Developments in on-line gauging of Complex Extrusion Coating- An update

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Abstract

This paper focuses on the developments in on-line gauging systems for the measurement and control of multilayer product structures manufactured using high speed Extruder/Laminators.

Product developments for packaging applications have focused on new materials and multi-barrier layers to impart specific properties. The on-line gauging industry has responded to the challenges of precisely measuring and controlling the new complex product structures through developments in Sensor technologies and advanced process control strategies. Further the Sensor developments have been in the area of “non-nuclear” on-line gauging sensor technologies. Also, the on-line gauging industry has used the power of the PCs in enhancing product visualization displays and process diagnostics.

The end result for the Extruder/Laminator is a powerful Process Management tool in improving product quality and production economics.

Introduction

Extrusion coating process ranges from a single coat of a homopolymer on an unprinted substrate to multiples coatings of co-extruded polymers on printed substrates or metallized films. In many cases the product structure includes foil laminations. A typical example of a complex extrusion coating process comprises of multiple extrusion coatings of various polymers to impart specific properties, on a paperboard substrate and laminations such as foil. The end products are used in aseptic packaging applications. Continuous monitoring of the distribution of the individual coatings in the product structure during manufacturing is critical to imparting the desired functions such as barrier properties of inside layers, clarity of outside layers to preserve printed messages and protect the package from the environment, the tie layer to provide the adhesive strength etc.

The most effective barrier performance is achieved when the barrier layer is uniform in thickness. A high-speed manufacturing environment is characteristic of such a complex extrusion coating process.

The complex product structure poses challenges for the on-line gauging industry. Precise dynamic measurement of each individual layer of various polymers, often co-extruded layers such as PE/PA, PE/Surlyn etc. require sophisticated sensor technology for polymer layer discrimination. Nuclear sensors, the old workhorse of the on-line gauging industry, fall far short of meeting this challenge. Further, in many countries, stringent licensing requirements are pushing the on-line gauging industry towards providing non-nuclear solutions.

Historical developments of various sensor technologies for measurement of coating thickness or weight in web gauging

Beta sensor was one of the earliest on-line measurement technologies. A Beta transmission gauge utilizes a radioactive source that emits beta particles (high speed electrons) that pass through moving web to a detector placed on the opposite side of the web from the source. The mass (weight/area) of the web determines how many of the beta particles pass through the web to the detector. A characteristic of the beta particles is that to a first order, the response is independent of the composition of the material being measured. The source depends on the weight of the material being measured. The most common source materials are Promethium 147 for the lightest material; Krypton-85 for medium weight materials and Strontium-90 for the heavier materials.

Gamma transmission sensor is similar to the Beta transmission sensor except that the Gamma radioactive source emits gamma rays which are high energy protons that interact with the material and are reduced in intensity as a function of the weight/area of the material being measured. The interaction is highly
dependent upon the atomic number of the material being measured and the energy of the gamma ray. Hence gamma transmission sensors can be used for selective measurements in some applications with a high atomic number coating and a low atomic number substrate. The most common radioactive material used for a gamma source is Americium-241 which emits 60KEV photons.

X-Rays are very similar to gamma rays differing only from where they originate. Gamma rays originate from the nucleus of a decaying radioactive material and X-Rays originate from acceleration (deceleration) of high speed electrons. Once created, there is no distinguishing difference between a Gamma Ray and an X-Ray. They are both high energy photons. X-Rays are generated by having high speed electrons hit a target material and in the process are rapidly decelerated, giving off photons with an energy that is a function of the velocity prior to hitting the target material. The voltage applied to the X-Ray tube determines the velocity of the electrons and therefore the voltage applied to the tube determines the energy of the X-Rays. X-Ray sensors can be tuned for different measurement sensitivity to the materials being measured by varying the voltage being applied to the tube. X-Rays are non-nuclear; Low energy level X-Ray sensors (below 30 KEV) are not subject to any regulatory restrictions.

Capacitance sensors are usually single-sided sensors that contact a film web. They work on the principle that plastic materials act as a dielectric. By having the plastic film act as a dielectric for two metal plates contacting the film, the capacitance will vary with film thickness. For a given type of plastic the dielectric constant is fixed and therefore film thickness can be implied by capacitance. Capacitance sensors are affected by moisture and therefore are not suitable for measurement of hygroscopic materials such as Nylon. Capacitance sensors are usually found on blown films and not in Coating/Laminators.

Caliper sensors measure thickness of the products directly. They include air caliper, laser caliper etc. They require a reference roll over which the product passes and use eddy current reference for roll position from the sensor. They cannot discriminate between various layers in a multi-layer co-extrusion. They cannot measure the individual coating layer thicknesses directly, only the total thickness of the coated product. They are not suited for high-speed scanning. Thus, Caliper sensors are not suited for coating measurements in a complex extrusion coating process.

Infrared is a selective measurement technology that distinguishes various organic materials at the molecular level. Since many of the coatings and laminations are organics, Infrared sensors are particularly suited for complex extrusion coating/laminating applications. InfraRed Sensors provide a solution for the measurement of individual layer thickness in a multi-layer coating. They measure the amount of infrared energy absorbed by the various components in a multi-layer web. Since specific components exhibit characteristic absorption according to their fundamental chemical structure, web composition can be determined by analysis of the amount of source light that reaches the detector after it is either transmitted through the web or reflected back from the web. They can be calibrated to measure thickness or mass.

InfraRed Sensors have evolved over time to meet the challenging requirements of the complex extrusion coating industry. The conventional IR Sensors use a ratiometric measurement technique between a few selected wavelengths. Some IR sensors use the Beam Splitter configuration, while others use the Spinning wheel configuration. Conventional on-line InfraRed sensors suffer from spatial displacements of individual measurements. Since the spinning filter wheel requires a finite time to rotate, each filter sees a slightly different spot on the web.

Some design improvements have been made to the filter wheels to increase number of wavelengths and increase the speed of the filter wheels. However, some inherent limitations remain in its applications to the manufacturing environment where frequent material changes are common. This requires physical changes of filter wheels that cause production line downtime.

**Advanced on-line InfraRed Sensor technology**

To overcome the afore-mentioned limitations, Full Spectrum Infra Red (FSIR) technology was developed. This on-line Spectrometer using special optics allows the FSIR sensor to monitor infrared absorption in the near-IR spectrum, 1.35 to 3.4 microns. By simultaneously analyzing the entire near-IR spectrum, the FSIR
sensor can discriminate between multiple components as well as discern between components that exhibit similar, but not identical IR absorption. Also, full spectrum data allows numerical compensation for variations in the optical density of the web.

The FSIR sensor (SpectraBeam™) is an on-line infrared spectrometer specifically designed for use in an industrial process. It has the ability to detect the signature of the multi-layer moving web, enabling the quantification of what materials and how much of these materials are present in the web. It simultaneously samples the entire near IR spectrum, eliminating the substrate and background effects that are inherent in sensors that sample a spectrum over a period of time. This also removes the spatial displacement problem demonstrated by conventional IR sensors. A thermoelectric cooler provides excellent temperature stability.

Software-based spectral analysis using Chemometrics, in contrast to the hardware filtering techniques used by conventional IR sensors, provides a high degree of product measurement flexibility. Chemometrics refers to a broad class of mathematical manipulation techniques used for quantitative and qualitative analysis of complex overlapping spectra. Thus, effects of printing, additives etc. can be easily minimized or eliminated from coating measurements. For example, pattern-recognition software can be employed to eliminate effect of printed substrates on coat weights. New component measurements can be easily implemented on-line through recipe-based calibration.

HR- FSIR was the next stage in the development that resulted in the sensor capability to measure closer to the edges of the high speed-moving web. The elliptical geometry (6 x 25 mm) lets the sensor measure closer to the coating edges on the substrate or foil, while at the same time providing enhanced streak-detection capability. Better edge-control of the web and narrower edge-trims allowed the paper coating manufacturer to improve the full-width quality of the rolls at reduced cost, as a result of better edge control and reduction in edge scrap.

Factors to be considered in the selection of on-line gauging sensor technology for precise dynamic measurement of coatings

Multiple layers of different polymers are extruded onto substrate and foil. Substrates may be paper or paperboard of a wide range of weight/thicknesses, coated or uncoated, printed or unprinted. Foil, metallized films or blown films may be used for lamination. The wide range of material combinations and weights (thin coatings on thick substrates) pose a challenge in terms of precise measurements of the various coatings, often multilayer, on a variety of substrates and laminations at high production speeds. Although a wide range of on-line sensors is available for measurement of basis weight or thickness, many of them have limitations in measurement application of complex extrusion coating process due to its exacting requirements. Critical evaluation of the various available on-line sensor technologies is essential in making the best choice to derive maximum quality and economic benefits. Combination of multi-frame multi-sensor configuration is often necessary to provide accurate measurement of various coatings in a complex extrusion coating process.

Direct coating measurement is more precise than differential (subtractive) measurement technique where the first sensor measures the substrate and the following sensor measures the coated product. In this case the measurement error on coating is the RMS (root mean square) of the individual sensor errors. A thin coating on a thick substrate causes large errors in coating thickness measurement. Ability of the sensor to measure true coating thickness independent of the substrate is a prime consideration in the selection of the optimum on-line sensor

Non-contacting sensors are also a major decisive factor, as they mark the coated surface. Time constant of the sensor, signal to noise ratio are important considerations as well. Safety and licensing regulations restrict the use of Nuclear sensors in many countries. Sensitivity to material composition, additives, printing etc. need to be taken into consideration in the selection of optimal sensor technology for this application. Polymer discrimination is essential in multilayer coatings. Temperature sensitivity requires temperature compensation to minimize measurement errors.
Dimensional stability (tolerance to web flutter) under high speed scanning is also of critical importance for accurate dynamic measurement of a fast moving web. High speed scanning ensures faster control to be implemented.

The following table gives a comparative study of the various on-line sensor technologies in terms of the critical coating measurement criteria in a high-speed production environment for the complex extrusion coating/laminating process:

Table: Comparison of various Sensor technologies

<table>
<thead>
<tr>
<th>Criteria</th>
<th>SpectraBeam FSIR Sensor</th>
<th>Conventional IR Sensor</th>
<th>X-Ray Sensor</th>
<th>Beta Sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Noise Characteristics</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Nuclear Statistics</td>
</tr>
<tr>
<td>Tolerance to Web Flutter</td>
<td>Best +/- 5 mm</td>
<td>Best +/- 5 mm</td>
<td>Good +/- 3 mm</td>
<td>Fair +/- 1 mm</td>
</tr>
<tr>
<td>Temperature Sensitivity</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>X,Y,Z Sensitivity</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Composition Sensitivity</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Some</td>
</tr>
<tr>
<td>Dynamic Repeatability</td>
<td>Best</td>
<td>Best</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Multi-layer Coating Calibration Complexity</td>
<td>Moderate</td>
<td>Moderate</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Polymer Discrimination</td>
<td>Possible</td>
<td>Possible</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Multi-Component Measurement</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Exact Same-Spot for coating</td>
<td>Yes</td>
<td>No spatial displacement *</td>
<td>No synchronized scanning</td>
<td>No synchronized scanning</td>
</tr>
<tr>
<td>Substrate Effect</td>
<td>Minimum</td>
<td>Some</td>
<td>Yes</td>
<td>Some</td>
</tr>
<tr>
<td>Printing, additive Effect</td>
<td>Minimum</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>
As can be seen from this table, High-Resolution Full Spectrum InfraRed (HR-FSIR) provides an optimal measurement solution in this application. In some cases, a combination of multi-sensors on multiple frames is employed. X-Ray sensor may be a suitable substitute to Nuclear sensor for Aluminum Foil and Laminate measurement, in combination with HR-FSIR sensors for individual coating layer measurements.

**Reducing coating thickness variability**

Coating thickness variability comprises of three variations: Profile (cross direction or CD) caused by non-uniform extrusion die-lip opening; Long Term Machine Direction (LTMD) variations caused by factors such as drift in temperature and viscosity of melt; and high frequency Short Term Machine Direction (STMD) variations caused by Extrusion/Laminator equipment such as worn-out screws, out-of-round rolls etc.

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\text{Total variation} = \sqrt{(\text{CD})^2 + (\text{LTMD})^2 + (\text{STMD})^2}
\]

On-line gauging industry developed process control tools to reduce these variations. Sophisticated control algorithms were developed for CD control or AutoProfileControl (APC) which work in conjunction with advanced Auto Dies. The modern dies employ advanced design to reduce coating edge beads. On-line gauging systems employ precise die-mapping techniques to address linear material shrinkage, as well as non-linear shrinkage in the neck-in region. Sophisticated control strategies such as Accelerated Thermal Response (ATR) algorithms were developed to take full advantage of fast acting modern dies. PID control strategy ensures optimum CD control to achieve full-width coating uniformity.

LTMD variations are controlled through adjustments to Screw Speed or Line Speed. Advanced control for optimization such as Throughput control strategy is also available. In cases where product is sold by area, yield optimization control (Target Management Control or TMC) strategy is employed. TMC takes advantage of reduction in total variation to increase coated area per KG of polymer, while maintaining the specifications to ensure package design properties.

On-line gauging industry developed process analytical tools to help Extruder/Laminator Line Operators to identify causes of uncontrolled STMD variations. Fast Fourier Transform (FFT) algorithm helps identify the specific equipment that contributes to the STMD variations by highlighting the various frequencies and their magnitudes. This powerful process analytical tool enables the Maintenance staff of the Extruder/Laminator to fix the equipment promptly to reduce STMD. Combination of APC, MD controls and FFT result in maximum reduction in coat thickness variability. This enables the Extruder/Laminator production staff to optimize polymer coating yields through TMC.

**Process Visualization Tools**

ContourView Display Suite is a set of graphical tools that enable product quality to be closely inspected and improved in real-time. Multi-faceted data views such as ContourView, BlanketView and StabilityView, enable the Extruder/Laminator operators to better understand the process effects on product quality. The 3 dimensional contour view display provides detailed view of profile trends to help monitor long-term performance of profile control (APC).

**Extrusion/Laminator Customer Results**

The quality improvements and economic benefits derived through application of advanced HR-FSIR sensor technology in combination with process control technologies in complex extrusion coating processes have been significant.

Customer results achieved on Multiframe/Multisensor (HR-FSIR and differential Beta combination) for measurements of multilayer, multi-station coatings, in conjunction with Auto Profile Control of automatic thermal-bolt Dies, in paper coating applications are summarized below:
A) Multiple Case studies: Systems with HR-FSIR on ungauged Extrusion Coater/Laminators or replacement of alternate sensor-technology based systems, and AutoProfileControl.

Reduction in CD variations:
Outside layer: 60 to 90 %
Inside layers: 50 to 85 %
Laminate layer: 50 to 85 %

B) Auto Profile Control Response

CD variations reduced on average by 70 % within 20 minutes from start-up

C) Faster product change-overs

Product change-over times reduced from about 45 minutes to 15 minutes, a 67 % reduction.

D) Scrap reduction

Scrap reduction at the Laminator in the range of 50 % was achieved, which included start-up scrap, edge scrap and sampling scrap.
Additional scrap reduction at downstream slitting operations resulted as well.

E) Increased edge measurement and control

HR-FSIR enabled scanning to about 8 mm from each substrate/foil edge vs. 25 mm before, in cases where old gauging systems were replaced. This amounts to measurement and control of 2 % or more of the entire width of the roll, to achieve full-width flatter rolls.

Conclusions

The customer results in the complex extrusion coating industry derived from the application of the advanced FSIR sensor technology in conjunction with automatic controls, is proof of the superiority of the FSIR sensor technology in multilayer coating measurements.
The on-line gauging industry, in its quest for providing a tool for optimization of complex Extrusion/Laminating process, has developed optimal solutions in terms of a combination of sensor technologies, advanced process control strategies, sophisticated process analytical tools and process visualization techniques. The use of powerful PCs have enabled faster data acquisition and processing to deliver optimal solutions at reasonable costs.
In these days of rising polymer material costs and tightening margins, an advanced on-line gauging system is a powerful Process Management Tool in improving product quality and production economics for the complex Extrusion/Laminating coating industry.