Applications of tension and nip load profile measurement using a novel roll mounted electret film sensor

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ABSTRACT: An intelligent roll is a mechatronic system consisting of a roll in a web handling machine that also is used as a transducer for sensing cross-machine tension or linear load. The intelligent roll has electret film force sensors mounted on it in a helical arrangement. The sensors measure the force applied by the material being produced, such as a paper web, and thus provide information about the behavior and quality of the product. In addition to the force sensors, the intelligent roll system has an electronic signal processing module on the roll end and a digital radio link to transmit the data from the rotating roll. The receiver is connected to an automation network. An intelligent roll can be used to measure the tension profile online without separate scanning devices. An intelligent roll used as a reel or winder drum enables online measurement of linear load profiles during reeling and winding. Intelligent roll technology also enables temporary process and runnability analysis measurements by using tape-mounted sensors. Problems such as loose web edges, off-machine coater web shifting, winding problems, and reeling defects have been solved with these measurements. This paper describes the technology and presents three examples of its application to improve process runnability.

Application: A novel roll mounted sensor that makes use of new developments in polymer electret films can be used to improve runnability in a wide variety of applications including tension profile measurement, nip load profile measurement, and roll profile measurement.

Variations in the tension profile of a web adversely affect runnability in web handling processes [1-3]. In papermaking, these variations can lead to web breaks, flutter, wrinkles, and calender cuts [2]. In printing, tension profile variations can cause web breaks, wrinkles, and color registration errors [2]. The relationship between tension profile variations and the development of wrinkles in printing presses were specifically studied by Linna et al. [3]. Historically, profiles such as basis weight, moisture, and caliper were measured and controlled in the papermaking process [2,4]. However, tension profiles did not attract much attention until the late 1980s and early 1990s.

As a result of the interest in tension profiles, a variety of sensors were developed. Longitudinal web tension has typically been measured with a roll mounted on load cells; one load cell at either end of the roll. This arrangement provides a signal that represents the average value of the longitudinal tension but provides no information about the tension profile. A small improvement on this setup can be achieved by mounting multiple load cells under the bearing housings of sectional rolls. Perhaps a half dozen discrete tension levels can be measured in the cross-machine direction (CD) using this method. However, costs rise significantly as additional bearings and load cells are required and resolution is approximately 1 m. In addition, proper calibration and interpretation of the signals can become confusing.

Eriksson [1] used a novel three-load-cell arrangement to measure the forces and bending moment on a web. A load cell mounted axially on a roll was used to measure shear and two load cells mounted in the traditional position below the roll were used to measure tension and the bending moment on the web. Additionally a tension profile was measured with an electro-acoustic device.

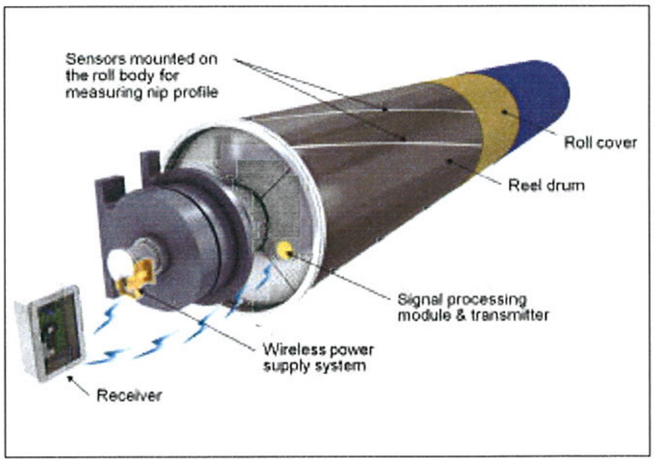
Tension profiles were measured by Linna et al. [2, 5] with a device called a Tenscan that used a laser beam to measure the transit time of sound waves passing through a web. A speaker generated sound waves in the web and the laser measured their speed. Similar to the equation for wave speed in a string under tension, this sensor relied on the relationship between wave speed, tension, and basis weight. However, basis weight can vary both in the machine direction (MD) and the CD, which can lead to measurement errors. The Tenscan unit was portable but cumbersome because the sensing head was mounted on a special aluminum beam. The sensor and beam required 50 cm of space in the MD for mounting. The Tenscan was also relatively slow and took approximately one minute for a profile. Typically, 10 profiles were measured for the parent roll in a reel and an average profile was calculated from those.

Hellentin et al. [6] used a CTSensor (cross tension sensor) to measure tension profiles. This device was a roll with numerous rotors floating on air-lubricated bearings. The pressure differential between the top and bottom of the bearings was related to the force of the web on each rotor. Differential pressure transducers were used to measure the air pressure and were sampled by data acquisition equipment. Also, web speed and temperature effects on the measured signal were negligible and the cross-machine resolution was 55 mm. However, each rotor needed to be calibrated individually by applying a variety of loads and curve fitting the voltage outputs to the loads. In addition, the rotors could stick if debris became lodged between them, which would cause erroneous readings.

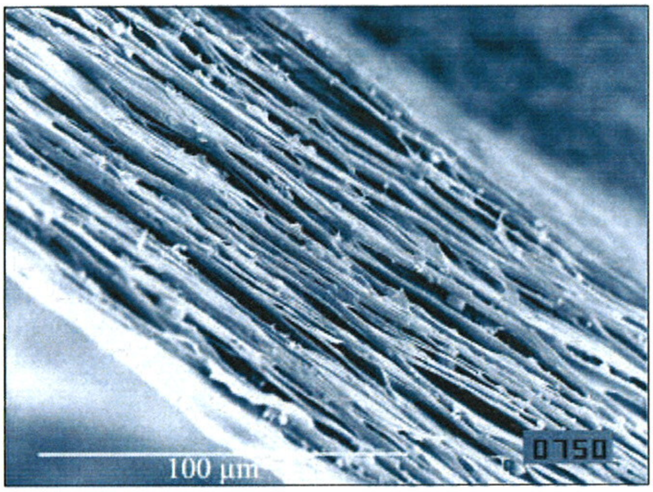
Linna et al. [7] and Conners et al. [8] used a noncontact tension profile sensor for their studies. A beam deflected the web, and a thin layer of air separated the round surface of the beam from the web. Pressure in the air layer was measured through small orifices in the beam and related to web tension. The resolution is based on the spacing between orifices, which is typically 100 mm to 300 mm. However, the web speed must be greater than 500 m/min for the air film to develop, limiting this sensor to higher speed processes. The sensor orifices also require periodic cleaning, which is accomplished by automatic means.

This paper describes the intelligent roll, which is a mechatronic system consisting of a roll in a web handling machine that also is used as a transducer for sensing cross-machine tension or linear load. It is a robust sensing system that has been in use for three years and can measure loads up to 50 kN/m. The intelligent roll can be calibrated quickly in units of linear load by applying a known nip load and scaling the output accordingly. This even can be done automatically by the control system in permanent installations. Calibration can also be verified with nip impression paper. Once calibrated, the output is very stable and only needs to be checked once per year as part of normal preventive maintenance. The intelligent roll also is not speed limited, its output signal is independent of basis weight, the resolution is approximately 50 mm, and it requires no machine-direction space for mounting. The intelligent roll consists of a high-precision roll with helical grooves machined in the shell, force-sensitive electret film sensors mounted in the grooves, a roll cover, signal processing electronics, a digital radio transmitter, wireless power transmission, and a receiver connected to the mill automation network [9]. **Figure 1** illustrates the construction of an intelligent roll. A portable version of this system, which is easily transported, uses the same technology for temporary measurements.

The intelligent roll creates new possibilities for optimizing the runnability of a web handling process. An intelligent roll can be used in place of a tension roll to measure web tension profiles online. Unlike previous tension profile measurement devices, however, the same technology can be used for nip load profile measurement. An intelligent roll can be used in place of a reel drum to measure the nip load profile and the roll profile online. This capability facilitates the online control of roll profiles and web tension profiles in permanent installations. The portable version of this system allows almost any roll to be converted into an intelligent roll by using tape-mounted sensors. This technology enables temporary roll



1. The intelligent roll and its components.



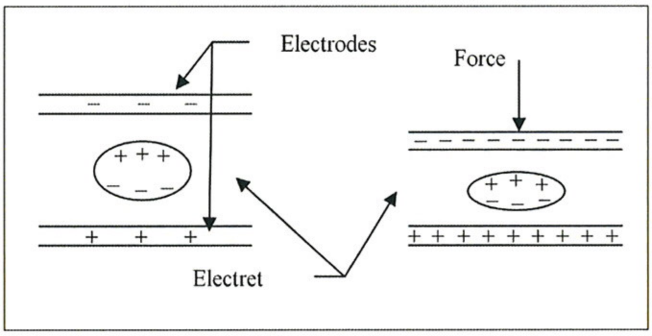
2. Scanning electron microscope picture of a porous polymer electret (image by Emfit Ltd, Vaajakoski, Finland, www.emfit.com).

profile, nip load profile, and tension profile analysis to be performed by field technicians. In this manner, economic benefits can be achieved by solving difficult problems without major capital investments.

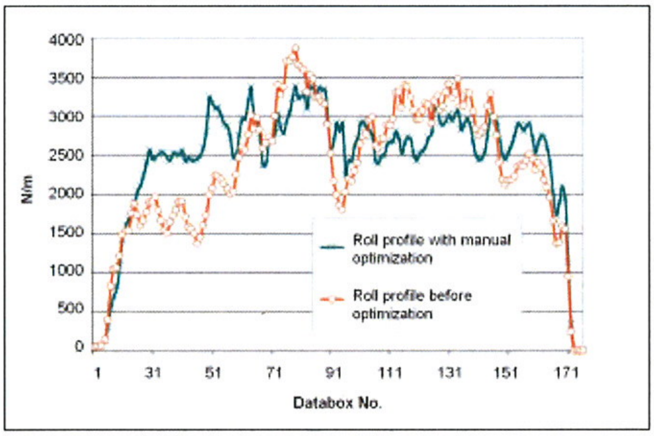
The intelligent roll eliminates the need for external measurement devices such as scanners and their associated space requirements. An intelligent roll acts like a conventional roll in the process, making it possible to measure how the web tension or nip profile behaves online in real time. Moreover, it can be located in various positions in the process, wherever the tension profile is critical or the nip-paper roll profile needs to be measured. The portable system enables the line to be equipped with several profile measurements simultaneously.

SENSING PRINCIPLE

An electret is a dielectric material that has quasipermanent charge storage and hence, a quasipermanent electric field. Electrets have been studied for some time, but interest increased in the 1960s with the development of polymer dielectrics that exhibited piezoelectricity [10]. In the mid-1980s, a novel porous polymer electret was developed in Finland that



3. A void in an electret sensor.



4. Example of a reeling nip load profile that shows peaks and valleys in the roll caused by variations in the caliper profile. The optimized profile (green) was measured after manually adjusting the zone controlled roll on a multinip calender.

had much higher levels of piezoelectricity than previous materials [10,11].

Porous polymer electrets are manufactured by stretching the polymer film in perpendicular directions to create voids (**Fig. 2**). The internal surfaces of the voids are then charged to opposite polarities with a corona method so they become macroscopic dipoles [12]. The structure of a simplified version of the sensor resembles a capacitor with two conducting electrodes separated by the electret, which is a dielectric. In operation, when the material is compressed by an external force, the voids in the electret decrease in thickness, which decreases their dipole moment. This will cause charge separation to occur on the electrodes of the sensor (**Fig. 3**). As a result, an open circuit voltage appears on the electrodes according to the relationship between charge and voltage for a capacitor, as shown by Eq. 1 [11].

$$V = \frac{Q}{C} \tag{1}$$

where
C = capacitance, F
Q = charge, C
V = voltage, V

In practice, the voltage at the electrodes of the sensor can be calculated with Eq. 2 [12].

$$\Delta V = \frac{\Delta Q}{C_S} = \frac{S_q \Delta F}{C_S} \tag{2}$$

where
Cs = capacitance of the sensor film, pF
S_q = sensor sensitivity, pC/N
ΔF = change in force, N
ΔQ = change in charge, pC
ΔV = change in voltage, V

This sensor generates output voltages only for changes in force; a constant force will not generate an output voltage.

In general, the sensitivity of an electret sensor decreases with time to a lower level that is then stable. This effect is easily avoided by pre-aging sensors before use. Pre-aging has the added benefit of making the sensor thermally stable up to 60°C-70°C.

IMPLEMENTATIONS OF THE INTELLIGENT ROLL

Nip load measurement

An intelligent roll can be used as a reel drum for online nip force profile measurements. The nip profile measured at a reel has a direct correlation with the diameter and hardness profiles of the paper roll. The reeling nip-load profile clearly shows the peaks and valleys caused by variations in the caliper profile. The high resolution of the profile measurement is based on the inherent nature of roll building. Thousands of paper layers are reeled on top of each other as the parent roll is wound, so thickness variations accumulate and can produce relatively large variations in the parent roll diameter profile.

An intelligent roll not only facilitates control but also reduces reeling problems. Because it measures the reeling nip load profile directly at the nip, an intelligent roll immediately reveals force peaks, discontinuities in reel build-up, skewed nip profiles, and "carrot-shaped" rolls (**Fig. 4**). Force control problems caused by friction and wear in the machine parts also are exposed. This results in less broke from reeling-related quality defects.

Using an intelligent roll as a reel drum combined with actuators such as calender zone controls, calender induction profilers, basis weight profilers, or coat weight profilers allows for closed loop control of roll profiles. This enables an immediate response to profile-related quality variations and runnability problems, and reduces the recovery time after grade changes.

Tension profile measurement

Another implementation of the intelligent roll measures the tension profile online without using a separate scanning device. This also improves the accuracy when compared to traditional methods such as load cells. With an intelligent roll, the tension is measured directly between the paper web and roll body. Therefore, the dead weight of the roll and thermal expansion have no effect on the measurement system.

An intelligent roll can be used for closed loop tension profile control to reduce runnability problems. Higher shrinkage at the edges of the web in the drying section leads to a tension profile that decreases near the edges. Also, variations in the moisture profile before the drying section can cause a nonuniform tension profile. An intelligent roll can be used to measure the tension profile and make corrections to the moisture profile before the drying section. However, tension profile control is more complicated than traditional profile control systems where one set of actuators controls one paper property. The actuators used to control the tension profile also will affect the moisture profile [8].

Two basic topologies can be used for tension profile control. The first topology is based on traditional moisture profile control using the paper machine press section steam box as an actuator. Moisture profile measurement and control are applied as normal. Tension profile optimization is added to the system in cascade with the moisture profile control. The tension profile is measured by an intelligent roll located in a suitable position and a moisture profile set point is calculated by the tension profile controller. This set point is sent to the moisture profile controller. A cascaded control system such as this is well understood and straightforward to tune. The tension profile control sets a certain range for operation, which limits the moisture profile variation. Thus, the tension profile may be optimized while keeping the moisture profile within its limits.

The other topology used for web tension profile control is based on two actuators affecting the tension and moisture profiles separately. The first actuator (press section steam box or first drying section moisturizer) is used to control the tension profile and the second actuator (a moisturizer) is used to correct the moisture error of the end product. This topology can decouple the moisture and tension control. The two controllers limit each other to reduce the moisture error caused by too much profiling in the press section steam box. The system also can be tuned with optimal weighting for each actuator versus each measurement. For example, the press section steam box can have 80% weight for controlling tension profile and 20% weight for controlling moisture. The second moisturizer can have the opposite weighting: 20% to control tension profile and 80% to control moisture profile. This control strategy is further described by Kniivila [13].

Portable system

Portable intelligent roll technology brings a new online nip load and tension profile analysis tool for paper and board makers and maintenance experts. This portable system provides information about cross-direction and machine-direction tension profile variations and nip load profiles. The system also makes it possible to perform bump tests to measure responses of upstream actuators to help optimize the paper web properties. The portable system allows quick and cost effective use of intelligent roll technology.

5. Installation of portable measurement sensors on a roll surface.

The portable technology requires temporary installation of intelligent roll sensors onto a roll surface (**Fig. 5**). A signal processing module with a transmitter must be attached to the roll head or shaft. The sensors provide a complete CD profile on each revolution of the roll, and the profile measurement is transmitted wirelessly to a receiver and from there to a computer. The portable system allows large amounts of data to be collected in a short period.

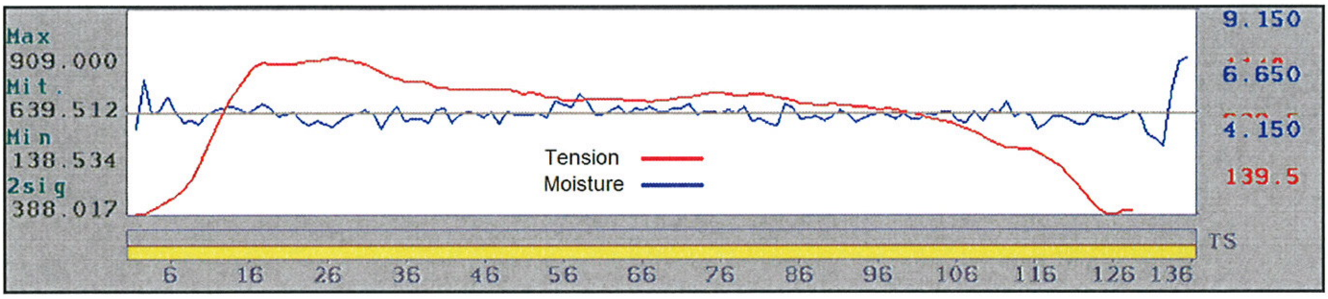
THREE APPLICATIONS OF INTELLIGENT ROLL TECHNOLOGY

Online control of web tension profile

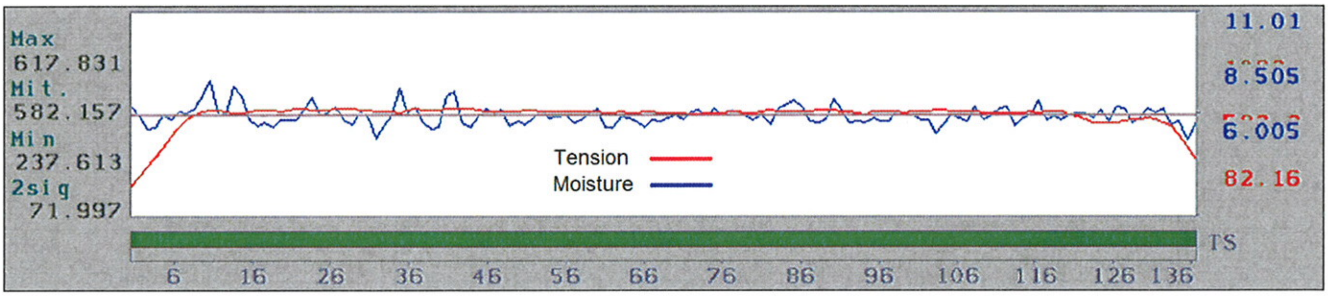
A linerboard production line had difficulties with runnability of its film sizer. Loose edges on the web often caused fluttering and wrinkling before the sizer. To remove wrinkling, the web tension level was increased 300 N/m above the usual level. A higher tension level naturally caused more frequent web breaks, and thus reduced production efficiency. An intelligent roll was installed before the sizer, along with a tension profile controller, to improve the web tension profile.

Controlling the tension profile is most effective when done as early as possible in the papermaking line. In the drying section, the web is stretched and dried at the same time, causing permanent changes in the tension profile. In this application, a moisturizer on the first drying section was used to control the web tension profile. Another moisturizer at the second drying section was used to remove the moisture error from the end product. Because the second moisturizer was located later in the process, it had only a small effect on the tension profile. Thus, the effects of the first moisturizer dominated the shape of the tension profile.

Figure 6 illustrates the tension and moisture profiles before the control system was turned on. The loose edges of the web were reflected in the profile by the low tension at the edges. This was most likely caused by the higher moisture levels seen at both edges. In addition, the tension profile is skewed, being high on the drive side of the machine and drop-



6. Profiles before the control system was turned on.

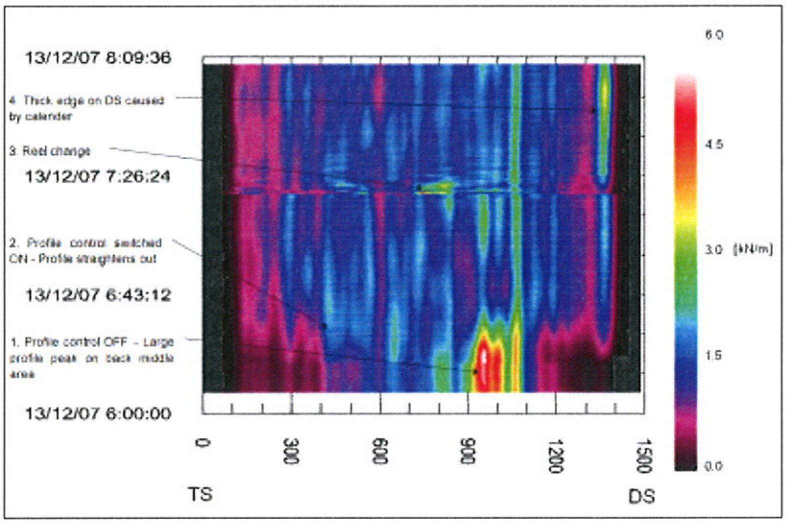


7. Profiles after the control system was turned on.

ping off toward the tending side.

After the control system was turned on, the profiles changed to those shown in **Fig. 7**. The control system lowered the moisture at the edges, which increased the tension in those areas. The tension profile also became uniform and was no longer skewed higher on the drive side. The relationship between moisture and tension is not always obvious because the second moisturizer corrects moisture error with little effect on tension. However, slightly higher moisture peaks do appear on the drive side (Fig. 7), resulting from the first moisturizer lowering tension in that area.

With the control system, the tension profile was clearly improved and the end product moisture profile still remained within limits. The improved profile reduced wrinkling and enabled a lower web tension, which resulted in fewer web breaks.



8. Roll profile as a color map measured with an intelligent roll.

Online control of roll hardness profile

Controlling the caliper profile of glossy paper grades has been difficult in the past because of difficulties in measuring caliper online. Contacting sensors are accurate as long as there is no debris on the sensing head, but they can cause web breaks and sheet marking. To prevent this, a noncontact sensing head can be used that travels over the web on a thin air film. These caliper sensors tend to be inaccurate because variations in the air film thickness are mistakenly interpreted as caliper variations. Web flutter, web temperature variations, and debris on the sensing head contribute to inaccuracies in measurement [4,14].

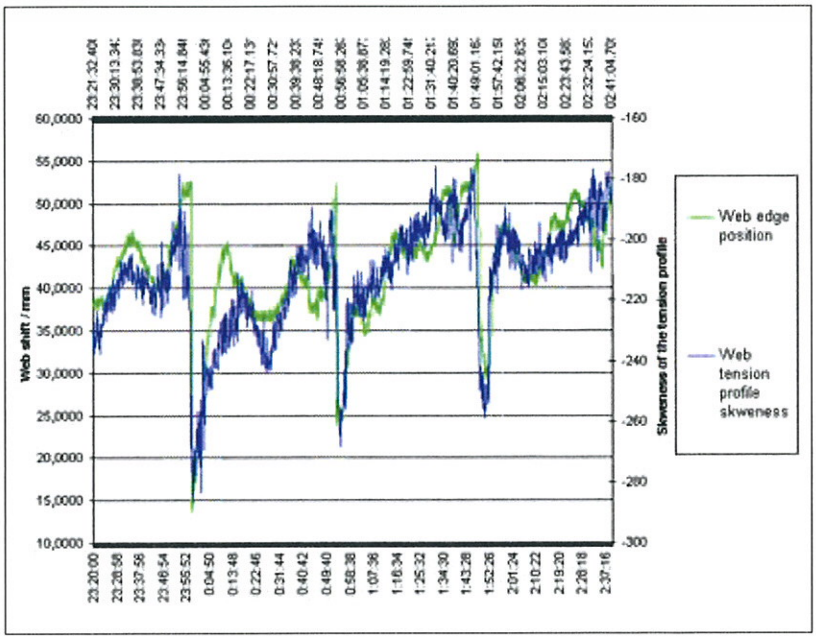
Inaccurate caliper measurements cause reeling problems, especially in the roll edge areas and after grade changes. Small caliper and density profile variations accumulate into large diameter and hardness variations of the paper roll when thousands of layers of paper are reeled on top of each other. This leads to runnability problems during reeling and winding due to bumpy rolls as well as reclamations from printing houses.

A super calendered (SC-A) paper production line with online multinip calendering was equipped with an intelligent reel drum and a calender control system using reel drum roll profile measurement. The roll hardness and diameter profile is measured through an intelligent roll nip profile. The control system calculates the set points for the zone control roll in the calender to optimize the paper roll structure.

Figure 8 shows the quality of the roll that is being produced. Initially, the roll profile control was turned off. Without the control, the roll profile has large variations and the roll has very soft edges. This obviously leads to runnability problems during winding. If the variations become large enough, the roll might burst from excessively high internal stresses.

After turning on the profile control, the profile becomes more uniform. Some narrow profile variations remain because of the resolution limitations of the zone controlled calender roll. This measurement also reveals two narrow variations in the profile that are caused by worn-out calender rolls. The high resolution of the intelligent roll allows roll wear to be detected early so that corrective measures can be taken to avoid unplanned down time.

With the online roll profile control, the SC-A production line has had increased efficiency and improved runnability at the winder. The intelligent roll-based control system also reduces the recovery time after grade changes.



9. Correlation of the web shifting and tension profiles at the coater.

Solving the lateral web shifting problem

A mill producing high quality wood-free coated paper had a constant problem with lateral web shifting in its off-machine coater. The lateral movement caused web breaks, especially during splicing, and difficulties in web edge cutting. The reason for the web shift had been a mystery for years; various modifications were made to the papermaking line to attempt to fix the problem, but none were effective. Over the years, the speed of the line was increased, but the web shifting became a bottleneck to increasing production. Time and material efficiency of the line also were lower than considered possible, which caused additional production costs and indirectly higher energy consumption.

We assumed that a tension profile variation was the reason for the web shifting. Several portable intelligent roll systems were installed along the line to separately identify the profile effects of each subprocess. The tension profile was measured before the machine calender, before the reel, at the rereeler, and after the coater unwind. The nip load profile was measured on the reel drum and rereeler drum. Web edge position sensors were installed in the coater to measure the lateral translation of the web. Approximately one profile per second was collected during an actual production run.

When the measurements were complete, the first observation was that the web shifting was directly correlated with the skewness of the tension profile measured after the coater unwind. The skewness was quantified by calculating angular coefficients of straight lines fitted to each tension profile. These coefficients were recorded for each paper roll and compared with the measured edge position of the web, as **Fig. 9** shows. In this manner, we determined that the skewed tension profile was the reason for the web shifting. The cause of the tension profile skewing needed to be determined next.

We observed that tension profiles measured at the paper machine did not correlate with the tension profile at the coater. This surprised the analysis team because they initially expected that the tension profile errors would originate in the paper machine wet end. However, this was not the case and the paper machine with all of its subprocesses could be ruled out.

Next, the team found that the tension and roll profiles at the rereeler correlated very well to the coater tension profiles. This narrowed the cause of the tension profile variation to either the rereeler or the paper machine reel. Finally, the paper machine reel nip load profile was measured, revealing that the nip profiles had excellent correlation to the tension profile at the coater. Because the paper machine reel was the first location in the line where this correlation occurred, it had to be the primary cause of the web shifting.

The analysis team concluded that the wound-on tension (WOT) profile of each roll was skewed and the amount of skew also changed during reeling. When the rolls with variations were unwound at the coater, the web shifting occurred. The nip load controls of the reel were updated and adjusted to have a uniform WOT profile. The reeling recipes also were adjusted to improve the roll structure.

After the reel control system was modified, the tension profile changes at the coater were reduced significantly. The web behavior was stable and web shifting no longer occurred.

CONCLUSION

This paper presented a novel tension and load profile measurement system based on new developments in polymer electret film technology. This intelligent roll measurement system turns the roll into a mechatronic sensor that can be located in place of a conventional roll in a web handling process. The roll can then be used for tension profile measurement or nip load measurement. In addition, a portable version of the system can be installed temporarily to troubleshoot web handling problems on a process line.

Three cases were presented showing the use of the intelligent roll in actual web handling lines. An intelligent roll was used to successfully improve runnability of a linerboard machine by providing feedback to moisturizers for controlling the tension profile. In another application, the intelligent roll was used to control roll hardness and diameter profile at a reel by using a calender profiling roll as an actuator. This improved runnability and efficiency on the winder. In the last case, the portable version of the system was used to identify and correct the cause of skewed tension profiles, which had caused lateral translation of the web in an off-machine coater.

Although all applications presented involved paper webs, the intelligent roll is not limited to this material. It can be used with polymer film, tissue, and even webs made of woven materials. These other materials provide new areas for future development of the intelligent roll. **TJ**

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ABOUT THE AUTHORS

Profile variations have a large effect on the runnability of a paper web, but existing profile measurement devices have had undesirable shortcomings.

Intelligent roll technology is a novel use of electret film force sensors that improves upon previous profile measurement devices by being easier to calibrate, independent of basis weight and speed, and requires no machine-direction space for mounting.

The force sensor has high sensitivity so it responds to very small deformations. Because the sensor and roll cover act together as springs in series, the overall stiffness must be properly chosen so that the sensor has sufficient deformation for measurement, yet the nip does not yield excessively. Testing was conducted to determine the optimal cover stiffness for various applications.

It is interesting that through slightly different implementations, the same intelligent roll technology can be used for tension profile measurement, nip load profile measurement, and for temporary troubleshooting.

As this new type of feedback device becomes available, mills can use it to measure either tension or load profile to optimize web properties in the cross machine-direction.

The next step is to begin using this technology on other web materials besides paper, such as plastic film or woven materials.

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