

Measurement and control of biaxially oriented films for coating, laminating, and packaging applications

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ABSTRACT: *Coating and laminating processors demand high-quality films of uniform gauge and flatness as substrates and laminates for cost-effective processing. The packaging industry also has a critical need for such films for high-speed processing and printing. This article analyzes the requirements of gauging and control systems for precise measurement and control of the biaxial orientation process.*

KEYWORDS: *biaxially oriented films, coating, computers, control systems, laminating, measurement, packaging, utilization.*

Films manufactured by the biaxial orientation process possess superior physical properties in terms of strength, shrinkage, and clarity. They are highly desired as substrates, laminates, and packaging materials by the coating, laminating, and packaging industries. Biaxially oriented films, for example, account for most of the world's flexible food packaging material. The biaxially oriented process enables a wide range of film thicknesses to be produced on the same equipment at substantially higher throughputs than traditional film processes. Thinner gauges, in the area of 0.006 mm for capacitor film, or heavier gauges for printed labels and tapes, can also be produced on the same equipment with certain modifications to both machinery and operating conditions. Various thermoplastic polymers have been successfully processed

into biaxially oriented films such as polyester terephthalate (BOPET), polypropylene (BOPP), polystyrene (OPS), etc. The stretch ratio may vary widely, depending upon the properties of a specific polymer.

Biaxial orientation process

Biaxial orientation is a technique developed for the sequential or simultaneous orientation of thermoplastics materials. The process usually is sequential and in line with extrusion, including the casting or chilling of the polymer melt, stretching in the machine direction over heated rolls, stretching in the lateral direction on a tenter frame positioned inside an oven, edge trim slitting, and winding. Corona treating also can be done in-line to prepare the final product for printing and to improve adhesion for lami-

nation or coating. Coextruded, multi-layer structures using three or more extruders provide barrier and heat-sealing properties needed in certain packaging applications.

A typical biaxially oriented polypropylene coextrusion system is illustrated in Fig. 1.¹ The major sections of the processing line are coextrusion and casting, machine direction orientation, lateral stretching (tenter and oven), and treating and winding units. The appropriate locations to gauge the thickness are after casting (upstream gauge) and before winding (downstream gauge).

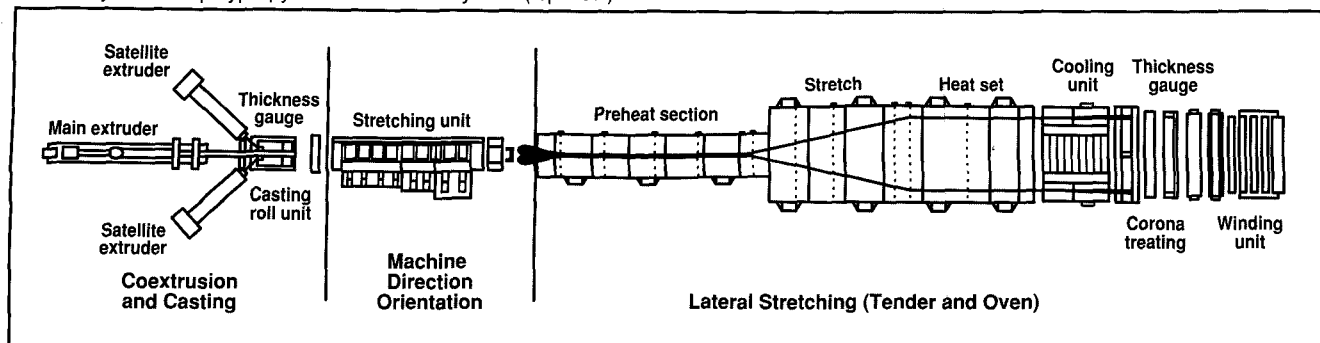
The purpose of the casting machine is to cool the polymer melt uniformly and at a predetermined rate. The specific design of the casting equipment is a function of the polymer characteristics. For example, a highly crystalline polymer such as polypropylene requires rapid quenching, whereas an amorphous material such as polystyrene requires gradual cooling.

After casting, the extruded sheet is usually gauged and then passed to the machine direction orientation (MDO) unit where it is raised to the desired temperature for orientation, having been reheated over a predetermined number of rolls. The number of pre-heat rolls is determined by the throughput and heat transfer efficacy. The sheet is finally raised to the desired machine direction orientation temperature and passed through a

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¹Modern Plastics Encyclopedia '92, McGraw-Hill, New York, 1991, p. 312.

1. Biaxially oriented polypropylene coextrusion system (top view)



single- or multistage draw section. The stretch ratio in the MDO unit may vary from 2.5:1 to 8:1 or higher, depending on the properties of the specific polymer being used. A two-stage draw is common in BOPP systems; for certain specialty products, three- or five-stage MD stretch ratios are available.²

The annealing section of the MDO follows the stretch section and is usually a duplication of the preheat section with fewer rolls—usually two or four.

After the sheet has been cast, stretched in the machine direction, and annealed, it passes through an edge guide system and into the transverse direction orienter (TDO) or tenter frame. The tenter has two horizontal chain systems so that the cast sheet is drawn or stretched in accordance with a divergence pattern. The chains are driven by horizontally mounted sprockets at the exit end of the unit. Turn-around idler sprockets are at the entrance end. A system is supplied to maintain tension of chain and compensate for thermal expansion. This system is typically hydraulic and includes an automatic slack and broken chain detector.

Although sliding-type tenter clips which require lubrication are usually used for polypropylene, polystyrene, and polyvinyl chloride, the more sophisticated polyester producers use bearing clips and a monorail design. This design uses sealed bearings to prevent lubricants from contaminating the film.

The width of the tenter frame is adjustable throughout the total length, making possible the desired lateral stretch ratio. For instance, polypropylene is commonly oriented laterally between 6:1 to 10:1, whereas polyester, polystyrene, and polyvinyl chloride are commonly stretched between 2.5:1 and 3.5:1. The tenter frame is positioned within an oven having insulated panels and a series of independently controlled temperature zones.

The finished film is guided by driven rolls through slitting to remove the edge, and sometimes through center slitting and corona treating to one or more turret-type winders.

Need for a gauging and control system

The ultimate function of the biaxial oriented line is to produce the best quality films to the desired gauge with minimal product variations. The process involves a series of steps, such as cooling, preheating, stretching in machine and lateral directions, and cooling again. The process equipment is comprised of a multitude of rolls, drives, oven, and tenter. Even with well-designed process equipment, the process dynamics cause variations in the process. In order to achieve the best results in the final film, the dynamic process variations need to be continually monitored and controlled in conjunction with continuous product gauging. The polymer material characteristics and stretch ratios determine the shape of the extruded sheet at the cast end that would result in a flat

profile at the film end. For example, polypropylene and polyester require a "W" profile at the cast end to achieve a final flat profile, whereas polystyrene requires a flat cast sheet profile rather than a shaped profile, as larger stretch ratios are the norm for BOPP and BOPET films.

Continuous control of the die opening to respond to dynamic process variations is necessary to achieve flat profiles, and continuous control of line speed is needed to respond to throughput changes to achieve the desired gauge. For continuous automatic and unattended optimum control of the process, it is necessary to gauge both cast sheet (upstream) and final film (downstream) and to combine the data appropriately to respond quickly not only to the variation between the die and the cast sheet but also between the cast sheet and final film.

Hardware for an optimum gauging and control system

Biax lines are getting wider, the world's largest being an 8.4-m BOPP line. Hence systems with fast scanning speeds of 250–300 mm/s are needed. These speeds require sturdy frames and precision frame technology.

Noncontacting gauges are needed because the final film applications in packaging require optical clarity and aesthetic qualities. The sensors also must conform to stringent performance specifications to provide precise measurements at fast scanning speeds. They also must be able to detect streaks. Strontium-90 nuclear transmission gauges for thick cast

²Film Handling Equipment—Biaxial Orientation, in *Modern Plastics Encyclopedia* '92, McGraw-Hill, New York, 1991, p. 312.

sheet measurement and super Krypton-85 nuclear transmission gauges for final thin film measurement have been quite successful. These sensors have performed the exacting task of measuring the large transition from thin film to edge beads within a narrow width, every scan. A high degree of reliability of the sensor and frames is, of course, a prerequisite of a gauging system.

Auto profile control of the die requires a flexible lip die design, e.g., autoflex dies, and microprocessor-based hardware to adjust individual die-bolt power levels to make appropriate die-lip adjustments.

A continuous and precise monitoring of process variables, such as melt pump or screw speed or measuring line speeds at upstream and downstream ends using precision tachometers, is also a necessity.

Software requirements

A high degree of sophisticated software technology is a must to address the challenges of the biax process. The two main issues are precise alignment of final film variations all across the wide web to a much narrower die-bolt section and fast response to process dynamics in various sections of the processing line.

Precise alignment of final film variations to the individual die-bolts is based on two separate alignments: die-bolt to cast sheet and cast sheet to final film. For many materials, a "W" shaped profile at the cast end is needed to achieve a flat final film. This desired profile needs to be achieved immediately upon startup, and a gauge at the cast end is essential for such a task. The final film quality needs to be continuously monitored. Hence a two-gauge system is absolutely essential for precise control of a biax line.

A software approach to align final film variations directly to each die-bolt presupposes stability in the MDO and TDO section of the process. It may not provide sufficiently fast responses of process control, especially if dynamic process upsets occur in those sections.

A better approach would be to align precisely the final film to the cast sheet and cast sheet to die bolts.

Mass conservation technique for precise alignment

A precise alignment technique based on conservation of mass provides a superior approach. The alignment algorithm is based on the obvious assumption that each profile, cast and final film, represents the same total mass. The film gauge should be placed before trim, otherwise the trim amount should be used in the algorithm. Starting at given reference positions in the cast and film profiles, the gauge accumulates film readings until the percent of total film is equal to the percent of total cast, which is calculated by dividing the current cast reading by the sum of the cast profile values. Dividing the film amount (current percent of film total) by the fractional number of summed film readings results in an aligned output value. The reference positions are sheet edges or known cast and equivalent film positions anywhere in the web cross section.

The alignment precision can be enhanced by the same-spot technique. This technique ensures exact tracking of the cast sheet measurement by the film sensor under all dynamic changes in the processing line, including sheet wander. A stretch/shrink algorithm further enhances the alignment precision. Deviations, D_i , relative to cast scan average, C_{avg} , are calculated from aligned film measurement, F_i , as follows:

$$D_i = (F_i - F_{avg}) \times C_{avg} / F_{avg} \quad (1)$$

This deviation output profile (delta profile), produced from cast and film input profiles, is aligned to the cast sheet for cascaded Auto Profile Control (APC) feedback. The delta profile is added to the cast sheet profile every scan prior to the die bolt alignment. The auto profile control is executed on the modified cast profile every scan relative to the desired target-shaped profile to produce a final flat film.

The APC align algorithm precisely aligns cast sheet to the die-bolts. This alignment algorithm is position-based. Starting with die bolts nearest the center sheet and working toward the edges, we can calculate a bolt's centerline position on the web by moving a tuned distance for each bolt. The neck-in characteristics of the polymer material must also be addressed. For bolts involved in the neck-in regions near the edges, the tuned distance between the bolts is iteratively reduced according to neck-in parameters. Total neck-in is the difference between total used bolt width minus sheet width. Nonuniform neck-in on each side may also be addressed by the software. The number of deckled bolts on each end of the die is determined automatically by the APC alignment algorithm.

Control requirements

Having precisely aligned the film variations to the appropriate die-bolt, the control system must address the issues of fast response APC control. Since short-term machine direction (STMD) variations are outside the band width of a die bolt heater control loop, STMD should be removed from the profile data used for APC. This is done either by a smoothing algorithm to produce a smoothed profile as input or by use of heavy cross-machine smoothing (feathering). Since flexing of a die-lip at a particular die-bolt has effects on two to four adjacent bolts, a feathering algorithm is needed under these conditions. Output array values are determined by calculating a weighted average of web measurements on both sides of each die bolt centerline to extend to two to four adjacent bolts. The weight magnitudes vary as a function of die-lip flexing.

Auto Profile Control (APC) adjusts the die-bolt power levels to provide a web profile to the desired target—for example, the desired shaped profile for cast sheet. The PID (Proportional, Integral, Derivative) control calculates current output power levels between 0% and 100% automatically, based on the modified cast profile and desired

setpoints (shaped profile) for cast sheet. The PID loop features include tunable reset windup limits on integral control, deadband for derivative control, and separate high and low output clamps. PID equations are programmed so that positive gains yield an increase in power level output for an increase in measurement. In other words, positive profile deviations (heavier gauge) result in increased power level output which elongates the die-bolt, closing the die-lip to reduce the gauge at that bolt.

A PI loop for cascade biax control between film and cast sheet produces a fast response without oscillation.

Multiple loop tuning of PID loops for individual or clusters of die-bolts provide control flexibility. For example, edge bolts (nonlinear section) can be controlled differently from the linear center bolt section.

Another software feature that enhances control is the auto-adjustment of PID gains for various process conditions such as changes in line speeds.

A recipe feature (menu storage) for setpoints for shaped profile and PID gains for various products is a powerful software package of the control systems.

While the flat film is achieved through automatic profile control, the average gauge thickness of the film is achieved through nominal control of line speed or melt pump or screw speed. Auto gain adjust feature is an added enhancement.

Process diagnostics

The total film variations are comprised of crossweb variations (profile) and downweb variations (machine direction, or MD). The MD variations are further comprised of high frequency variations (STMD) and long-term drifts arising from melt variations, temperatures, etc. (LTMD). The profile variation is controlled by auto profile control (APC), while the LTMD is controlled by nominal control of thickness through line speed or melt pump (screw) speed. This leaves the STMD as the uncontrolled component of the total variation. A soft-

ware package called Process Variance Analyzer (PVA) provides a breakdown of total product variations into individual components. The efficacy of control is highlighted through the profile and LTMD variation numbers. The STMD number indicates the uncontrolled process variations.

Fast Fourier transform (FFT) algorithm

This powerful software package breaks down the STMD into individual frequencies that can be related to specific equipment variations in a process. Thus the magnitudes of uncontrolled variations and the causes thereof are exactly identified by FFT. This is a powerful analytical aid to a biax process engineer. Furthermore, an enhanced version of the FFT software package provides trends of magnitudes of different components of variation over longer periods of time. These trends identify deterioration of various process equipments in the biax line. Process and maintenance engineers can use this information to rectify the equipment problems in a timely manner to reduce substantially the STMD components of total variations.

Results

Installation of a precise measurement and control system on a high throughput biaxial oriented line has resulted in measurable benefits. Optimal, continuous, and unattended APC (profile) and nominal (thickness) control, in conjunction with the FFT features, has resulted in a substantial reduction in total product variations. Roll variations within 2% on all products on the biax line have been the norm since system installation. Continuous process improvements, assisted by high process visibility from customized displays, have further reduced the overall variation.

Smooth transitions at product changes which maintain first quality without any scrap contribute substantially to the financial bottom line. Management Information System (MIS)

reports and host link capabilities document results to biax line management and quality to their customers.

The resultant best quality films supplied by the biax film manufacturers to their customers in the coating, laminating, and packaging industries have enabled them, in turn, to manufacture better products at higher throughputs with minimal scrap and downtime. Thus a successful partnership between the gauging system supplier and the biax film manufacturer has, in turn, contributed to successful business relationships between the biax film manufacturer and its customer base. This partnership has benefited consumers at large in terms of best quality products at competitive prices. ■

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