and analysis for these processes.

This article will focus on two topics in rubber extrusion which can benefit from the enhanced sensor and data environment of Industry 4.0: (1) Independent control of multiple key dimensions on an extrudate by the use of two or more methods for size and shape control; and (2) systematic and automated troubleshooting of extrusion line material and operating problems.

Both of these methods are based on in-depth ways of interpreting and using existing line operating and profilometer data. The scope of these topics will be limited to a few examples, but a fuller range of examples is included in the references.

In addition to the two above topics, Industry 4.0 capabilities may be useful for simulation of extrusion dies and extruder performance, preventive maintenance, feed optimization, and tracking materials from mixing through extrusion/calendering, inventory and tire building.

One possibility for tracking rubber through the mixing, extrusion/calendering operations would be periodically attaching low-cost bar or QC labels to the rubber exiting the extruder or calender. The data on (or associated with) these labels could be read, recorded and transferred to more permanent and expensive

Executive summary

The much-touted Fourth Industrial Revolution is ushering in large scale sensing, data acquisition and analysis capabilities among interconnected devices on the factory floor. Two rubber extrusion line applications that can benefit from this increased capability are (1) size and shape control of individual extrudate dimensions and (2) systematic real-time troubleshooting.

Generally, control of extrusion lines is limited to size control (controlling linear weight by adjusting screw speeds relative to line speed). In this paper, seven methods of controlling individual dimensions or classes of dimensions relative to each other (shape control) are enumerated and documented. One method, control of key extrudate dimensions by screw speeds, is outlined and demonstrated by recovery from an upset on a triplex line. A proposed cascade control method uses end of line (cold) profiles to create (hot) profile specifications at the head. Two shape control methods—key dimensions controlled by screw speeds and swell control, for example by online mastication—are illustrated as ways of manipulating operating conditions to meet the hot profile specification.

Real-time continuous troubleshooting can be accomplished by comparing patterns of observed correlations among measured variables (with transport time offsets) to the correlation patterns expected among these same variables for various line upsets. Expected correlation patterns are given for surging, material property (viscosity/swell) change, screen pack plugging and others.

As an illustration, observed correlation peaks at transport time offsets confirmed surging as a cause of variation on a rubber extrusion line. Procedures also are proposed to reveal high levels of screw and barrel wear, and to detect missing or thin liquid coatings on an extrudate by thermal monitoring of the coating.

This article contains many insights and procedures which may prove beneficial if employed one-off or in combination to resolve specific issues on rubber extrusion lines.

Fig. 1: Size and shape changes for a rectangular extrudate undergoing swell and drawdown. Equilibrated swell is indicated by the open square at the upper right. The ShH vs. Sz coordinates during drawdown are indicated by the filled squares.

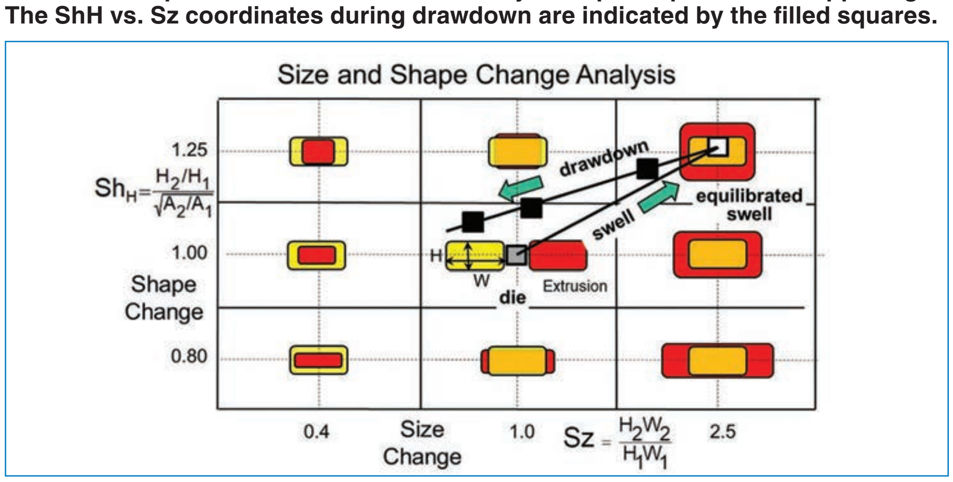
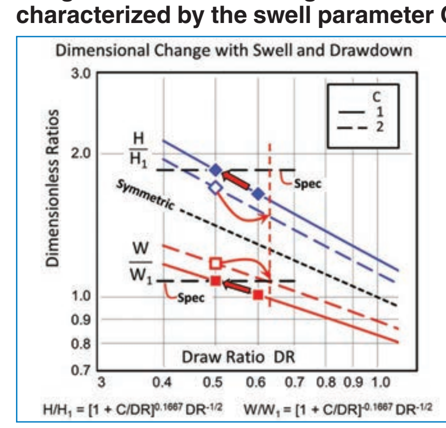


Fig. 2: Plots of drawdown of thickness and width, both normalized for die dimensions, of a rectangular specimen are given for different degrees of swell characterized by the swell parameter C.



RFID tags at the tire building machine.

Controlling dimensions

Size and shape change

The concept of size and shape change in extruder profile dimensions provides a geometric basis for analyzing dimensional change and a method of classifying dimensional change technologies as primarily size (cross-sectional area) change and shape (individual dimensions) change, although there is interaction between size and shape methods.

Dimensional changes between two locations—for example the die face and the end of the line—can be thought of as size changes and shape changes between these two locations.

Size changes are defined as $Sz = A_2/A_1$ where A_1 and A_2 are cross-sectional area at locations 1 and 2. Size change without shape change for rectangular geometries is represented by the red rectangles along the three sets of images arranged horizontally in **Fig. 1**. Within each set, as the cross-sectional area increases, the thickness-to-width ratios are all the same.

Shape changes are the ratios of dimensions at the same position on the extrusion, for example centerline thickness, at locations 1 and 2, but normalized with the square root of the size change. If all dimensions changed proportionately between locations 1 and 2, there would be a size change but no shape change.

Shape changes for a rectangle are represented by the three series of red rectangles in the vertical direction in **Fig. 1**. In a vertical series the size of the red images is unchanged, but the ratio of the thickness to the width dimensions increases in going from the lower to the higher images. Shape change for thickness H is given by the symbol $Sh_H = (H_2/H_1)/(A_2/A_1)$.[1,2]

Size and shape change for extrudate swell and drawdown for a rectangular cross-section also are shown in **Fig. 1**. The center of the drawing represents the die exit where the extrudate and die are exactly the same size and shape. For the compound shown here, the equilibrated (or relaxed) swell cross-sectional area increased by a factor of 2.5 relative to the die, and thickness increased relatively more than width with a shape factor Sh_H=1.25. In practice equilibrated swell samples are cut at the die and placed in hot water to contract.

Next, the extrudate was drawn down to three different levels. The draw ratios from equilibrated swell to very high draw are DR = 0.40, 0.55, 0.93, and 1.25. DR is defined as the cross-sectional area of the die A_1 divided by the area of the extrudate at the end of the line A_2; $DR = A_1/A_2$, except for equilibrated swell where $DR = A_1/A_E$.

The Sh_H vs Sz values for the equilibrated swell and each draw ratio are plotted in **Fig. 1**. The drawdown data fall along a line which does not intersect the Sz and Sh_H coordinates (1, 1) for the die. Drawdown cannot be used to compensate for extrudate swell.

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The author

Jim Stevenson has more than 40 years of experience in processing rubber and plastics. His experience with rubber extrusion includes extruder operation, die design, feeding and takeaway operations, instrumentation and process control.


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This work was done at production facilities and the rubber extrusion facility at the former GenCorp Inc. on triplex pin barrel, 3.5-inch cold feed, and dual hot feed extruders. He co-invented dynamic head technology, which enables the extrusion and takeaway of curved weatherstrip and quick die changes.

Stevenson retired in 2011 as a corporate fellow at Honeywell Aerospace, where he worked on composite materials, polymers and metal powder processing. Upon retiring, he founded Stevenson PolyTech L.L.C., a consulting company which specializes in plastics and rubber processing.

For the previous 18 years, Stevenson held technical and management positions, and headed GenCorp's rubber extrusion facility in Akron. This work was the basis for the three-day Rubber Extrusion Technology short course, which has been presented more than 45 times.

Before joining GenCorp, he was an associate professor in the Chemical Engineering Department at Cornell University, where he was a founding member of the Cornell Injection Molding Project and conducted research on polymer flow.

Stevenson earned his bachelor's in chemical engineering from Rensselaer Polytechnic Institute and his master's and doctorate degrees from the University of Wisconsin. He has published one book, more than 60 papers on polymer processing and flow, and holds more than 20 patents.

Fig. 3: Seven shape change procedures that allow change of individual extrudate dimensions or groups of dimensions relative to each other.

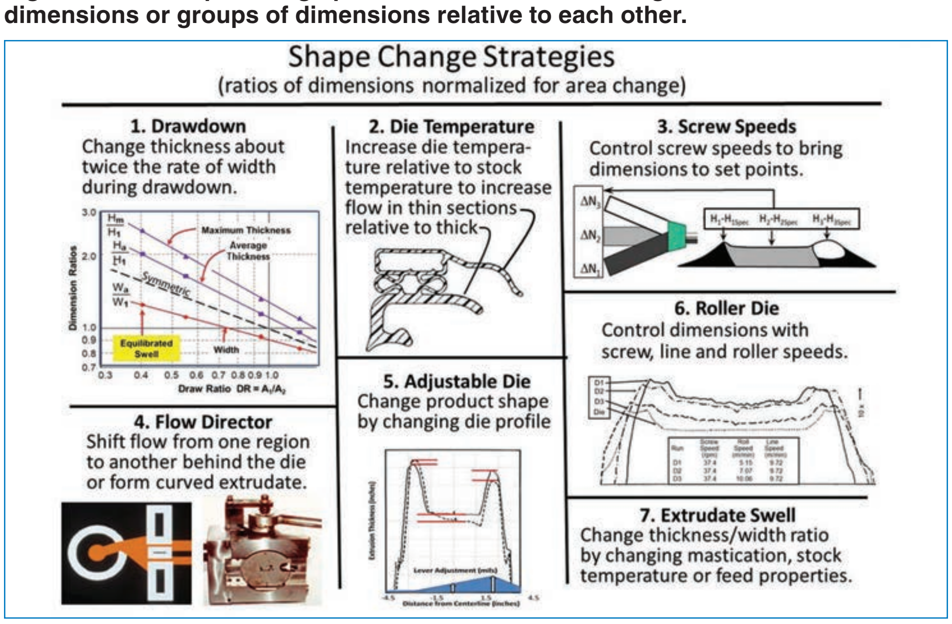
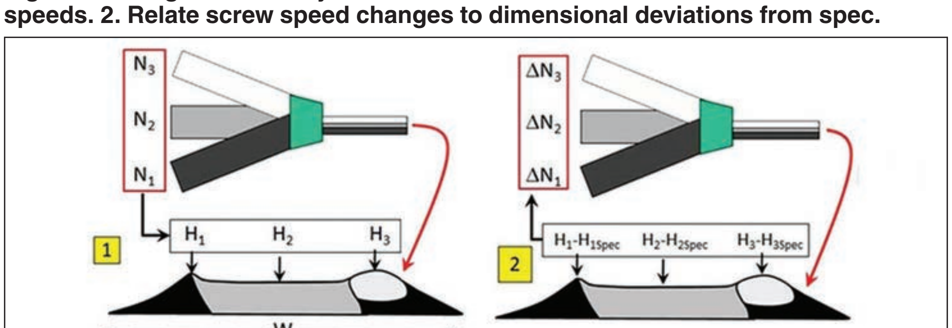


Fig. 4: Two stages necessary for dimensional control: 1. Relate dimensions to screw speeds. 2. Relate screw speed changes to dimensional deviations from spec.



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Size change is primarily accomplished by changing the ratio of the screw speeds to the takeaway speed, although size changes do induce secondary shape changes; for example thickness and width dimensional changes are not proportional during drawdown.

The thickness H/H_1 and width W/W_1 dimensions, normalized with the die dimensions, fall very close to a straight line on a log-log plot during drawdown as illustrated in **Fig. 2**. The lines in **Fig. 2** are based on the equations given at the bottom the figure where C is the drawdown parameter. The thickness data change at about twice the rate of width data with drawdown, a typical observation. Experimental drawdown data are shown in Drawing 1 in **Fig. 3**.

Consider the situation where the thickness and width specifications are given by the horizontal dashed lines in **Fig. 2**. Say the die was cut for a compound with swell parameter C = 1 (solid line). The two filled symbols falling on the C = 1 curve are thickness and width dimensions at two different drawdowns.

If the line is operating at the higher of the two drawdowns, it is straightforward to reduce the drawdown (heavy red arrows) to the lower drawdown, which puts the thickness and width dimensions in spec. If swell for another batch of rubber is different from that for which the die was cut, say C = 2 (long dashes), the open symbols at the specified draw ratio, DR = 0.5, are not in spec.

If the draw ratio is increased to bring the width into specification (a move indicated by the lower curved arrow), the thickness is even further out of specification as indicated by the upper curved arrow. This example illustrates the importance of consistent material properties, including swell, in the feed and the potential benefits of altering swell as part of a control strategy.

Shape change methods

A number of shape change methods are available for controlling individual dimensions or groups of similar dimensions on an extrusion line. These methods, illustrated schematically in **Fig. 3**, include:

1. Drawing down the extrudate where percentage changes in thickness are about twice the percentage changes in width.[6] This effect contributes to the secondary shape change that occurs with size change as previously stated.

2. Altering flow balance between thick and thin sections in the die by manipulating die temperature relative to the stock temperature.[7] Higher die temperatures increase flow through thin sections.

3. Controlling key thickness and width measurement in a layered profile by manipulating individual screw speeds.[8]

4. Shifting flow from one region to another in the die cavity by use of a flow director.[9]

5. Manipulating adjustable elements in a die to shift flow; for example to make shoulder heights equal or center a wire in a coating.[10]

6. Manipulating the screw, roll and line speeds on a single roller die.[11]

7. Changing the thickness to width ratios throughout a profile by changing the extrudate swell through changes in the level of mastication,[12] stock temperature[7] or composition of feed stocks.

Control of dimensions with screw speeds

Shape change method 3 was developed and demonstrated by using three screw speeds to control independently three thickness dimensions on a sidewall.[8] Development of this control system is a two-stage process, designated 1 and 2, and illustrated in **Fig. 4**.

First the relations between changes in the three screw speeds N_1, N_2 and N_3 are related to changes in the three key thickness dimensions and one width dimension, H_1, H_2, H_3 and W. These relations were established by modeling how each sidewall dimension is related to the three screw speeds. Then the constants in the model were evaluated in a designed experiment with 11 sets of screw speeds corresponding to the corners and center (3 runs) of a cube.

From this experimental data, the model constants were evaluated and statistically insignificant constants were dropped. The dimensional relation for W also was dropped because of its high correlation with the dimensional relation for H_2. The equations relating three dimensions to three screw speeds were written in matrix form.

For the second step in this procedure the matrix is inverted to give the three equations for adjustments in screw speeds ΔN needed to eliminate deviations in the three (or fewer) dimensions from their set points. The expression for ΔN3 is:

In **Equation 1**, the differences between the spec thickness minus measured

$$\Delta N_3 = [N_3]_{update} - [N_3]_{meas} = \alpha\{-0.1089([H_1]^{1.690}_{spec} - [H_1]^{1.690}_{meas}) + 0.1915([H_2]^{1.189}_{spec} - [H_2]^{1.189}_{meas}) + 0.0220([H_3]^{2.284}_{spec} - [H_3]^{2.284}_{meas})\}$$

thickness, both raised to the same power, for all three dimensions gives the incremental change in screw speed ΔN to reduce errors in all three dimensions. The parameter α is the controller gain.

The control strategy represented by these three ΔN equations was tested in a series of five experiments in which each screw speed, or all three screw speeds or the line speed were changed abruptly. Then to recover the initial dimensions, screw speeds were changed manually as directed by a computer taking dimensional measurements and solving the three equations for ΔN.

The results for the 10 control actions following an abrupt 35 percent increase in screw speed N_2 are shown in **Fig. 5**. The figure shows the dimension H_3 decreases with increasing screw speed N_2, a counter intuitive result that is also predicted by the model.

After 10 control actions, the three dimensions were returned to within 2 percent (most within 1 percent) of their initial values for the three single screw speed upsets and one line speed upset. These trials demonstrate a method and clear evidence that it is possible to control individual dimensions, in this case three dimensions on a triplex line.

Without shape control, the screw speeds of the three extruders would most likely be set at values expected to produce the desired output for the part, and line speed would be adjusted to give the specified

Fig. 5: Control actions following an abrupt 35 percent increase in screw speed N_2. Dimensions at the top of the figure include measured dimensions (line with more noise) and predicted dimensions based on the screw speeds in the bottom of the figure.

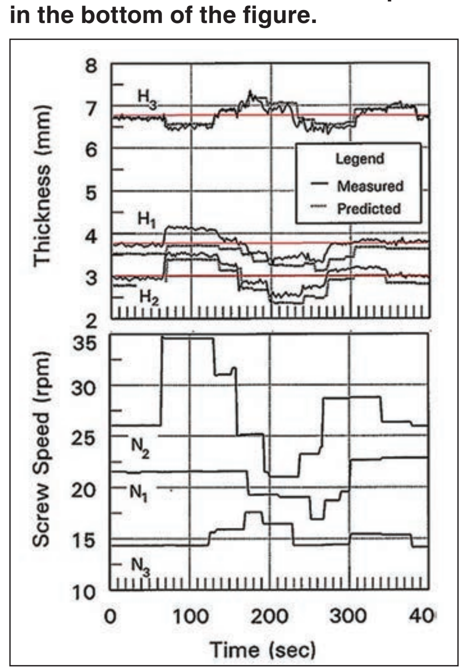


Fig. 6a: Two headed arrows indicate key width dimensions and single headed arrows indicate locations of key thickness dimensions with flat bottom of the profile as a baseline.

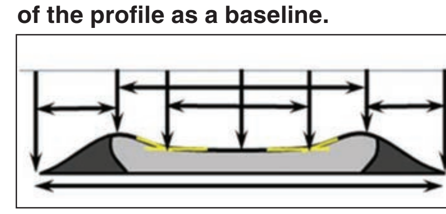


Fig. 6b: The five red vertical arrows indicate thickness swell and the red horizontal arrow at the top indicates width swell for the light central compound between the peaks.

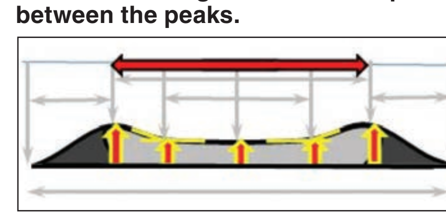
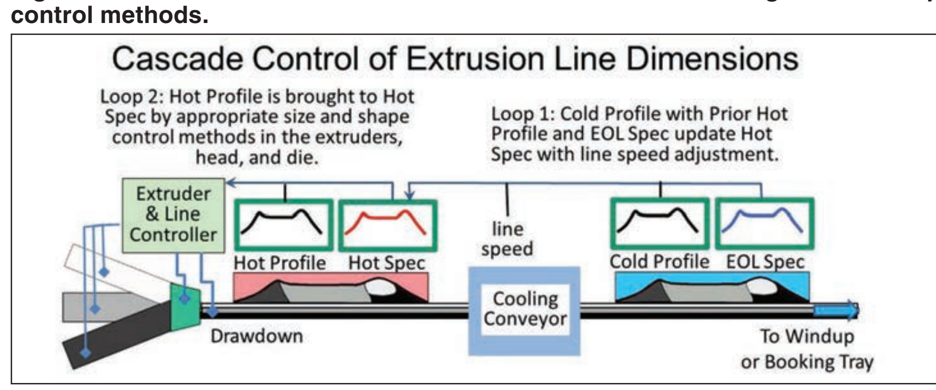


Fig. 7: Schematic of cascade control of extrudate dimensions using size and shape control methods.



linear weight or some preferred average value for the key dimensions.

Manipulating swell, screw speeds

A rubber extrusion line is intended to produce at the end of the line a stable and defect-free extrudate meeting dimensional and linear weight specifications. The dimensions of the extrudate at the die exit are set by the die itself. The end of line (EOL) dimensions start with the die exit dimensions and are altered by individual extruder output(s), as just discussed, by swell of the compound(s), and by line speed, which changes thickness relative to width and linear weight. A general cascade control system is proposed below and applied to the variables just mentioned.

For process control it is more convenient to record measurements and make calculations for key dimensions rather than entire profile. For purposes of this article, key dimensions are thickness and width measurements, which may be located at maxima, minima, junctions or edges. See **Fig. 6a**.

They may be averages over restricted ranges or even angles. Often key dimensions correspond to caliper measurements made by a profilometer.

To characterize and control swell properties, the tendency of a compound to swell needs to be determined online. For this purpose, the swell parameter is defined as an average of key thickness measurements for that compound divided by the width for the area occupied by the compound.

For the profile shown in **Fig. 6b** the average thickness could be an unweighted (or weighted) average of the five vertical arrows divided by the width for the central compound given by the arrow between the peaks. The swell parameter is an approximate gauge of swell; the dimensions for calculating the parameter can be influenced by adjacent materials and other factors. Not every shape is suitable for swell parameter characterization; for example the shape of the wing tips in **Fig 6b**.

Swell can be reduced by increased mastication and stock temperature of the rubber stock in an extruder. One way to change mastication is to change the inlet pressure set point to a gear pump fed by an extruder.[12] To achieve the increased inlet pressure set point, the extruder must run faster and thereby further masticate the rubber and generate heat, both of which reduce swell.

Being virtually a positive displacement pump, the gear pump will maintain a nearly constant output rate.

Typically two locations are used for measurement along an extrusion line: just outside the extruder head (hot dimensions) and at the end of the line (cold dimensions). See **Fig. 7**.

Specifications at these two locations generally can be stated as several key dimensions and linear weight

The cascade process control strategy that follows is designed to compensate for variations in swell and adjust the output rates of individual extruders to meet a hot profile spec near the head. This hot profile spec is intended to produce an on-spec cold profile at the end of the line. At intervals, the cold profile at the end of the line is used to update the hot spec profile while taking into account the influence of line speed on linear weight and drawdown on thickness and width dimensions .

When the extrusion line was set up for a particular product and compound(s), the die was cut and operating conditions were selected to produce an on-spec product at the end of the line (or after storage). During production, various upsets to line operation can occur, such as within batch or especially between batch changes in compound properties. The purpose of the extrusion line control system, following startup, is to produce a product as close as possible to specification by counteracting upsets.

As an example, consider a control algorithm using line speed to meet the linear weight spec and two shape change actions: controlling swell and controlling dimensions through screw speeds. The two shape control actions can be performed in parallel (simultaneously) or in series (sequentially).

1. In series operation, actions to control swell are taken and once the line has adjusted (settling time), actions to control individual dimensions through screw speeds are taken. This cycle (Loop 2) is straight forward but takes time for both actions to settle out; these two cycles need to be repeated four or more times before the hot spec profile is updated by data from the cold profile (Loop 1).

2. In parallel operation, the results of actions to control individual dimensions through screw speed adjustments and control swell—such as by inlet pressure adjustments on a gear pump—are predicted and adjusted as needed so the predicted combined actions meet the hot profile spec. The two sets of actions are then undertaken and are expected to settle out in less time than the two sequential actions in 1 above.

Runs on extrusion lines producing tire components are not long, so the second procedure may be preferred. This second procedure is illustrated in **Fig 8**.

The above cascade control illustration represents one of several ways size and shape control can be implemented. Other shape change methods are sketched in **Fig. 3**. The illustrated method above may be simplified, for example by omitting swell control. The control methods chosen need to be tailored to the specific control issues on the extrusion line and the available resources.

The profile shown in the above example is symmetric. To overcome lack of symmetry in the extrudate, e.g. uneven shoulder heights, one could use adjustable tooling (Nos. 4 & 5 in Shape Change Strategies in **Fig. 3**), which can involve adjustments of the die itself or use a flow director which biases flow to one region of the die and away from another.

The effects described in this section, including the mechanisms and interactions of size and shape change, occur whether intentionally exploited for control purposes or unintentionally as the result of changes in operating conditions or line upsets. Knowledge of these effects may itself be of benefit in understanding unexpected changes in line performance.

Real-time troubleshooting

Commercial extrusion control systems combined with laser dimensional scanning accumulate a large amount of data that is traditionally used for process control, alarming, and traceability. But is there more information buried in this data, perhaps with a few additional sensors?

Material and extruder operation

Consider diagnosing a problem with line operation by looking for cross-correlations among measured variables that are characteristic of the problem. These cross-correlations would be offset by the

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Fig. 9: Expected relations among measured responses to various process upsets.

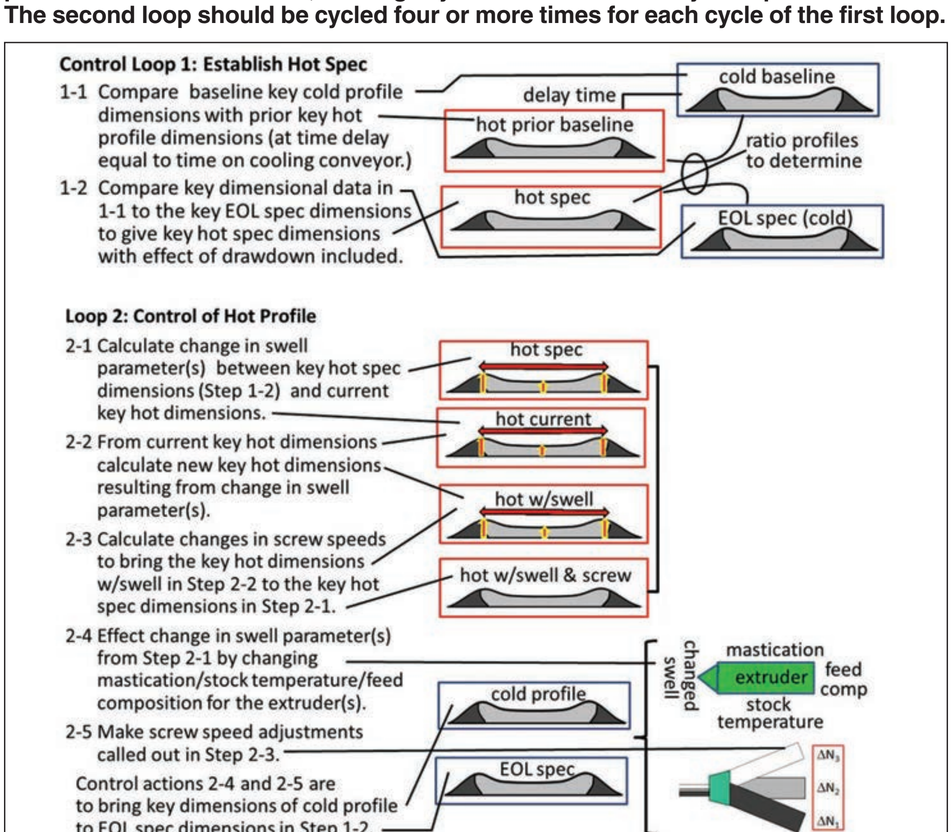
Expected Responses for Various Process Upsets

Key: ↑ large increase; ↑ small increase; ↓ large decrease; ↓ small decrease. Process Upsets ⇩ Measured Responses ⇨

Process Upsets	Time scale	H thickness	W width	H/W swell	Wt weight/length	P pressure (screw tip)	Tn line tension	N screw speed	U line speed	T stock temperature
Surging (upcycle)	short	large increase	large increase	small increase	large increase	large increase	large decrease	small decrease	small increase	—
Screw Speed Increase	vary	large increase	large increase	small increase	large increase	large increase	large decrease	large increase	small increase	small increase
Viscosity/Swell Increase*	long	small increase	small decrease	large increase	small decrease	large increase	large increase	small decrease	small decrease	large increase
Screen Pack Plugging	long	large decrease	large decrease	large decrease	large decrease	large increase	small increase / small decrease	small decrease	small decrease / small increase	large increase
Feed Interruption	short	large decrease	large decrease	small decrease	large decrease	large decrease	large increase	small increase	small decrease	—

* resulting from batch change or feed stock property change (less mastication, higher MW)

Fig. 8: Two cascade control loops. Loop 1 establishes the hot profile spec from cold baseline profile. Loop 2 uses two control methods (swell and screw speeds), first predicted and then enacted, to bring key hot dimensions to key hot spec dimensions. The second loop should be cycled four or more times for each cycle of the first loop.



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extrudate transit time between measurement locations. The reference paper[13] for this work included separating the data into short-term and long-term trends, which were analyzed separately. Only short-term trends are considered here. Long-term trends could be isolated by the use of averages, which then could be analyzed for cross-correlations.

For example, the output of the line is surging (periodic increases and decreases in output due to unstable operation). For the upcycle portion of the surge, the product size represented by thickness H (or diameter D), width W and linear weight Wt would increase as would head pressure P.

Because the velocity of the extrudate emerging from the die temporarily increases, line tension Tn at the die would decrease and possibly the line speed U would increase because of the lower tension. The screw speed N might decrease because of the increased load. Stock temperature likely would not be affected.

All of these sensor data need to be related to the same location on the extrudate. For example, the rubber experiencing a pressure P surge in the head might exert tension Tn on a roller two seconds later and register a thickness measurement increase 30 seconds later.

Fig. 9 is a diagram showing the expected changes in measured variables for various line upsets with an upcycle surge in the top row. Other rows in the diagram show operating upsets (screen pack plugging) and material property changes (increase in viscosity and swell). The effect of a process upset on the measured variable may be an increase or decrease, which may be large or small, as shown in **Fig. 9**.

Fig. 10 shows a plot of cross-correlations over various times for one shoulder height H_A with various online measurements for a coextruded tire tread (cap and base). A peak or valley in the data show a high positive or negative correlation at the time offset of the peak.

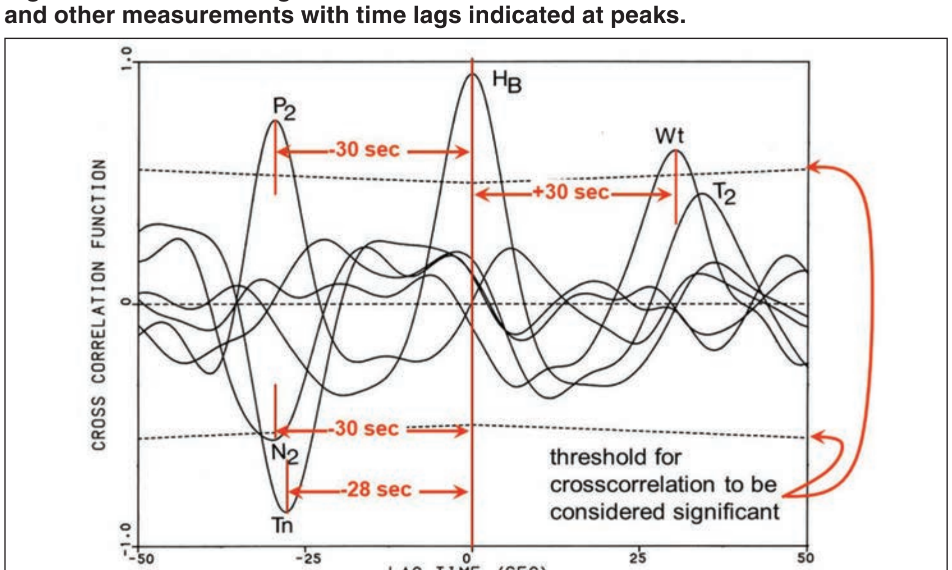
The figure shows the expected very high correlation, 95 percent, between the two shoulder thicknesses H_A and H_B at a 0 time offset, a high correlation, 60 percent, between H_A and weight Wt at the time offset of 30 seconds between the shoulder and weigh measurements. A high negative correlation, -81 percent, was observed between H_A and line tension Tn at an offset of 28 seconds between these two measurements.

The negative correlation between H_A and screw speed N_2 (-0.53 at 30 seconds offset) shows screw speed on extruder 2 was slowed down just enough to be considered significant. This pattern of correlations indicates extruder 2 is surging.[13]

This example suggests that the addition of a line tension sensor may be a powerful tool in distinguishing between different causes of line upset. See **Fig. 9**.

A tension indicator also detects line operation under high tension, which can lead to large and variable lengthwise contraction and curvature of the extrudate.

Fig. 10: Positive and negative cross-correlations between shoulder thickness HA and other measurements with time lags indicated at peaks.



Screw and barrel wear

Another troubleshooting use of online data is to watch for evidence of screw and barrel wear. A well-known indicator of wear is a decrease in output rate relative to screw speed. The output per revolution (kg/hr-rpm) can be monitored over many months for one or more compounds.

If a decrease in output rate per screw revolution for compounds—each compound analyzed separately—can be detected from the natural scatter in the data, wear may be the cause. For this comparison, output rate is normalized with screw speed because operators will likely turn up screw speed to maintain specified output rates.

Wear can be roughly estimated from the percentage rule (percent loss in output is equal to the increase in clearance due to wear as a percentage of the channel depth). If wear is indicated, then screw and barrel measurements are warranted.[14]

Coating thickness

Coatings often are applied to vehicle weatherstrips for appearance or improved performance (low friction or wear resistance). The coating may be thin or absent because the applicator becomes clogged or the coating material runs out. Because the coating is generally liquid and black, visual or mechanical means of determining coating thickness are not feasible.

Because the coating is applied at room temperature to hot extruded rubber, the temperature changes on the coated surface immediately following application of the coating was investigated as a means of determining coating thickness.[15] As shown in **Fig. 11**, a characteristic temperature drop was identified and shown to correlate with coating thickness (**Fig. 12**).

The arrows in **Fig. 12** indicate a temperature drop of 16°F corresponds to a coating thickness between about 1.8 and 2.9 millimeters. For real-time monitoring of coatings, a measurement unit with a point infrared sensor can establish a baseline temperature on an uncoated region, and a single or linear array of infrared sensors can identify the rebound maximum temperature for analysis by the extrusion line data acquisition system.

Follow up

This article presents a wide range of procedures, each demonstrated experimentally, for upgrading extrusion line operation. As issues, resources and priorities are unique for each extrusion line within a manufacturing plant, these procedures (or adaptations of them) would need to be examined to identify those potentially beneficial for plant operations.

Suppliers to the rubber industry, particularly those adopting Industry 4.0 capabilities, may also find benefit in the ideas (or variations) presented in this article.

Acknowledgment

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Also note that many Tire Industry 4.0 presentations were given at the 2018 Future Tire Conference May 30-31 in Cologne, Germany.

In addition, see articles in the "Game Changing Technology" special report in the June 11, 2018 issue of *Rubber & Plastics News*.

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Fig. 11: The surface temperature at the coating location drops rapidly after application of the coating and then rebounds giving a characteristic temperature drop that depends on coating thickness.

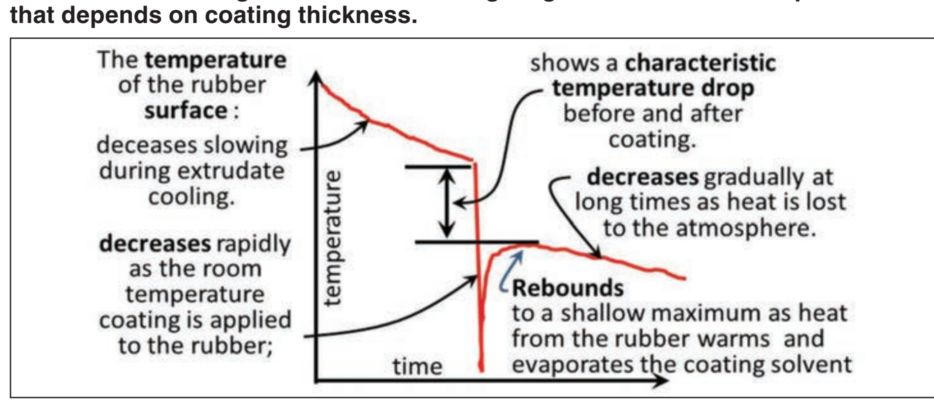

Fig. 12: Calibration of temperature drop vs. coating thickness.