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RECENT DEVELOPMENTS IN THE TECHNOLOGY AND UNDERSTANDING OF THE CALENDERING PROCESSES

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Recent developments in industrial practice are briefly reviewed and then improvements of our understanding of calendering are reviewed under the headings: the assessment of surface properties, the compressibility of paper, the effects of calendering variables on paper properties (for hard (iron) roll calendering, soft roll calendering and temperature or moisture gradient calendering, and the effect of calendering on paper strength) and rolling contact phenomena. The Concluding Comments list the implications of these industrial and scientific developments for future technical development and research into the calendering processes.

The last 8-9 years have seen further expansions and rationalisations within the paper industry so it is not surprising to read regular reports of new finishing lines on new or modernised machines. Particularly noticeable, however, have been the numerous installations of new supercalenders for LWC grades and the development of competing uncoated filled mechanical printing grades, also supercalendered. Also, there is a trend for makers of standard machine calendered newsprint to produce higher quality mechanical printing grades which require a supercalender finish.

These developments have increased the already considerable interest in the possibility of reducing the costs of supercalendering compared in detail by Muller & Schmidt with machine calendering and with on-line soft roll calendering, using an 8 roll machine (1). Although the analysis needs to be updated in the light of experience with modern 2 x 2 roll tandem soft calenders, not then in service, the relative importance of running costs, capital investment and production losses through down time are carefully compared. Supercalendering of newsprint produced at 1000 m/min was estimated to cost DM16/ton compared with about DM4 for conventional machine calendering, before down time losses adjust them to DM25 and 27 respectively. (At that time, the on-line alternative was apparently far more expensive). The higher selling price of the supercalendered paper was not allowed for.

Since 1980, there has been a rapid application of on-line soft roll calendering, in place of the conventional machine calendering with hard (iron) rolls. Excluding the gloss calenders developed about 1962, there are probably nearly two hundred installations, which, it may be said, give a supercalender type finish to papers which were usually not finished that way, or which were lightly supercalendered. Obviously, there has been considerable interest in seeing how far this on-line process can go to produce conventional supercalender grades.

Before reviewing the scientific developments in these operations, it is useful to review briefly the practical improvements which have been made since about the time of the review by Peel, Kerekes and Baumgarten (2).

1. DEVELOPMENTS IN INDUSTRIAL PRACTICE

The name "calender" is used here to include all the continuous web smoothing and gloss generating machines, which can be grouped either as "on-line", that is in series with and running at the same speed as the paper machine or coater, or "off-machine", like the conventional supercalender. They can also be grouped as "hard roll", that is with only chilled iron or hardened steel rolls, or "soft roll", that is with combinations of hard rolls and soft rolls or just soft rolls. Soft rolls may be of conventional materials, compressed cotton or cotton/wool, or compressed synthetic fibres, all on normal supercalender filled roll shafts, or they may be of elastomeric covers on steel shells. Brush calenders are in a separate category (3,4).

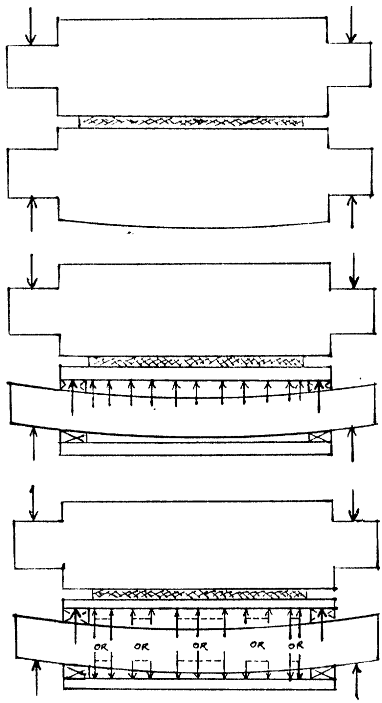
The developments considered here are those which are now almost standard on modern machines and which are relevant to paper properties.

1.1 Control of line load

This is the most effective operating variable and, in order to be able to vary it and also to keep its cross direction (CD) profile under control, sophisticated engineering has been required. There are two common sources of non-uniformity which must both be allowed for in the line load level and profile if a uniform paper quality and reel are to be produced. These are: (1) an incoming paper web which has distinctly non-uniform properties in the CD, e.g. in grammage or moisture and (2) the tendency of the rolls to deflect as beams supported at their ends under loads applied across their faces.

The first type of non-uniformity should not really be presented to a calender. Nevertheless, thickness can usually be controlled to build a reel well enough (see section 1.2) but, of course, the non-uniformities will still be there as smoothness, gloss or density variations, for example.

The deflection problem (Figure 1a) has probably now been finally solved. The ordinary swimming roll, introduced in 1960, applies a controllable but uniform hydrostatic pressure to half of the inner surface of the load bearing shell (Figure 1b). If the correct pressure is applied, it greatly reduces the variation in line load applied to the paper, across the machine, which results from the deflections of the rolls. These result from loads applied at the journals (hydraulic or dead weights of bearings, etc.), from the CD reaction forces and, in the case of internally loaded variable crown rolls, from the internally applied loads. The importance of these various loads depend greatly on their sizes and the machine width.



1a. Crowned roll with complex calculation of shape, which gives a uniform CD profile of line load at only one average value (refs. 116, 117, 118)

1b. Swimming roll with shell supported by a controllable but constant hydraulic pressure. Such support and overhung loading can give CD profiles of line load which are nearly (often sufficiently) uniform but not exactly so (ref. 5)

1c. Controlled crown rolls which use hydraulic elements grouped in zones (here in 5 groups) can give virtually uniform CD profiles of line load, particularly if thrusts may be directed either upwards or downwards as indicated (ref. 6, 7)

Fig 1 Solutions to the problem of the deflection of loaded calender rolls

It may be shown that such uniform CD internal pressures cannot produce exactly uniform CD line loads on the paper, unless two such rolls are in contact. So-called W or M profiles are produced (5) (Figure 1b).

This imperfection is often unimportant and smaller than other sources of variation. However, in other cases, it is important, for example in wide and heavily loaded machines and in supercalender stacks, which have large overhanging loads applied through journals from bearings, etc. In these machines, it is usually necessary to have a zone controlled variable crown roll as the bottom roll, with which the anti-deflection support to the shell may be varied across the machine. This type of roll uses numerous loading elements across the machine instead of a single chamber of hydraulic oil (Fig 1c). Control is assisted if "self-loading" rolls are used. Then, the load normally applied at the journals is now applied internally by the same elements. The design must then permit the vertical movement of the shell with respect to the shaft.

Sometimes it is necessary to direct the "support" away from the shell to obtain a satisfactory profile (Fig 1c)(6,7). Direct support of overhung weights has been found to be an improvement in supercalenders (8,9).

Periodic, high frequency (70-800Hz) variation of line load gives rise to barring with hard roll calenders, hardly ever with supercalenders and occasionally with soft roll machine calenders. One cause is resonant vibration of the stack which is not damped down because energy is continuously supplied as new paper is pulled through the stack. The frequencies observed reflect the masses of rolls and the resilience of the paper and do not necessarily relate to integral relations between roll diameters and wave lengths. However, substantial vibrations can lead to corrugations or wear patterns, which would so relate, and become another source of barring (10,11,12).

In a different technology, some similar results have been found. Wear or plastic deformations, the result of resonant vibrations, were considered to be the cause of corrugations formed in copper and aluminium discs in contact with steel (13), but a different mechanism - creep - was thought to be the cause of corrugations in railway tracks (14).

1.2 Other CD controls

The surface temperatures of iron rolls can be maintained at about ± 1.5°C by circulating water, steam or oil before allowing for the effects of non-uniform paper. The temperatures used vary from about 50°C to 160°C when heated in this way. There is probably an upper limit of about 180°C for internally heated rolls running at usual machine speeds, imposed by permitted thermoelastic stresses within the metal, and external heating will be necessary if higher temperatures are required.

For the control of local variations of surface temperature, and hence line load, several devices are now employed and are reviewed or described, for example, by Henry (15) and by Crotogino and Gendron (16). Induction profilers are reported now to give 2σ thickness variations as low as 0,3 μm, when 1.3 - 2.5 μm were obtained previously, with 40°-60°C temperature differentials(17). They are also effective on supercalenders.(18)

It is interesting to note that the supercalendering of coated paper scarcely changed the relative thickness variations, whose coefficient of variation remained about 2.5-4% (21,77). This was so for their machine, cross and residual components, but the absolute values were lower, of course. This was attributed to the variability of the base paper, whose grammage variability (2.2-3.0%) was much higher than that of the coated paper (1.3-1.6% before and 1.0% after supercalendering).

Control of web temperature, locally or overall, is possible with new designs of steam showers for use with calenders. The steam heats the paper 20-30°C mainly by condensation and hence moistens it too (0,5-2%)(19).

1.3 Roll temperatures

There are unpublished reports of the use of much higher temperatures than usual, say well over 100°C, in machine calenders to achieve the advantages of temperature gradient calendering (20), discussed later, and also in soft roll calenders to achieve particularly high finish with coated grades, as implied in the patent of reference (102). However, with good control of iron roll temperatures, supercalenders can now commonly run with iron surface temperatures at about 100°C, say 20-30°C higher than previously.

Elastomer covered rolls in machine calenders, operate at up to about 300 kN/m line load and up to about 140°C iron roll surface temperature. Less severe conditions are often sufficient. The surface temperatures of the soft rolls are usually in the 50-90°C range but the highly heat resistant supercalender type of rolls filled with aromatic nylon fibres can probably run up to about 130°C.

1.4 Soft roll calendering

The most common type of soft roll calendering is the off-machine supercalender, using a sequence of hard roll/soft roll nips with increasing line load. This feature is undoubtedly mainly historic. A large stack used gravity to provide most of the line load. The top and bottom rolls could be cambered for a maximum and fixed line load but the paper could be more or less heavily calendered by by-passing various numbers of nips. The use of many nips overcame the limitations in the maximum line load imposed by the mechanical properties of the soft, filled roll. Also, wrinkling problems associated with CD paper expansion under high line loads are less and the effects of damaged roll surfaces are reduced. The modern supercalender represents the most effective or severe machine used and has benefitted from numerous improvements in design to be more automatically controlled and efficient (e.g. 9,22,23).

The gloss calender, used mainly for board, is an early successful example of using the softening action of heat and moisture to smoothen the surface with less mechanical work. They seem to have always used synthetic soft rolls.

The modern soft roll machine is usually on-line and usually of single nip design. Therefore, it usually consists of a pair of single nip calenders in series, with roll positions reversed in the second (Figure 2). However, many single nip calenders are used on assymmetrically finished papers or to reduce two-sidedness. They are developments of the hard roll on-machine calender made possible by the high marking and wearing resistance of new synthetic cover materials and their ability to run continuously for months on-machine (e.g. 24,25,80a).

Soft roll calendering usually means using nips of one hard (iron) and one soft roll because two soft rolls are often not sufficiently effective. The nip width is wider and the peak pressure lower than for those of a hard/soft combination at maximum permitted line load. Also, the soft rolls cannot run as hot as an iron roll. There are, nevertheless, applications where more gentle calendering is preferred, e.g. for matt coated paper.

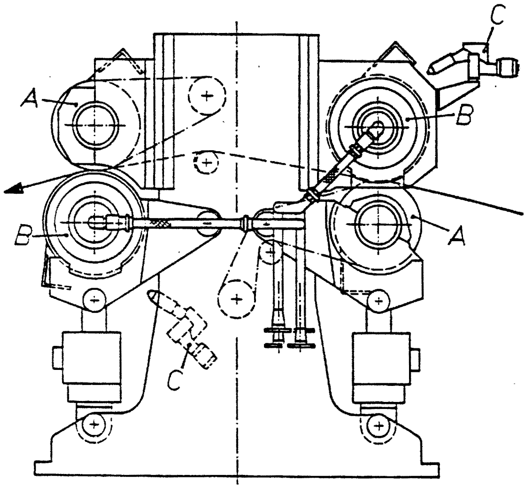


Fig 2 A common type of on-machine soft roll calender showing:— A—a controlled crown roll (in this case the iron roll), B—elastomer covered roll and C—scanning infra red thermometers to monitor temperature variations

The advantages of soft roll calendering have long been recognised to be lack of mottle, higher print quality and less loss of strength, when compared with iron roll finishing (25a,30). This must be a consequence of the smaller extremes of local pressure variations reached in the nip when a soft nip is used and as the naturally non-uniform paper sheet passes through it (Figure 3).

It follows that paper may be safely calendered in a more plastic state and this was realised with gloss calenders. Supercalenders may also operate at 1-2% higher moisture levels, provided the final level is commercially acceptable of course (25a). The soft roll technique has now spread to the breaker stack (26).

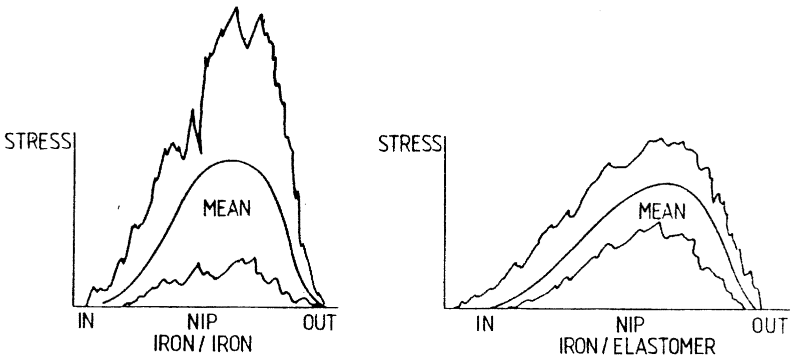


Fig 3 Hard nips presumably have a wider range of variations of the local compressive stresses as the paper passes, compared with soft nips

2. DEVELOPMENTS IN THE UNDERSTANDING OF CALENDERING

2.1 Assessment of surface properties

It is important to review the ways in which the effects of calendering are measured. In practice, this refers to print quality, the analysis and assessment of which has an enormous technical literature, and gloss, both unprinted and printed. It has been endlessly stated in this literature that (1) the final printing characteristics of a paper depend on all parts of its manufacturing process, not just the finishing operations and (2) the final judge of its quality is the reader, regardless of intermediate evaluations with instruments. To the researcher or project worker trying to improve the finish of a paper, this means that (1) he must not forget the influence of earlier parts of the process in his conclusions and recommendations, and (2) he must use the right methods of assessment in his experiments.

Regarding the first point, the quality of formation is well known to affect the uniformity of many subsequent operations, including the severity of mottle in hard calendering and the receptivity of the paper towards coating colours and inks. Davidson reported that good formation and high scattering coefficients were successful in predicting newsprint suitability, assessed with subjective, pluralistic assessment of solid areas and half-tones, whilst smoothness tests did not. The printing process was rotary offset and the smoothness tests were Bendtsen and Parker Print Surf. Wire mark was not apparently important (27). Pheney, on the other hand, from extensive rotogravure printing trials, concluded that missing dots on the wire side of supercalendered papers could not be compensated for in the press (28). Pressing also introduces two-sidedness, with the side in contact with the last felt surface being rougher. It was found that, for several configurations, including the use of a smoothing press, that this effect was not eliminated in subsequent calendering (29). There are obviously limits to what calendering can do, imposed by earlier parts of the process.

Their work also leads into the second point, regarding test methods. First, a comment on two sidedness, which can often be much reduced by supercalendering and, particularly, by tandem soft roll machine calenders, in which very different line loads and iron roll temperatures can be used in the two nips, if necessary. Smoothness tests can show that wire and top side measurements are equalised, but, of course, the surface structures must remain different, which presumably is what Pheney found.

Davidson's comments on smoothness tests are confirmed by numerous studies. Thus, Lyne et al used sophisticated subjective and statistical techniques to identify what was considered good in a letterpress printed newspaper. Mottle, contrast, show through and colour were identified, particularly mottle, and, in turn, certain laboratory tests were found to correlate well with the rankings. It was observed that high mottle, high show through and low contrast were usually associated, which suggests that quality of formation is the underlying source of all these characteristics. Parker Print Surf roughness correlated very well with mottle but Sheffield & Bendtsen did not (29a). Crotogino found Parker Print Surf to distinguish well between the printing characteristics of machine- and super-calendered newsprints, whilst Sheffield did not (30).

Similar problems in relating smoothness tests with print quality was reported in a series of papers on the printing qualities of offset and gravure grades by Bergmann, Schwab and von der Heyde (31,32,33). Schwab, for example, reports comprehensive correlations between paper properties and commercial print rankings, in which Parker Print Surf, a quantitative optically measured surface structure parameter (based on large angle illumination and vertical observation), oil and ink transfer and 2 or 3 more properties correlate particularly well, though not as well as proof printing. He concludes that the surface structure parameter (OSTW%), ink transfer (FA g/m^2) and compressibility (relative, with KAM aparatus) are the most useful. When combined in an arbitrary way (OSTW + FA + 5 (1 - K)), they give a very high correlation.

Bergmann, however, later reported how Bekk smoothness did correlate well with gravure print quality provided the comparisons were limited to the same mill. Otherwise, they did not (34).

Regarding relations between smoothness testers, it is hardly surprising that they are very limited in usefulness, as Baumgarten, Gottsching and Volk found for the Bekk, Bendtsen and FOGRA instruments (35). Bradway showed how fibre coarseness and changes in sheet density can affect instrumental assessments of roughness in different ways (36). The fairly recently introduced KL (Kunz-Lippke) optical method measures the scatter undergone when a narrow beam of light impinges at 75° on the paper surface. Its correlation with Parker Print Surf is reported to be very high but this must apply to restricted circumstances because the paper is not under pressure in the KL method, whereas one of the main reasons for the success of the Parker instrument is that the paper is under pressure. The KL measure is of undoubted usefulness for on-machine control of calendering and is claimed to be quite separate from gloss (37). A different way of assessing this type of light scattering has been patented by Lucas as a graininess or smoothness sensor (38).

Even the Parker instrument's relation with print quality can be misleading as Schwab (see above), Bristow (39,40) and Fabbri (41) separately reported. Fabbri found that PPS roughness and compressibility, as separately measured paper properties, did not correlate with rotogravure missing dots in Heliotest and IGT gravure print tests as well as a new parameter did, based on values of P.P.S. roughness measured at two different pressures. Bristow found that the pressure used in a Parker Print Surf instrument to reduce the roughness to a certain value (2 μm) correlated much better with a print evenness measure than the normal P.P.S. roughness did. He introduced the concept of surface compressibility.

Lepoutre and Alince found that the surface compressibility of coated papers cannot be measured in this way (42). A minimal base roughness was recommended. Mangin subsequently argued that the absolute compressibility of the surface may be measured as the difference between two differences, viz. that between the differences of the roughnesses of the base paper and of the coated paper, each measured at 1 and 2 MPa pressure (43).

Of other methods of assessing smoothness, the development of surface profiling techniques continues, with most of the published work directed to coating structure. Two and three dimensional representations of surfaces have been shown to profile useful numerical indices of roughness (44–47). Planimetric measurements have been made with scanning electron photomicrographs (48). In a later paper, Stephan relates gloss (y) and a statistically calculated depth of the roughness, x, so:

$$\ln y = a + bx$$

where a and b are constants for certain formulations. The relation covers changes brought about by using different coat weights and by supercalendering (49).

Gloss, of course, is a distinctly different property from print quality, and is discussed by Borch in (50). There seem to be no published comments on the reliability of using existing standard test methods to relate measures to subjective assessment, although the standard methods do not enable small scale uniformity or the most appropriate geometry to be measured. Local variations in gloss measured over areas of 0,12 mm^2, were measured in an instrument designed by Bryntse and Norman (51). In fact, the instrument measured the reflectance of a linearly polarised laser beam over a wide angle around the specular angle, either as the total light or as two components, polarised in planes parallel to or perpendicular to its path. Thus, specularly and diffusely reflected light could be distinguished and the fluctuating intensities, as the sample moved past the measuring place, were presented as power spectra. Thus, there was a very large amount of information in the output and it is surprising that more use has not been made of it.

Oitinnen was concerned with both unprinted and printed gloss in extensive studies of surface properties. Paper surfaces have a microscopic roughness, which may be measured by a surface profiler and expressed as an r.m.s. value, after filtering out small variations. They also have an optical roughness, measured by light reflection, which is particularly variable in coated papers. The dependence of the light reflectance, that is, gloss, on the surface profile is complicated by the inclusion, in ordinary gloss measurements, of singly and multiply scattered light and of light reflected at non-specular angles, because of the wide apertures employed. Oitinnen attempted to allow for this by using a narrow aperture goniophotometer and went on to show that, even so, a second profile parameter, taken from the autocorrelation function, is needed to show this dependence. Print gloss increases with the amount of ink transferred but very differently for high gloss and matt coated papers. This is partly due to the microroughness of the surface - and, therefore, on the roughness of the base paper - and partly due to absorption effects. (52,53)

In another paper, the interrelations of 75° Hunter gloss, 75° specular reflection, the two surface profile parameters, coating pigment sizes and shapes and the coat weight were examined for a range of LWC papers (54). The finishing conditions were not given but were apparently similar so that useful comparisons could be made. Hunter gloss and specular gloss were both very dependent on coat weight and type of pigment. It appeared that they were affected separately by the microroughness coming from the base paper, measured by the profile parameters, and by the optical roughness which arises from the nature of the coating. The usefulness of a two parameter description of the profile was again shown. The shape of pigment particle did not, on its own, affect the specular reflection-roughness relation but it did affect the Hunter gloss-roughness relation. The dependence of optical properties and physical roughness is well expounded in these studies but they are complex.

Loumann used light scattering concepts to show that coating pigment particles larger than 1.4 μm diameter should produce a light diffusing matt surface which would, nevertheless, be smooth for printing. This was borne out in trials (47).

It is appropriate to report here a patented blackening sensor, in which the varying spatial distribution of a reflected, narrow light beam, caused by blackened spots, is related to the intensity of the effect (55).

2.2 Compressibility of paper

Early laboratory studies of the relations between pressure, time of application and other conditions, on one hand, and changes in paper properties, on the other, were reviewed in (56) and (57). They were generally carried out under more closely controlled conditions than could be maintained in calendering trials and were intended to provide reliable basic information for application to calendering.

There are also many accounts in the literature of wet pressing in which attempts are made to relate mat compression to mat structure and fibre properties. Han, for example, reviews several pre-1969 studies (58). Recently, Ellis et al (59) derived a thickness-pressure-time relation which is in two parts, one from fibre bending and one from fibre compression. The former is considered to be rapidly effective, and certainly complete after 10 milliseconds. These pressing models, together with experimental results, lead to the evaluation of various constants to service the reasonable mechanisms proposed but they are still largely empirical and apply to conditions far removed from calendering.

Back has studied paper compression in a versatile hammer apparatus using high platen temperatures, but it is more appropriate to discuss this in a later section (60-62).

The dynamic compression of paper in an IGT press was measured to separate elastic, plastic and time dependent parts of the deformation, using a spring and dashpot analogy (63).

Rodal reviewed several of the earlier studies of paper compression with a view to identifying realistic rheological parameters for describing its complex elastic-plastic deformation in calendering (64). A logarithmic strain ($\epsilon = \ln l/l_0$), a Kirchoff stress ($\sigma = Pl/Al_0$) & a non-linear relation ($\sigma = E\epsilon F(\epsilon)$) are proposed, where l_0 is the original thickness, l the thickness under applied load P over paper area A. F is a shape function, later identified in terms of a critical strain, at the onset of elasto-plastic buckling, and a minimum strain, that at which F is minimal. Several constants and parameters need to be, and may be, determined by experiment to enable this model to be used. It was concluded that calendering conditions should be selected so that the tangent modulus ($d\sigma/de$) is minimal and the paper is hot enough for it to be a very flat minimum.

Two groups of researchers have tried to relate fibre properties and structural features of paper to its response to compression. Osaki and Fujii consider paper compression to occur in two regimes, namely, at low and high pressures (65). At low pressure, fibres bend and voids are reduced but fibres are not compressed. Contact points between fibres increase (from n(P) to n(max)) and the average contact area at each point, S_0 , is effectively constant. Assuming no lateral sheet expansion, the following relationships are developed for a sheet initially l_0 thick and l thick under P.

Paper compressibility k* : $Pk^* = \ln l_0/l$ (assumption)

Number of contact areas : $n_0 \rightarrow n(P) \rightarrow n(max)$

Contact area :

$$S_0 = n_0 s_0 \rightarrow S(P) = n(P) \times s(P) \sim s_0 n(P) \text{ at low } P.$$

Change in contact areas : $\Delta n = -nC_0 \frac{l - l_{min}}{l} \frac{\Delta l}{l + \Delta l}$ (assumpt.)

Fibre compressibility, κ : $kP^* = \ln V_0/V = \kappa P/S(P)$

This leads to a relation

$$\begin{array}{llll} \ln \kappa/k^* & = \ln n_0 s_0 & + \; C_0\left[\ln l_0/l - \frac{l_{min}(l_0 - l)}{l l_0}\right] \\ \text{say} \quad a & = \quad b & + \quad c \end{array}$$

k may be taken from fibre properties (1 GPa^{-1} was used), k* is measured (see above), and so by plotting a versus c, the relation may be checked. It was confirmed to be linear, for one pulp, and, by using S_0 = 12.6 μm^2 (from an electron micrograph) it appeared that n_o was $1.2/mm^2$. Also, it was calculated that the number of contact points would increase by 5.8 times. These estimates were considered reasonable.

At high pressure, after n has reached n(max), fibres themselves compress. It is shown that k* decreases steadily with pressure, up to 2MPa but the transition from one regime to the other is not shown.

Ionides, Mitchell and Curzon consider a sheet of paper to consist, in effect, of distributed piles of n fibre crossings (66). An applied compressive pressure (FN/mm^2) is the integration of the forces compressing each pile of n fibre crossings, which provide different reactions according to the size of n. Thus, if the compressed sheet thickness is Z_f and a fibre diameter is d, the force on a pile of n is taken to be:

$$f(n) = \frac{GE}{1-\sigma^2} (nd - Z_f)^m$$

where G and m are, in effect, shape constants and E and σ are the modulus of elasticity and Poisson's ratio respectively. In order to integrate the forces from the various piles, the distribution of piles of n fibres is taken to be Poisson, with n = 5 for a 60 g/m^2 sheet. The final pressure - compression relation is shown to have several features which are confirmed by experiment.

These models are certainly steps forward in understanding the mechanics of compression, and hence of calendering or printing. However, they both still include a number of empirical features about fibre properties which could be made much less so by experiments on fibre deformation and by subsequent incorporation of various fibre properties into the models for verification of the mechanisms proposed. Then perhaps less pilot plant calendering will be necessary, as Ionides et al suggest!

Models could also be tried for coated paper. There are many technical papers on the subject of coating structure, pigment shape and size, etc. However, the author has not found a study specifically of the different extents of compression suffered by the coating and the base paper during calendering, bearing in mind the inverse relation between associated local values of coat weight and base paper grammage, although it is close to the subject studied by Mangin (38) and discussed in section 2.1.

2.3 The effects of the variables of the calendering process on paper

Our understanding of these processes has been extended in recent years by the work reviewed in this section. As is common in applied science, empirical knowledge and practical experience often precede the understanding but the latter, once established, helps to accelerate the application of new processes and stimulates interest in further progress. The section is divided into parts dealing with these aspects.

- The inter relation between the main process variables in iron roll calendering but excluding techniques designed to create large physical gradients within the sheet in the z direction.

- Soft/hard nip calendering, whose advantages are becoming steadily more appreciated and whose mechanism is still controversial.

- Temperature and moisture gradient techniques, which are being developed far beyond the levels which have always been employed, knowingly or otherwise.

- Strength changes, which have attracted more interest recently.

- Rolling contact phenonema.

In some of the reported research, the measurement of paper properties has not taken account of the conclusions concerning test methods, reviewed in the earlier section. Also, most interest lies in smoothness and gloss, so that certain properties, e.g. opacity, formation and surface strengths are not so frequently examined. Formation, that is the uniformity of the appearance of the sheet when viewed with transmitted light, is often improved by calendering (e.g. 67) and the author is aware that this is particularly so for paper calendered with soft nips at high moisture levels.

An isolated but important observation at a Haindl paper mill was that the smoothness of supercalendered paper is lowered if the winding tension is increased. It appears that an increase of about 50% corresponded to a Bekk reduction from about 600 to 500 seconds. This could be also brought about in the press room (68).

2.3.1 Inter-relations between process variables in iron roll calenders

The "process variables" are those design features and operating conditions which can be practically and directly controlled, namely roll sizes, number and types of rolls, line loads, speed, roll surface temperatures, overall ingoing web temperature and moisture content. They control indirectly the "basic variables" of the physics of calendering, namely the forms, types and duration of the surface stresses applied to the paper, combined with the temperature and moisture content combinations through the sheet and through the nip. Apart from laboratory compression experiments mentioned previously, Kerekes had considered a viscoelastic model of paper passing through a nip (69), Haglund and Robertson had considered how the local thickness variations are effected and controlled in an iron/iron nip (70) and Baumgarten and Gottsching had produced experimental results to relate some of these variables, viz (71):

$$\frac{D_o - D}{D_o} = a_o + a_L \log L + a_V \log V + a_R \log R + a_Z \log Z + a_T T + a_M M$$

D_o ,D are the initial and final thicknesses. L kN/m is line load, Vm/min surface velocity, R mm rolls' radius, Z number of passes, T°C roll surface temperature and M % paper moisture content. The constants would be usually used to calculate changes (L_1 to L_2 etc.) and a_o is not quoted here. For newsprint, a_L etc. are respectively 0.26, - 0.055, - 0.103, 0.16, between 3×10^{-4} and 12×10^{-4} depending on speed, 0.01 - 0.02.

The most comprehensive study of the inter-relations under strictly controlled conditions was made by Crotogino (72,57) whose "calendering equation" may be written:

$$\frac{D_o - D}{D_o} = A + \frac{D_o}{W}(a_o + a_L \log L + a_V \log V + a_R \log R + a_T T + a_M M)$$

in which the symbols have the same meaning except T, which is mid-nip web temperature. An example, for a newsprint furnish, gives the constants A, a_0 etc as - 0.5, 0.0498, 0.0968, - 0.0208, - 0.039, 0.000943, 0.00545. It is seen that the thickness or bulk reduction is calculated nip by nip using the expression in the brackets called the "nip intensity factor". The equation has been confirmed in mill trials but it underestimated the effects of a second stack (73).

Derezinski developed a computer simulation of a multi-roll calender stack which can calculate the exiting paper caliper and temperature CD profiles as functions of time (74). The compression model follows Robertson and Haglund. The compression forces across the nip must balance and result in net zero bending movements acting on a roll. The work done in compression is converted to heat in the paper which is partly transferred to the roll and partly to the air. An energy balance is set up to include this and the input of heat from circulating water in the rolls and loss from rolls into the air, assisted by air showers. The rolls expand in response to their "equilibrium" temperature profiles. This complex model was claimed to predict the effects of several calender stacks.

The foregoing relations enable quantitative "equivalences" between variables to be estimated e.g. reductions of line load for higher temperatures or smaller radiuses. Examples are given in a design procedure for machine calenders described in (75). One advantage of iron roll breaker stacks has been to effect a large smoothing action at about 20% moisture and 70°C - 80°C with one nip and save at least 2 nips later in the calender, which is in good agreement with these relations.

It is known that thickness and roughness for machine calenders are generally uniquely related, so that both may be predicted but the use of very small rolls apparently produces smoother paper at the same thickness (76). The Institute fur Papierfabrikation at the Technical University of Darmstadt built a magnetic calender in which rolls 28 - 48 mm in diameter are loaded magnetically against a normally sized roll. This will be discussed in section 2.3.2.

2.3.2 Soft roll calendering variables

As explained earlier, one must distinguish between "process and basic variables" and, here, a new process variable appears, the type of roll. The general direction of changes in surface properties with line loads, temperatures, etc. are the same as with iron roll calenders and have been reported by Baumgarten (77) and Tuomisto (78) for supercalenders and by Peel (79) and Pav and Svenka (80) for the new soft roll calenders. The latter authors also show the form of an empirical regression relationship between a paper property, y, and four variables, namely average nip pressure (that is, line load/nip width), speed, iron roll temperature and number of nips (x_1 to x_4). It is the addition of terms of the form x_i, $x_i x_j$ and x_i^2.

The properties of the soft roll are obviously of great importance but it appears that most development work has been towards making rolls which are mechanically usable. That is, they should, of course, be stiff enough to be effective but they should not mark permanently with creases or folds of paper, they should not wear or heat up excessively, etc. These involve the subsurface levels of shearing stresses, the thermal conductivity of the materials and the dependence of their mechanical properties on temperature. Only very few types of soft rolls are offered commercially, representing those which have been found sufficiently robust, and these are based on synthetic rubbers, polyurethane, epoxy resin and aromatic nylons (e.g. 80a). Some are made with reinforcing fibres. Most are solid covers on iron or steel shells but some are made from sheets of special papers in the same way as conventional filled rolls. Nevertheless, the patent literature shows that very wide ranges of polymers are being investigated, together with proposals for multilayer covers and carbon fibres.

From the papermaking point of view, the soft roll needs to be smooth and to have an elastic modulus in a certain range (probably between about 1 and 10 GN/m^2), so that a sufficiently high maximum or average pressure may be reached in the nip. The desirable modulus is not easy to specify because, for some applications, less stiff materials could be used with higher line loads or temperatures. For others, however, for which the replacement of an off-machine supercalender is the aim, all variables need to be operated at their highest limits, a common feature of advancing technology. There is, therefore, a need for very stiff covers to permit extreme conditions to be used as well as for relatively flexible covers for use with some board grades and with less well formed sheets, in order to avoid mottle.

The author tries to avoid using the word "hard" to describe a stiff material because he believes the elastic properties alone, not combined with a plastic feature, defines a soft roll's performance. Unfortunately, moduli are less frequently reported or measured and the Shore hardness tests are easy to carry out. Within a narrow range of material, Shore D hardness and modulus probably correlate well enough but it is not so generally. The measured values of Shore D hardness and elastic modulus of several filled roll materials were related as follows (81). The density of the woollen/cotton paper II was increased during the test.

Roll filling	Woollen/Cotton paper				Cotton fibre		Asbestos/ cotton paper
	I	II			I	II	
Shore D°	82-86	78-81	82-83	86-88	76-79	77-81	88-90
Elastic modulus GN/m^2	5.5	4.94	4.35	5.23	7.71	8.48	11.1

The desirable stiffness/hardness of cotton filled rolls is usually decided by a user's experience of the combination of paper quality and roll life, since marking, recovery, permitted line loads, speeds, temperatures and roll hardness and composition are inter-related. It seems well established that harder cotton rolls produce glossier paper, mainly because they can calender more severely by using higher line loads and densifying the paper further. The North American preference for glossier paper may be the reason why harder rolls are generally used there. It is not clear whether, at similar thicknesses, harder rolls can produce a smoother or glossier sheet (82). Kanz seems to say they do (83) but Tuomisto's work reports the opposite (78).

It is difficult to separate the effects of some of these variables in order to provide scientific information. For example, softer rolls tend to run hotter, which may be a sufficient answer for practical purposes but not for increasing our understanding. The author's experience with several synthetic covers showed that the combinations of paper properties produced seemed to favour stiffer covers slightly but the results could have been dominated by small moisture and temperature gradient effects. One careful experiment, in which these were unlikely to occur, showed no measurable effect (Figure 4).

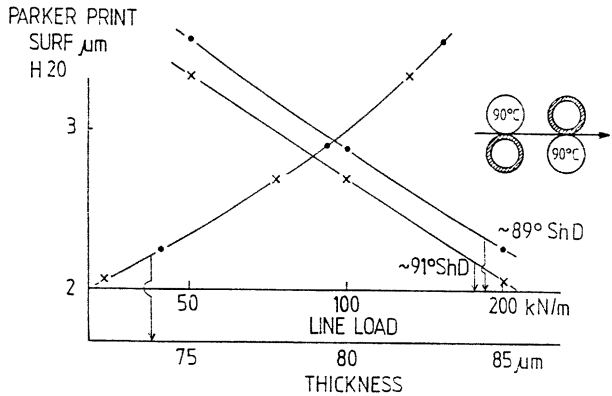


Fig 4 Line load – roughness and thickness – roughness relations for soft roll calenders with covers of different Shore D hardness (84)

Similar remarks may be made about the use of few or many nips, in circumstances when one has a choice to use different combinations of loads and number of nips. Peel reported comparisons of "standard thickness roughness and gloss values" (that is, interpolated values from graphs of thickness versus roughness or gloss, as the line load is changed) for several papers calendered with different soft nips using one, two or four passes (84). No distinct pattern emerged but there was a small bias towards (a) higher gloss and smoothness with the use of more passes, at the standard thicknesses, and (b) lower gloss with the same smoothness (Parker Print Surf) with more nips. However, the differences were so small that the conclusion was that the effects could have been overridden by uncontrollable moisture and temperature effects. The opinion was given that reports from mills that more nips are beneficial are probably correct but the explanations are wrong - the better combinations of properties result from optimising all the complex conditions at one's disposal in a multi-nip and multi-stack operation. The implication is that the temperature and moisture conditions need careful optimisation in the simple straight-through on-machine calenders.

Svenka and Winkels have also reported very similar relationships between roughness and density and between gloss and density regardless of whether 2 or 4 nips were used (25).

There seems, therefore, to be little support for searching for ways to separate the surface flattening action into a vertical compressing and a "nip or shearing effect". There must be surface shearing stresses, of course, as a result of

(a) the geometric difference of path length between the paper surfaces and the middle of the paper as it passes through curved rolls;

(b) transmitted driving force;

(c) vertical compression of a soft roll, leading to dissimilar roll surface speeds at, say, mid-nip and elsewhere;

(d) tangential (circumferential) compression of a soft roll, also leading to dissimilar roll surface speeds and shown to be a much larger effect than (c) for materials with low Poissons ratios, as is the case for filled rolls (85);*

(e) deformation of paper surface asperities or high spots pressed against the dissimilar iron or soft roll surface.

Of these causes (a) - (d) occur in rolling nips and (e) in flat pressing too. These surface shearing stresses could simply cause temporary, elastic strains or they could contribute to plastic deformation of asperities, with or without the relative movement between the roll and paper surfaces known as microslip (87). Whilst agreeing with the existence of these forces, Pfeiffer has earlier concluded that microslip is not important compared with vertical compression and moulding (88).

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*The tendency of a reversing nip to run with a tight ingoing web and a slack outgoing web, discussed by Laumer, is probably more correctly explained by this form of roll deformation in a supercalender (86).

Other authors have argued similarly that surface shear is irrelevant to calendering (e.g. 64). It is certainly difficult to decide how useful surface shear effects are and if they should be deliberately brought into the process. Braking the exit roll of the machine illustrated in Figure 5 increased Bekk smoothness by 30% and gloss by 20% (89).

Gloss development is often associated with the concept of slippage because polishing and brush calendering can increase gloss very greatly with hardly any change in roughness (60). Nevertheless, gloss can be produced without such action and develops quite separately from printing roughness when higher surface temperatures are used in calenders (e.g. data in 20,25). It is generally accepted that gloss depends on the surface having many small optically flat regions, not exactly parallel, but generally so. Such surfaces could be generated by the very low pressure, high velocity brushing or by pressing against a hot roll or by some intermediate process, all of which would heat and plasticise high spots.

Surface shearing could be an explanation of two sets of results from the Technical University of Darmstadt. As mentioned in section 2.3.1 a magnetic calender with combinations of iron roll diameters between 28 and 600 mm and 48 and 600 mm produced smoother paper, at the same thickness, with the smaller rolls (76). A more conventionally sized laboratory calender produced even rougher paper. A unique roughness/thickness relationship was also not found for filled rolls of 50 mm diameter in contact with iron rolls of 200 mm diameter, (89). In the machine illustrated in Figure 5, several nip sequences were possible. At nearly the same bulk, very different smoothness and gloss values could be produced, as these three illustrate. (H: hard (iron) roll; S: Soft (filled) roll).

Filled roll diameter	Small	small	large(lab)	large(indust.)
Nips	8 x H/S	5 x H/S 3 x S/S	6 x H/S 1 x S/S	10 x H/S 1 x S/S
Iron roll temp °C	100°	80°	80°	105°
Bekk Smoothness, sec	1600	550	950	1100
Gloss %	50	32	35	50

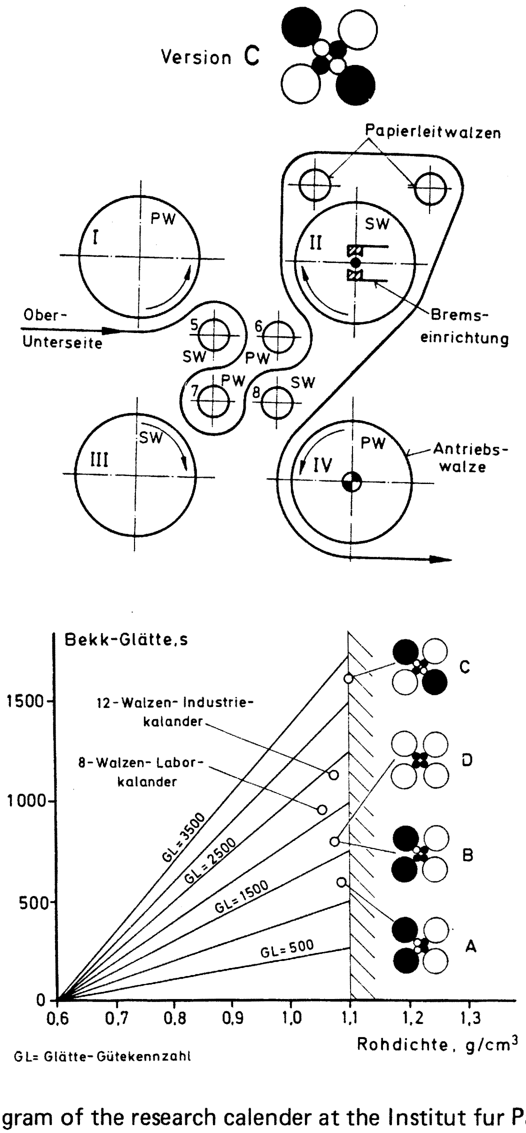

Fig 5 Diagram of the research calender at the Institut fur Papierfabrikation, Technische Hochschule, Darmstadt showing the facilities for using various sequences and combinations of paper (soft) rolls (P) and hard (steel) rolls (S); and how different smoothness values may be reached at the same bulk (89) (courtesy of Das Papier)

It does therefore appear that surface stresses resulting from rolling can be effective. It is possible only to speculate that they are more effective when the ratios of paper thickness/nip width are not too small. If they are, perhaps the conditions nearly approach flat pressing.

The foregoing leads to another feature of hard/soft nips, namely their diameters. For calender design and for transferring pilot plant results to the industrial scale, the absolute values of line loads and nip widths are important. The calendering equations given above show how larger diameter rolls require larger line loads for iron/iron nips, for which gemometry gives the nip width w to be

$$w = R^{1/2} \left((C_0 - C_N)^{1/2} + (C_R - C_N)^{1/2} \right)$$

where C_0, C_N and C_R are the ingoing, mid-nip and recovered thicknesses respectively and R is the radius of the two similar rolls. If the radii are different, the effective nip width is probably best estimated by using the smaller radius as R.

Soft rolls deform and, if the nip width is much larger than the thickness of paper, the paper may be ignored and nip widths calculated from the mechanical properties of the soft material. The Hertz formula is often quoted although it is not accurate for soft rolls (see section 3 and 134).

$$w^2 = \frac{16 L R_1 R_2}{\pi (R_1 + R_2)} \left(\frac{1-\sigma_1^2}{E_1} + \frac{1-\sigma_2^2}{E_2} \right)$$

where L is the line load, R_1, E_1 and σ_1 are the radius, elastic modulus and Poisson's ratio of roll number one, etc., respectively. Some engineers in the industry prefer to report the effects of calendering in terms of the average nip pressure, that is line load/nip width, which should overcome the problem of relating the results of one pair of rolls to another of different size or even of different stiffness (25). One may also adjust speeds, so that the contact times are similar. There appears to be no published information to show how valid it is to use these relations which, in the author's experience, can be useful but which depend, to a great extent, on the accuracy of the nip width information.

Finally, soft nips permit calendering at high moisture levels, as practised in some linerboard mills and with gloss calenders. The application of the modern stiff soft covered rolls to the breaker stack has been described in patents (e.g.135) and is now practised (26). It enables much heavier calendering to be done there than with iron rolls and a supercalender quality to be made on-machines.

2.3.3 Temperature and moisture gradient calendering

It has always been known that the production of smoothness or gloss in papers using calenders has to result in the loss of thickness or bulk, usually an undesirable association. It has been realised too for many years that this loss can be reduced if the plastic deformations can be increased near the surface and reduced in the interior by trying to maintain hotter, moister conditions near the surface. Steam showers have done this on supercalenders and many references are made in the literature to what seems to have been well known to papermakers, namely that higher roll temperatures permit not only the use of lower line loads but produce better bulk (e.g. 90,91). Again, increasing iron roll temperatures in a supercalender from 60° to 100°C permitted the use of one third the line load to give the same gloss and better printability (92).

Gloss calendering of board, using soft rolls to press coated board against very hot and smooth metal rolls, has produced smooth, glossy boards with less loss of bulk than conventional calendering could do for over twenty years. Developments of techniques to soften surface layers with very hot rolls and controlled moisture penetration have been described for decorative laminate overlay papers (80°-160°C) (93) and to avoid bulk reduction in board (5-10% penetration) (94).

The methodical exploitation of this principle for paper appears to have been started by Kerekes and Pye (95), as described by Crotogino in his detailed study of what is now called "temperature gradient or TG calendering" (20).

The potential of the process was shown by Back & Olsson for board grades in experiments with an apparatus developed for the simulation of presses but modified to simulate a calender (60). This was a hammer and anvil apparatus in which a polished, flat steel hammer drops on to a board sample resting on either another steel plate supported by a rubber buffer or on the rubber buffer on top of the steel plate. With this equipment, pressure pulses of peak values and durations equivalent to calender nips were applied. The arrangement of supporting materials showed how an iron/iron nip compared with iron/rubber.

The board studied was uncoated and coated bleached sulphate and the results clearly showed that higher roll temperatures, up to around 250°C, can produce smoother and glossier boards at similar thicknesses or stiffnesses. The surface layer was flattened and also stiffened to produce outer layers with higher elastic moduli. The less mottled effects of using steel/rubber combinations was also observed.

The application of temperature gradient calendering to newsprint was demonstrated by Crotogino (20). At the same thickness, newsprint was about 0.2 μm smoother (Parker Print Surf), much glossier (e.g. 20% compared with 10%) and required less ink to achieve a print density of 0.85 (e.g. 1.5 g/m^2 compared with 2.0 g/m^2). Later work with a different newsprint furnish showed that the smoothness-bulk relation was not improved by TG calendering. It appears that close control of the temperatures - moisture conditions throughout the sheet are probably needed to exploit this method of finishing (96). Nevertheless, large benefits were shown for recycled boxboard (97) and other examples have been published (79).

Further hammer and anvil studies with printing paper grades, by Back and co-workers have confirmed these advantages of calendering at temperatures up to 250°C, and shown how calendering sequences should control two sidedness and that the gloss and smoothness developed are not closely related, with high gloss associated with greater speckle. Speckle was more reduced by having several low pressure impulses rather than few high impulses (61,62).

The use of moisture to induce softening gradients in paper was shown to be practical by Lyne (98) and in the work just reported (96). Water sprays seem to be less effective than steam (99), the use of which increases both temperature and moisture content - at least, if it is saturated. Water sprays cool the paper and rolls. Both water and steam can cause sticking problems with certain types of coating.

Temperature gradients are probably more easily controlled by using hot rolls, because the very short contact times prevent the achievement of a uniform temperature. Kerekes's theory may be used to show that heat should not penetrate a newsprint sheet passing between rolls 100°C hotter than it, unless the speed is less than 50 - 100 m/min (100). On the other hand, steam application cannot be made with less than about fifty times longer time for heat and moisture penetration to take place. The same applies to water sprays or liquid film applicators. The penetration of liquid water depends on the degree of sizing, however, and it is clear from their applications that they can achieve moisture gradients. Steam is probably more controllable at higher speeds and reports of the use of steam showers have recently been made. Interest so far centres on the overall increase in response to calendering, not in gradient efforts. (e.g. 19,101).

Several patents have been awarded concerning gradient calendering, e.g. (102,103). The first states that good surface smoothness and gloss depend on the adequate compression of sub surface layers, which, in turn require to be heated above the glass transition temperatures of the fibre materials. These are known (104) and are related empirically to their moisture content. It is possible, furthermore, to calculate the relationship between the temperature of the paper, as a function of depth, the temperature of a hot roll in contact with it and time of contact. In principle, therefore, one may calculate what roll temperature is required for a particular paper, moisture content and speed. In support of this, graphs show that the gloss/roll temperature and smoothness/roll temperature relations have distinct increases of gradient between about 100-130°C.

The second patent is a specification of the kind of paper and calendering conditions (including 150°C - 300°C) proposed to make photographic paper.

There are limits to gradient calendering imposed by the tendency of some coated paper surfaces to stick to hot rolls and by a yellowing tendency with lignin containing pulps (61).

2.3.4 Effect of calendering on paper strength

Commercial machine calendering nearly always reduces tensile and tearing strength of papers. Commercial supercalendering usually does but often has little effect on tensile strengths. Moffat, Beath and Mihelich showed clearly how the weak spots in newsprint changed from the areas of low grammage in uncalendered newsprint to those of high in machine calendered paper, concluding that fibre or bond damage at the more highly compressed zones was the cause of the 25% or so reduction in measured tensile strength (105). Moffat later reported comparisons between uncalendered and hard and soft nip calendered newsprint which showed how strength was preserved with a soft nip. He also showed how hard nip calendering had apparently changed the distribution of mass density at the 0,05 mm^2 level, making it more uniform, presumably by a squashing and extrusion effect (106).

(With regard to dimensional changes in paper during calendering, they are substantial in the cross direction, around 0,5% (107,108). Machine direction changes depend on the applied winding tension, but, for untensioned sheets, passed through a supercalender nip, about 0,1% shortening was observed, consistent with the circumferential compression of the soft roll (87)).

The bursting strength of newsprint calendered through an iron nip to a standard thickness was about 5-10% lower than that calendered through an iron/soft nip to the same thickness (84). Figure 6 shows the dependence of changes in properties of newsprint on iron roll temperature during soft roll calendering. We note the rise and fall of opacity from the uncalendered value and the apparent maxima in certain strength properties (25).

Charles and Waterhouse showed how in-plane and out-of-plane elastic properties and tensile strengths decreased with supercalendering, particularly in the CD and with sheets whose fibres were more MD oriented. Although opacity decreased, it was concluded that bond breaking occurred (109). On the other hand, calendering at higher moisture content increased linerboard strength (110).

Mitchell showed that the replacement of chemical pulp in newsprint with TMP required heavier calendering to reduce bulk, resulting in unacceptable losses in tensile and CD tear strengths (111). They could be overcome by calendering at higher temperatures and moisture levels.

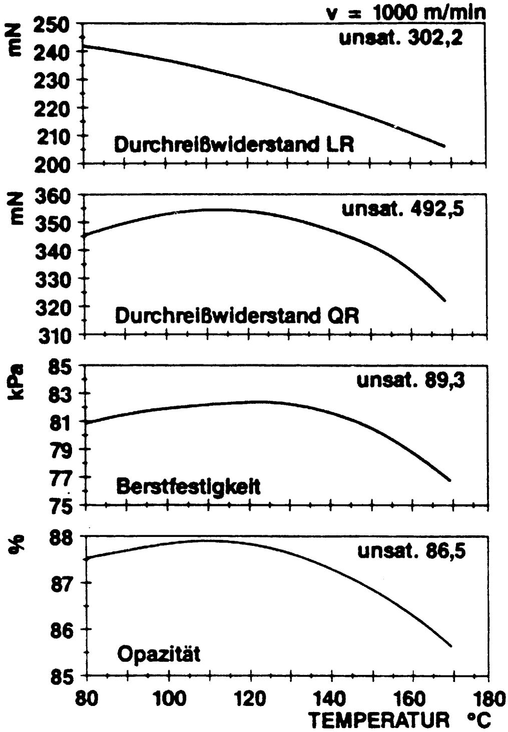

Fig 6 The effect of calendering temperature on some physical properties of newsprint at 80ml Bendtsen. From the top: Machine (LR) and cross direction (QR) tearing resistance, bursting strength and opacity, together with uncalendered values (unsat.) (*25*) (courtesy of Das Papier)

Recently, Greve, Ovaska and Gottsching review some published results, which, for supercalendering, show (1) small changes in machine direction breaking length, positive and negative; (2) small increases (~ 4%) in cross direction breaking length; (3) large reductions (~ 30%) in tear resistance, particularly in the CD (112).

They then report how tensile strength decreases with line load (or remains nearly constant) at low moisture content (7%), but increases at 10% or more (e.g. Figure 7). At similar values of Bekk smoothness, these higher values are substantial, in the 10-20% range. The CD tearing resistance did not respond in this way, however, and always decreased with increasing line load. It is also interesting to observe that the opacity - tensile strength relations were quite different for papers calendered at different moisture levels.

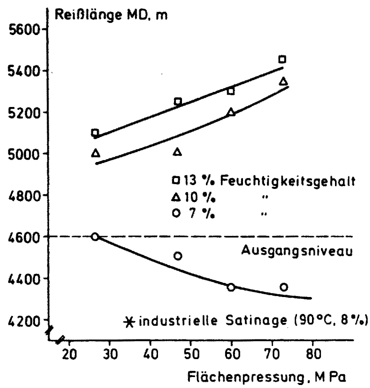

Fig 7 The changes of breaking length as TMP paper was supercalendered at different average nip pressures and moisture contents. The uncalendered (Ausgangsniveau) and industrially achieved values are also shown (*112*) (courtesy of Wochenblatt für Papierfabrik)

The work of Greve et al. was carried out with the special compact research calender shown in Figure 5, capable of many paper run and roll combinations. The inner rolls are only 50 mm in diameter and it is just possible that certain effects of calendering result from the smaller nip dimensions. However, their work shows the sensitivity of the different strength characteristics of paper to moisture, which probably explains the various conflicting data reported in the literature. Seth and Page have shown that tearing strength is dependent on fibre strength to a greater extent than was formerly appreciated so it would be important to establish how bond strengths or fibre strengths are changed during calendering under different conditions (113). Soviet work has shown that severe calendering during the manufacture of capacitor tissue does not change the crystallinity of fibres but the size of the crystallites is reduced (114,115).

3. ROLLING CONTACT PHENOMENA

Earlier work on the rolling contact of elastic cylinders was briefly reviewed in (85). Many mathematical studies, and some experimental, since then have extended methods of calculating various features of elastic rolling into more realistic but more complicated situations (119-125). Allowance may also be made for the viscoelastic nature of the rolls, which is more realistic for modern soft covers (e.g. 126-129). Elastic/plastic contacts receive much attention mainly because of interest in rolling resistance and the wear and failure of materials, but this is not really relevant here.

A few studies have been made in which the deformations of layers passing through rolls are considered. Viscoelastic layers and rigid rolls were studied in references (69,130-133) with paper calendering or printing being the motive in 69, 132, 133, (this is also the case in references 120 and 122), wherein an incompressible layer passes through two elastic layer covered rolls. Interest was mainly in calculating creep effects, that is, speed differences.

This work is reported as a short reference source and cannot be usefully reviewed here. These analyses are likely to be of use for calculations in specific research projects. Unfortunately, the mathematical complexity would often require the solutions to be extensively reworked to provide related results other than those actually presented. Nevertheless, it is clear that the form of the original Hertz relations between nip width, peak pressure, etc. is quite different from that of recent analyses. For example, Deshpande (120) shows nip width to be proportional to the one third power of line load, not the one half power of Hertz given in section 2.3.2.

4. CONCLUDING COMMENTS

The research on the assessment of the surface properties of paper has these implications for the calendering processes.

1. The quality of the formation of the sheet is a dominant factor in deciding print quality, and is one which calendering can modify to only a limited extent. Nevertheless, calendering with soft rolls seems to be one obvious way of reducing the importance of formation.

2. If a single, air leak index of printing roughness is required, only the Parker Print Surf roughness should be used. Other air leak tests can be used only if the samples to be compared come from a restricted population, e.g. from the same paper machine or from the same kind of calender.

3. Even so, more reliable correlation with print quality requires the Parker instrument to be used with at least two pressures to provide information combining surface roughness and its dependence on pressure. This seems to be so for uncoated papers but not for coated.

4. Surface properties of coated papers depend on the smoothnesses of the base paper and of the coating layer. A smooth coating base is desirable.

5. Surface profiles can provide good correlation with print quality.

6. Gloss can be related to surface shape, allowing for the separate contributions to non-uniformity made by the base paper and the coating, which are complicated but, on the whole, explainable in terms of light scattering theory.

Other work on the understanding of calendering has these implications.

1. The effects of paper compression on bond and fibre strengths could be usefully related to the observed regimes of low and high pressure and to the use of compressing surfaces of different stiffnesses. It is likely that such studies could include the use of models of the paper, as fibre piles whose deformation characteristics are moisture and temperature dependent and of coating.

2. There will obviously be continuous research into the development of soft rolls of even greater robustness and capable of being used under more extreme conditions.

3. Technical and economic comparisons between temperature gradient and conventional calendering, with and without the use of soft rolls, is required.

4. More information is also required on the relation between different soft roll covers and paper surfaces produced with use. It should be achieved by experiments in which the separate effects of interacting basic physical variables can be distinguished so that our understanding advances.

5. The role of shear in rolling still seems to be unclear and, although it may not have much application in real situations, it does seem that a rigorous comparison of flat pressing and roll pressing could identify the parameters once and for all. Some of the recent mathematical studies of rolling contact could assist.

6. The more careful control of moisture is likely to be required as soft calendering becomes more common and the strength changes possible with such control are more widely appreciated and understood.

7. Calendering of base papers could receive more attention in spite of problems which increase with some coating methods if the base is very smooth.

8. Breaker stack calendering has received a new impetus with the use of soft rolls and could be considered as a further step towards the unification of the pressing and drying operations. Future developments here will probably require the use of methods to reduce severe fabric marking.

5. REFERENCES TO LITERATURE

1. Müller, K & Schmidt, S. Economic Aspects of alternative finishing processes. Papier 35, 1, 1-12 (1981)

2. Peel, J.D., Kerekes, R.J. & Baumgarten, H.L. A review of current practice, understanding and needs. Symp. Calendering and Supercalendering, University of Manchester, Inst. Sc.Tech. (1975)

3. Pleines, H.D. Brush polishing of coated board and supercalendered coated papers. Tappi, J., 71, 3, 125-8 (1988)

4. Baumgarten, H.L. The thermomechanical development of the surfaces of paper and board. Proc. 17th EUCEPA Conference, Vienna (1977).

5. Stotz, W.G., New solutions in calender design, Pulp Paper Canada 82, 7, T251 (1981)

6. Weisshuhn, E. & Holik, H. The elimination of caliper profile disturbance factors in machine calenders. EUCEPA Symposium on controls for pulp and paper industry, Stockholm & Paper (London) 20 Sept (1982)

7. Brendel, B. The Hydro Vario roll - a new effective tool for the papermaker. Papier, 42, 7, 325 (1988)

8. Müller, G. Factors influencing the control of nip load distribution in a multi-nip calender. Annual Convention of APV (Akadem. Papier Ingen, Verein), Tech. University Graz Austria (1984)

9. Stotz, G, Schuwerk, W. A new generation of supercalenders. Tappi Finishing Conference (1988)

10. Parker, J.R. Lateral roll deflections and power utilisation in machine calender stacks. Canadian Pulp Paper Assoc. Annual Mtg. (1980)

11. Emmanuel, A. Some experiences with barring on a newsprint machine and diagnosis of roll corrugations. Appita 38, 4, 269 (1985)

12. Chen, Y.N. & Boos, G. Calender barring on paper machines - theoretical model development. Tappi J. 58, 7, 98 (1975)

13. Johnson, K.L. & Gray, G.G. Development of corrugations on surfaces in rolling contact. Proc. Inst. Mech. Eng. 189, 13 (1975)

14. Grassie, S.L., Gregory, R.W., Johnson, K.L. Report of research on rail periodic slip and wear. Cambridge Univ. Engin. Dept. Tech. Report 21, (1982)

15. Henry, W. Cross-machine controls - an update. PIMA 66, 11, 40-45 (1984)

16. Crotogino, R & Gendron, S. Control systems for calenders and supercalenders - potential and limitations. Pulp Paper Con. 88, 11, 44 (1987)

17. Knecht, W. Fast response CD caliper control. Tappi Finishing Conf. (1988)

18. Vyse, B. Effect of Calcoil induction heating on supercalendering. Tappi Finishing Conf. (1987)

19. Hilden, K.K. & Sawley, D. Calender steam showers: a new effective way of hot calendering. Tappi, J., 70, 7, 87 (1987)

20. Crotogino, R.H. Temperature graident calendering. Tappi J., 65, 10, 97 (1982)

21. Busse, W., Gottsching, L. Basis weight and thickness deviations in paper as influenced by the paper machine, coating and supercalendering. Papier 38, 5, 209-217 (1984)

22. Malkia, H. Practical applications of new calendering techniques. Tappi J. 71, 5, 83 (1988)

23. Koncel, J.A. On machine supercalendering and automatic developments high light (Appleton-Wartsila) seminar. Paper Trade J., 169, 10, 52 (1985)

24. Minkenberg, R. & Urban, P. A new role for on-machine calender stacks. Tappi J., 69, 12, 39 (1986)

25. Svenka, P & Winkels, H. On- and off-machine supercalendering of coated and uncoated papers. Papier 42, 10A, V191 (1988).

25a. Sara, H. Experiences with TMP in the production of SC newsprint. Pulp Paper Canada 83, 1, T19 (1982).

26. Anon, Tappi J., 72, 1, 11 (1989)

27. Davidson H.W., Paper surface and printability in connection with molecular and cell structure. Papier 40, 7, 334 (1986) (from 6th Cambridge Monotype Seminar 1985)

28. Pheney, R. Evaluation of print quality and smoothness by laboratory printability tests. Gravure Bull. 32, 4, 36 (Winter 1981).

29. Pikulik, I.I. & McDonald, J.D. Pressing induced two-sidedness. Tappi J., 70,, 4, 75(1987).

29a. Lyne, M.B., Parush, A, Richter, F., Jordan, B.D., Donderi, D.C. & Ramsay, J.O. Multidimensional analysis of paper related factors in the subjective evaluation of print quality. Proc. 7th Fundamental Res. Symp., Cambridge, (via P.I.R.A., England) 731 (1981).

30. Crotogino, R.H. Supercalendered and conventionally calendered newsprint. Tappi, J. 63, 11, 101 (1980)

31. Bergmann, W. Web offset paper Wochenblat. Papierfabrik. 110, 2, 45-50 (1982)

32. Schwab, O. Uncoated gravure paper. Wochenbl. Papierfabrik. 110, 1, 9 (1982)

33. Von der Heyde, H. Coated gravure paper Wochenblat. Papierfabrik 110, 1, 17 (1982)

34. Bergmann, W. Relations between test measurements of coated papers and their printability behaviour - critical consideration. Wochenbl. Papierfabrik. 112, 6, 188 (1984)

35. Baumgarten, H.L., Gottsching, L. & Volk, W. The development of paper testing methods suitable for standardisation and their precision, exemplified by 3 smoothness test methods (Bekk, Bendtsen, FOGRA) in 3 parts. Papier 34, 9, 377 and 11, 504 (1980) and 35, 1, 13 (1981)

36. Bradway, K.E. Comparison of Smoothness evaluated by different test methods. Tappi, J. 63, 11, 95 (1980)

37. Hartig, W. Optical measurement of smoothness of paper with the K.L. instrument. Papier 39, 1-6 (1985)

38. Lucas, J.M. (Domtar Inc) Graininess sensor. US Patent 4213708 (1980)

39. Bristow, J.A., Ekman, H. Paper properties affecting gravûre print quality. Tappi J. 64, 10, 115 (1981)

40. Bristow, J.A. Surface compressibility of paper. Svensk Papperstidn. 85, 15, R127 (1982)

41. Fabbri, I. Smoothness and compressibility in rotogravure printing. Cellulosa Carta 32, 1, 21 (1981).

42. Lepoutre, P. & Alince, B. Predicting the roughness of blade coated papers. Svensk Papperst. 85, 6, R51 (1982)

43. Mangin, P.J. Using the Parker Print Surf instrument to measure compressibility of coated papers. Tappi J. 69, 1 90A (1986)

44. Climpson, N.A. The Paperscape: an instrument for measuring paper surface topography. 15th Annual ATICELA Conference, Florence (1982)

45. Kent, H.J. The influence of coating structure on the printability of LWC paper. Wochenblatt fur Papierfabr. 112, 7, 243 (1984).

46. Stephan, A., Voss H., Hottentrager, E. Investigation of the relation between coating morphology and board quality with a surface profiler. Wochenblatt fur Papierfabr. 108, 14, 523 (1980)

47. Loumann, H.W. The relation between surface reflection and printing smoothness. Wochenblatt fur Papierfabrik 111, 14, 496 (1983)

48. Voillot, C. Quantitative application of S.E.M. Measurement of surface effects of calendering. ATIP Rev. 37, 10, 592 (1983)

49. Stephan, A. Findings and conclusions from roughness to gloss measurements. Papier 40, 7, 309 (1986)

50. Borch, J. in Handbook of physical and mechanical testing of paper and paperboard, ed R.E. Mark, pub. Marcel Dekker (1984)

51. Bryntse, G. & Norman, B. A method to measure variations in surface and diffuse reflectance of printed and unprinted paper samples. Tappi 59, 4, 102 (1976)

52. Oitinnen, P. Surface reflection of coated papers and boards. Adv. in Print. Sci. Technol. (IARIGAI Conf. Lillchammer, Norway) 15, 344 (1979) pub. Pentech Press (1980)

53. Oitinnen, P. The limits of gloss in prints. Paperi ja Puu 65, 11, 718 (1983)

54. Oitinnen, P. Surface structure of coated paper and the formation of gloss. Proc. 7th Fundamental Res. Symp., Cambridge 635 (1981)

55. Lucas, J.M. & Grocovetsky, S. (Domtar Inc) U.S. Pat. 4252443 (1981)

56. Colley, J. & Peel, J.D. Calendering processes and the compressibility of paper. Paper Tech. 13, 350 (1972)

57. Crotogino, R.H. Machine Calendering - recent advances in theory and practice. Trans. Tech. Sect. Canad. P.P.A. 7, Dec., TR 75, (1981)

58. Han, S.T. Compressibility and permeability of fibre mats. Pulp Paper Canada 70, 9, 65 (1969)

59. Ellis, E.R., Jewett, Ceckler, W.H. and Thompson, E.V. Dynamic impression of paper (3). Compression equation for cellulose mats. Am. Inst. Chem. Eng. Symp. Ser. 8, 232, 1-7 (1984)

60. Back, E.L., Olsson, A-M. The effect of temperature on gloss calendering of board as evaluated in a press simulator. Proc. EUCEPA Conf. Budapest (1981) and Svensk Papperstidn. 86, 3, R31 (1983)

61. Back, E.L. Mataki, Y. Potentials of hot calendering for printing paper. Part 1. Svensk Papperstidn. 87, 12, R83 (1984)

62. Back, E.L., Mataki, Y, Bristow, J.A. & Ekman, H. Potentials of hot calendering for printing paper. Part 2. Nordic Pulp Paper Res. J. 1, 3, 4 (1988)

63. Watanabo, K., & Amari, T. Dynamic compressive modulus of paper. Reports on Progress Polymer Physics Japan 25, 409 (1982)

64. Rodal, J.J.A. Soft nip calendering of paper and paperboard. Proc. TAPPI Finishing and Converting Conf. (1988)

65. Osaki, S, Fujii, Y. & Kiichi, N. Theory on compressive properties of paper. Reports Progr. Polymer Physics Japan 23, 375 (1980) and z-direction compressive properties of papers, ibid 25, 413 (1982)

66. Ionides, G.N., Mitchell, J.G. Curzon, F.L. A theoretical model of paper response to compression. Trans. Tech. Sect. Canad. P.P.A., 7, 1, TRI (1981)

67. Komppa, A & Ebeling, K. Correlation between the areal mass and optical densities in paper. Proc. 7th Fundamental Research Symp. pub. Mech. Engin. Public. Ltd. (via P.I.R.A., England) (1981)

68. Schmidt, S., Palm, C., Fleissner, P., and Breunig, G. Smoothness measurement for process control. Papier, 37, 1, 1 (1983)

69. Kerekes, R.J. Speed and loading effects in a calender nip. Trans. Tech. Sect. Canadian P.P.A. 2, 3, 88 (1976)

70. Robertson G. & Haglund, L. Local thickness reduction in calender nip. Svensk Papperstidn. 77, 14, 521 (1974)

71. Baumgarten, H.L. & Gottsching, L. The influence of calendering parameters on the thickness changes of some printing papers. Symposimum on Calendering and Supercalendering, U.M.I.S.T., Manchester, GB (1975)

72. Crotogino, R.H. Towards a comprehensive calendering equation. Trans. Tech. Sect. Canadian P.P.A. 6, 12, TR89 (1980)

73. Crotogino, R.H. Hussain, S.M. and McDonald, J.D. Mill application of the calendering equation. J. Pulp Paper Science, Nov. TR 128 (1983)

74. Derezinski, S.J. Digital computer simulation of paper calendering. Tappi Eng. Conf. 591 (1981)

75. Crotogino, R.H. & Gratton, M.F., Hamel, J. A design procedure for machine calenders. Proc. Tappi Finishing Converting Conf. (1988)

76. Heckers, W. Supercalendering of paper. Wochenblatt Papierfab. 109, 6, 171, (1981)

77. Baumgarten, H.L. The supercalendering of mechanical pulp containing printing papers. Papier 32, V163, 10A (1978)

78. Tuomisto, M.V. Supercalendering in North America and Europe. Tappi J. 72, 1, 68 (1989)

79. Peel, J.D. What can we learn from pilot calender trials? Proc. TAPPI Finishing Converting Conf. (1988)

80. Pav. J & Svenka, P. Influence of operating and machine parameters on smoothness and gloss. Wochenblatt fur Papierfab. 115, 10, 433 (1987)

80a. Suguri, M. Supercalendering rolls and on-machine calendering rolls of synthetic resins. Japan Pulp Paper 33-38, Sept (1988)

81. Bentley, S., Peel, J.D. & Kitching, R. The elastic constants of supercalenders roll materials. Paper Tech. 15, 2, T50 (1974)

82. Kalliola, L. Supercalendering of coated paper. Tappi, J., 66, 10, 44 (1985)

83. Kang, H. Supercalenders - hard versus soft filled rolls. Pulp Paper Internat. 24, 7, 48 (1982)

84. Schmidt, H. & Peel, J.D. Papers at Tappi Coating Conf. (1988) and 23rd EUCEPA Conference, Harrogate, GB (1988)

85. Peel, J.D. & Andson, F.L. The application of elasticity and

86. Laumer, E.P. Troubleshooting at the reversing nip of a supercalender Tappi J., 70, 5, 175 (1987)

87. Peel, J.D. & Jones, N. The elastic properties of supercalender roll materials and microslip. Proc. EUCEPA Conf. London (1966)

88. Pfeiffer, J.D. The finishing action of a supercalender nip. Proc. Tappi Finishing Conf. (1970)

89. Chareza, C., Greve, T. & Gottsching, L. Supercalendering and printablity of SC paper. Papier 39, 10A, V187 (1985)

90. Muller, G. Optimisation of production and operation of supercalenders. Proc. TAPPI Finishing Conf. (1979).

91. Krenkel, B. Wochenblatt fur Papierfabrik. 104, 4, 129, 104, 17, 621 (1976), 105, 11, 431 (1977)

92. Munch, E.E.A., Schlunke, J & Schmitz W. Hot supercalendering. Paper (London) 192, 5, 229 (1979)

93. Tarnawski, W.Z. & Klepaczka, A. One sided gloss calendering of paper. Przeglad Papier, 37, 7/8, 259 (1981)

94. Attwood, B.W. (Black Clawson Co) U.S. Pat 4596633 (1986)

95. Kerekes, R.J. & Pye, I.T. Effects of calendering temperature and loading on the properties of newsprint. Pulp Paper Canada 75, 11, T359 (1974)

96. Crotogino, R.H. & Gratton, M.F. The effects of Z-directional moisture and temperature gradients in the calendering of paper. Proc. Tappi Paper Physics Conference (1987)

97. Gratton, M.F. Seth, R.S. & Crotogino, R.H. Temperature gradient calendering of foodboard. Tappi J, 71, 1, 81 (1988)

98. Lyne, M.B. The effects of moisture and moisture gradients on the calendering of paper. Proc. 6th Fundamental Res.Symp. Oxford, publ. P.I.T.A. (via P.I.R.A.), G.B. (1977)

99. Dunfield, L.G., McDonald, J.D., Gratton, M.F. & Crotogino, R.H. Gravure printability of steam treated machine calendered paper. J. Pulp Paper Sci 12, 2, J31 (1986)

100. Kerekes, R.J. Heat transfer in calendering. Trans. Tech. Sect. Canandian P.A. 5, 3 TR66 (1979)

101. Nurmi, E. (Moistening of paper web during supercalendering) Brit. pat. 2150163 (1985)

102. Vreeland, J. (S.D. Warren Co.) US Patent 4624744, (Nov 1986)

103. Tashiro, N. & Uehera, H. (Mitsubishi Paper Mills Ltd. Jap. pat. Kokai 126397/1985 (A.B.I. P.C. 57-00955)

104. Back, E.L. & Salmen, L. Glass transitions of wood components hold implications for molding and pulping processes. Tappi J. 65, 7, 107, (1982)

105. Moffat, J.M., Beath, L.R. & Mihelich, W.G. Major factors affecting newsprint strength. Proc. 5th Fundamental Research Symp. Cambridge pub. PITA (via PIRA, GB) (1973)

106. Moffat, J.M. Newsprint calendering: constraints and possibilities. Proc. UMIST Symp. Calend. Supercalend. Manchester (1975)

107. Meinecke, A. Working with a machine calender. Wochenblatt fur Papierfab 113, 22, 858 (1985)

108. Baumgarten, H.L. Changes in web dimensions during calendering and supercalendering. Symp. Calend. Supercalend. UMISt (Manchester) (1975).

109. Charles, L.A. & Waterhouse, J.F. The effect of supercalendering on the strength properties of paper. Proc. TAPPI/CPPA/PITA Paper Physics Conf. (1987)

110. Soszynski, R.M. & Seth, R.S. Improving the stength of linerboard CONEX 85 Internat. Packag. Conf. Proc. (Beijing, P. Rep. China) (1985)

111. Mitchell, J.G. Calendering alternatives for reducing the bulk of TMP newsprint. Pulp Paper Canada 81, 4, T102, (1980)

112. Greve, T., Ovaska, J., Gottsching, L. The effects of supercalendering on the mechanical properties of printing papers. Wochenblatt. Papierfabrik. 115, 20, 897 (1987).

113. Seth, R.S. & Page, D.H. Fibre properties and tearing resistance. Tappi J. 71, 2, 103 (1988)

114. Esaulenko, G.B., Mirontsov, L.I., Bezruk, L.I. & Privalko, V.P. Thermoelasticity and the morphology of cellulose dielectrics. (in book pub. Riga, U.S.S.R. 1983) A.B.I.P.C. 58 06069

115. Gardenina, A.P., Gulko, L.P., Morozovskii, A.R., Esaulenka, G.B. Effect of compressing on the structure and dielectric strength of capacitor tissue (pub. Kiev, U.S.S.R., 1983) A.B.I.P.C. 58 04584.

116. Nayak, L & Johnson, K.L. Pressure between elastic bodies having a slender area of contact and arbitrary profiles. Internat. J. Mech. Sci. 21, 237 (1979)

117. Lundberg, G. Forschung auf die Gebiete des Ingenieurwesens 10. 201 (1939) (quoted in 116)

118. ANON. Chap 2 in Calendering and Supercalendering, pub. Lockwood Trade & Co. (1963)

119. Meijers, P. The contact problem of a rigid cylinder on an elastic layer. Applied Sci Research 18, 353 (1968)

120. Deshpande, N.V. Calculation of nip width, penetration and pressure for contact between cylinders with an elastomeric covering. Tappi J., 61, 10, 115 (1968)

121. Anscombe, H. & Johnson, K.L. Slip of a thin solid tyre press fitted on a wheel. Int. J. Mech. Sci. 16 329 (1974)

122. Hahn, H.T. & Levinson, M. Indentation of an elastic layer bonded to a rigid cylinder I & II. Inter J. Mech. Sci. 16 489 and 503 (1974)

123. Nowell, D. & Hills, D.A. Tractive rolling of dissimilar elastic cylinders. Tractive rolling of tyred cylinders. Int. J. Mech. Sci. 12, 427 and 945 (1988).

124. Nowell, D., Hills, D.A. & Sackfield, A. Contact of dissimilar elastic cylinders under normal and tangential loading. J. Mech. Phys. Solids 36, 1, 59 (1988).

125. Barquins, M. Adherence and rolling kinetics of a rigid cylinder in adhesive contact with the flat, smooth surface of a soft rubber-like material. J. Adhes. (GB) 26, 1, 1 (1988)

126. Morland, L.W. Exact solutions for rolling contact between viscoelastic cylinders. Quart. J. Mech. Applied Math. 20, 1, 73 (1967)

127. Harvey, R.B. On the deformation of a viscoelastic cylinder, rolling without slipping. Quart. J. Mech. Appl. Math. 28, 1 (1975)

128. Oden, J.T., LIN, T.L. & Bass, J.M. Finite element analysis of the general rolling contact problem for a viscoelastic rubber cylinder. Tire Sci. Tech. 16, 1, 18 (1988)

129. Starzhinskii, V.E., Doroschkina, T.A., Mozharovskii, V.V. & Osipenko, S.A. An experimental study of contact parameters for a cylinder with a polymer coating. Mekh. Polim. (USSR) 13, 2, 344 (1977): transl. in Polym. Mech. (USA) 13, 2, 307 (1977)

130. Alblas, J B & Kinpers, M. The contact problem of a rigid cylinder rolling on a thin viscoelastic base. Inter. J. Eng. Sci. 8, 5, 363, (1970)

131. Margetson, J. Rolling contact of a rigid cylinder over a smooth elastic or viscoelastic layer. Acta Mech. (Austria) 13, 1, 1(1972)

132. Soong, T.C. and Li, C. The steady rolling contact of two elastic layer bonded cylinders with a sheet in the nip. Internat. J. Mech. Sci. 23, 263 (1981).

133. Soong, T.C. & Li, C. The rolling contact of two elastic layer covered cylinders driving a loaded sheet in the nip. Trans. ASME. J. Appl. Mech. 48., 4, 889 (1981)

134. Racine, J.G. Jap. Pat. Kokai 215097/87 (A.B.I.P.C. 58:10204)

135. Ainsley, J.A., Khaing, S. & Peel, J.D. Contact stresses and microslip in calender nips. Symp. Calend. Supercalend. UMIST (Manchester) (1975).

Transcription of Discussion

RECENT DEVELOPMENTS IN THE TECHNOLOGY AND THE UNDERSTANDING OF THE CALENDERING PROCESS

J. D. Peel (Review Paper)

Professor H. Kropholler UMIST

Is there an optimum value of E as iron has a value of 200 giga Newtons whereas the soft roll is 1-10 giga Newtons and you are saying that the harder you get the better. In this case do you mean the steel?
Secondly, is there any interest in actually measuring nip pressure?. I believe that there is such a measuring device in the Bureau of Standards in Washington?

Dr. J.D. Peel Kusters

I did not mean the metal roll about which I have no information. With regard to the optimal value of the elastic constant of the cover I think that you would be better to use the softest that you can. You have to work between two limits - hard enough to reach the pressure for the smoothness you need, but soft enough to avoid a wide range of pressures occurring with the flocs and non-uniform areas. So what is best for your grade may be a compromise. In general with the covers available on the market today, the stiffer ones are probably more useful because you can more easily reach the smoothness you need. As to measuring pressures, this can only help us to understand the situation better.

Dr. B. Lyne International Paper

I was intrigued by your remarks regarding braking as a technique for enhancing gloss. Does braking induce slip - is the retarding of rotation that severe?

Dr. J. Peel

At UMIST some years back we observed this effect by putting a brake on one of the rolls and increasing the driving force across the nip and Darmstadt have given facts and figures about this in the paper I quoted. If you put the brake on hard enough you will get slip, obviously - but you will definitely increase shearing stresses over the surface. Darmstadt reported 20-30% increases in gloss by this method.

Dr. H.L. Baumgarten PTS Munich

Temperature much always play a part. The extra energy put in will be transferred as heat in the nip to the paper surface. But also in such friction calenders the surface temperature of the paper is increased in the nip when the break is put on the rolls. This will increase the paper gloss, because part of the additional driving energy is transformed into heat between the roll surfaces and the sheet.

Dr. P. Kolseth STFI

I do not think that you mentioned the paper sheet widening in the nip. Could this be important? Is this also one of the reasons why you want to use many nips instead of just two? In the laboratory you usually run with a narrow web.

Dr. J.D. Peel

There is some information on this in the paper. Excessive widening and associated creasing could well be one reason why one runs often with several nips. I have not yet come across a case where this was a hindrance, at least in our pilot plant work. That is a reason why people did not use less nips.

Dr. K. I. Ebeling James River

Do you have information for the use of high surface temperature of calender rolls as a way to pacify the surface fibres before coating? In other words will such a treatment glue the fibres so that they will not rise from the surface layer?

Dr. J.D. Peel

It may be possible, but I do not have any information on this.We have done some work on calendering before coating but I have not done any or read of any work on high temperature before it. It will be one of our future projects.

Prof. D. Wahren Stora Technology

With regard to improved formation, could you comment on the relative merits of soft versus hard calendering? If you have a very well formed paper do you get as much benefit from calendering between soft and hard rolls as you do when comparing performance with poorly formed sheets?

Dr. J.D. Peel

There are a number of reports where paper formation improves after calendering. K. Ebeling has reported this, for example. Are you talking about formation as you see it?

Prof. D. Wahren

No, actually print mottle.

Dr. J.D. Peel

Is this print mottle on the coated sheet? If so the areas of the paper where you are calendering will have different densities. With hard calendering the ink receptivity is different.

Prof. D. Wahren

Does that mean that if you have a very well formed sheet you would not gain anything by soft roll calendering?

Dr.J.D. Peel

If the paper was very well formed, the differences would be very small. (Later comment: The difference between using hard and soft roll calendering will depend also on how smooth the paper has to be, that is how heavily it has to be calendered with either system).

Dr. H.L. Baumgarten

Or let us say: if the sheet has a perfect mass and moisture formation you should be able to finish the paper with a single hard and hot nip and with little thickness reduction.

D.G.N. Stirling Wiggins Teape

As loading contents of papers increase, has work been carried out on the effect of calendering on strength of papers with different kinds of loadings - particularly as loading increases to above 20%?

Dr. J.D. Peel

I do not remember a paper that I have reviewed dealing specifically with that. John Waterhouse may remember something from his reviews.

Dr. J. Waterhouse Institute of Paper Science

No, We have not found any practical work which had studied this. I have some slides here which in part address Professor D. Wahren's question and some other comments which have been made with respect to the effects of formation on hard and soft nip calendering. Perhaps after coffee there might be an opportunity to make a short presentation?

Dr. H. Baumgarten

Perhaps we could review the slides during the coffee break and then we will try to fit in your presentation at the end of the session.