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FUTURE DIRECTIONS IN CALENDERING RESEARCH

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ABSTRACT

Calendering is the papermaker's last chance to reduce thickness variations along the length and width of the finished sheet, and to improve the sheet smoothness. A smoother sheet results in improved print quality, while more uniform thickness profiles improve the winding process. The calendering operation thus improves the quality of the finished product. In recent years there has been an increase in the loads, speeds and temperatures at which soft-nip calenders, whether on or off line, can be operated without mechanical failure of the cover; the result has been an improvement in the surface and printing properties achievable with mechanical printing grades of paper, and an increase in the production rates which can be sustained. As a result, these calenders have slowly replaced traditional machine calenders in new and retrofit installations.

The best available design and trouble-shooting tools for modern machine calenders are based on empirical models, whose coefficients have not been related to fundamental paper or fibre properties. New furnishes therefore require experimental determination of these coefficients, and extrapolation to new calendering conditions involves some risk. As well, there are no published models, empirical or otherwise, for the design and trouble-shooting of soft-nip calenders, an unfortunate state of affairs given the increased number of installations of these machines.

The purpose of this review is to outline the current understanding of the process, and to identify areas where further research

could be useful to allow better prediction of paper properties arising from a change in the equipment or operating conditions.

INTRODUCTION

For most grades of paper, the last step in the papermaking process is calendering. This operation reduces paper thickness and roughness by pressing the sheet between rolls in one or more nips. The high loads encountered in the nip between two smooth calender rolls flatten high spots in the rough sheet by permanently deforming wood fibres on the surface of the sheet, thus reducing its roughness. Fibres inside the sheet are also deformed, reducing the thickness. The process is the papermaker's last chance to reduce thickness variations along the length and width of the finished sheet, and to improve the sheet smoothness. A smoother sheet results in improved print quality, while more uniform thickness profiles improve the winding process. The calendering operation thus improves the quality of the finished product.

Peel [1,2] has compiled comprehensive reviews of calendering practice and theory, updating an earlier review by Baumgarten et al. [3]. In the decade since Peel's last review, the major change in the technology has been an increase in the loads, speeds and temperatures at which soft-nip calenders, whether on or off line, can be operated without mechanical failure of the cover; the result has been an improvement in the quality and uniformity of surface and printing properties achievable with mechanical printing grades of paper, and an increase in the production rates which can be sustained. As a result, these calenders have slowly replaced traditional machine calenders in new and retrofit installations.

In spite of the significant efforts chronicled by Peel [1,2] and, more recently, by Crotogino [4], the best available design and trouble-shooting tools for modern machine calenders are based on empirical models, whose coefficients have not been related to fundamental paper or fibre properties. New furnishes, therefore, require experimental determination of these coefficients, and extrapolation to new calendering conditions involves some risk. And while the behaviour of a single-nip online calender can be predicted from pilot plant experiments, there are no published models, empirical or otherwise, for the design and trouble-shooting of multi-roll soft-nip calenders or online supercalenders, an unfortunate state of affairs given the increased number of installations of these machines. In particular, a simple description of the process could lead to improved cross-direction control of online supercalenders.

The purpose of this review is to outline the current understanding of the process, and to identify areas where further research could be useful to allow better prediction of paper properties arising from a change in the equipment or operating conditions, and improved control systems for more uniform product properties.

We begin with an overview of the underlying physics of the process, then go on to discuss practical tools such as the calendering equation. We end with an outline of where these tools are lacking, and what work needs to be done to develop models to guide the design, development and trouble-shooting of modern soft-nip calenders.

THE WEB'S VIEW OF THE PROCESS

It is worthwhile considering the process of paper compression in a calender nip from the point of view of the web, and of the fibres of which it is made.

Typical dimensions

A typical softwood mechanical pulp fibre is 1 to 3 mm long, with diameter 10 to 20 µm and a wall thickness of 1 to 5 µm. A typical calender roll has a diameter many orders of magnitude larger than this, so that the curvature of the roll is essentially nil when observed from the fibre's perspective. Similarly the nip length is at least as long as a long, straight fibre lying in the machine direction. Finally the depth of indentation of the roll into the nip, of the order of 20 to 40 µm in the case of lightweight grades, is similar to the diameter of an un-collapsed mechanical pulp fibre. These dimensions are illustrated in Figure 1, where the proportions between calender rolls of radius 250 mm, ingoing nip length a = 3 mm and sheet initial thickness 120 µm have been maintained, and again in Figure 2, where the curvature of the rolls has been exaggerated for clarity.

With a nip length of the order of 5 mm and sheet speeds of the order of 1000 m/min, residence times in the nip are of the order of 300 µs. At a line load of 100 kN/m, average pressures in a nip of length 5 mm are of the order of 20 MPa. The process thus applies an impact resembling a hammer blow to the sheet, where the dimensions of the hammer are larger than those of a typical softwood fibre. It is not surprising that fibres on the surface suffer permanent deformation, or that the structure of the web deforms to reduce the thickness of the sheet.

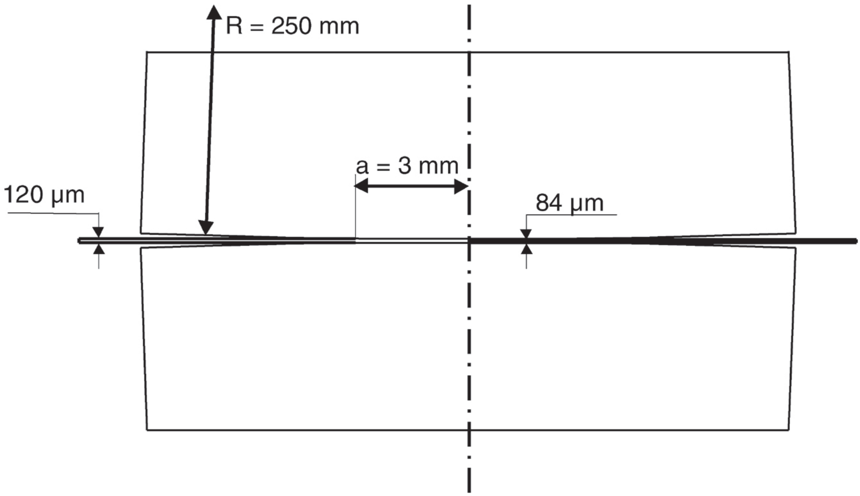

Figure 1 Newsprint sheet in a hard nip, to scale.

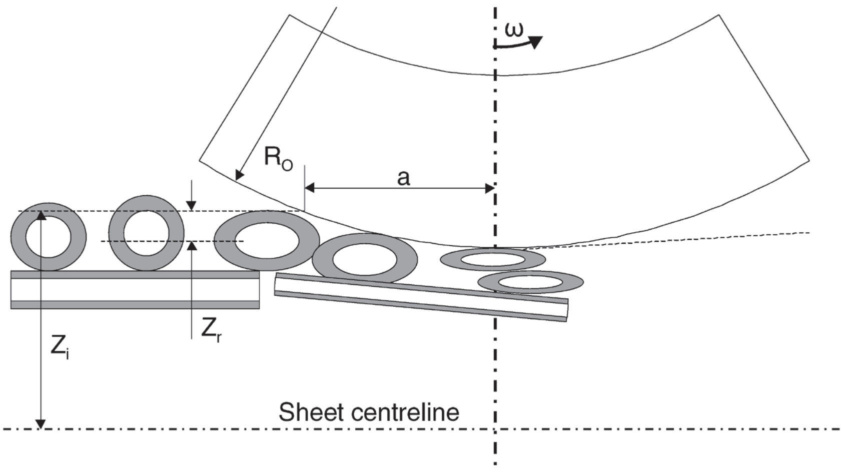

Figure 2 Fibre deformation in a hard nip, not to scale.

Local density variations in the web

The local distribution of fibres in the plane of the sheet, and the distribution of fibre properties within a typical fibre population also have an effect on how the web sees this impact.

Fibre wall thicknesses may range from 1 or 2 μm in an earlywood fibre, to as much as 10 μm in a latewood fibre. In a typical newsprint sheet, with a sheet thickness of about 100 μm, the diameter and wall thickness of fibres have a large impact on the number of fibres making up the thickness of a sheet at any given point. Some areas may consist of a small number of fairly rigid, thick-walled fibres while adjoining areas may be made up of a larger number of more conformable fibres. This is especially true of sheets made from mechanical pulp fibres, where coarse fibres remain. These coarse fibres will offer a different type of resistance to a compressive load compared to a conformable fibre; the coarse fibre will resist deflection longer but is more likely to fracture if some limiting load is exceeded.

These fibre properties, including wall thicknesses and coarsenesses, are functions of fibre morphology and of previous manufacturing steps such as refining, bleaching and wet pressing. The effect of these factors on the compressibility of sheets has been described by Ting et al. [5]. Sheets made from well-beaten pulps, containing more conformable fibres and being therefore denser, were less compressible. The effect of wet pressing was similar. Finally, there were differences in fibre conformability between two species from the eucalyptus family, indicating that species has a strong influence on the conformability and deformation characteristics of fibres.

Fibre deformation, illustrated in Figure 2, is thus a function of the fibre's characteristics, such as diameter and wall thickness, but it is also a function of the surrounding and supporting web structure. A coarse, stiff fibre embedded in a shive made of thin-walled, early wood fibres is unlikely to deform; rather, it will be pushed deeper into the more easily deformed shive. Similarly, any fibre located in an area of locally low density will be deformed very little as the load is carried by adjoining high density areas.

Depending on the quality of the formation, there may be large flocs separated by inter-floc voids. The local pressure in the nip is therefore much larger in the dense areas, and may approach zero elsewhere. The effect of calendering a local high-density area depends on the type of fibre in that area, and on the hardness of the roll surface.

A high-density area may be defined as one where the local density of the mat in the nip reaches the density of cellulose, even though the average sheet density in the nip may be significantly less. A striking example of an area of local high density is illustrated in Figure 3.

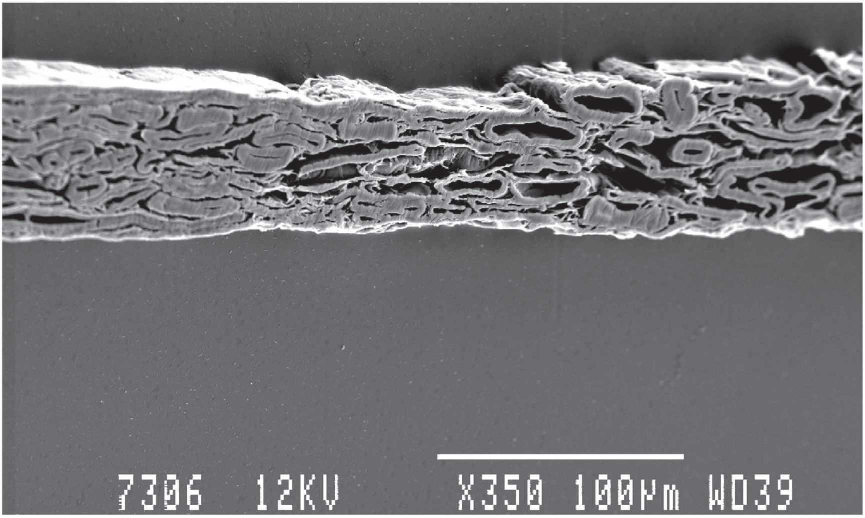

Figure 3 Micrograph of a machine-formed, calendered standard newsprint sheet made from 100% softwood TMP. The section plane is in the cross direction. To the left of the figure, local density is extremely high, approaching that of cellulose, while the density to the right is substantially lower. The high density area carried a large portion of the load through the nip, leaving the low density area relatively undeformed.

When these high-density areas reach the nip centreline, all pores and fibre lumens are completely closed up and no void spaces remain. The pressures applied in these areas are very much larger than the average or peak pressures which would be encountered if paper were a homogenous continuum, as a large portion of the line load is supported here. These excessively high pressures may lead to calender defects such as blackening. The scale over which the load will vary is similar to the scale of typical shives (1 mm) or flocs (10 mm), and is thus similar to the typical nip length. Coarse, thick-walled late wood mechanical pulp fibres will tend to fracture in these areas, as shown in [6,7], while more conformable early wood or kraft fibres will deform and bend.

The preceding discussion of local non-uniformities in the uncalendered sheet holds true for coated or filled sheets, where the density, uniformity and weight of the coating or filler must also be considered.

The effect of high-density areas is somewhat less in the case of a soft nip, where roll deformation acts to spread the load into less dense areas. However, this leads to another set of problems. While a hard nip tends to reduce caliper variability in the CD, at the expense of density variability, a soft nip tends to preserve density while maintaining or increasing caliper variability. The result is that paper calendered in a soft nip is harder to wind, and building reels of constant density becomes a challenge. There is a definite lack of proper control systems for soft nips, especially multi-nip stacks such as supercalenders.

Machine and cross direction deformation of the web

Paper subjected to a compressive pulse in a calender nip also deforms in both the machine and cross directions.

The permanent extensions of paper in the machine (MD) and cross-directions (CD) are small compared to the permanent *z*-direction deformation [8–10]. This can be understood by considering a fibre lying in the machine direction on the surface of a sheet 120 μm thick, as illustrated in Figure 2. Typical fibre dimensions are 2 mm long and 10 μm in diameter. As it enters the calender nip one end of the fibre is both flattened and displaced downward from the surface towards the sheet centreline 60 μm below. If the in-nip strain is 0.50, the downward displacement is about 30 μm. The new length of a fibre with one end at the nip centreline and one end just entering the nip, as deduced from geometry, is 2.0002 mm, which represents a negligibly small lengthwise strain of 0.01%. A fibre closer to the sheet midplane will see even less machine direction strain since the downward displacement goes to zero at the sheet centreline. Whatever the magnitude of the strain imposed, it is more likely to result in straightening or un-kinking of a fibre rather than pure lengthwise strain, so the tensile modulus of the fibre doesn't really come into play.

The change in width of fibres lying in the cross-direction is likely to contribute more to the machine direction strain than the lengthwise fibre strain described above. When a fibre of diameter 10 μm is compressed, the width of the fibre will increase to 12 to 14 μm in the nip depending on the wall thickness and how much open lumen remains. The increase in width corresponds to an in-plane strain on the scale of the fibre of 20% to 40%, a large amount; however, the strain on the scale of the sheet is much smaller since fibres expand into inter-fibre voids as they compress and do not necessarily force adjacent fibres to displace. A change in the width of a fibre is likely to cause strain in the fibres crossing it and bonded to it; the extension of a fibre caused by 5 fibre crossings per mm of fibre length, each crossing extending 3 μm, is 15 μm, corresponding to a total lengthwise strain of the order of 1%. This amount is consistent with measured MD and CD strains [8–10].

Overall, MD strain in a calender is probably due to the large radial deformation of CD oriented fibres being constrained by small deformations, and by un-kinking of the MD oriented fibres to which they are bonded. The three-dimensional structure of the sheet shifts and stretches, dissipating the large radial deformation of individual fibres. These conclusions are supported by experimental work of Mann et al. [11], whose measurements of in-plane Poisson's ratios show that large z-direction strains result in very small CD or MD strains.

In an industrial calender, these machine-direction strains are applied to a sheet under tension and which is, therefore, already strained in the MD. At each nip, some of this tension-induced strain is made permanent by the z-direction deformation; in effect, the sheet length increases slightly. This reduction in the recoverable MD strain leads to a reduction in sheet tension as the sheet moves from nip to nip around a wrap, which can in turn cause calender bubbles to form when the sheet tension is low enough. Described in detail by Hamel et al. [12], calender bubbling arises when air expelled from the sheet in the nip is subsequently trapped between the sheet and the wrap. Low initial sheet tension and low porosity are contributing factors, as are high nip loads.

Calender bubbling also tends to occur at specific cross-direction locations. Sheet width increases slightly following calendering, but the initial CD tension is essentially nil, so any significant CD extension of the sheet will lead to formation of a bubble. The specific CD locations where bubbles occur imply the existence of CD variations in either paper properties such as elongation or porosity, or of calendering variables, such as local line load, due to roll flex or distortion.

Surface properties

Calendering also alters the surface properties of the sheet.

The relationship between the reduction of bulk and the development of surface properties has been well established for machine calendering (13–15). As long as the temperature and moisture content of the web are uniform through its thickness, the measures taken to compress the web will also change the surface properties. As the calendering intensity is increased by increasing the nip load, or the web is made more pliable by raising its temperature or moisture content, the calendered paper becomes denser, smoother and glossier. For machine calendering the surface properties are very well correlated with paper bulk or density. Changes in calendering conditions within the range normally encountered in a machine calender will not lead to significant departures from these relationships.

However, when substantial temperature or moisture gradients through the thickness of the web are introduced, departures from some of the surface-property-bulk relationships can be observed [16–19]. For example, when a web is calendered between two very hot rolls, the surface of the paper will become hotter and more pliable that the interior of the web. Hence the surface fibres are able to replicate the smooth roll surface more easily, while the colder fibres in the middle of the web resist densification. The result is a glossy yet bulky paper. Gloss is the surface property most affected by such a procedure; changes in roughness are less remarkable. This effect is far more pronounced in heavier board grades [18].

The relationship between the surface properties and bulk also changes when paper is calendered between a hard roll and a soft roll [15,20]. The soft nip will distribute the pressure more uniformly over the surface of the paper than the hard nip. Qualitatively, the following reasoning might help to explain some of the observed differences between hard and soft calendered paper. In a hard nip small variations in mass distribution in the plane of the web (formation) tend to be translated into density variations and surface property variations. In a soft nip, the mass variations will tend to be translated into thickness variations rather than density variations, and the surface properties will be more uniform. Reality appears to be far more complex. Consequently, most publications about soft calendering steer clear of discussions about the relationship between bulk and surface properties [21–23].

Another, yet thornier issue is the relationship between calendering conditions, bulk, surface properties and the printing properties of the paper [24]. However, a discussion of this topic is beyond the scope of this paper.

RHEOLOGICAL MODELS OF CALENDERING

In the case of paper in a calender nip, it is necessary to consider variables in two separate categories: those which alter the strain history applied to the sheet, and those which alter the paper response and thus the stress history resulting from that strain history. Boltzmann's superposition principle provides a relationship between the applied strain history $\varepsilon(t)$ and the resulting stress history $\sigma(t)$:

$$\sigma(t) = -\int_0^t \psi(t - t') \frac{\partial \varepsilon(t')}{\partial t'} dt' \tag{1}$$

The response function $\psi(t)$ describes the material's response to the strain history. Variables affecting the strain history are line load, sheet speed, roll radius and the elastic properties (modulus, Poisson's ratio) of the roll cover. Parameters affecting the paper response are the fibre and web properties arising from previous processing steps such as pulping, bleaching, forming, pressing, drying or previous calender nips, as well as web temperature and moisture content. The strain history of paper in a hard rolling nip is a parabolic function of time, as described next; ongoing research, described further on, has led to a better understanding of the strain history of a deformable strip in a soft nip. The response function for paper, also discussed further in this review, remains unknown.

Strain history in a machine calender

In the case of a calender nip consisting of two hard rolls, the sheet compressive strain in the nip is a parabolic function of time:

$$\varepsilon(\mathrm{t}) = \varepsilon_n \left(\frac{\mathrm{Vt}}{a}\right)\left(2 - \frac{\mathrm{Vt}}{a}\right) \tag{2}$$

where t is the time from initial contact and V is the sheet speed (in m/s). Given R, the equivalent roll radius, the ingoing nip length *a*, shown in Figure 4, is

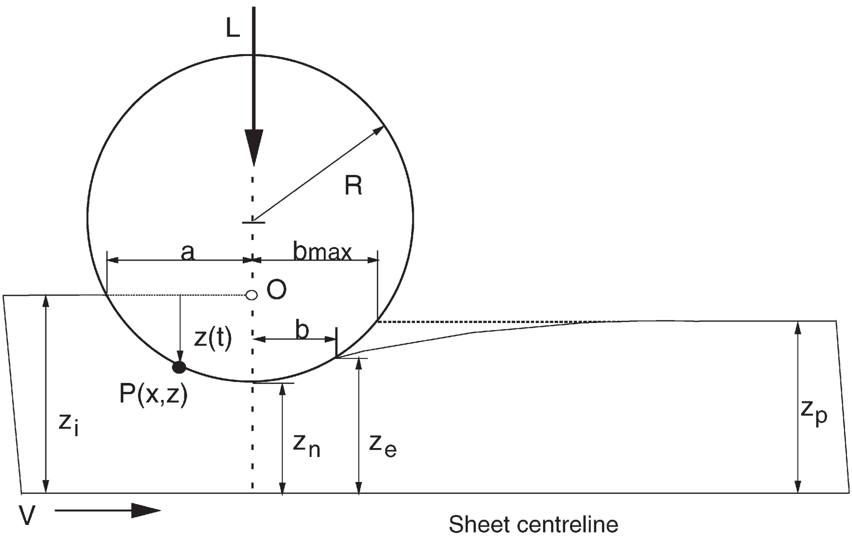

Figure 4 Geometry of a calender nip.

defined as follows when R is very much larger than the initial sheet half-thickness z_i:

$$a = \sqrt{2Rz_i\varepsilon_n} \tag{3}$$

where in-nip strain ε_n *is*

$$\varepsilon_n = \frac{z_i - z_n}{z_i} \tag{4}$$

Here z_n is the in-nip half-thickness. Finally the maximum strain rate, encountered at the nip entrance, can be obtained by differentiating Equation 2 and evaluating at t = 0:

$$\left(\frac{\partial\varepsilon(t)}{\partial(t)}\right)_{\max} = \frac{2\varepsilon_n V}{a} \tag{5}$$

Described in more detail in [25–27], Equations 2 to 5 are valid when the paper thickness is very much smaller than the roll radius, and when the compressibility of the paper web is very much greater than that of the softest roll. Typical industrial values for machine calendering of newsprint, taken from the author's work [6,25–27], are given in Table 1.

Table 1 Typical industrial calendering variables, for newsprint in a machine calender, using Equations 2 to 5.

Typical calendering parameters:	
Sheet speed V	25 m/s
Line load L	100 kN/m
Roll radius R	0.2 m
Initial sheet thickness $2z_i$	120 µm
In-nip strain ε_n (estimated)	0.4
Calculated variables:	
Ingoing nip length *a*	3.1 mm
Ingoing nip dwell time *a*/V	124 µs
In-nip thickness	64 µm
In-nip sheet apparent density	1350 kg/m^3
Maximum strain rate	6500 s^{-1}
Impulse L/V	4000 Ns/m^2
Mean pressure L/2*a* (assuming full elastic recovery)	16 MPa
Peak pressure 3L/4*a* (assuming full elastic recovery)	24 MPa

Stress and strain in a soft-nip calender

When roll deformation becomes significant compared to paper deformation, as in a soft nip, Equations 2 to 5 are no longer valid. Johnson [28] presents an analysis of the stresses arising when two elastic rolls, of different elastic moduli and Poisson's ratios, are pressed together to form a nip. A qualitative summary of that mathematical analysis will be presented here.

Johnson's analysis predicts that shear stresses due to the different elastic properties of the two rolls may be sufficient to generate areas of slip between the two rolls. In the absence of paper in the nip, the areas of slip are located between the two rolls, close to the nip entrance and exit; in these areas the shear forces are large and the compressive loading small. This is illustrated in Figure 5, showing the indentation of a hard roll into the elastic surface of a soft roll, and the deformation of a unit element of the deformable cover as it moves from the nip entrance, past the nip centreline, and on to the nip exit.

Figure 6 shows qualitative diagrams of the shear and normal load profiles arising from the geometry in Figure 5. Figure 6A illustrates an elastic roll cover, while Figure 6B illustrates a viscoelastic cover. At the nip entrance, the

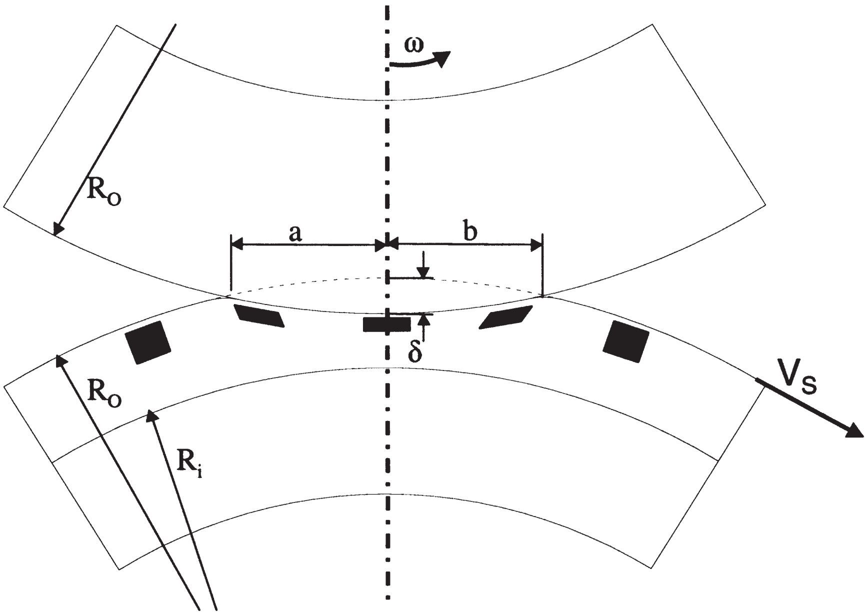

Figure 5 Deformation of a soft roll, not to scale.

shear force q(x) is climbing rapidly, while the normal force p(x) is increasing less rapidly. This arises for the following reason. The surface or peripheral velocity of the soft roll, V_S, is equal to the ωR_O; as the roll is deformed, its radius R_O decreases. The angular velocity ω remains constant, so V_S must decrease. By the same token, the surface velocity of the relatively undeformed hard roll remains essentially constant. In this entrance area, there may be a point where the ratio q(x)/p(x) exceeds the value of the static coefficient of friction μ, causing slip to occur. Once p(x) increases to the point where q(x)/p(x) is less than μ, tangential strains are applied to the soft roll.

Further into the nip the shear force begins to decrease, reaching zero in the vicinity of the nip centreline. (The shear force will be zero, and the normal force at its maximum value, exactly at the nip centreline only when the material is perfectly elastic; any viscoelastic behaviour tends to skew both curves towards the ingoing side of the nip, as shown in Figure 6B.) In the vicinity of the nip centreline, the normal force is large, so no slip is possible,

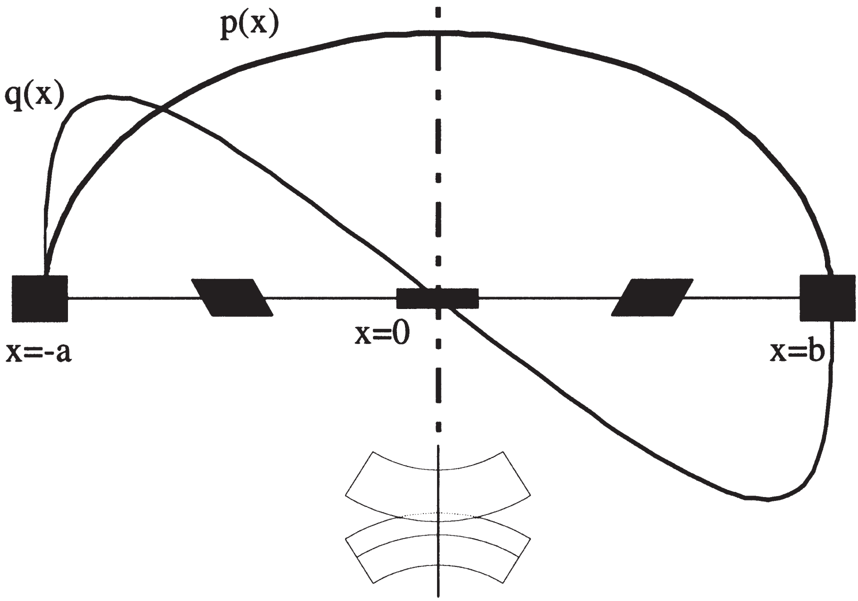

Figure 6A Deformation of a unit element of an elastic soft cover. The compressive load p(x) is a maximum, and the shear load q(x) is zero, at the nip centreline; the nip is symmetric, and b is equal to a.

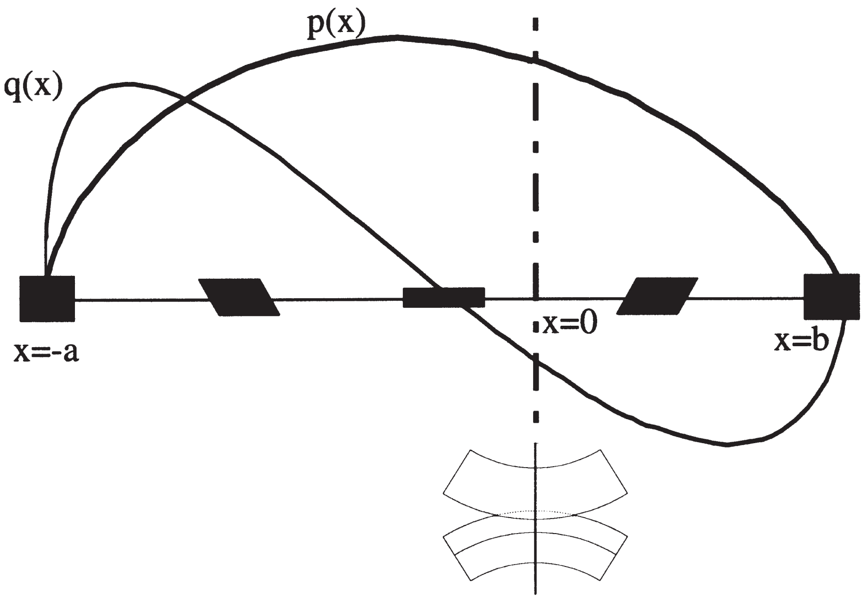

Figure 6B: Deformation of a unit element of a viscoelastic soft cover. The compressive load p(x) is a maximum, and the shear load q(x) is zero, at a point displaced to the ingoing side of the nip; the nip is asymmetric, and b is less than a.

even for low coefficients of friction. Moving towards the nip exit, the magnitude of the shear force increases again (although the sign has changed, reflecting the opposite direction of the loading), and a new zone where slip may occur is encountered towards the nip exit.

Figure 7 illustrates, in a qualitative fashion, the effect of inserting a deformable web into the soft nip of Figure 6A. As the sheet moves into the nip, a unit element is compressed by the normal loading imposed. Similarly, the tractive forces arising from the shearing loads applied at the surface of the sheet may result in slippage between the roll and sheet. However, the analysis is complicated here by the fact that there may be two different coefficients of friction, one at each interface; as well the shearing forces may be sufficient to cause in-plane deformation within the body of the sheet. With paper in the nip, the displacement required by the different deformation in each roll will therefore occur wherever the resistance to motion is least: between the hard roll and the paper, between the soft roll and the paper, or within the plane of

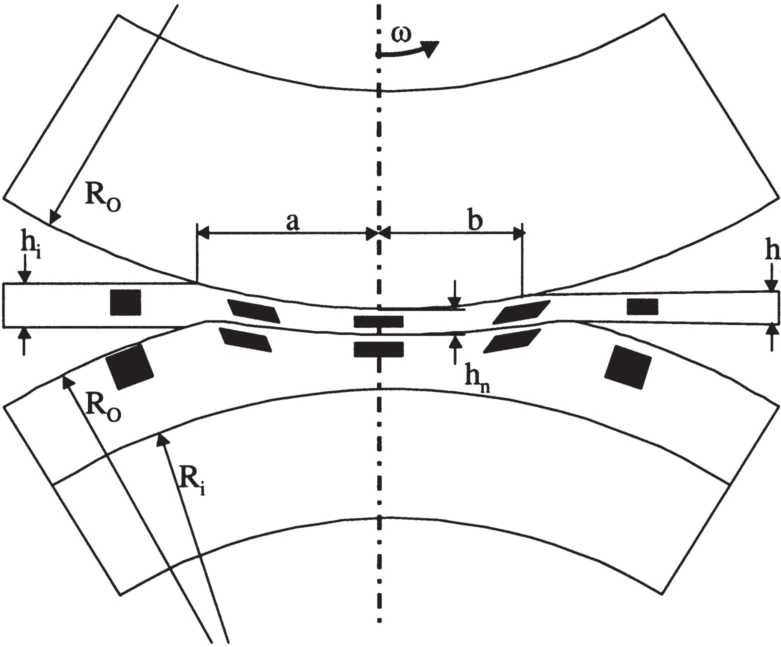

Figure 7 Web deformation in a soft calender nip, not to scale.

the sheet, depending on the relative magnitude of the two static coefficients of friction and the in-plane shear modulus of paper.

These forces are illustrated again in Figure 8, where the focus is on the fibres making up the sheet as they move through the soft nip. Fibre fracture has been identified as a probable cause for strength losses in machine calendering [6,7], where the loading is essentially compressive and shear forces are negligible; it can be suggested that the cyclic shearing load applied to the bond between a fibre lying in the machine direction and another one lying in the cross direction, as illustrated in Figure 9, may be an additional mechanism for strength losses, in this case due to bonds weakened by a cyclic stress. If this mechanism is indeed a factor in strength losses, it may be particularly prevalent in soft nips where the shear forces are more likely to be large.

To illustrate this hypothesis, Figures 10A to 10C show a series of cross sections of a machine-formed calendered newsprint sheet made from 100% softwood TMP; the section plane in each micrograph is in the machine direction. In Figure 10A, it is easy to visualize frictional forces gripping the sur-

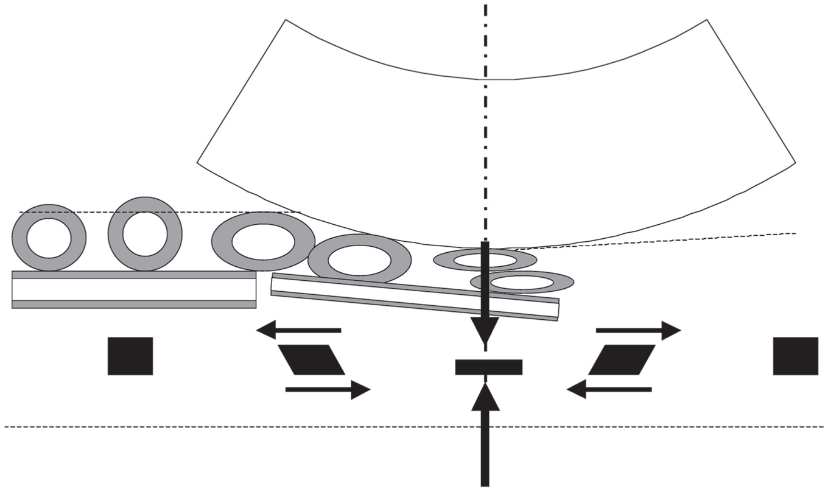

Figure 8 Compressive and shearing forces acting within a sheet in a soft nip, not to scale.

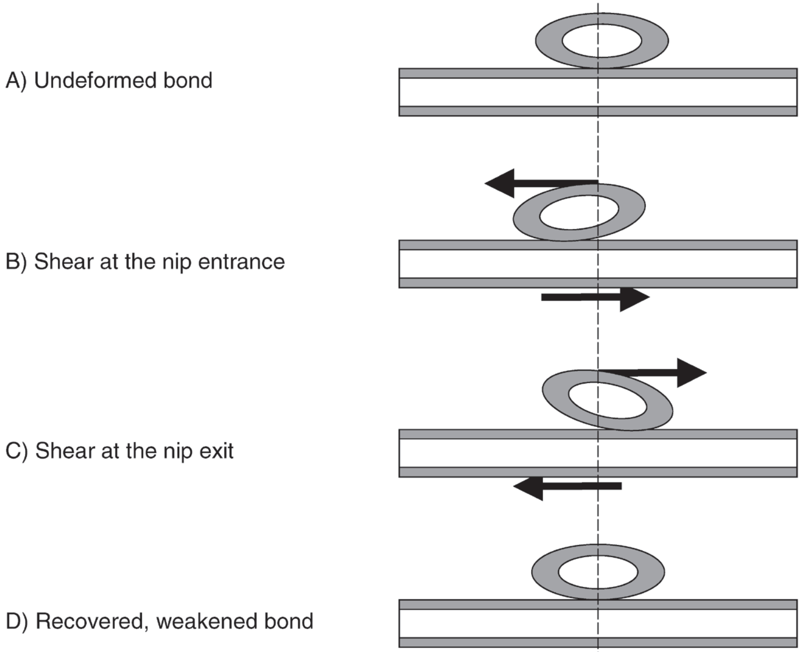

Figure 9 Shearing forces acting on an inter-fibre bond in a soft nip.

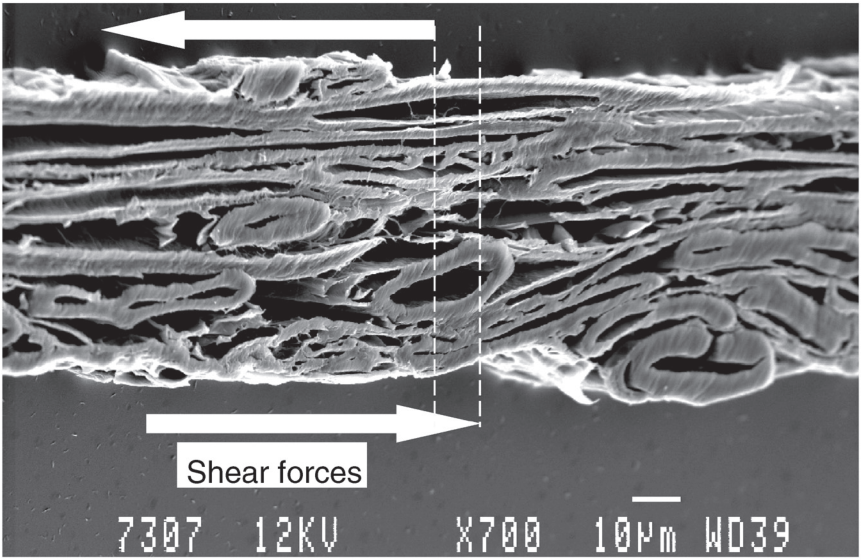

Figure 10A Micrograph of a machine-formed, calendered standard newsprint sheet made from 100% softwood TMP. The section plane is in the machine direction. The arrows indicate the direction of the shear forces applied at the ingoing side of a nip; at the nip centreline the shear forces become zero, then reverse direction on the outgoing side. The total shear deformation could be as large as several micrometres, depending on the shear modulus of the sheet and the applied load; the dashed lines indicate a shear deformation of 10 µm.

faces of the fibre network, then stretching it first left, then right as the sheet makes its way through the nip. Shear forces leading to a shear-deformation of 10 µm are illustrated; a deformation of this magnitude would be sufficient to rock the fibre at the centre of the photo to either side as it passes through the nip.

In Figure 10B, there is a large coarse fibre, slightly to the left of centre, with fractures in the wall of the type which would be expected from excessive compressive loading. In Figure 10C, a large fibre lying on the surface also exhibits fractures.

Johnson shows that the shearing forces acting between two rolls with dissimilar elastic properties are made up of two components. The first arises from Hertz theory, and exists when the rolls have identical properties, or, if the rolls are dissimilar, in the absence of friction. In the case of identical elastic properties, the tangential or machine direction deformation of the two rolls are identical. With dissimilar rolls, the deformations will be different; in the absence of friction, the two rolls will slip and there will be no additional shear force at the contact area.

The second component of the shearing force arises between dissimilar rolls when friction is high enough to prevent slip. Due to different elastic properties, each roll wants to deform a different amount under the same loading; the presence of a large enough static coefficient of friction constrains the deformations to be identical, leading to an additional shear loading.

The exact behaviour will depend on the material properties of the cover, such as elastic and shear moduli, Poisson's ratio, frictional coefficients at both interfaces and the strength of the viscoelastic response, as well as on the geometry of the roll, especially the depth of the cover. The behaviour of the sheet in the nip will also influence the shearing forces. If the sheet cannot support large shearing forces (i.e., if it has a very low shear modulus compared to the shear moduli of the rolls), it does not inhibit tangential roll deformation due to Hertz theory and can therefore be thought of as a lubricant between the two rolls.

When a deformable cylinder rolls in contact with an essentially undeformable roll, the angular distance through which it rotates is that of an

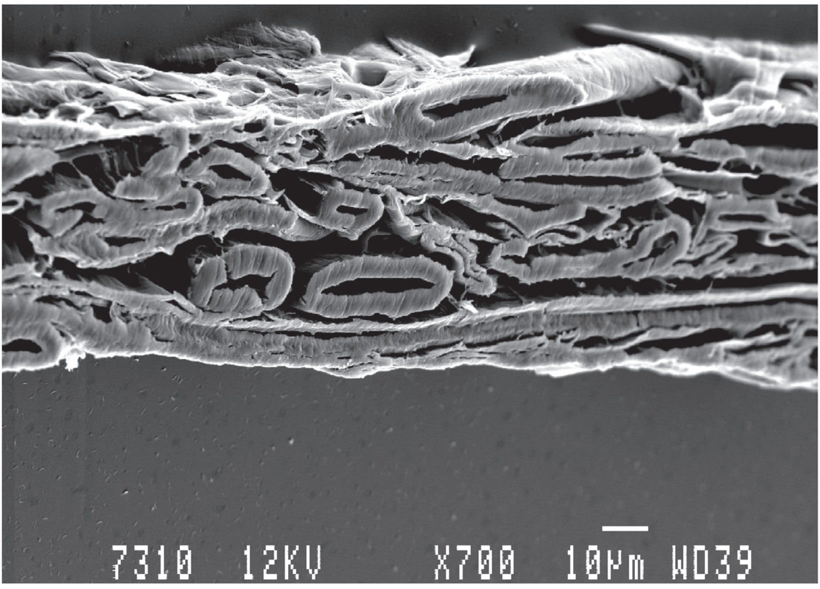

Figure 10B Same sample as in Figure 10A. A coarse fibre in the body of the sheet (centre left) exhibits fractures of the internal wall in a location consistent with tensile failure under a compressive load.

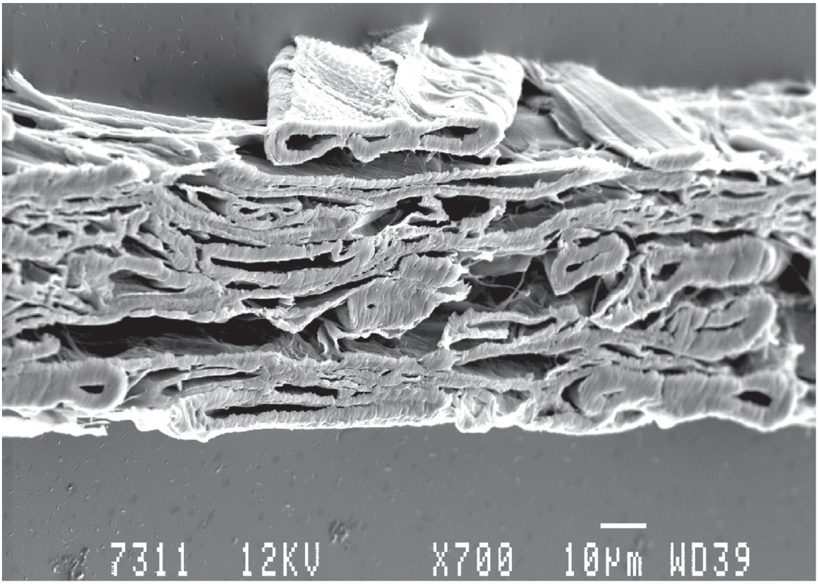

Figure 10C Same sample as in Figure 10A. A large mechanical pulp fibre lies on the surface in the CD, and is more or less well bonded to similar fibres lying in the CD in the body of the sheet. This fibre also exhibits fractures of the internal wall.

undeformable roll of somewhat different circumference. In each revolution, the roll appears to move forward a distance which is greater (or less) than its undeformed circumference by an amount known as the creep ratio, which can in turn be used as an estimate of the magnitude of the relative displacement of the two surfaces of the sheet. Johnson [28] presents equations for the creep ratio ξ_x for the two extreme cases of no slip and unrestricted slip between two elastic rolls. In the case of no slip,

$$\xi_x = \frac{2\beta a}{\pi R} \tag{6}$$

where $1/R = 1/R_1 + 1/R_2$, R_1 and R_2 are the roll radii, a is the ingoing nip length and β is a function of the shear modulus G and poisson's ratio v of the two rolls:

$$\beta = \frac{1}{2}\frac{\left(\frac{1-2v_1}{G_1}\right) - \left(\frac{1-2v_2}{G_2}\right)}{\left(\frac{1-v_1}{G_1}\right) + \left(\frac{1-v_2}{G_2}\right)} \tag{7}$$

Note that β, which is a function only of elastic properties of the two rolls, is 0 for identical roll properties. In the case of unrestrained slip,

$$\xi x = \frac{0.914\beta a}{R} \tag{8}$$

If the soft cover is characterized by a low shear modulus and a high Poisson's ratio, the soft roll tends to flow out of the nip, lengthening the nip and leading to shear stresses on the soft roll cover acting outwards from the nip centreline. In this case, β and the creep ratio are positive. In the case of a material with a high shear modulus and low Poisson's ratio, the nip is shortened and the shear stresses act inwards on the roll cover. The result is that β and the creep ratio is negative, and the loading on the sheet is the opposite of what is shown in Figure 5: the sheet is loaded first in compression, then in tension. Figure 11 illustrates the two different modes of deformation, and Table 2 presents numerical values of β and ξ_x for two sets of soft roll properties.

A large number of authors have supported or extended the analysis of Johnson, who provides an extensive list of references. References [29–38] are a selection from the literature on the mechanics of rolling contact published since Johnson's work was completed. In particular, Soong and Li [29,30] analyzed a pair of soft roll covers pressing a thin, incompressible sheet in a

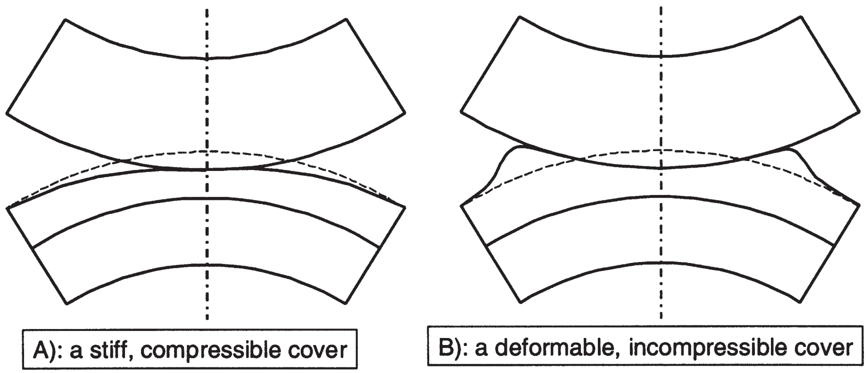

Figure 11 Deformation of a soft roll, not to scale. The dashed line is the undeformed roll surface. **A)**: low Poisson's ratio, high shear modulus. The volume of soft material is reduced in the nip, and the nip is shortened. **B)**: high Poisson's ratio, low shear modulus. Material is extruded from the nip, total roll cover volume is maintained, and the nip is stretched.

Table 2 Creep ratios in a soft nip made of elastic rolls, Equations 6 to 8, for two different soft rolls pressed against a steel roll. Depending on the sign of the parameter β, which is a function only of the elastic properties of the two rolls, the relative tangential deformation of the soft roll at the ingoing side of the nip may be positive (tensile) or negative (compressive).

Soft Roll			
Poisson's rato υ_1	0.05	0.45	
Shear modulus G_1	300	80	MPa
Radius R_1	0.5	0.5	m
Deformation δ	50	50	μm
Hard Roll			
Poisson's υ_2	0.27	0.27	
Shear modulus G_2	80	80	GPa
Radius R_2	0.5	0.5	m
Calculated data			
Ingoing nip length a	5	5	mm
β	–0.112	0.090	
Creep ratio ξ_X, no slip	–0.00142	0.00115	
Creep ratio ξ_X, full slip	–0.00205	0.00165	
Relative deformation $a\xi_X$	–7.12 to –10.22	5.75 to 8.26	μm

nip. This work also dealt explicitly with the phenomenon of both sliding and static friction, although shear loading within the sheet is not treated. The analysis was extended in [30] to include the effect of sheet tension on shear deformation of the soft cover; conditions for slippage were presented. The authors devised a numerical method for estimating the compressive and shear stresses present at each point; if at any point the calculated shear stress is greater than the product of the frictional coefficient and the compressive stress, slip is assumed and the stress conditions are recalculated for that point. In the numerical examples presented in [29], the nip load was an order of magnitude higher than in soft calendering and several orders larger than in a hard nip, and the sheet stiffness was much larger than that of paper. Nonetheless, their analysis suggests that for an incompressible rubber roll cover with Poisson's ratio $v = 0.5$ no slip occurs when the coefficient of friction between roll and sheet exceeds about 0.3.

This finding is an interesting one. As shown by Pfeiffer [39], hard nip calendering improves smoothness and gloss by replicating the smooth surface of the roll onto the sheet, rather than by a burnishing action caused by slip between the sheet and roll. However, as shown by Johnson, the mechanics of soft nips imply that, for certain levels of compressive load and coefficient of friction, there are areas in the nip where slip may occur. This raises the possibility that at least some of the smoothing action of a soft nip is due to slip. Soong and Li's findings, combined with the observation that a dull, matte hard roll in a supercalender makes paper with lower gloss than a freshly-ground roll with a new mirror finish, imply that no significant slip exists between the roll and sheet in a soft nip, and that for the soft calender, like the machine calender, replication of the roll surface onto the fibres, coating stock or filler on the web surface is the dominant mechanism altering the surface characteristics of the sheet, even at high shear loadings. Furthermore, it must be concluded that if the shear forces at the contact area between the sheet and roll do not lead to slip, they must result in a shearing deformation in the body of the sheet, as shown in Figures 5 to 10.

To conclude, the lack of slip between sheet and roll, combined with the potential for large tangential displacements of the soft cover relative to the hard roll in the nip, lead to the conclusion that there may be a substantial, brief and reversible shear deformation of the sheet in a soft nip. This, however, needs to be verified experimentally, and the analysis of Johnson and others needs to be extended to cover conditions typical of a paper web in a calender nip.

The shoe calender brings with it yet another level of complexity, in the form of the elastic properties of the belt or backing strip; this will not be addressed here.

In the end, it appears that there exists no analytical, empirical or numerical description of the stress or strain fields created when a thin, deformable, viscoelastic strip is pressed in a rolling nip made up of elastic or viscoelastic covers bonded to a rigid core. Such a description is an essential component of a useful model for soft-nip calendering.

Material response function

A number of rheological material response functions have been proposed to describe paper calendering [27,40–48], with mixed results.

Browne et al. [27] proposed a model with four viscoelastic elements, two elastic and two viscous, with the expectation that it would be possible to relate the two stiffnesses G_M and G_K (characterizing the elastic elements) to the stiffnesses of a typical fibre and of a typical mat, and that the ratios of the viscous elements η_i to the elastic elements would define time constants characteristic of the recovery of a fibre and a mat after compression. It was further expected that these material properties would depend on previous processing steps such as pulping process, forming and pressing, as well as web moisture content and temperature, but that they would not be functions of the applied stress or strain, or their time derivatives. However, the nature of a fibre mat turned out to be too complex to be described with such a simple model: all material properties were strong functions of processing conditions in general, and of line load in particular.

At this time there is no workable model of paper response to a short duration dynamic pulse. Most published material functions are either too simple to describe all aspects of paper behaviour [27], or require large numbers of empirical constants to make them describe adequately the observed behaviour [48]. Many were developed from data acquired at long pulse times, and do not adequately describe paper response at short pulse times, including paper recovery after the nip. None have been related to fundamental paper or fibre properties such as fibre coarseness or flexibility.

These difficulties arise because machine-made paper is a complex network of fibres deposited in a mat in a forming section. In sheets made from mechanical pulps, fibre coarseness and bending stiffness both cover a wide range; as a result, individual fibre stiffness in the z-direction is also extremely variable. Furthermore, the distribution of fibres in the mat is neither uniform nor random: in the formation process, fibres are dragged to areas of low basis weight by fluid flows, sufficiently to ensure the deposition process is non-random, but not sufficiently to ensure a perfectly uniform deposition (although this is the goal of the forming section). The result is a structured material which is very difficult to model from first principles.

As well, the response of this material to an applied pulse is a function of variables such as sheet moisture content or temperature, which act to alter its viscoelastic properties. Generally, increasing moisture content and temperature render the fibres and the structure more pliable, more easily deformed and less prone to fracture or other damage.

Web temperature and moisture content are both affected by roll temperature. Moisture content decreases from nip to nip as water is evaporated; while the rate of moisture loss is typically 0.2% moisture per nip in a hard nip, it can be as high as 1% per nip in a hot, soft nip. Heat transfer to the web was analyzed by Kerekes [49], and the properties of the sheet as the temperature changes were described by Burnside and Crotogino [50]. Kerekes analyzed heat transfer to a web in a rolling nip, in a wrap between nips and in an open draw. Dwell time in a nip at industrial speeds is short enough that very little heat makes it through to the centre of the sheet; only the surface is heated. Nonetheless, a large portion of the heat transfer to the web occurs in the nip. This finding led to the development of temperature gradient calendering [19], where the plasticized surface fibres are deformed to a greater extent than the cooler fibres in the sheet centre; the result is better surface properties with less strength or bulk reduction.

In a wrap, there is more time for heat transfer; however the side not in contact with the roll is cooled. At the end of a typical industrial wrap, there is still a temperature gradient in the sheet, although much less pronounced than the gradient applied in a nip. In an open draw, heat transfer is due to convective transfer to the still air surrounding the web. The full set of theoretical predictions were tested on a 5-nip machine calender running at industrial speeds, and were found to be in good agreement with measured temperatures once the slight decrease in moisture content through the stack was taken into account.

Burnside and Crotogino [50] then measured thermal properties of paper, such as thermal conductivity and contact coefficient, as functions of paper bulk. As bulk decreases through a calender stack, this provided insight into the effect of heating various rolls in a multi-nip stack. As bulk decreases, conductivity and contact coefficient increase, making heat transfer to the web more effective in later nips and thus altering the paper response to the applied pulse. Finally, Hamel and Dostie [51] evaluated the relative magnitude of convective, conductive and radiant heat transfer, and developed equations for convective transfer from a rotating roll in a multi-nip stack, allowing evaluation of different calendering techniques.

Moisture content also acts to increase the conformability of fibres. There is a limit to this effect, which occurs when there is sufficient water in the sheet to affect the overall compressibility of the web structure. At moisture contents in excess of 12% or 15%, the sheet becomes less deformable as free liquid water in the sheet resists deformation. The extremely high loads in areas with excessive free water can lead to defects such as blackening. However, Gratton et al. [52] showed that steam showers could be used in machine calendering to increase the compressibility of fibres, making smoother, glossier, denser sheets with less calendering effort. It was also found that the improvement in surface properties occurred only on the side to which steam had been applied.

It is thus essential that the effect of moisture content and web temperature on the paper response to a pressure pulse be a part of any rheological model of calendering.

Towards a full rheological model of calendering

In order to be useful for predicting the effect of multiple nips, the ideal material response function describing paper behaviour in a calender nip should accurately predict the nature of the thickness recovery after the nip, which is partial and time-delayed, and which may involve an instantaneous component. As well, any constants arising from the analysis should be related to physical properties of the fibre or web. It seems reasonable to expect that these material constants would be functions of behaviour-modifying properties such as sheet moisture content or temperature, which alter how the sheet behaves by making fibres and webs more or less pliable or ductile, but not that they should be functions of stress, strain or their time derivatives. (The same holds true of coating formulations and fillers used in value-added grades.)

Furthermore, parameters for any physical model of calendering must be obtained from experimental work which adequately duplicates the short dwell time of a calender nip. The viscoelastic behaviour of a material will be most obvious over a relatively narrow range of treatment or processing times; at other time scales the material may appear either viscous or elastic. The Deborah number, the ratio of a response time typical of a material and a time typical of the process, is a non-dimensional number which provides a useful guide to the strength of the viscoelastic response. Defining τ to be a generic material response time, such as a strain recovery or stress relaxation time, the Deborah number ξ for paper in a calender nip is defined by

$$\xi = \frac{\tau}{a/V} \tag{9}$$

where the ingoing nip dwell time a/V describes the order of magnitude of the processing time. As described next, there are two different interpretations of the Deborah number, depending on the nature of the response time τ. In either case viscoelastic behaviour is most obvious when ξ is of order 1.

The response time τ in Equation 9 could be a strain recovery time, which is the time constant governing strain recovery after removal of a load. When this strain recovery time is long compared to the processing time a/V (resulting in a large Deborah number), the material behaviour appears viscous or plastic since no apparent recovery occurs until many processing times have elapsed after removal of a load. Similarly, a recovery time significantly shorter than the processing time leads to apparently elastic behaviour since the strain recovery occurs immediately on removal of a load.

Alternatively, the response time could be a stress relaxation time, which describes the reduction in stress experienced by a material subjected to a fixed strain. When τ is a stress relaxation time, and is much larger than a/V, ξ is much larger than 1 and the material appears elastic since relaxation of the applied stress does not begin to occur in the short time the load is applied. If the stress relaxation time is very short compared to a/V, ξ is much smaller than 1 and the material appears viscous since there is little residual stress in the material when the load is removed.

Only when the magnitudes of the material response and processing times are similar does viscoelastic behaviour become obvious. As pointed out by May et al. [53], material behaviour in a rolling nip will be viscoelastic for a given material time τ, whether stress relaxation or strain recovery, if the Deborah number $V\tau/a$ is of order 1. They showed that the parabolic stress profile expected when a purely elastic material is pressed in a rolling nip is skewed to the ingoing side of the nip as the material becomes viscoelastic; the amount of skew would reach a maximum at $\xi = 2$, reflecting the fact that the ratio a/V describes only the ingoing portion of the symmetric parabolic pressure pulse.

Experimental results show that paper behaviour is viscoelastic. Keller [54] measured pressure profiles in a soft nip typical of industrial practice. With no paper in the nip, the profile had the approximately parabolic shape characteristic of an elastic material, implying the cover material was not viscoelastic. With paper in the nip, however, the profiles clearly show the strongly skewed parabolic shape typical of a viscoelastic material. As well, Browne et al. [26] found values of strain recovery times τ ranging from 10 to 30 ms at a sheet speed of 930 m/min, decreasing with increasing speed; given a/V of the order of 300 to 500 μs, ξ is in the range 20 to 100, also decreasing as speed increases. The viscoelastic behaviour of the strain recovery after calendering is thus likely to be more pronounced as machine speeds are increased; this is unaffected by the presence of a soft nip.

The behaviour of paper in an industrial calender nip is thus certainly viscoelastic, both in stress relaxation and in strain recovery, and any experimental effort aimed at deriving model parameters needs to take this fact into account, since this viscoelastic behaviour may not be evident when the processing time in the experimental apparatus is sufficiently different from that in a calender nip.

Models built using large amounts of computer power to assemble a sheet from a statistically valid range of fibres in a manner which accurately replicates the forming process may eventually produce a useful model. Such work is presently underway [55], but whether such a model can be a workable solution without excessive complexity remains to be seen. Jorge Luis Borges [56], an Argentine author of surrealist fiction, once wrote of a society where geographers were obsessed with producing maps showing finer and finer levels of detail, at larger and larger scales; the logical end result, the creation of which proved to be the downfall of geography in that society, was an exact map showing every grain of sand in their entire empire at a scale of 1:1. The question can be asked whether a computer model of the billions of fibres in a sheet represents an excessive level of detail.

In the meantime empirical models, discussed next, describe machine calendering well enough for engineering purposes.

EMPIRICAL MODEL OF MACHINE CALENDERING: THE CALENDERING EQUATION

While a complete and industrially-useful rheological model of paper calendering does not presently exist, an empirical design guide for machine calenders, the calendering equation, is available. This development has been presented by Crotogino [4], and will be summarized here.

Briefly, Chapman and Peel [57] and Colley and Peel [58] described the relationship between operating parameters in a platen press, such as dwell time and mean pressure, and paper response properties such as permanent thickness reduction. This relationship was revised by Kerekes [59,60], based on work by May et al. [53], so that the calendering parameters web speed and nip load could be used to predict thickness reduction instead of dwell time and pressure. Crotogino [61] extended Kerekes' work to multiple nips so that it can be used to predict the thickness reduction in successive nips of a calender. The resulting calendering equation can be written

$$\varepsilon = \frac{B_f - B_i}{B_i} = A + \mu B_i \tag{10}$$

where B_i is the bulk of the paper entering the nip, B_f is the bulk of the paper leaving the nip, A is a constant, and μ is the nip intensity:

$$\mu = a_0 + a_L \log L + a_S \log S + a_R \log R + a_\theta \theta + a_M M \tag{11}$$

Here, a_0 is an intercept and a_L, a_S, a_R, a_θ, a_M are constants describing the relative importance of the variables line load L (in kN/m), web speed S (in m/min), equivalent roll radius R, sheet temperature and moisture content M. Equations 10 and 11 are bounded by two limits:

$$\frac{-A}{\mu} \leq B_i \leq \frac{(1-A)}{2\mu} \tag{12}$$

The lower limit represents the point below which no further bulk reduction is possible unless the nip intensity is increased. In this region,

$$B_f = B_i \ when \ B_i \leq \frac{-A}{\mu} \tag{13}$$

This limit is frequently encountered at the top of a second stack, where the nip intensity μ is lower than that already applied to the paper in the bottom nip of the first stack.

The upper limit states that for any value of nip intensity μ, there is a limit above which increases in the initial bulk no longer have an effect on the bulk leaving the nip. In this region,

$$B_f = \frac{(1-A)^2}{4\mu} B_i \quad \text{when} \quad B_i \geq \frac{1-A}{2\mu} \tag{14}$$

While the calendering equation is an empirical relation whose limits are artefacts of the original choice of Equation 11 as a basis for curve-fitting, it nonetheless accounts for all of the important calendering process variables, and describes well the operation of industrial machine calenders [62]. Furthermore, laboratory calendering measurements using uncalendered, machine-made paper have been successfully used to predict the operation of full-size calenders treating the same paper. This led to the development of a design procedure for industrial calenders using mill measurements, laboratory calendering measurements and the calendering Equation [13].

The calendering equation was next used as the basis for a comprehensive model for CD caliper control. Pelletier [63] and Journeaux [64] had modelled local roll deformation due to heating by profiling air jets. Changes in the CD nip shape could now be predicted. In order to predict the effect of a given CD nip shape on local nip load (and thus on local in-nip and permanent strain), Browne [25] measured paper thickness in the nip of an experimental calender. Although the face width was only 75 mm, this calender had realistic roll diameters and could be operated at typical industrial speeds and loads. The calender was instrumented with displacement sensors measuring roll separation and thus thickness of the paper in the nip. This work showed that the relationship between in-nip and permanent strain could be described using a logarithmic fit:

$$\varepsilon_n = c_0 + c_1 \log \varepsilon_p \tag{15}$$

where ε_p is the permanent recovered strain as defined in Equation 10, and c_0, c_1 are constants. Furthermore, when only strains of industrial relevance are considered, a linear fit to the data was statistically no worse than the logarithmic expression in Equation 15:

$$\varepsilon_n = \varepsilon_0 + m\varepsilon_p \tag{16}$$

where ε_o is an intercept and m a slope whose value, for standard newsprint grades made of mechanical pulp fibres, was about 0.75.

Browne examined only the effects of nip load, speed and roll radius. Kawka [65] extended this work to include the effects of paper moisture and temperature, and showed how the work of Pelletier, Journeaux and Browne could be combined in a model-predictive control system for CD calender profiles [66]. This body of work, combined with the understanding of heat transfer rates to paper from a nip or a wrap and the effect of heating the sheet on paper response, as outlined in the work of Kerekes and subsequent authors [17–19,49–52], has led to a complete set of empirical design tools for selecting and controlling hard-nip machine calenders.

Empirical models: what's missing

There are, however, limitations to the calendering equation. After the paper leaves the nip of a calender, there is time-dependent partial recovery of the initial thickness [27]. Figure 12 illustrates this with data from [67], where strain normalized by the in-nip strain is plotted against Vt/a, the non-dimensional dwell time defined in Equation 2. The dotted line crossing the time axis at $Vt/a = 2$ is the parabola defined by Equation 2; strain recovery after the nip would follow this line in the case of a perfectly elastic material exhibiting immediate and complete strain recovery upon removal of the load. Thickness measurements made online as the sheet exited the nip at 552 m/min showed only partial recovery at a distance 300 mm after the nip ($Vt/a \cong 100$), and essentially complete recovery 1 m after the nip ($Vt/a \cong 330$). Measurements at $Vt/a \cong 10^8$ were made after conditioning for 24 hours. The solid lines are the result of curve fitting, and are characterized by values of r^2 in the range of 0.65 to 0.75; nonetheless the data implies that contact between paper and rolls ceases very soon after the centreline of an industrial nip as the paper fails to recover quickly enough.

Paper behaviour is thus viscoelastic; Figure 12 shows that recovery depends on the calendering conditions. When measuring the coefficients of the calendering equation, the paper thickness is measured a considerable time after the paper has been calendered, at a normalized time $Vt/a \cong 10^6$ ($t = 5$ minutes). This time delay is much longer than the time between the nips of a calender stack, typically of the order of $Vt/a \cong 200$ ($t = 50$ ms). The predictions of bulk reduction in using the calendering equation will thus be a little on the low side: the predicted final bulk will be greater than the actual final bulk. This has mainly been a problem in twin stacks, where the first few nips in the second stack have nip intensities lower than those already applied to the paper at the bottom of the first stack [62].

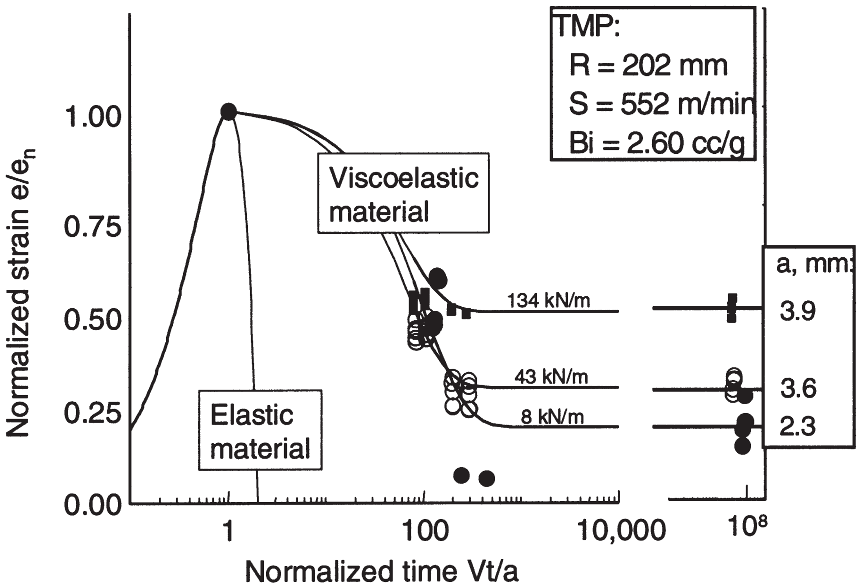

Figure 12 Thickness recovery after a calender nip. The parabola with vertex at [1,1] and crossing the x-axis at $Vt/a = 0{,}2$ describes a perfectly elastic material with complete, instantaneous thickness recovery.

Variations of nip load, roll radius, paper temperature and paper moisture across the width of a commercial calender will also introduce errors. However, the effects of CD non-uniformity will result in reduced calendering effectiveness and a somewhat higher bulk than one might predict from a very accurate version of the calendering equation. Hence the errors in the prediction introduced by the poor estimate of thickness recovery and the errors introduced by poor CD profiles in commercial calenders will compensate each other to some extent.

A further shortcoming of the calendering equation, in common with rheological models discussed previously, is the lack of any relationship between its coefficients and other measurable paper or fibre furnish properties. The coefficients need to be determined experimentally for each different furnish, and this process needs to be repeated when furnish properties or wet-end conditions such as formation, retention or fines content change sufficiently.

Finally, there exists no comparable design tool for soft-nip calenders. As the CD caliper of paper leaving a soft nip is more variable than in a hard nip, the winding of such papers is considerably more difficult. To a large extent, the soft calender cannot be used to correct CD basis weight or density variations arising earlier in the paper-making process as effectively as a hard nip, and this fact must be borne in mind when trouble-shooting winder problems. Better control systems for soft nips would undoubtedly lead to improved paper performance in winders.

FUTURE WORK

There exists a complete set of engineering tools, based on a mix of empirical and theoretical work, for the design, control and trouble-shooting of machine calenders [13,15,17,49–51,66]. These tools, while adequate for engineering purposes, are not generally based on physical properties of fibres or webs, and so cannot be used to evaluate or select the best calendering conditions for new pulp types or products. Pilot scale work remains essential in predicting how best to calender a new furnish or paper product, or how to achieve a given level of printing quality. Relating the coefficients of the calendering equation to underlying physical properties of fibres and webs, or developing new engineering tools based on an understanding of these properties, remains a challenge.

Some of the properties which need to be considered are elastic properties of fibre walls as well as axial, tensile and bending stiffnesses of whole fibres, including time constants governing the deformation and recovery of initial fibre and web dimensions following application of a compressive pulse. The effect of temperature and moisture content on these variables also needs to be understood. Permanent deformation mechanisms, ranging from permanent deformation of a fibre or web to fibre fracture or bond failure, all need to be considered.

No similar set of tools exists for soft-nip calenders. Among the challenges are the fact that absolute roll deformations are of similar magnitude to web deformations. In machine calendering, the elastic modulus of the hard roll surface is several orders of magnitude higher than that of the sheet, and roll deformation can conveniently be ignored when modelling the process; this is no longer the case in soft nips. As well, the soft cover may have viscoelastic properties which may have to be considered, although it is possible that the viscoelastic behaviour of the web dominates, and that treating the roll cover as an elastic, deformable solid may be adequate.

A soft nip is also longer than a hard nip; this allows the use of higher line loads without peak pressures becoming excessive. As the viscoelastic behaviour of paper is strongly time-dependent, the change in nip dwell time will have an effect on paper response.

Nip mechanics imply that the potential for slippage exists in a soft nip; where the slippage occurs, and what is its effect on paper strength and surface properties, remain unanswered questions. Slippage may occur between the paper web and one of the two roll surfaces, or within the body of the sheet, depending on the relative magnitude of the two friction coefficients and the in-plane paper shear modulus. The evidence considered here suggests that typical conditions in a calender nip do not lead to slip between roll and sheet, implying that there must be a cyclical shearing deformation of the web as it traverses the nip. The effects of soft calendering conditions on the development of surface properties and printing properties also remains a mystery. The replication of the roll surface onto the sheet arising in the absence of slip must also be a function of the sheet properties, such as fibre source, pulping and bleaching processes, forming, pressing and drying conditions, as well as the type and weight of coating or fillers used.

Any eventual calendering equation for soft nips must explain all of these factors. Perhaps the ever-growing power of our computing facilities will allow us to model paper webs in sufficient detail to address how paper structure, surface properties and performance are affected by the processing conditions in calender nips [55].

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Transcription of Discussion

FUTURE DIRECTIONS IN CALENDERING RESEARCH

T.C. Browne and R.H. Crotogino

Paprican

Additional reference presented;

Stenberg et al. (*JPPS*, **27** (6): 213–221) performed shear loading experiments on a variety of sheets and found, among other things, that a shear strain of 2.5% could be applied in the MD with a shear stress as low as 2.5 MPa, and that the MD shear modulus could be as low as 14 MPa, a very small amount when compared with shear moduli of materials typically used to manufacture calender rolls.

Vincent Craig Australian National University

You address the question of whether slip or distortion is happening in the nip, and you disregard the idea of slip because of the lack of a burnishing effect. If you look at visco-elastic polymers when they've been extruded, when there is slip at the extrusion die, it leads to a roughening of the surface, known as a shark-skin, of course, you can get a stick-slip effect. Could this be possible in this case, and maybe you've disregarded slip prematurely?

Tom Browne

I don't believe that there is stick-slip. First of all, its a very narrow region that the ingoing edge and the outgoing edge where you can get slip – it would only occur over a very small portion of the nip, so if you had a stick-slip, stick-slip, you would probably only get one or two cycles of it. The other thing is that it is not a continuum, the polymers are a continuous material and they behave quite differently. The fibres can move a little and get gripped by the roll and move around a little bit at the surface, before they actually have to begin to slip.

Discussion

Hannu Paulapuro Helsinki University of Technology

Calender blackening has sometimes been a very serious problem especially with wood containing magazine papers. Can you see any good means to avoid this in the future when the requirements for smoothness and gloss still increase?

Tom Browne

Blackening is an area where the density has exceeded the density of cellulose, and we've begun to extrude the cellulose into a glassy blob, so really the problem is in the forming section. Calendering can only fix so much. I know this sounds like blaming the guy before you, as the papermakers blame the pulping and so on, but in fact there is only so much you can do if you are given lousy furnish or a lousy formation.

Vinicius Lobosco STFI

I took a look at your mechanical analogue model of the sheet deformation where you were trying to connect this with physical properties of the sheet. I'm a little skeptical to that because if you have a dashpot in series, this means that if you have an infinite compression at the end, you will have negative thickness. I don't expect that you ever succeed with this – why don't you try with just the friction element?

Tom Browne

With the single dashpot, you obviously have to state that the deformation will be brief; it is obvious it will not be negative – there will be a small amount of permanent deformation that then carries through and doesn't get recovered, the problem with the frictional element is that there is a certain amount of force required to overcome the initial friction and then it slips. I like the idea that you could compress it easily and carry it through and I believe that mathematically it is easier to deal with a dashpot than a coulomb frictional element. In any case, it didn't work.

Derek Page Institute of Paper Science & Technology

Your paper is entitled "Future directions for research" or something like that and I'd like your comment on this as a possible worthwhile direction. The question of the effect of calendering on strength properties needs addressing.

If you look through the literature you'll find that people who have calendered at relatively low moisture contents show that the strength drops. People who have calendered at high moisture contents show that the strength rises. The reason for the rise in strength at high moisture content is presumably due to extra bonding. In the literature there are comments that the reason why the strength drops if it is dry is that you destroy the bonding. Now it has always seemed odd to me that you could destroy bonding by pressing fibres closer together. On the other hand, you have shown that under extremely dry conditions, you do appear to damage fibres. Now we can test from our knowledge of paper physics the difference between sheets that have been weakened by fibre strength reduction and sheets that have been weakened by bond strength reduction. I would like to know what your feeling is about that being a future direction for research.

Tom Browne

It is an obvious direction for future research; I was looking at it from the more industrial point of view of what the guys in the mill need today? They need a calendering equation for soft nips, because the guy that is running the soft nip calender, when he is told that the machine speed will be increased next month, he needs to know what to do to his calender to keep the properties. It makes a lot of sense to do fundamental research on the mechanism of shear weakening in a calender.

Ilkka Kartovaara Stora Enso Oy

I have a comment that also refers mostly to the future directions in calendering. The modeling of calendering has very much been focused on the density and caliper, while actually from a paper quality point of view, the caliper and density changes with a little exaggeration and undesirable side-effect. It is not what we are looking for in calendering. The main effect that we are looking for is the replication of the very smooth roll surface to the paper surface. When we start calendering research, maybe we should focus more on understanding replication phenomenon, and try to model it from maybe fibre point of view.

Tom Browne

I guess with coated papers and filled papers it becomes an even greater issue because you have more opportunity for replicating onto a surface that is more continuous.

John Parker Consultant

I wonder if you have noticed your diagram which showed PPS roughness plotted against bulk [not in preprint], that when the bulk becomes equal to that of cellulose, the roughness becomes zero?

Tom Browne

Good point. I don't believe I've ever calendered sheets to that final density.

John Peel Retired

There is an intriguing comment in your paper, following the discussion of the visco-elastic nature of paper. You say that after, the centre of the nip, paper is quite often likely to be not in contact with the roll. I've never thought of that before, but that reduces the contact time even more, which is the biggest problem we've got now with high speed operations. I'm wondering if you'd like to make a comment on the future of extended nip type calenders, which I've thought would be the answer for LWC, although engineering wise it would be very difficult now.

Tom Browne

If we can lengthen the nip and put the load in more gently, that would be good – it is possible to go to much higher loads in a soft nip and that's because the nip is longer and the peak pressures are not so high. This was the advantage in moving from a hard nip, which is a very short, intense nip to spreading the load over a larger area. If we could spread the load over yet a larger area, that would certainly be good. As you point out, there are some serious problems with engineering of these extended nip calenders. Another point is that as the sheet speed is increased and if this recovery is fairly long, as you go to the second nip, you may not have completely recovered from the first one, so this is another issue of these calendering equations where you work your way down the stack and calculating the final bulk out of each nip, but if the ingoing bulk is not what you think it is, in other words if the recovery has not been complete from the preceding one, you are going to wind up with accumulative error by the time you get to the bottom.

Pekka Mauranen KCL

The industrial expertise shows that the calendering moisture has a strong influence on the mechanical properties of paper. What about the observation that usually hard nip calendering seems to reduce mechanical properties more than soft nip calendering due to the fibre weakening, or weakening of the bonds. This could be studied by studying *z*-direction strength. Do you have any data or idea about that, because usually we speak about tear or tensile?

Tom Browne

I think that in the soft nip the pressures are not as high, the line load maybe higher but because the nip is so much longer, that load is spread over a greater area. So I believe that we are not breaking fibres as much as we are in a hard nip where we have a much shorter, sharper impulse. The *z*-direction strength of the sheet would be one way of testing bond failure as opposed to sheet cracking or fibre cracking.