A look at the history of the pneumatic tire

By Lawrence R. Gooch
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The history of the pneumatic tire and the machinery required to make it are inextricably intertwined. As with many apparently novel and later totally ubiquitous and utilitarian ideas, the realization of the pneumatic tire could not occur until the fundamental technologies required to transform a concept into a practical product and a ready market for that concept were in place. The wheel had been around a long time.

Executive summary

The development of the rubber calender in relationship to the invention, commercialization and evolution of the pneumatic tire provides the structure for this overview. The gradual migration from low-speed, labor intensive processes and the development and implementation of pre- and post- calender equipment is reviewed.

Changes in equipment in response to changes in reinforcing materials; the improvement over time in the accuracy and stability of feed-forward control capability; the development and implementation of feed-back measurement and control; and the resulting gradual emergence of calender operations as integrated process systems is outlined. Limitations of measurement and control technology with respect to certain properties and the fundamental dependence on the preceding material preparation processes are highlighted.

TECHNICAL NOTEBOOK
Edited by Harold Herzlich

Over the centuries, it had undergone many improvements. Bicycles had been in existence long enough that bike racing had become a bit of rage in the British Isles and on the continent. The hard rubber tires then available did little to smooth out the road.

In response to that problem, John Boyd Dunlop, a Scotsman and resident of Belfast, developed and patented the first practical pneumatic tire. When bicycle racers using his tires began winning races, the market was ready.

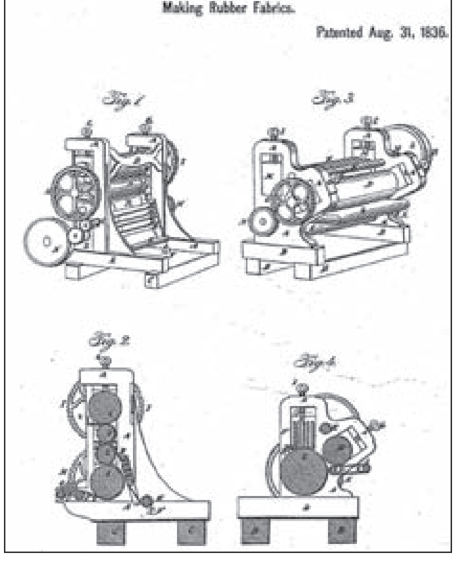
In order to make possible the pneumatic tire, a means of coating cloth with rubber to make it impermeable to air was necessary. Two men on opposite sides of the Atlantic would make major and complementary contributions to that process, and interestingly enough, Charles Goodyear, of whom we shall learn more shortly, would be involved with both.

In England, Thomas Hancock, an inventor, and in the business of building of coaches, became interested in the emerging use of rubber to produce water-proof clothing. Seeing a market opportunity in the purchasers of his coaches, he set about to improve the processes then in use. At the time, rubber was coated on fabrics using a variety of techniques, all requiring that the rubber be dissolved in a solution.

In an effort to recover and utilize the scrap, Hancock would develop a masticator, and in the course of doing so, would discover that masticating the rubber improved its processing and performance properties. He would patent his masticator and a spreader used in the coating process in 1837.

In the U.S., Edwin Chaffee of the Roxbury India Rubber Co., working on a method of reducing the amount of solvent required to rubberize fabric, developed and patented a machine that in fact required no solvent. Chaffee's 1836 patent, which is both a device and a process patent, describes what is essentially two separate pieces of equipment.

Fig. 1. Drawings from Edmund Chaffee's 1836 patent.



Chaffee considered the two assemblages a single machine, most likely owing to a common base and power train (not detailed in the patent). The first of the two is a clear antecedent to the two-roll compounding mill; the other is an equally clear antecedent to what we now call a calender.

Chaffee softened and warmed the rubber on the first assemblage, then manually transferred the softened stock to the second, which could be operated in a variety of modes to transfer the softened rubber to a fabric or leather substrate.

Two of the necessary basic elements were now in place: A means of masticating or softening rubber and working ingredients into the rubber matrix without first creating a solution, and a means of transferring the softened compounded mass to a fabric or substrate either by pressure laminating or frictioning.

What remained was the need for a means of treating the rubber to stabilize it, something Charles Goodyear was already working on. In 1839, he would discover the basic chemistry and the steps necessary to "cure" rubber. In 1844, after developing the process sufficiently to make it practical, he was issued a patent for the process.

In England, Hancock, working with some samples of Goodyear's earlier work, successfully reverse-engineered the process and beat Goodyear in filing for a British patent. A colleague of Hancock would coin the term vulcanization, by which the process came to be known. In the U.S., Goodyear would purchase Chaffee's machine, and two others like it, and eventually settle in Naugatuck, Conn.

Fig. 2: Mill room, circa 1859 (from the Scientific American 1859 article on the New York Belting & Packing Co. in plant in Newtown, Conn.)

The machinery—before the tire

In 1854, Almon Farrel, founder of Farrel Machine and Foundry in nearby Ansonia, Conn., would book an order from Charles Goodyear for two calenders—a three-roll 20" x 48" and a four-roll 20" x 48" machine.

Compounding and calendering rubber both employ a speed differential between adjacent rolls, tearing and shearing the rubber both against the surface of the moving roll and internally, against itself. The abrasion of the material against the surface of the roll demands a hard surface.

Casting iron in a metal mold or chill cools the outer portion of the piece quickly, trapping the carbon in the melt in the crystal lattice of the cooling iron, and producing as a result a very hard outer surface. (For those who may have struggled to de-mold other cast objects—the shrinkage in iron casting is sufficient to free the cast cylinder from the mold.)

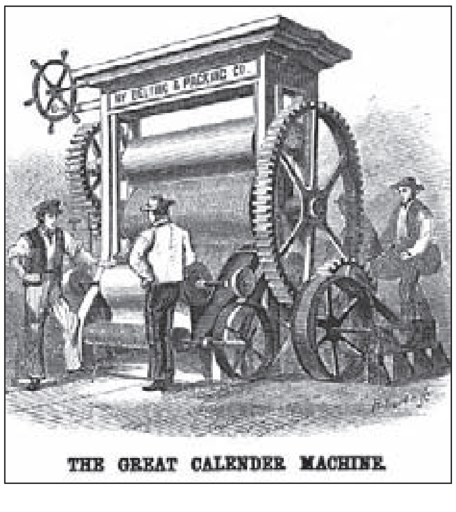
The process of making such chilled rolls was known and in use in Europe—Walzen Irle having cast chilled iron rolls as early as 1820. Farrel was forced to order the rolls for these two calenders from Europe. This provided the impetus for Farrel Foundry & Machine to master the process, as there was not only a strong market for quality rolls in the emerging rubber industry, but such rolls were also foundational in the paper and metals industries.

In order to illustrate the state of the art with respect to the machinery that was in place when Dunlop patented his tire, we can make reference to an 1859 article in "Scientific American" on India rubber manufacturing.

After discoursing on the origins of the rubber industry and the trials of Goodyear, the author reports on a tour of the manufacturing plant of the New York Belting and Packing Co., located on the Potatook River in Newtown, Conn.

The article is illustrated with a series of pictures of the plant and its equipment, to include washers, grinders (crackers), mills, a calender, and "steam chambers" for vulcanizing.

Fig. 3. Calender, circa 1859.



The firm was at the time making fabric-reinforced rubber belting for industrial drives, mandrel-built fabric-reinforced rubber hoses in sizes from ¼ inch to 12 inches in diameter, and a wide range of fabric-reinforced packings and gaskets. The plant was powered by a 50-foot diameter water wheel, supplemented at the time of the tour by a newly installed steam engine of 200 horsepower.

The author

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He holds a bachelor's degree from WPI University, a master's in metallurgy from Stevens Institute of Technology and an MBA from the University of New Haven.

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Gooch

His work in the rubber and plastics industries began as a summer intern with the Farrel Corp.

Following a tour of active duty as an officer with the U.S. Army and graduate work at Stevens, he returned to work at Farrel in various technical and sales capacities. He left Farrel to manage a millwrighting, rigging and machinery re-engineering and rebuilding operation.

Since 1990, he has headed Gooch Engineering Associates, providing engineering and technical services relating to plant layout, process design, mixing and compounding equipment, mills, calenders and calendering operations.

He is the author of several papers on subjects pertaining to calenders, calendering, mixing and compounding equipment, and the design of process facilities comprised of such equipment.

Fig. 4: U.S. Tire Dunlop tire ad, 1913.


The UNITED STATES DUNLOP (Straight side) TIRE
is the premier automobile tire of the world

The Genuine Dunlop Tire

MORE THAN A 600% INCREASE IN SALES IN LESS THAN A YEAR'S TIME

UNITED STATES TIRE COMPANY

Cannot Rim-cut, of Course

New York Sun Full page Ad 1913

The tire and the calender

The first pneumatic tire was invented by a Scotsman, Robert Thompson, in 1845. As with many other rubber products of the period, the uncured rubber was not up to the task, and nothing practical came of this effort—to the point that Dunlop, in 1888, could reinvent the pneumatic tire believably claiming no prior knowledge of Thompson's effort.

Less than 10 years later, the Michelin brothers, Andre and Edouard, would fit a set of pneumatic tires to an automobile and drive it in a race. The pneumatic tire, soon to be a bias ply tire inflated by a separate inner tube, was on its way.

Overview

Calenders and mills, the fundamental tools of the rubber industry in general and key to the material preparation stage for tire building, began a long slow evolutionary process that continues into the present.

Using the composition of a contemporary tire cord calender line as a lens, we list some of the technological developments that have been part of that evolution: Metallurgy, metal fabrication and machining; bearings, tribology, the composition and method of application of lubricants; power generation, transmission, and control; metrology; web, cord, wire handling and tension control; heat transfer; hydraulic and pneumatic energy usage and control.

With respect to the materials comprising the tire: the progression in rubber reinforcement or cord materials and the knowledge and techniques of treating those materials to couple the reinforcement to the rubber; the production, treatment, and handling of steel wire for bead and eventually steel belt components; the steady progression in the understanding of rubber chemistry and compound development.

As described in the article on the New York Belting and Packing Co., water or steam power was used to drive the machinery. Power was distributed through the plant by a system of line shafts, belting, and gears. Speed variation would be accomplished by means of shifting gearing, or moving a drive belt from one set of pulleys to another. Mill rooms were arranged with the equipment in long lines with a drive or "line" shaft passing underneath the machinery to be driven.

Lighter duty line shafts, driven from the same or a secondary power source, and suspended from the overhead beams, drove smaller equipment through a system of belts, pulleys, and clutches. In the latter part of the 19th century, direct current (DC) electric motors would begin to make an appearance in manufacturing plants.

The electrical power necessary to drive those motors initially was generated on site, owing to limitations in the distance that direct current can be transmitted at using voltages without a significant power loss. The legacy of line-shaft transmitted power and existing plant layouts saw initial installation of electrical motors simply replacing the steam engine.

Fairly quickly, calenders were fitted with an independent motor, as there was considerable advantage to being able to vary the speed of the rolls easily. The cost and size of electrical motors, together with the ability of multiple machines driven by a single prime mover to share power as needed to overcome transient loads, resulted in the persistence of line shaft drive mill lines well into the 20th century, with examples still in place in older rubber plants.

Early calendering operations were essentially batch processes. Any preparation of the substrate to make it ready for the calendering operation was carried out remote from the calender. All of the take-up and let-off equipment was mounted directly on the calender frame and driven from the calender main drive motor.

As pre- and post-calender web handling lines extended away from the calender, the need to coordinate all of the driven elements in such a manner that increasing or decreasing the speed of the calender resulted in a proportional increase or decrease in speed of the other equipment in the line continued to be solved by driving all of that equipment from the calender main drive motor or power source.

Line shafts, cascaded belt or chain drives, jaw and friction clutches, shifting levers, bevel and straight gearing, delivered the power needed to drying and cooling drums and take-up equipment. Speed ratios or draw were accommodated with slip clutches and variations of variable speed pulley drives.

In 1896, Milton Reeves patented a variable speed transmission that would evolve into the Reeves Vari-Speed Pulley and Reeves variable speed Moto-Drive. The P.I.V., using a unique variable tooth chain drive, was patented in Germany in 1928. These devices permitted adjusting the speed ratio between the primary drive source and secondary driven elements in the calender train.

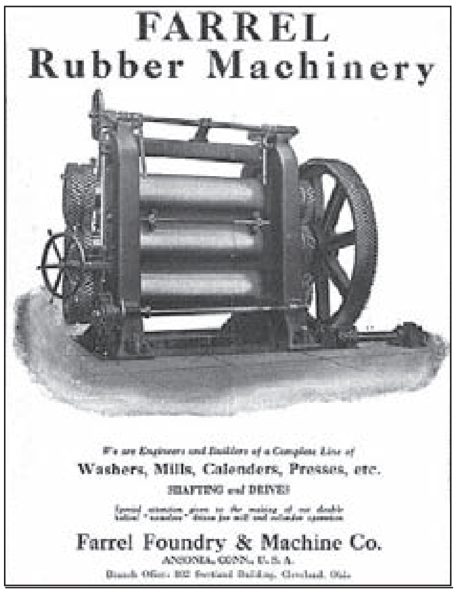
Gradually, individual DC drive motors coupled to driven elements by means of gear reducers, either directly or in combination with open gearing and chain and sprocket drives, began to take the place of these devices.

Alternating current (AC) electrical power, generated off site by local and regional power companies, fairly rapidly replaced locally generated DC power. Where the cost of replacing motors was prohibitive, or the ability to vary drive speed was considered essential, AC power was converted to DC by means of rotary converters or motor-generator (MG) sets.

MG sets were somewhat superior in terms of speed control and would remain in use until the development of semi-conductor technology enabled the economical production of solid-state conversion

See **Tire***, Page 16*

Fig. 7. 1920 Farrel ad showing calender.

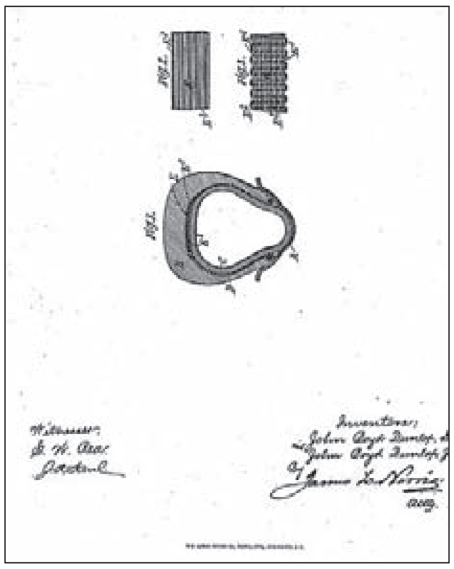


FARREL
Rubber Machinery

We are Engineers and Builders of a Complete Line of
Washers, Mills, Calenders, Presses, etc.
SHAFTING and DRIVES

Farrel Foundry & Machine Co.
ANSONIA, CONN., U. S. A.

Fig. 6. 1894 Dunlop U.S. patent.



Inventors;
John Boyd Dunlop, Sr.
John Boyd Dunlop, Jr.
by James L. Norris
atty.

Fig. 8. Firestone's 1923 announcement, balloon tires.

BALLOON
GUM-DIPPED
CORDS

Firestone

Fig. 5. 1912 nonskid tires.

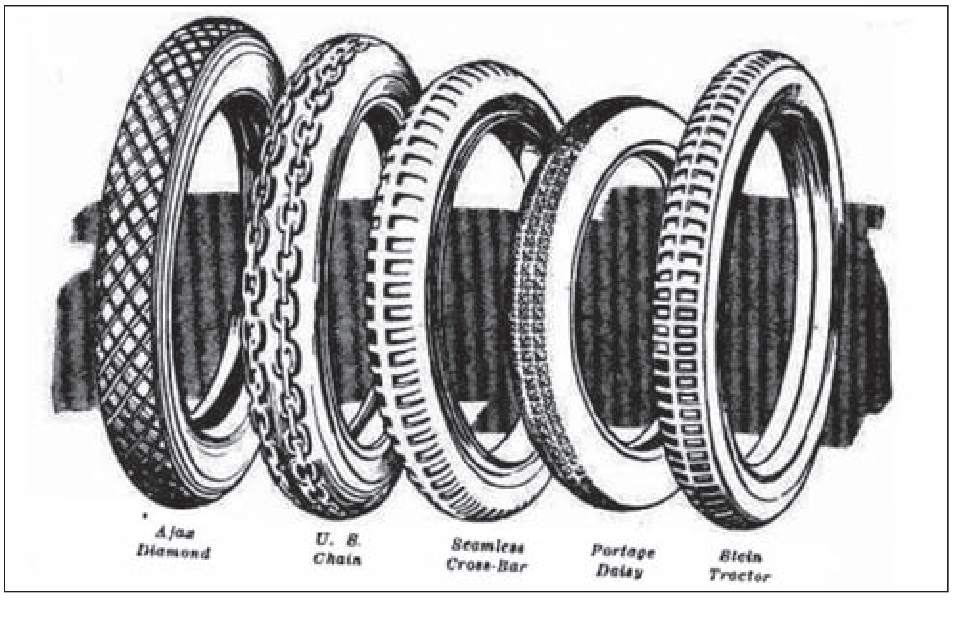


Fig. 9. Goodyear product line, 1920s

Tire

Continued from Page 15

of AC to DC. With the continuing development of solid state control and power conversion, new installations employ variable frequency AC drives and motors with efficiencies that were unrealizable even a few years ago.

Bearing technology has progressed from plain journals running in partial Babbitt or Babbitt-lined bearings to precision antifriction roller bearings. Lubrication has evolved from tallow blocks in bearing cavities to central oil systems circulating synthetic oil filtered and temperature-controlled to maintain target viscosity.

Calender drive trains, originally driven from a single prime mover, with a choice of running adjacent rolls either at a predetermined friction ratio or at even speed, have progressed to individually driven rolls with infinitely variable friction between any roll pair. Roll adjust systems have evolved from manually powered screw and nut systems with the nose of the screw bearing against the bearing box to full hydraulic roll positioning systems.

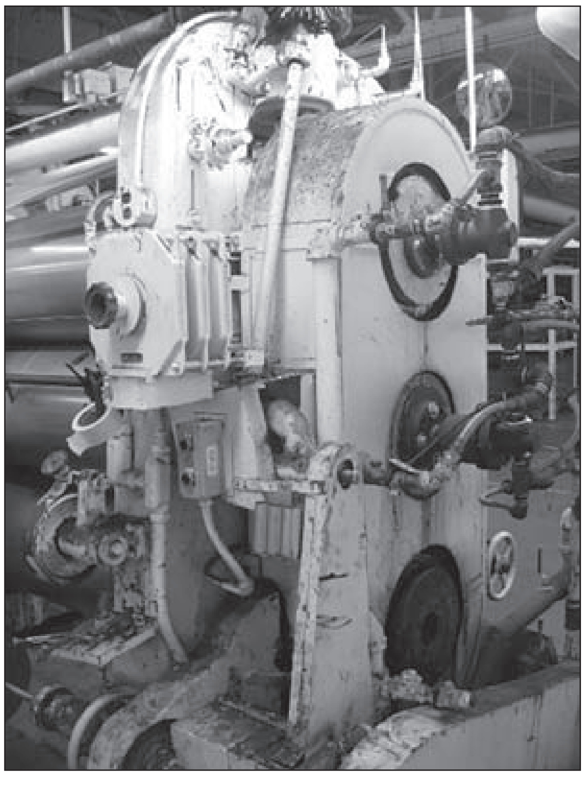
Each of these improvements was driven by the need for increased uniformity and higher usable output per unit of input. As each was implemented, the capability of the calender was increased, adding flexibility and reliability.

As tires progressed from crude fabric reinforced tubes strapped to wooden or metal wheels and rims, to heavy wall rigid tire carcasses with equally heavy duty fabric reinforced inner tubes, then bias ply tires with soft flexible inner tubes to tubeless bias ply tires, belted bias ply, and then steel-belted radial tires, each progression requiring ever higher reliability and uniformity of material and product, the equipment and methods of material preparation progressed to make those changes possible.

The beginning

It is now just under 125 years since the Michelin brothers mounted a set of pneumatic tires on an automobile and went racing. Rubber mixing was then done on open two-roll mills. Compounded rubber was warmed and fed to calenders to impregnate a square-woven flax linen fabric, soon to be replaced with cotton.

Fig. 10. Three-roll vertical calender, circa 1940: Rheostat for speed control; let-off with friction clutch mounted on calender frame; take-up mounted on calender and gear-driven from calender roll through a friction clutch.



Rubber for other components was run as unsupported sheeting and slit to the desired widths. The majority of the rubber components required to build a tire were produced on variations of a calender. John Royle had patented the screw extruder a few years before, but it would see its first success coating wire with gutta percha before becoming a fixture in tire production.

A typical calender was comprised of three chambered rolls vertically disposed, one above the other. A set of connecting gears was mounted at each end of the machine—even speed gearing on one end, and a friction set on the other end.

The friction set was comprised of a small gear or pinion on the drive roll and larger gears on the top and bottom rolls, the friction ratio being determined by the number of teeth on the pinion and gears. One key was supplied for the top roll and one for the bottom—moving the key from one end of the roll to the other determined which gear drove the roll.

The roll necks (journals) were supported in plain or "sleeve" bearings. Often, the bearing housings were split. The middle or drive roll, which could be loaded either up or down depending on the way in which the calender was operated, was fitted with a bearing in both the top and bottom half of the bearing housing.

The top roll would have a bearing only in the upper half of the housing, the lower roll only in the bottom half. A large bull gear, outboard of the drive end connecting gear set, would be driven by a pinion, mounted on a line shaft passing under the calender or on a jackshaft supported in pillow blocks and connected to a motor driven reducer.

The central chamber in the rolls was created by casting them with a central sand "core," knocked out after the roll was cast, leaving the chamber. Steam or water for heating or cooling could be admitted to that chamber through "stuffing boxes" on the water end.

The opening between the top and middle roll and bottom and middle roll could be adjusted, each end independently, by means of a large "ships wheel" and a system of clutches, jack shafts, bevel gears, worms, worm gears, and adjusting screws.

As described earlier, all of the take-up and let-off equipment for handling the web was mounted directly on the calender. Let-off tension was controlled by a manually adjusted slip clutch or brake. Take-up spindles were driven from the bottom roll by gearing. Slip clutches in the take-up spindle drive permitted the spindle to slow as the wound bundle increased in size. In some instances, the bundle would be surface-wound against the bottom roll or a driven roll mounted on the calender frame.

Fabric requiring coating on both sides would be run through the calender twice. Provided attention was paid to bank size and loading, relatively close tolerances in the thickness of the finished sheet could be obtained. Low speeds and short runs minimized the need for cooling.

Fabric preparation might involve "ironing" in what amounted to a steam mangle. Drying was accomplished off line. Gum components for the tire were prepared on the same calender or one very like it, perhaps smaller in size.

Moving forward a few years, the components of the tire had become much more sophisticated. A separate inner tube now served to hold the air; the tire casing consists of rubberized cord plies, cut on a bias and assembled in alternating "hand;" bead, chafer, a breaker layer, sidewall and tread components are added.

A description of the rubber manufacturing process in "Pneumatic Tires—Automobile, Truck, Airplane, Motorcycle, Bicycle," published in 1922, reveals that there were a variety of approaches to coating and encapsulating the reinforcing cords with rubber. Some manufacturers, prior to the calendering step, dipped the cotton fabric to coat it with a rubber solution; some used a spreader to alternately coat both sides of the fabric. In either case, a drying operation was necessary to remove the solvent prior to calendering.

Some, Goodyear among them, used a process very similar to the current practice: cotton cord was dried to remove any moisture, then coated directly in the calender with rubber warmed on mills.

Early production of tread stock was accomplished by "complexing" strips of varying width to build up the necessary thickness and profile. A variety of special-purpose profile calenders begin to appear, shaping rubber to the desired profile and thickness.

"Tubers"—extruders, first used for hose, lead pipe, and wire coating, begin to appear in the material preparation area of the plant. Tube production is accomplished in a variety of manners, depending on the manufacturer and the application. Almost all involve calendering sheeting to be formed over a mandrel; some involve fabric reinforced sheeting.

In 1921, The Rubber Age listed six builders of mills and calenders: Adamson Machine Co. of Akron, Allen Machine of Erie Pa., Birmingham Iron Foundry of Birmingham (Derby) Conn., Farrel Machine and Foundry of Ansonia Conn., Vaughn Machine of Cuyahoga and Wellman Seaver Morgan of Cleveland.

An article in the July 25, 1920, issue of The Rubber Age and Tire News opens with the sentence: "Electric Drive is now successfully being applied to all the machines involved in the manufacture of rubber products in all branches of the rubber industry." Another article in the Aug. 25 issue of the same journal written by C.W. Drake of the Canadian Westinghouse Co. entitled "Electricity in the Rubber Industry" covers the subject in more depth, outlining some of the technical matters.

In 1923, Firestone introduces the balloon tire, which becomes extremely popular for passenger cars. By 1929, Goodyear is offering both straight side high pressure tires and a full spectrum of the new balloon tires.

Rubber compounding still is being carried out on open mills, a practice that continues to the present in specialty and low volume applications.

Fernley Banbury's mixer, having been proved out at Goodyear in 1916 and 1917, is making steady inroads in replacing compounding mills and nudging out competitive mixer designs.

As early as 1922, the chapter in "Pneumatic Tires—Automobile, Truck, Airplane, Motorcycle, Bicycle" describing a proper

Fig. 11. Four-roll vertical gum calender, circa 1955.

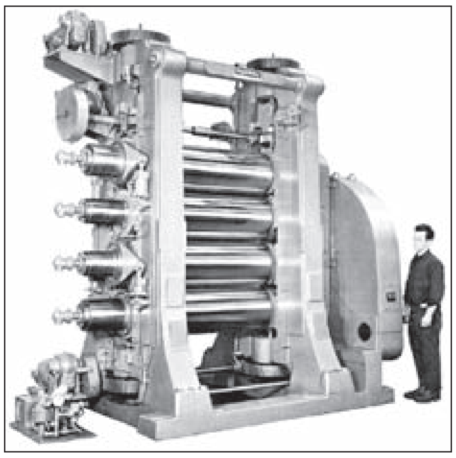
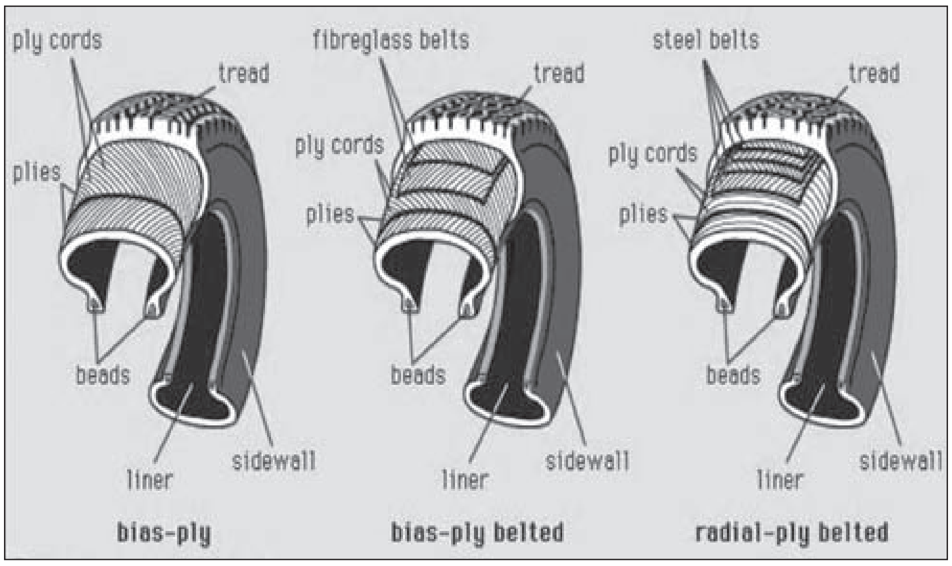
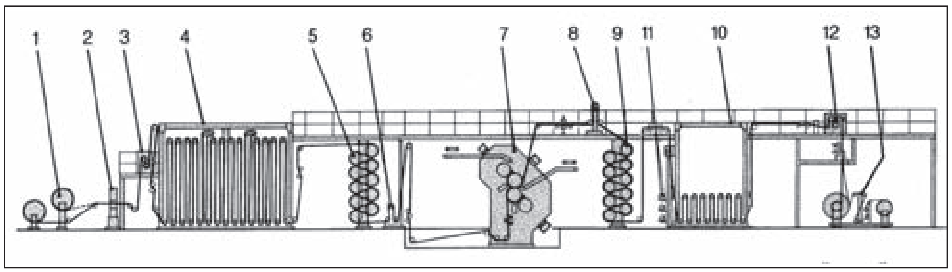


Fig. 12. Bias-ply to radial tire construction migration.





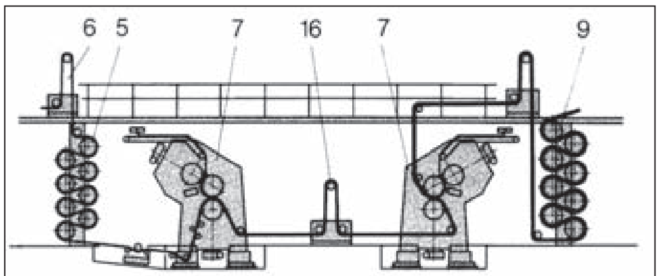


Fig. 13: Typical tire fabric cord calender line (top), 1980s to present, single four roll calender; and tire fabric cord calender line (right), 1980s to present, tandem offset calenders.

design for a new tire plant assigns the mixing function to the Banbury Mixer. (Interestingly, as late as the 1929 version of Goodyear's publication "The Story of the Tire," no mention is made of the mixer in the description of the manufacturing process.)

Birmingham Iron Foundry has merged with Farrel Machine and Foundry to form Farrel Birmingham in 1927. By 1929, Stewart Bolling Co. has been formed in Cleveland and is now making mills, calenders and other rubber processing machinery.

The basic calender has not changed very much at this point. Tire cord calenders in North America pretty much standardized on 24" diameter and 66" face rolls. Drivetrains are cleaner. Calender frames have larger cross sections and cleaner lines. Guards of one sort or another enclose major powertrains. Babbitt bearings have given way first to bronze stave or half-liner bearings and then to full circle bronze bearings.

More robust bearing housings have begun to replace earlier split bearing housings. The manual "ships wheel" for adjusting roll position has been replaced with a motor and transmission. The remainder of the roll adjust drive train remains essentially unchanged.

Square-woven cotton fabric still is being calendered in limited quantities for chafer strip and the breaker layer. Twisted cotton cord with "pick" fiber is now being used in the carcass plies. The calender line has begun to stretch out, with let-off and take-up machinery now off the calender proper.

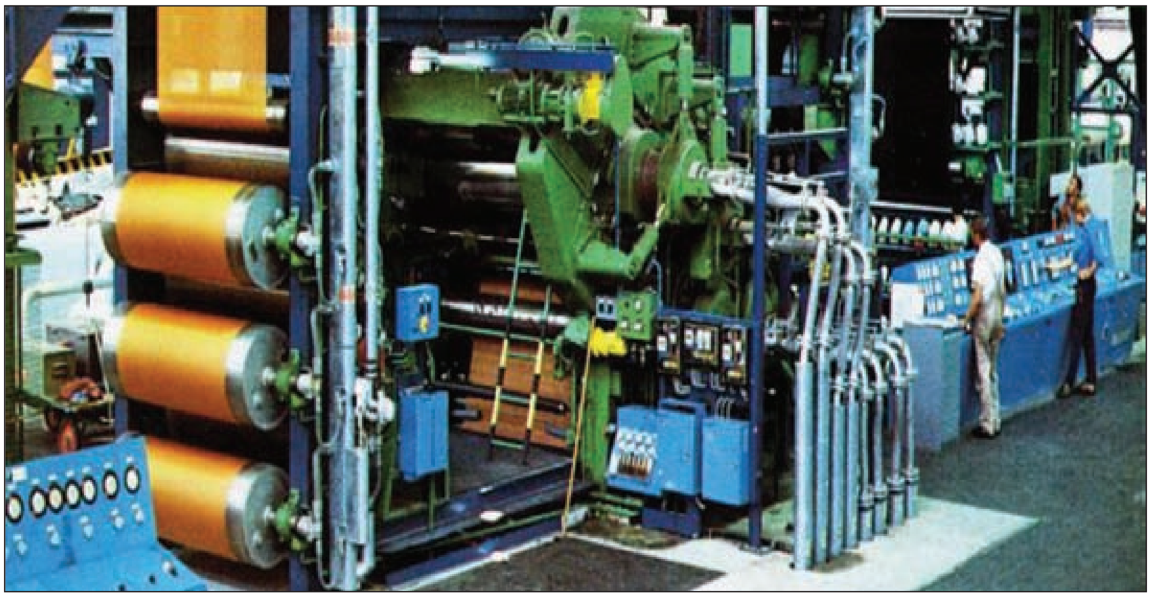
Drying of the cotton cord in line using steam heated drums, rather than batch-drying off-line is beginning to predominate. Web guiding and spreading equipment is being installed much of it borrowing from the experience of the textile industry. Heating and cooling of the calender rolls still is controlled by steam and water, admitted as required. Run lengths are increasing, as is speed.

Warm-up is accomplished on mills. Mixing and compounding operations are separate from calendering. Cord lines are dedicated to that function, with other calendering operations carried out on specialized machines.

"Tubers," some used in conjunction with smaller specialized calenders, have begun to take over some of the calendering operations in the preparation of tread and other profiles.

Although there is evidence in the patent files of efforts to measure thickness on line using adapted dial indicators riding against the web, measurement of sheet thickness is predominately accomplished manually, using "snap gauges." Off-line quality control measurements use sample weight to check cross sheet profile.

Fig. 14. Fabric tire cord calender line, circa 1985. Note the large operator control desks with analog indicators, potentiometers, switches and push buttons for all control functions.



The golden age

Move forward to the late 1930s, through the war years, and into the early 1950s. The development of synthetic rubber, begun in Europe prior to and during World War I, continued in the U.S. in the 1930s. The effort was accelerated and commercialized during World War II.

As production of passenger car tires resumes after the war, roughly three quarters of the rubber used in the production of tires is synthetic. Rayon has replaced cotton as the reinforcing cord in tires, and nylon has begun to compete with rayon. Better control of tension, both pre- and post-calender, is required. Tension measurement and control technology begins to be applied to the calender line.

Tension control in the pre- and post-calender zone is accomplished by air-loaded three-roll dancer/compensators with chain-driven potentiometers trimming the speed of the preceding or following drive. Tension control at let-offs is beginning to see force measurement using rolls supported on load sensing devices controlling pneumatically actuated brakes.

Rayon requires treating with a coupling agent to develop a bond with rubber. Some manufacturers install dipping lines in-house as an off-line preparatory process. Some install dip lines ahead of the cord calender, putting the two processes in line. Others elect to purchase the fabric pre-treated.

Each approach offers different challenges. Eventually, most tire manufacturers will push the dipping operation back at the fabric suppliers.

The ability to double-coat tire cord in a single pass is now part of all new cord lines. As early as 1920, installing two three-roll calenders in tandem had been tried by some manufacturers, and that arrangement is now predominate. Experimentation has begun using four-roll inverted "L" calenders to double-coat in a single machine.

During the war, Farrel Birmingham built a group of four-roll inverted "L" calenders that were installed in three U.S. Rubber plants—Eau Claire, Detroit, and Quebec (Dominion)—to double coat fabric for the production of truck tires for the war effort.

Independent drive of the various sections of the calender train becomes common. Thickness measurement technology has not moved forward—the hand-held snap-gauge still rules. The four-roll calenders sold to U.S. Rubber are fitted with 32" diameter rolls in order to overcome roll deflection concerns by using stiffer rolls.

Drivetrains remain largely unchanged—typically a single motor drive utilizing a right angle or parallel-shaft reducer, the output shaft fitted with a pinion driving a bull gear on the middle roll of three-roll calenders, and the No. 3 roll of four-roll inverted "L" calenders. For the four-roll calenders, even speed connecting gears were mounted between rolls Nos. 2 and 3, and friction connecting gears between rolls Nos. 2 and 1 and rolls No. 3 and 4.

Longer fabric runs are accomplished by splicing the tail end of a roll of fabric to the leading end of the next roll. Accumulators (festoons) provide storage for the time required to make the splice at the let-off end or cut and transfer to the new core on the take-up end. Motion control is by means of limit switches, mechanical linkage to potentiometers, and manual setting of pressure regulation. The operator interface for speed control is a large rheostat—itself a successor to the multi-position rotary switch.

Machine and personnel safety interlocking and machine control are accomplished by hardwiring directly through the sensing and operator interface devices. Machine tool relays handle any necessary control logic. Speed, current, and temperature displays, where required, use analog meters.

In a hint of things to come, in 1949 Farrel books an order from Goodyear for a 28" x 70" four-roll straight "Z" calender with roller bearings and drilled rolls, roll crossing for crown correction on both the top and bottom offset rolls, and pre-loads on all rolls.

Shaping of rubber for the production of tubes completes the shift from calenders to extruders. Relatively small two-roll and four-roll calenders are used for the production of gum components. The technology employed in these calenders is the same as that employed in a majority of the larger cord calenders: Chambered rolls running in bronze sleeve bearings, single motor drive.

Power transferred from the fixed roll to the adjustable rolls by means of connecting gears. The four-roll calenders were vertical, intended to produce a sheet of rubber in both the upper and lower nips, the two sheets thus formed to be assembled—"complexed"—in the nip between the middle two rolls. In order to solve the problem of adjusting the middle nip independently of the upper and lower nips, the bearing housings for the upper pair of rolls were carried in a sliding frame or cartridge. (Farrel called this the yoke.)

This frame or cartridge was fitted with a roll adjusted mechanism to adjust the No. 1 roll with respect to the No. 2 roll. The frame containing both rolls and their bearing housings was supported in the calender frame and was itself adjusted with respect to the No. 3 by a screw and nut roll adjust mechanism mounted at the top of the calender end frames.

The 1950s saw the development and gradual market acceptance of the tubeless tire. Butyl rubber for inner liner is added to the materials to be calendered. The first beta ray-based on-line rubber thickness measuring gauges are introduced by TracerLab (later LFE) and Industrial Nucleonics, better known, perhaps, as AccuRay, the name given to the device. By this time, extruders were in general use for tread production.

Tire cord calender lines sold during this period were built to double-coat in a single pass, and the calenders sold to go into those lines were most often either inclined "Z" calenders or three-roll calenders (used in tandem) with the top roll offset from the vertical by 30 or 45 degrees. The evolution in roll disposition from vertical to inverted "L" to straight "Z" then to inclined "Z" and later to "S" actually follows a rather logical path.

Earlier, a four-roll vertical calender for the production of two sheets of gum to be combined or "complexed" in the same machine was described, and in that description, the problem noted was the ability to adjust the middle nip independently of the upper and lower nips.

Aside from the fact that a four-roll machine with the rolls arrayed vertically one over the other gets to be a bit high, the weight of a pair of rolls and their bearings, which would have to be adjusted as a unit, is significant. Moving the No. 1 or top roll to an offset position in a horizontal plane with the No. 2 roll accomplished two things:

- The two rolls could be adjusted independently of each other. At the range of adjustment involved in production, such adjustment would have a negligible effect on the other nip.
- Secondly, feeding the nip with No. 1 Roll offset in this manner was a considerably easier proposition.

A third and fourth advantage attend the design: A disturbance in the sheet forming nip between rolls Nos. 1 and 2 has very little if any effect on the loading in the laminating nip between rolls Nos. 2 and 3; when a splice needs to be passed through the calender, the No. 2 roll can be lifted briefly without otherwise disturbing the calender set-up.

The logical extension of this thinking was to move the bottom or No. 4 roll to an offset position opposite that of the No. 1 roll, resulting in the straight "Z." This improvement isolated the laminating nip from disturbances in either sheet forming nip and made the mechanized feeding of both of those nips much easier.

As anyone who has worked on or around a straight "Z" set-up for double-coating can attest, the roll adjust drivetrains, in particular the final worm and worm wheel housings, crowd things miserably. Access to the No. 2 roll is tight in any case, and having access to that area with the No. 1 more or less directly overhead, begged from some improvement.

The solution was to tilt the "Z" so that the planes containing the Nos. 1 and 2 and Nos. 3 and 4 rolls were at angle of 30 or 45 degrees to the horizontal. In the following decades, calender builders worked with variations on this notion with the objective of improving access to the sheet on the No. 2 roll without comprising too greatly the independence of the sheet forming nips from the laminating nip. These configurations were sometimes referred to as "S" or stretched "Z."

There were a few tire manufacturers in this era who felt that double-coating in two separate or tandem calenders remained the best approach from a process control and monitoring standpoint. The offsetting of the top roll facilitated mechanized feeding of the rubber, while reducing the interference between the feed and laminating nip—not as effectively as the "Z," but nonetheless an improvement.

The bearings of choice remained for the most part the well-proven and understood sleeve bearings. The larger calender suppliers, working in conjunction with lubrication suppliers, had evolved a very good understanding of the limitations and capabilities of relatively low RPM large diameter bronze sleeve bearings and the means of lubricating them to ensure their reliable performance.

The primary drawback to a sleeve bearing is that the internal diameter of

See **Tire**, *Page 18*

Tire

Continued from Page 17

the bearing must be larger than the diameter of the shaft it supports in order for it to function. This clearance, although not large, is large with respect to the thickness of the sheet being produced—often three to six times larger than the target thickness of the sheet.

When the machine is in operation, if the load, operating conditions, and oil viscosity are kept constant, the journal will maintain a steady position in the bearing, and very accurate results can be obtained.

The difficulty lies in maintaining that steady state equilibrium. As production of new machinery for the emerging plastics and flooring industry ramped up after World War II, manufacturers of calendering equipment in the U.S. began addressing this problem by adding a second bearing to each roll journal outboard of the main journal.

Applying a force to this bearing would preload the roll into or at least close to its loaded operating position, and would significantly reduce the effect of minor load fluctuations on that operating center.

The secondary benefit, in the case of an adjustable roll, was that the preload (called "zero clearance" by some builders) also took up the clearance in the adjusting screw and lifter mechanism coupling the bearing box to the screw. This improvement, often in conjunction with the addition of splice relief in the No. 2 roll adjust, was a frequent retrofit to existing calenders.

It had long been understood that rolls deflect under load. The time-honored method to compensate for this was to grind the roll body so that it had a barrel shape that more or less approximated a portion of a cosine curve.

Because the amount of deflection varies with the load imposed, the ground-on crown produces accurate results for only one load condition. Without a means of varying the effective crown, the only alternative to correct for a high or low center in the web is to alter the operating conditions to change the roll separating force or load.

Ever-increasing line speeds coupled with the demand for tighter sheet tolerance and greater productivity led calender builders to design machines in which one of the two rolls in the sheet forming nip could be crossed or skewed with respect to its neighbor. The concept was not new. Patents embodying the essential elements go back at least to the late 1930s and probably earlier.

Which builder gets credit for the initial commercialization of the concept is a bit murky, but by 1947, Farrel was offering it on their post-war 28" "Z" calenders, and in the mid-1950s, they were selling a completely redesigned inclined 24" "Z" to the tire industry with crossing on both outboard rolls and hydraulic preloads on all four rolls.

As illustrated by the Goodyear order for a 28" x 70" four-roll "Z", drilled rolls had begun to make their appearance shortly after the war. The first applications appear to have been in the burgeoning post-war PVC industry. The basic notion was to get a heat transfer fluid closer to the surface of the roll to improve control of the roll surface temperature and improve the rate of heat transfer from or to the process.

As with most new ideas, there were a variety of interpretations in the execution of the concept, but in the end, after suffering some unpleasant consequence with other approaches, the drilled tripass roll emerged.

A series of holes numbering in total a multiple of three is drilled around the periphery of the roll body, just below the depth of the chill (see the earlier description of chilled iron rolls).

Each set of three drills is connected in series so that fluid directed to one end of the series passes three times across the face of the roll. Unlike the older chambered rolls, there is a central bore of uniform diameter extending from one of the roll to the other, closed at the drive end by a closure plate.

A duo-flow rotary union and an internal roll pipe with a baffle in the central bore serve to direct the heat transfer fluid through each of the parallel three-drill circuits.

If the fluid velocity through the drills is high enough to ensure turbulent flow, the temperature differential across the face of the roll can be held to a range of 2 to 3°C. The differential between the heat transfer fluid and the roll surface temperature depends on the temperature differential between the product, the percentage of the roll surface covered, and the line speed, but offsets of less than 5°C are commonly attained.

The calender drive train undergoes a change in this era. Driven in part by the introduction of roll crossing, gearing is removed from the roll necks and combined in a single large gear case, eventually termed a unidrive.

This case combines the reduction gearing necessary to convert motor speed to the desired roll speed with the connecting gearing required to drive each roll at the appropriate friction ratio with respect to the master roll—usually No. 3. Four output shafts are connected to the drive end of each roll by drive shaft or spindle with a universal of some type at each end.

At this point in the evolution of rubber calendering and calender technology, the utility of variable friction was either not yet recognized, or if recognized the additional cost was not deemed justified.

The transition from vertical roll disposition, in which all of the forces acting on the calender frame are more or less on the same axis, to inverted or straight "L" and the various "Z" and offset configurations, introduced some serious concerns in the design of the frames. Windows in the frames had to be large enough to permit installing the rolls and the bearing boxes through the end frames.

The resulting openings could, and in some instances did, significantly reduce the stiffness of the frames. Studies were carried out to determine the effect of tie bars across the box windows in stiffening the frames.

Window shapes were altered to provide for tie bars, and roll installation often required a removable piece to permit fitting the roll through the box window.

Roll position sensing and remote readout of roll position became more or less standard during this period. Selsyn transmitters driving mechanical counters were employed, and their use would continue into the 1990s, when encoder and digital counters and displays replaced them. The same technology was used to provide remote indication of the amount of roll crossing employed.

The combination of drilled rolls and recirculating hot water temperature control systems added a new level of control to the process. The controllers themselves were electromechanical. Some were combination units with circular chart recorders.

Fig. 15. Modern steel cord calender.

Web handling equipment had progressed steadily over the previous 50 years—a variety of expander rolls, spreading rolls, fabric straighteners, and guiding equipment emerged. Fife and Mount Hope evolved and were marketing hydraulically actuated guiding systems.

The age of the radial tire

The 1970s mark an interesting period and the onset of what would become a rapid march to electronic controls. Polyester and steel wire begin to predominate as reinforcing fibers. In the previous decade, most U.S. tire manufacturers (with the exception of Goodrich) had decided, with the encouragement of the auto makers, to stay with bias ply tires. Goodyear banked on its Custom Superwide Polyglas—a bias ply tire with a fiberglass belt to carry it into the '70s.

Other manufacturers offered similar products. Consumer preference however, was shifting from a soft ride to better handling, better performance in adverse conditions, higher tire mileage, and better fuel efficiency.

The increasing penetration of the U.S. automobile market by imported cars arriving mounted on radial tires, the decision by Ford in 1968 to put the Lincoln Continental on radials, and a commitment by Michelin to build radial tires in North America, provided the impetus for the tire companies to begin the shift to radials. The tripling of the cost of gas in 1973 served to accelerate market demand.

Tire manufacturers scrambled to put radial tire production in place. The major obvious difference in calendering requirements brought about by the shift to radial tires was the increased requirement for steel reinforced plies.

Less obvious was the need for significantly improved control of calendered sheet gauge and quality. Creel and wire handling concerns dominated the new technology in tire cord calendering. Wire handling techniques and rubber-to-metal coupling chemistry acquired in the reinforced hose industry were adapted to the tire industry.

Tension and let-off devices developed for lower wire count applications were employed in large multiples mounted on specially designed racks in humidity controlled rooms. Eyelet boards, special rollers, comb rolls and pressure rolls became part of the new hardware ahead of and at the calender.

While tire building machines could not be converted readily to the production of radial tires, calenders could be. Other than the need to be able to coat wire as well as fabric, there was no significant change in the basic technology of the calender. Often the path to needed calendering capacity for both new plants and modernized ones was the relocation or refurbishment of older machines.

The excess capacity in bias ply tire construction rendered a lot of equipment surplus and available for rebuilding and upgrading. With a little ingenuity, depending on the available space, fabric/cord lines be converted to combination lines. If it was necessary to avoid production interruption, the decision was occasionally taken to install a new dedicated wire line.

There were few orders for new calender equipment that resulted from the conversion to radial tires, and what orders there were often went to European builders—in part owing to the shift in ownership of most of the major tire manufacturers, and in part owing to the

See **Tire***, Page 20*

Tire

Continued from Page 18

very long lead time domestic suppliers were experiencing for such key components as bearings.

During this period, Farrel would carry out a thorough redesign of its tire cord calender, resulting in a 28" x 74" "S" design with antifriction roller bearings, crown correction by roll-bending in both forming nips and the laminating nip, individual roll drive, and splice relief in the laminating pass. In an effort to reduce both manufacturing and installation costs, the drivetrain now comprises four individual parallel shaft gear reducers of standard design rather than a unidrive.

One was sold in 1974 to Pirelli for Brazil, a second later built in Brazil, also for Pirelli, and a variant with roll crossing instead of roll bending was sold to Carlisle for roofing in 1978. Adamson carried out a similar design effort and sold two 32" x 100" four-roll "S" calenders with roller bearings, sophisticated roll bending on all four rolls, and gauging or cushion cylinders in the roll adjust drivetrain to Goodyear in 1975 for conveyor belting.

During this era, Farrel developed a two over two four roll calender for inner liner. The calender was basically two two-roll horizontal calenders in a common frame, arranged for simplified mechanical feeding of the rubber. A small number of these were delivered to one of the domestic tire manufacturers.

As an example of the way in which the conversion to radial tires affected the domestic calender builders during this period: A domestic tire manufacturer required a new calender for an existing tire plant being renovated completely and converted from bias ply to radial tire production on a fast-track basis. Farrel met this requirement by upgrading a four-roll machine originally built by a competitor, and taken in trade on a machine being built for a non-tire application.

Roll bending as an alternative to roll crossing as a means of varying the effective crown of a roll or roll pair becomes common during this period. Roll bending is somewhat similar to preloading, except that the second bearing is farther from the main bearing, in order to provide a moment arm. The main bearing becomes a pivot or fulcrum.

A force may be applied to the roll at the outboard bearing to either oppose the roll separating force generated by the material in the nip, or cooperate with that force. In the first instance, the effective crown is increased (positive bending); in the second it is decreased (negative bending). The reaction point may be either the calender frame, or the opposing roll in a roll pair.

Roll bending is mechanically simpler than cross axis, serves to accomplish the preloading of the roll as well as adding the ability to vary the effective crown, is linear in response, and the resulting effect is somewhat more nearly accurate across the nip than roll crossing.

The range of correction is limited by the allowable stress in the roll neck and the rating of the main bearing. (When in positive mode, the bending force adds to the load on the main bearing.) Roll crossing normally offers a greater, although not linear, range of correction, and does not add to the radial load on the main bearing.

Roller bearings gradually have become the bearing of choice for calendering equipment. Properly specified and installed, they provide very good axial run-out of the roll and bearing assembly, and they offer the opportunity, with well-engineered roll positioning systems, of providing close control of the center of rotation of the roll. The clearance necessary for a roller bearing to function is very much smaller than for a plain or sleeve bearing.

Load bearing capacity at low speed is superior to a sleeve bearing. Preloading the roll into position is not required. In those applications where roll bending is not part of the design, a pullback cylinder or cylinders can be added to the bearing boxes of the adjustable rolls to take up the clearance in the roll adjust mechanism.

Lubrication remains important, and functioning seals to keep debris and process material out of the bearing are essential. While grease is acceptable from a temperature standpoint, recirculating oil systems offer the advantage of steady replenishment of the lubricant without risk of an undetected blocked passage and/or depleted lubricant.

In the previous decade, solid-state drives for DC motors had begun to come on the market and by the 1970s were being used in new equipment and rapidly replacing remaining MG sets. Solid-state drives employ relatively low voltages at low current levels for control, greatly simplifying control wiring. Lower voltage devices become adequate for speed control and feedback.

Tachometer generators begin to be replaced by encoders or pulse generators. Moving forward in the next decade, speed regulation of DC drives, formerly dependent on analog voltage signals or current feedback, would approach one-quarter of a percent of base speed.

The use of on-line thickness measuring systems expanded to permitting those systems to control the roll-positioning and crown correction systems on the calender. Measurex was formed out in California with an emphasis on control and reporting.

LFE and Industrial Nucleonics, now Accuray, are both offering some form of automatic control. Each of these suppliers was forced to develop new measurement techniques and protocols to cope with the problem of measuring rubber thickness when coating wire.

The backside of the No. 2 roll got more and more crowded. Blister breakers needed to share space with chunky gamma backscatter thickness sensors. Scanning the full sheet width over the No. 2 Roll is pretty much out of the question for space reasons. Fixed point sensing is used, and even then the measuring heads are a bit bulky for the space.

Electronic controllers for temperature and other process conditions begin to appear, replacing the older electro-mechanical units. The first programmable logic controllers made their appearance as the previous decade closed; by the end of the seventies, programmable logic controllers and the "data highway" have become part of the tools and the vocabulary.

The ability to connect sensing devices and output/actuator devices to a remote chunk of electronics and then use a small cable to connect that device to another relatively small chunk of electronics in which resided the logic necessary to control a process made both installation and troubleshooting of control systems much easier. Moreover, and perhaps especially, it made it possible to rework the control logic quickly and easily, usually without hardware additions.

Digital age arrives in the plant

The decade of the 1980s would be marked by the introduction and rapid proliferation of the personal or desk-top computer and equally rapid advances in the evolution of programmable logic controllers. In North America, there were four major players at this point in time: Modicon, GE Fanuc, Allen Bradley, and Reliance Electric.

Progress was steady, and fairly rapidly operator interface devices began shifting from push buttons, selector switches, joy sticks and potentiometers, first to keyboards and mice, and then to touch screens. A keyboard provided an interface with the system and could be used to call up operating instructions and recipes.

Data acquisition was part of every discussion on new control systems and upgrades. Electrical drives for DC motors, solid state controls for electric heaters, soft-starters for mill drives, all got smarter, more capable, and less expensive. CRT displays with selectable screens, recipe storage and retrieval, shift reports, became part of the control package. CRT screens were first supplemented by LED based displays, then displaced by flat screen technology.

Closed circuit TV already had made an appearance in the previous decade—the cost would go down rapidly, the reliability and the quality of the image improve inversely to cost, making it possible for the lead operator to monitor such difficult to measure variables as bank size and feed strip continuity visually from the main control panel location.

Two major improvements or changes were initiated in the tire cord calendering line in this era: The first was a strong and persistent effort both to mechanize and automate the winding operation. Core and liner handling, shuttle carts, swinging arms, queuing racks, and a variety of material handling interfaces were tried.

There being no proven path to follow, each of these efforts required considerable trial and effort to perfect. The persistent eventually found a way to correct the unanticipated weaknesses in the system, the pragmatic often reduced the scale of the attempt and made do with the result.

The second was an adventure into the notion that a partial pre-cure of the tire plies would help to ensure that the subsequent tire building operations would not distort the cord distribution or otherwise damage the cord encapsulation or spacing, thereby reducing quality issues and improving consistency in the finished tire. There may also have been some advantage gained in the final cure cycle.

Working on the same principle as a microwave oven, the radiation, in this case in the form of a focusable electron beam, would be passed through the web. The interaction of the beam with the rubber would heat the rubber uniformly, rather than heating it from the outside in.

The equipment required shielding to contain the beam and protect the work force. Large concrete vaults were built. Web paths were modified either by running the web over the winding station to the vault then doubling back to the winding station or by stacking some of the functions above the vault. One tire manufacturer abandoned the experiment when the calender was relocated to another plant.

Anecdotally, if the line were stopped for any reason, the now warm partially cured rubber would stick to the transport system, requiring an extended effort to clear the line for operation again.

With respect to the calender itself, this

Fig. 16. Contemporary calender line control desk. Digital data display on flat screen VDU, touch screen HMI; Video display screens for monitoring rubber feed to calender.

decade saw increased interest in hydraulic roll positioning systems. Farrel had designed and patented an hydraulic assist roll adjust system back in 1969. The system was essentially a large servo valve, with a small motor and ball screw adjusting a metering piston. It required no external position measuring system—a change in load and therefore position changed the orifice at the metering piston, resulting in an immediate adjustment in the pressure to compensate.

It had been fielded and proven on several non-tire calenders, including a three roll vertical calender sold to the Firestone Industrial Products division and installed in the Fall River plant. The systems that were fielded worked well, and at least one is still in operation in a mechanical goods plant.

The two Adamson calenders mentioned earlier were built with large bore short stroke hydraulic cylinders in the roll adjust stack and fitted with manifolds that would permit the fitting of a servo valve permitting hydraulic roll positioning. The current owner experimented with this on one of the two calenders, but did not find that the system performed with sufficient reliability to merit going further.

In the early 1990s, Farrel built its last tire cord calender. The calender was installed as part of a new combination wire and cord line for the Cooper Tire plant in Albany, Ga. Built to specifications prepared for Cooper by Louis Perry and Associates, it is fitted with a hybrid nut and screw and hydraulic roll adjust system. The calender since has been relocated to Cooper's Tupelo plant, and some 23 years after it was first commissioned, the system apparently still is working satisfactorily.

Comerio Ercole of Busto Arsizio in Italy have been fielding a full hydraulic roll positioning system for several years. At least one calender fitted with the system has been installed in U.S., although the application is not for tire production. In theory, a full hydraulic system should be able to hold a roll in position by promptly and immediately responding to load changes.

The problem is that the displacements involved are very small, and the system has mass and inertia. The measurement devices available are temperature sensitive, and the resolution necessary is very high. Large cylinders not vertically disposed will have a frictional component between piston and cylinder wall that has the potential to create mechanical hysteresis. Nonetheless, valve and sensor technology continue to advance, and such systems will continue to improve.

Moving into the present, for the last two decades work has continued on the means of measuring sheet thickness. The present approach enjoying reasonably widespread application in North America uses two sets of three fixed point sensors, one set over the No. 2 and one set over the No. 3 rolls. The sensing device rides on the web, and measures the displacement from the roll face.

The control system operates the roll positioning and crown correction system to keep both the upper and lower coating weight within tolerance. At least two vendors now offer a system that can watch the wire entering the calender nip on a wire line and detect and alarm for missing, paired or crossed wires.

To this point, we have only obliquely referred to the process of feeding rubber to the calender. From the beginning of the industry, two-roll mills have been used to warm compound previously prepared elsewhere in the plant for feed to the calender.

As things moved along, and thickness tolerance tightened, it was eventually realized that maintaining a bank in the forming nip or nips that was consistent in size, shape, and viscosity improved the consistency of the calendered sheet. Hand feeding with pigs, if done carefully with attention to the preceding principles, worked, and works, as long as production rates are reasonably low.

As line speeds increased, conveyors were added to transfer rubber in strip form from the mill to the calender. Faster speed required more material, and most cord calenders ended up with a warm-up and a feed mill for each nip. Adding a mill feeder to the warm-up mill to transfer rubber slab from a pallet or pallets to the mill, adding a mill blender to one or both mills, along with a means of adjusting the feed rate to the warmup mill and a means of adjusting the strip width to the calender, enables the feed system to the calender to run pretty much automatically.

A single mill man/material handler is required to keep the pallets cued at the mill feeder and to tend to occasional strip breaks in the feeding system.

One of the main and continuing concerns is that mill operation is inherently dangerous. A careless move or a lack of attention at a critical moment can result in a very serious injury, either from the mill or from the mill knife. Steady improvements in safety equipment, guarding, operator training, and management focus on training and safety have made mill accidents a much rarer event then they once were. Nonetheless, there is still a desire to avoid the use of a mill.

Up though the 1960s, the majority of the extruders in use in a tire plant were relatively short machines designed to be fed a strip of rubber warmed up on a mill. Cold feed extruders with longer barrels and more aggressive screws were developed and employed to produce profiles and strips. The production rate was not high enough to make these useful for calender feed.

Fig. 17. Calender machine panel.

Forty years ago, pin barrel extruders, which provided more intensive mixing in a shorter barrel became practical, began to see employment for calender feed. Early installations often employed a surge mill between the extruder and the calender. The mill provided a small reservoir for accepting extruder output during short-term line slowdowns and a reservoir of material in the event of an unexpected extruder stoppage.

Running calender rolls together with no material in the bank is not a good thing, and a calender running at 50 or so meters per minute will exhaust the feed bank very quickly. More recently, calender installations have eliminated the surge mill, feeding extruder output directly to the calender.

Perhaps the final challenge in cord and wire calendering is the development of a system that can reliably inspect the sheet as it exits the calender and determine whether the "squeeze" in the laminating nip is what is required to get the job done. A somewhat lesser but important challenge is the problem of reasonably accurately and consistently measuring the temperature of the rubber being fed to the nip.

Conclusion

One should not close an overview of the evolution of calendering technology in the manufacturing of tires without a nod to Total Quality Management and the various quality control programs it has spawned. The fundamental notion is that one cannot inspect quality into a product. Quality is achieved when each step of the process is monitored as it occurs and adjustments made as necessary to keep the variation at each point within acceptable bounds.

In summary, a great deal has changed, and yet, in many ways, nothing has changed. The objective of a calendering operation remains as it was at the dawn of the industry: To continuously produce a sheet of rubber, uniform in thickness in both the cross sheet and machine direction.

When we add the requirements of coating fabric, cord or wire, we can extend the objectives to transferring that uniform sheet or sheets to the fabric/cord/wire with a uniform "strike through" or squeeze so that the reinforcement is thoroughly bonded to or encapsulated in the rubber and the fabric is not distorted or the cord or wire spacing altered. The job of the calender is to accomplish these objectives in the face of material and operating condition variation.

Over the last 120 years, the quality level of tires has undergone tremendous improvement. A flat tire is a very rare event, and when one does occur, it is almost always due to a road hazard. Tire failures are unusual, and more often than not, the cause is due to age, excessive wear, overloading or a misapplication.

Tires rarely require balancing. Cars handle better in all manner of road conditions. Tires last 50,000 miles or even more. The calender line as an integrated system continues to evolve in step with the ever increasing quality of the tire.

The present state of the art offers very close measurement and control of all of the machine operating variables in the calender line. There are still some remaining issues to resolve, but the tools exist to control web flow, wire tension and spacing, to detect most cord and wire spacing errors when they occur. The roll shape and position in the calender can all be controlled to produce a flat sheet and a uniform laminating force or squeeze.

The temperature of the rolls and the rubber warming machinery, whether pin barrel extruders or mills, can all be controlled with a reasonably high degree of accuracy. There are some troubling aspects of the calender that occasionally prove challenging—perhaps the most persistent being the combination of stock guides and selvedge plows that divert edge trim back into one of the two sheet forming nips.

The other variables are the material to be coated and the rubber fed to the calender. Substrate quality has undergone steady improvement, but there are still occasionally issues with incoming material and/or in-plant handling. Rubber compound quality remains an ongoing concern. Attention to the warming and feeding process is critical.

The key to a quality calendered product is a quality feedstock uniform in composition and viscosity delivered at a constant rate of flow. The calendering operation should not be tasked with tightening the quality band—it can and should be tasked with maintaining it.

The other contributor to variability is the condition of the equipment. Very small differences in sheet thickness entering the coating nip can result in localized regions of higher pressure, spreading cords or wires.

Rolls wear over time, resulting in a loss of crown and roll shape. Heat transfer passages that have become lined with mineral deposits alter the heat transfer characteristics of the roll, drying drum, or cooling can. Blockages in a heat transfer passage can result in a roll that runs out of round. Measurement tools that are out of calibration or adjustment will yield measurements that are less than useful.

Blocked or obstructed lubrication passages will result in poor roll adjust response, failed bearings or drive train issues that affect performance. Heat exchangers and control valves will see their performance deteriorate over time.

We have reached a condition where electronic control and recipe management does enough of the work of controlling the operation of the calender line that often the operators are no longer sufficiently familiar with the principles of operation that they could take over the line and operate it without those controls. The challenge ahead is in two parts:

- The first is personnel: Training and motivating operating personnel to understand not only how to manipulate the controls, but what is being adjusted and why, and how these adjustments may or may not affect the quality of the calendered product.
- The second begins with plant management and works its way back down to the operating personnel on the line: No matter how technically sophisticated any production line may be, it will not produce consistent quality output if it is not kept in the best possible operating condition.

Time and resources must be allocated and employed in a consistent manner to maintain the line. The maintenance function cannot be divorced from the production function.

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