Extrusion Profile Geometry Measurement Methods and Case Studies

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ABSTRACT
This paper introduces new technology for on-line dimensional measurement of profile extrusions using sheet-of-light laser triangulation methods. The technology is described and contrasted with prior technologies. Case studies are presented that demonstrate the ability of the technology to detect problems normally encountered in profile extrusion such as dimensional changes due to batch change, feeder interruption, irregular upsets, and periodicity. Startup behavior is also explored. The paper concludes that many dimensional problems in profile extrusion can be easily recognized with on-line monitoring.

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Extrusion Profile Geometry Measurement Methods and Case Studies

OVERVIEW

There are many variables that affect the size and shape quality of rubber profile extrusions. First, the physical properties of the rubber compound vary according to the visco-elastic properties of the natural rubber, the carbon black particle size and structure, the uniformity of mix dispersion, and the aggregate heat history of the compound before it reaches the extruder, among other factors. The consistency of the rubber flow through the die varies with the heat history applied by the extruder, and the resulting visco-elastic properties of the compound under the pressure and temperature conditions at the die. These properties, combined with the flow-limiting geometry of the die result in varying degrees of die swell once the rubber exits the die. As the extrusion proceeds through downstream operations variations in heating and cooling affect the final geometry. Pullers, cutters, and windups further vary the line tension and cause distortion in the profile geometry. In addition, feed interruption during batch change causes variations in die pressure that affect the flow rate.

Historically, complex profiles have been periodically checked using 10x optical comparators. This requires the operator to cut a thin sliver of rubber, place it on the magnifier, and visually compare the sample to a 10x specification on a transparent film. Thin slivers of rubber profiles are easily distorted by the operator, and these systems are faulted as having high operator-to-operator variation. Studies have shown that 10x optical comparator measurements have 5 times the spread as comparable non-contact on-line measurements.

In order for off-line statistical checking to work it is essential that the sample tested is representative of the population as a whole. This study shows that periodic checking can easily miss important process upsets.

Simple profiles are sometimes monitored continuously on-line via non-contact optical width gages. Traditionally, these operate on the principle of measuring the shadow cast by the extrusion when presented under a sweeping point of laser light. The challenge is that many profiles have critical features that cannot be recognized with a shadow measurement principle. In addition, measurement error is introduced by movement of the profile with respect to the sensor. Profiles with multiple compounds, inserts, reinforcements, and flocking are also problematic for shadow measurement.

This paper is presented in two parts. The first relates the methods of on-line profile measurement, and describes how new Laser Profile Triangulation technology is employed for on-line profile measurement systems. The second part presents several case studies showing common problems in profile extrusion and how they are recognized by these on-line measurement methods.

LASER TRIANGULATION

Laser triangulation is a method of distance measurement. As shown in figure 1, a laser light source projects a point of light onto the measurement surface at distance D1. The laser light is reflected at angle $\alpha$ through a lens and onto a detector at position d1. When the measurement surface is positioned closer to the laser source at D0, the reflected light falls on the detector at position d0. When the measurement surface is positioned farther from the source at D2, the reflected light falls on the detector at position d2. The range of the D2-D0 can be scaled to the range across the detector d2-d0 so that the detector output correlates to the actual distance between the sensor and the measured surface.

Early laser triangulation sensors used analog devices such as gallium arsenide to detect the change in position of the reflected laser light. These came to market in the 1970’s and are referred to a Position Sensitive Detectors (PSD). PSD’s output a varying voltage or current proportional to the position of the light on the detector. Charge Coupled Devices (CCD) are now in wide use as detectors. CCD’s are light sensitive microchips of the type used in digital cameras. A CCD detector may contain, for example, 1024 pixels that result in a detector resolution of 1024 parts across the measurement range.
PROFILE TRIANGULATION
In the mid-1990's, Bytewise Measurement Systems and others developed profile triangulation sensors that substituted a laser line source for the laser point source, and substituted a 2-dimensional CCD array in place of the single-axis pixel array. This is illustrated in Figure 2. A profile triangulation sensor using a one mega pixel detector (1024x1024) could now acquire data comparable to 1024 fixed-point laser triangulation sensors. These were marketed as “sheet of light” laser sensors. These sensors could acquire a single profile of 1024 points at frequencies up to 15 samples per second, which is suitable for online rubber extrusion measurement. Note that Complimentary Metal-Oxide Semiconductor (CMOS) detectors are used in place of CCD detectors where higher frequencies are required. CMOS detectors achieve frequencies of 2,000 to 8,000 Hz in similar applications.

MULTIPLE-SENSOR SYSTEMS
Multiple profile triangulation sensors can be combined into a fixed frame to view the outside profile of the extrusion. The sensors each take a snapshot simultaneously. The profiles are transformed into a common coordinate system and sent to a “measurement server” software component that performs a best-fit match to a reference measurement or CAD template. As a result, the profile can move up and down, side-to-side, and rotate with no affect on the matching routine.

Virtual calipers allow for key dimensions of the profile to be measured. Target and tolerance values are associated with each key dimension. Numerical outputs are available from the virtual calipers as Ethernet messages or as analog signals.

The measurement server results are made available for distributed operator interfaces. Multiple operator interfaces can be running on Win32 platforms showing the current measurement results. This allows the operators at both ends of the process line to see the current measurements. Supervisory and engineering personnel located throughout the facility with network access to the measurement server can also see the measurements.

The operator interface software presents the cross-section template (either a CAD or reference measurement data), the measured profile, and virtual calipers. Additionally, a powerful “on-line comparator” view can be enabled which shows the deviation from the current measure and the template. A vector from each measurement point to the nearest template point is established. This vector is then drawn with a magnification factor that allows it to be visualized on a higher scale than the raw data. The error vector is color coded with green, yellow, and red to indicate tolerance conformance. Different tolerances can be established for each segment of the template.
SOFTWARE CONSIDERATIONS

Sensor systems consist of the sensor, power supply, cable, data acquisition card, PC, and software. Software can be divided into several functions including real-time data acquisition, calibration transform, parameter calculation, visualization, test-plan management, data history management, reports, and external communications, as shown in Figure 5.

Empirical accuracy has been established for a 150mm wide FOV sensor. A multi-step certified gage block was used for all measurements. This gage block provided for 16 thickness parameters and 4 width parameters for a total of 20 measurement parameters per test. All measurements were repeated 75 times for each parameter. All measurements (20 parameters times 75 repetitions) were repeated at 9 locations within the field of view of the instrument. Positions were right, center, and left in the horizontal axis, and top, middle, and bottom in the vertical axis.

Error of Measure is a means to express the capability of the measurement system that includes both the bias and repeatability components of variation. EOM encompasses the 99% confidence interval.

Resolution is defined as the smallest dimensional change that can be recognized. Resolution for the Bytewise profile sensors is 0.001mm, or one micrometer, in the thickness axis. Width resolution is 0.2% of the width FOV. Accuracy is a function of sensor resolution, system design, and analysis method. Accuracy for multi-sensor systems varies from 0.05% for the full scale FOV, to 0.2% of the FOV, depending on system characteristics.

The EOM was calculated for each parameter at each location. The 9 resulting EOM’s for each parameter were averaged to yield an average EOM for each measurement parameter. The EOMs for the 16 thickness and 4 width parameters were averaged together to yield an average thickness EOM and an average width EOM.

The Average Thickness EOM was 0.023mm. There is a 99% certainty that a thickness measurement is within 0.023mm of the true value. The Average Width EOM was 0.14mm. There is a 99% certainty that a width measurement is within 0.14mm of the true value. The worst case of the 9 EOM values was approximately two times the average.

\[ EOM = \text{Bias (absolute value)} + 2.515 \sigma \]

Real-Time Applications take a single profile, perform a calculation to extract measurement values, and output the measurement values for visualization, grading decisions, and automatic feedback. This is done at the sensor frequency.

RESOLUTION AND ACCURACY

Real-Time Data Acquisition
Calibration Transform
Parameter Calculation
Visualization
History
Test-Plan
Communication
Reports

Figure 5 - Profile Sensor Software Functions

Figure 6 - Multi-Step Gage Block for EOM Testing
CASE STUDY – STARTUP BEHAVIOR
Startup of a new run generates a substantial amount of scrap, and reduces the line yield. On-line monitoring is employed to reduce the startup time through a better understanding of startup behavior. By observing the real-time optical comparator the user can immediately see the dimensional result of process and equipment set point changes. The example above illustrates how 4 different dimensions on a single profile come into specification at different points in time. Some Profile360 users who have focused on minimizing startup time claim reductions around 50%.

PROCESS UPSETS DUE TO BATCH CHANGE
This process upset coincided with a batch change. The second batch of rubber had different visco-elastic properties that lead to a reduction in die swell. This decrease in die swell indicates that the second compound had a lower uncured modulus of elasticity. Therefore all dimensions shifted to smaller values. Note that dimensional values are quite stable (low standard deviation) both before and after the batch change. On-line monitoring enables the line operator to observe the effect of the compound change and adjust the process conditions to compensate. Units are micrometers.

PROCESS UPSET DUE TO FEED INTERRUPTION
As one batch of compound reaches the end the operator takes the leading edge of the next batch and compresses the ends together before feeding the joint into the extruder. This can result in a heavy or light joint. In some cases there can be a gap in the extruder feed. This type of process upset will cause a temporary change in profile dimensions. Traditional off-line periodic methods of quality checking are unlikely to detect these upsets. The graphs above illustrate some typical upsets due to feed interruptions. On-line monitors are employed to alarm when these events occur so that the operator can intervene.
OTHER PROCESS UPSETS
Thickness Channel C shows a sinusoidal upset with a peak-to-peak magnitude of 0.7mm over 40 Seconds (about 40 meters).

Thickness Channel E shows a peak-to-peak change of 0.6mm over 70 Seconds (about 70 meters) followed by a step-change shift of 0.5mm over 100 Seconds (about 100 meters).

If this condition occurred in a factory that checked profile geometry off-line every 30 minutes there would be a 2.2% likelihood of detecting the upset in Dimension C and a 9.4% likelihood of detecting the upsets in Dimension E.

PERIODICITY
It is typical for extrusion lines to exhibit some degree of periodicity, or a cyclical pattern of dimensional variation. This case shows a 0.7mm peak-to-peak variation on a repeating 6 minute 20 second cycle. Periodicity has many different causes, such as puller drive control, puller belt splice effect, windup cycle control, cutter cycling, thermal cycling of the heating bath system, and screw beat. Data such as this can be analyzed to determine the time-frequency of the period, which can then be used to diagnose the extruder line and down-stream processes. Reduction in the magnitude of these periodic changes reduces the standard deviation of the dimensional values and results in a better Cp and Cpk.

CONCLUSIONS
Since its introduction over 100 years ago, the rubber extrusion industry has progressed through several generations of technology for profile geometry measurement. Off-line optical comparator methods were popularized over 50 years ago. These technologies enabled users to characterize the dimensional quality of samples, but could not characterize the quality of a population as a whole. Recent advancements in on-line technology enable precise and continuous characterization of the dimensional quality of complex profiles. These empower users to implement several value-creating programs:

1. On-line measurement can be used to continuously monitor the dimensional quality of any profile, and alarm the operator when any problem occurs. This can identify problems not possible with periodic off-line checking.

2. On-line measurement can be used during the startup of any run to assist in reducing the time required to reach stability.

3. On-line measurement can be used to quickly evaluate all lines in the factory to identify cyclical conditions that would affect all profiles. Remediation of such problems will benefit all profiles run on each line.

4. On-line measurement can be used to assist tooling development. Snapshot files can be exported as .dxf point files that can be opened in the die design CAD application and compared to the intended design. As die trials are run, on-line measurement can be used to see how stable the process behaves in production. This information can be used to optimize the extruder setup.

5. On-line measurement produces data histories that can be used to compare any run with its historical performance, and verify the effect of quality improvement initiatives.
REFERENCES

2. Confidential auto company source, Gauge R&R Study, 2005


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