The Tire Cord Calender As Process System
Operating For Consistent Product

Abstract

Examines rubber calendering as a process system, with a particular emphasis on tire cord calendering. A review of the process and machine variables, with an overview of the linkage between on-line gauge measurement and machine control parameters. Discusses the relationship between material preparation and gauge control, and examines the relationship between product quality and system maintenance.

INTRODUCTION:

We generally recognize that a Tire Cord Calender is in reality a complex system, or perhaps more accurately, a “super system” – comprised of several complex subsystems. We can readily intuit that the success of the “super system” is dependent on the successful functioning of the various subsystems and the individual elements that comprise those subsystems. We also have an instinctive feel for the sensitivity of the process to variability in the functioning of those subsystems. For example, we know we can tolerate some variability in the temperature of the circulating oil without effecting the ability of the calender to function; contamination of the lubricating oil, while it will not cause an immediate failure, will, if uncorrected, lead to a bearing failure; a stoppage of the lubrication system will rapidly result in failure and a shutdown. In some instances, our knowledge of the sensitivity of the “super system” to performance variation in the subsystems and components is empirical, in some instances theoretical, and in some instances, we make decisions on how to treat with that variability based on a failure analysis.

What is less obvious is that the calender, with its various mechanical, hydraulic, electrical, and electronic components, is itself a subsystem of the process system. Successful calendering depends on adequate control of all of the elements of the “system”. The overall system, of course, encompasses all of the materials and material preparation steps and equipment that come before the calender, and all those that come after it in the post calender train, up through delivery of calendered goods to the next step in the tire building process.

In the discussion that follows, we will deal primarily with the calender, and the compound that is delivered to it. There are a number of variables and concerns relating
to the quality, consistency, and delivery of the cord or wire to the calender that are
worthy of a paper or papers on their own merit. The same is true with the post calender
train. The application of electron beam technology to the in-line post-calender partial
pre-cure of tire ply has proliferated in recent years, with an accompanying increase in
complexity and reliability concerns for the post calender train.

REVIEW:
The simplest form of rubber calendering is the production of un-supported or un-
reinforced sheet. The operations necessary to produce an unsupported sheet include the
following:

- Warming the feedstock – softening the stock and raising its temperature by
  mechanically working it, either on a mill, in a cold-feed extruder, or by a
  combination of extruder(s) and mill(s).
- Delivering the warmed stock to the calender.
- Accepting, or feeding the stock in whatever form it is being delivered to the
  calender. Distributing it over the width of the nip, and delivering it to the
  pressure area ahead of the roll nip.
- Metering the stock – so that the mass flow through the nip is exactly equal to that
  needed to produce a sheet of the target thickness and untrimmed width.
- Extrusion – forcing the stock through the gap between the two rolls,
- Densification – rejection of any gases or air entrained in the feed bank, and
  compressing the stock sufficiently to produce a smooth, void free surface with
  uniform elasticity and recovery over the full width of the sheet.
- Gauging – bringing the material to a uniform thickness, in both the machine and
  cross-sheet directions.

All but the first two of these operations can be carried out in a single nip. If a second nip
is employed, it is usually only to apply a bond-breaker or carrier film to the rubber sheet
– and may take the form of an air-loaded laminating roll running against a calender roll.

Coating a fabric or substrate in the calender adds to the operations listed above:

- Transferring the rubber sheet from the calender roll to the substrate.
- Forcing the rubber into the interstices of the substrate sufficiently to meet the
  requirements of the coating process.
There are three processes for accomplishing these operations:

The first is laminating or skimming. In this instance, the substrate and the rubber are traveling at the same rate of speed, and the rubber is essentially pressed into or onto the substrate. The degree of penetration is dependent on the density of the weave, the viscosity of the stock, and the pressure applied in the laminating nip. There is usually no material bank in the laminating nip.

The second is frictioning. In this case, the stock and the substrate are traveling at different speeds, and the rubber is “scrubbed” or “frictioned” into the substrate. In older three-roll single motor drive calenders, the prototype for the process, the stock is on the middle or No.2 Roll, and is traveling faster than the substrate. Typically, the frictioning nip runs with a small bank of material. The process is most frequently used for coating densely woven substrates with a relatively thin layer of rubber.

Both skimming and frictioning employ two nips – one to form and meter the sheet, the second to effect the transfer. The third process for transferring rubber to a sheet or substrate is bank coating. Bank coating may be carried out in one nip or two. It is similar to frictioning in that the roll carrying the substrate and the roll applying the rubber are moving at different speeds. The major differences are in the size of the bank, the thickness of the coating being applied to the substrate, and surface finish imparted to the sheet. Bank coating is typically used where a relatively heavy layer of rubber is being applied to a substantial substrate, and the curing process will determine the surface finish. Conveyor belting is a classic example.

Traditional applications for calendering in the tire industry include coating cord and wire for tire plies and belts, coating fabric for chafer strip production, and the production of un-supported sheet for inner liner and tread components. Over the last few years, there have been reports in the trade press of smaller specialized calenders employed in conjunction with warm-up extruders to produce components on a continuous, as needed basis, for in-line tire production. Details of these concepts, and the degree to which they have proved to be both workable and practical, thus far remain the proprietary knowledge of the developers. We acknowledge the development here only to underscore that changing methods and improving technologies are a constant in all industries. The principles of calendering and successful calender operation remain constant, even if the
size of the machine on which they are applied, or the component being produced on it, should change.

While our discussion is directed at the Tire Cord Calender\textsuperscript{1}, the principles are applicable to almost any elastomeric calendering operation.

**PROCESS AND MACHINE VARIABLES:**
Tire cord calendering is a coating process. In modern tire cord lines, it is a double-coating process, with two layers of rubber being produced separately, then simultaneously laminated to an array of cords or wires. Sufficient laminating force is applied to force the rubber to “strike through” the cord, fabric, or wire, encapsulating the individual strands in rubber, and finishing with a rubber sheet containing reinforcing wire, cord, or fabric.

Referring back to our introductory notes, the process is similar to skimming – in the laminating pass, the substrate and the stock are traveling at nominally the same speed, and there is no bank in the laminating nip. In practice, with modern calenders having individually driven rolls, lines are often run with a slight lead on the No.2 or No. 3 roll, in effect running in a very light friction mode.

The objectives are as follows:

- Produce a web that is uniform in thickness from edge to edge and in the machine direction.
- Produce a web whose weight per unit area of rubber on the top and the bottom are within specification. (We usually think of equal weights on top and bottom – cord or wire centered in the web – but in certain applications, an unbalanced weight coat is the target.)
- Maintain a uniform wire or cord spacing in the web – uniform EPI across and down the web.
- Fully encapsulate each strand of reinforcement with a void-free matrix of rubber.

The process variables are:
• The work history of the feed stock or compound - the degree to which the viscosity of the rubber has been reduced as the result of the shearing action in the break-down, mixing, and warming processes.

• In-process storage, or aging - the degree of cross-linking that has occurred since the introduction of the cure system to the compound.

• Formulation – what is in the polymer matrix – structural modifiers, fillers, extenders, internal lubricant, anti-oxidants, anti-ozonants, cure systems…

• Stock temperature – the proximate cause of that part of the apparent viscosity variation that is independent of formulation, polymer breakdown, and degree of cross-linking.

The machine, or system, variables, include:

• Line Speed

• Friction Ratio in the Forming Nip

• Friction Ratio in the Laminating Nip

• Roll Temperature

• Roll Gap – Water and Drive End

• Crown Correction (Roll Bending Pressure or degree of Cross Axis applied)

• Splice Relief or Laminating Pressure (“Squeeze”)

Broadly put, machine variables are manipulated to manage uncontrolled variation in the process variables. The act of calendering imposes a load on the calender roll. In response to that load, the roll deflects, or bends. The load is transferred to the calender frame through the roll bearings and the roll adjust system. Some portion of the load also causes compression in the roll adjust mechanism, and stretching in the calender frame. Building a robust calender minimizes the amount of deflection, compression, and...
extension – but they still occur. If the load is constant, then we can adjust the calender, or manufacture it, in such a way as to produce a flat sheet when it is subjected to a particular constant load.

The difficulty, of course, is that different jobs produce different loads: Thinner stocks produce a higher load on the calender than thick; stiffer, more viscous stocks higher loads than soft; faster line speeds higher loads than slow. The modern tire cord calender addresses this difficulty by using roll crossing or roll bending to compensate for the roll deflection. From the machine standpoint, the real complication ensues when the load imposed on the calender roll varies during the production of a particular product. Regardless of how robust the calender construction may be, deflection will occur, and the amount of that deflection will vary as the load varies.

OVERCOMING AND CORRECTING FOR PROCESS VARIATION:
The fundamental principal that should guide all calender operations is consistency. We want to keep the roll separating force, and therefore the roll defection, as constant as possible. Some variation is inevitable – and can be anticipated. For instance, we cannot start the calender at line speed – we ramp up to it. The surface temperature of the calender rolls will not come to equilibrium until the line has been running for at least a few minutes. Other sources of change include a change of product, compound, and/or substrate.

Other sources of variation are expected, but less predictable – the occasional line problem that necessitates a slow-down while corrections are made; an interruption in the feeding and warming system, etc. These problems tend to have multiplicative effect – a slowdown inevitably results in more warm-up time and reduced viscosity of the feedstock, as stock is held in the warm-up equipment. This is followed by a rather abrupt change in viscosity as the over-warmed feedstock is fed into the calender, to be replaced by feedstock that once again is at or near the “normal” work history and temperature. Other disturbances often follow an unplanned line speed change – increase in bank size, poor movement of material in the feed bank, typically followed by near-starvation of the bank as the line is ramped back up to speed.

Perhaps last, but certainly not least, variation in the feedstock process variables will produce changes in roll loading.
Our objectives should be two-fold. We want to minimize the changes in roll loading by minimizing the variation in the feedstock, the way the feedstock is warmed and delivered to the calender, the size and shape of the feed bank, and in the various machine variables that affect roll loading. Secondly, when change occurs, we want it to be low in amplitude and long in period.

Over the last fifty years, great strides have been made in our ability to measure the thickness of the sheet that the calender is producing. All of our measurement technologies have limitations. “Noise” is always present. In its simplest form, “noise” is apparent signal collected along with the actual data. We would like to measure accurately differences in thickness that are on the order of five to ten percent of the total thickness – in English units, a half a mil or less. It does not require a very high “noise” level to make it difficult to separate the signal from the background.

Depending on the measuring technology, we may be measuring thickness (actually, variation in distance between a source and the surface of the rubber on a roll); mass, measured as the loss in energy of a reflected beam of gamma or beta radiation; the change in capacitance between a metal surface and the roll resulting from variations in the dielectric characteristic due to changes in the amount of rubber compound between the two. A moment of reflection tells us that quite a few things might affect the readings produced by these techniques – some being due to real differences in thickness or weight coat, others due to changes in density or composition, or simply surface roughness.

The point of all this is that for any measurement to be useful, the measurement signal must be filtered and averaged. We are looking at trends – not true instantaneous thickness measurements. This is very definitely a good thing – the localized and regional short-term variation in weight coat thickness is not something we want to try correct – at least not with the calender. We are concerned with adjusting for trends, for steering the measured average thickness steadily between two closely spaced bounds – the upper and lower limits. The more consistently we can control the roll separating force, the tighter our practical upper and lower limits can be.

Most on-line measuring systems measure and control three zones: Water End Edge, Center, and Drive End Edge. All three are really “bands” – in the usual mode, each comprising roughly a third of the width of the sheet. (This statement assumes a single scanning sensing head. Some calenders are equipped with three fixed-point measurement heads – which of course, do not scan, and whose measurement “band” is a tight narrow
strip – much less than a third of the sheet width.) The sensed data is added to the last several measurements for that zone or point, the oldest data point in the series is dropped, and the result averaged. If the result is within tolerance, nothing else happens. What happens if the measurement is out of tolerance depends on the device, the built-in logic, and how any user programmable variables are set. It may do nothing until the out of specification condition has persisted for a certain number of scans, or it may immediately initiate a control action.

Prior to a control action being initiated, the measuring system control logic will have made some calculations. No change in roll positioning or crown compensation is truly independent. Opening or closing the roll adjust at one side of the calender will pivot the roll about the centerline of the main bearing on the opposite end of the calender – in other words, opening the water end of the nip a bit will also open the drive end – a much smaller amount, but it will still open a bit. Increasing or decreasing roll crossing will also change the openings at both the water and drive ends of the roll as well. Some control systems calculate the likely effect of the anticipated control action, and output simultaneous corrections to offset the undesirable or unwanted change.

After the control action is initiated, there will be a time delay before it is accomplished. There will be an additional time delay before the result of the change appears at the measurement device. These delays must be accounted for in the measuring system logic - in order to avoid initiating a second correction before the effect of the first can be measured. If the measured variable is fluctuating with a relatively short period, or in a random fashion, it is entirely possible that by the time the correction has taken effect, the disturbance that led to it will have passed. When the time constants are such that this occurs frequently, the control system becomes part of the problem, rather than part of the solution.

The majority of the calenders now in existence make use of some form of nut and screw to position the rolls. The nut and screw are driven through a gear train, usually comprised of a two-stage worm gear reduction system. These systems are capable of making very small and precise movements, but by the nature of their design and construction, there are lags in the response of the roll to position corrections. Fundamentally, the necessary clearances in the system mean that when a change is made in the opposite direction of the previous correction, the backlash in the gear train must be reversed. The friction between screw and nut, and in older designs, between the end of the screw and the bearing box, produces a certain amount of “wind-up” in the system –
energy and torque are necessary to initiate movement that “unwinds” as movement is accomplished. Over the years, many improvements were made in these systems to minimize these effects: Tighter clearances in the gear train, antifriction bearings between the turned device and its bearing surface, the use of brakes to reduce “coasting” when the drive motor is stopped; antifriction bearings between bearing boxes and box windows, among other examples.

All of these issues apply equally to the roll crossing (cross axis) system. For both the roll crossing mechanism and the roll nip or gap adjustment system, frequent changes accelerate the wear on mechanical elements, increasing backlash and slowly degrading response time.

In recent times, hybrid roll adjust systems have appeared, making use of a screw and nut for gross positioning and short-stroke hydraulic cylinders interposed between the screw and the bearing box for fine adjustment. Such systems have been explored for over fifty years, and employed for a variety of reasons: The ability to very quickly open a roll gap the full length of the cylinder stroke; the ability to pass a fabric splice without adjusting the roll positioning system; the ability to laminate in a constant pressure mode. Positioning the roll precisely using the hydraulic cylinder in the roll adjust stack-up, or even singly, with no mechanical adjustment ability, has always been attractive. In theory, it offers the possibility of an almost immediate and step-less response to a corrective action, and offers the possibility of combined functions in a single package. Friction in the adjusting system is reduced to the seals in the cylinder. In practice, there have been a number of issues to overcome.

Such systems include sensors for roll position and hydraulic pressure, logic to filter these signals and determine appropriate output, and output devices to adjust hydraulic pressure and modulate roll position. Sensors have effective ranges, sensitivities, resolutions, response times, environmental (temperature, electromagnetic noise, etc.) and signal to noise ratios to consider. Output devices have similar issues – hysteresis, response times, accuracy, and repeatability, among others. The logic itself is based on certain assumptions and models that predict the expected outcome from a given control action. Designing and tuning these systems so that they reduce product variation rather than induce it requires considerable experience, a recognition of the limitations of the measurement and control devices employed, and the willingness to spend considerable time investing the theoretical with the empirical.
Despite these difficulties, the latest tire cord calenders employ these systems, and the issues have been overcome to the extent necessary to keep the lines running successfully.

THE EFFECT OF MAINTENANCE ON OPERATION AND QUALITY:
It should be clear from the previous discussion that the subsystems that respond to gauge correction actions are complex bits of mechanical and hydraulic components. Unless they are functioning correctly, response will be erratic, unpredictable, and not repeatable, rendering the most sophisticated gauge measurement system worthless. Similarly, the most mechanically perfect calender will produce useless material if the gauge measurement system is not working correctly.

The primary cause of malfunctioning roll adjustment systems is lubrication failure, usually between the screw and the nut, and with lesser frequency, in the ‘lifter’ assembly that couples the adjusting screw to the bearing box. Unlike lubrication loss to a main bearing, which manifests itself as a hot bearing or a bearing rapidly shedding metal particles, lubrication failure in the roll adjust system is more invidious, and hard to detect. The reduction ratio in the roll adjust system is very high – high enough to break things if something stalls the drive train. Consequently, quite a bit of damage can be done before a loss of lubrication is apparent.

Hydraulic or composite hydraulic and mechanical roll adjust systems need clean, well filtered and conditioned hydraulic fluid. Pressure, directional, and positioning valves have close clearances, and do not cope well with dirt or particulate matter. Leaks in the system must be attended to – particularly leakage at the cylinders.

In either type of system, sensor operation must be checked and calibrated on a regular basis. The devices themselves must be protected from mechanical or thermal damage.

The gauge measurement system must be calibrated on a periodic basis, and appropriate preventive maintenance performed to keep it operating correctly.

Our focus has been on the measurement and control of the gauge or thickness of the rubber coating, and on the systems on the calender that directly adjust the roll nip. Every system is a contributor to the performance of the machine. Roll bearing, bearing preload and/or pull back systems, and the bearing lubrication system all contribute to keeping the roll rotating at or near a constant center of rotation – a key issue in maintaining control of
the gauge. The drive train must maintain constant roll speed, or fluctuations in gauge will result. Put another way, the equipment must be maintained properly to insure optimum performance. It is not enough that the rolls rotate.

SUMMARY AND CONCLUSIONS:
The sources of variability in product output can be divided into two broad categories: Variation in the feedstock, and variation in the operation of the calender. Variation in feedstock requires the calender to make adjustments to compensate for the variation. If we minimize the need to make compensatory adjustments, we reduce dependence on measurement, control, and mechanical systems.

Variation in the way the calender line is operated has several roots: One is production scheduling – short runs and frequent product changes are an anathema on stable operation and uniform gauge. Another is poor reliability in any system that supports the operation of the line. Anything that requires slowing or stopping the line to correct will result in the production of out of specification product – at least while the gauging system (or the operator) corrects for the problem. Another source of variability is poor operating discipline – usually the result of inadequate training. It is not enough that the operators know what to do, they should also know the why and the how. Understanding how speed variation, bank size, warm-up time, and other variables at least partly under their control affect the quality of the product is essential. They must be part of the quality team – not simply tools of it. Without this knowledge and understanding, they will make decisions that keep them out of big trouble, and blame the little trouble on other things. For example, they will tend to keep too large a feed bank, accepting gauge control problems in exchange for reducing the risk of bare spots on the substrate.

The successful operation of a tire cord calender line rests on the recognition that the line is a composite of several systems, and that each of those systems, including the operators and foremen, must be functioning correctly for optimum performance.

The important points:

- Delivery of consistent feedstock to the calender is paramount. All else is avoiding further variation and attempting to correct for variation at the input end of the process.
• The measurement and control functions of the on-line gauging system must be matched to the capabilities of the calender roll adjust and crown correction systems. It only creates excessive wear and induces product variation if the gauge control system attempts more correction than the system can handle. A new gauge cannot compensate for a worn calender, or the absence of certain important features in an older design.

• The calender, and all its support systems, must operate correctly. Erratic or unpredictable operation of any system, subsystem, or component, may either induce a variation in the product, or make it difficult or impossible to make an appropriate adjustment.

• The calender line is in dynamic equilibrium with the process and its environment. It achieves that equilibrium after it has been operation for some period of time. The more sophisticated and responsive the elements of the calender and train, the more rapidly that equilibrium can be attained. Changes in operating conditions shift the equilibrium point.

• The pre- and post-calender train and the feeding and warming system must operate reliably. Slow downs and unplanned stoppages will result in scrap.

• Operating personnel need to know how and why each element of the line contributes to the production of on specification material. Equipped with this knowledge, they will make better decisions with respect to the manner in which the line is operated.

In the majority of the existing tire plants around the world, the production of cord and wire ply material for building the tire is carried out in the plant. Quite often, there is only a single calender line for that purpose. The entire productive output of the plant rests on the reliability, quality, and consistency of the product produced on that line. Attention to its reliable and proper operation is essential, not only to the productive output of the plant, but also to the job security of each and every person that works in that plant.

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1 We have assumed a certain degree of familiarity with a calender, its components, and its construction, and have not provided detailed discussion or definitions of such things as roll crossing, roll bending, preloads, etc. For a fairly complete discussion of these matters, the reader is referred to The Modern Tire Cord Calender, a paper presented by the author at the inaugural ITEC in 1994.