

How paper properties can be developed using different methods of calendering

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The basic principle of hot calendering is that the cooler resilient fibers in the center of the sheet do not deform as much as the hotter outside fibers.

While the Chinese invented paper, we could say that the Arabs invented calendering. The Arabs pounded the finished paper to improve smoothness. Later, this technique was mechanized with mechanical hammers. It wasn't until the 1820s that rolls could be manufactured accurately and round enough to make what we today call a machine calender.

As a variation of this early machine calender, a softer material was used for one of the rolls. At first, the inner part of the tree (bowl) was used for this material. In fact, the term "bowl" is still used in reference to the discs used to make a filled roll. Synthetic roll covers had to wait for the technology of the plastics and bonding to evolve.

Without understanding exactly how, the papermaker managed to use the machine calender and the supercalender to make a better sheet of paper. We will try to understand what he did and why. For in knowing this, we can design new products that take advantage of the unique properties of paper.

Paper as a plastic material

Most of the changes that occur in a calender depend on the elastic properties of the paper itself. Although some changes occur within the coating, they are not primarily responsible for the development of the coated surface. Calendering affects the exposed surface in a manner that depends largely on what is happening inside the sheet. The most significant effect that calendering has on the coating is to replicate the surface against which it is pressed.

Under the microscope, we can see the fine roll grinding scratches on the calendered surface of the coating and on the fibers of an uncoated sheet. Because the iron or steel roll can be ground smoother than the soft roll, more of the sheet gloss is developed against the hard roll even in isothermal conditions. Consequently, the finish on the iron or steel roll is important.

Although there are shear forces in a calender nip, the coefficient of friction is high enough to prevent slipping

I. Load ranges for machine calenders, supercalenders, and on-line soft calenders

	Load, pli	Load, kN/m
Machine calenders	400-1000	70-175
Supercalenders	1200-2000	210-350
On-line soft calenders	1000-2500	175-440

in the nip up to the point where the pressure is nearly relieved as the paper leaves the nip. The production of gloss does not depend on slip in the nip. The shear forces do, however, tend to align the pigment particles (such as clay particles) in the coating.

Although most of our discussion here is related to coated paper, the principles described apply equally well to uncoated papers. When there is no coating, the outermost fibers replicate the roll surface reasonably well. At high temperatures, lateral flow of the fibers can be seen.

When a piece of paper is subjected to a compressive load, it will respond in three different ways. First, it responds as an elastic medium that compresses like a spring. Second, it behaves like a plastic material that flows under stress. Third, it has a "memory" of what happened to it previously.

In simple terms, the paper can be thought to compress uniformly until it reaches its elastic limit. Then, it permanently deforms in proportion to this excess load and to the time it is in the nip. Finally, as it leaves the nip, it expands back to its original size minus the deformation that occurred.

Of course, it cannot be that simple. Its elastic curve is not linear, creep (deformation) begins at relatively low loads, and the rate of creep is not uniform (with time or load). Furthermore, paper is not a homogeneous material, and the expansion of the web is not complete as it leaves the nip.

It is the nonuniformity of the paper that determines much of its behavior. Even if we assume the average fiber structure to be uniform, there are high and low spots on the paper surface that control its behavior. Thus, parts of the sheet begin to deform before others contact the calender surface, and deformation is not uniform across

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the paper surface. We can see the result in the mottle we observe from any calendering operation.

The soft calender roll allows the calender load to be distributed more uniformly across the web. While a hard roll must deform the flocks before it can act on the surrounding paper, the soft roll itself deforms, leading to more intimate contact with the sheet. In practice, the harder roll will produce the higher gloss. It also generates the irregular appearance of the glossy surface we call "mottle." For these reasons, the machine calender, which uses all hard rolls, is applied primarily to control the caliper of the final sheet and build a good reel.

The soft roll also produces a much wider nip. Under the same line load, the actual pressure in the nip is lower for the soft roll than for a harder roll. This softer roll gives the sheet more time in the nip, producing smoother sheets of lower gloss (dull and matte finishes). The relationship of nip load to nip width can be described by a simple relationship first described in the 1950s (1) based on the Hertzian equations for stress analysis.

The formula is:

$$W^2 = [8 L D_1 D_2 (1 - \nu^2)] / [\pi E (D_1 + D_2)] \quad (1)$$

where

- W = nip width, in. or m
- L = nip load, lb/in. or kN/m
- D = roll diameter, in. or m
- ν = Poisson ratio (0.2 to 0.45), dimensionless
- E = elastic modulus of the cover, psi or Pa.

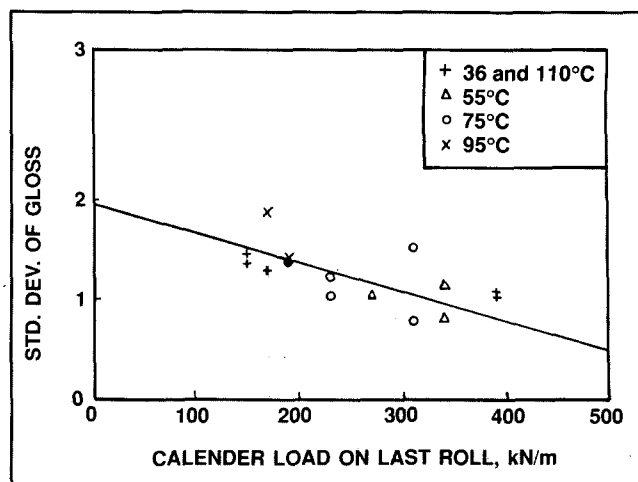
Common load ranges are given in **Table I** for machine calenders, supercalenders, and on-line soft calenders. As we increase calender load, a larger and larger fraction of the paper surface contacts the roll. Finally, a point is reached where virtually all of the surface is in contact with the calender roll. The high points are stressed much more than the low ones. Since more creep occurs in the highly stressed areas, the high points are somewhat self-correcting (but never completely so).

Figure 1 shows the standard deviation of gloss, which reflects the degree of the uniformity of contact, as the calendering pressure is increased. All of these samples were calendered to the same gloss level but at different temperatures and different speeds. The line drawn through the points indicates an improvement in standard deviation at higher pressures. If we were to look at gloss variation in small areas (not apparent in the figure), we could see the evidence of incomplete contact of the surface to the calender at lower pressures.

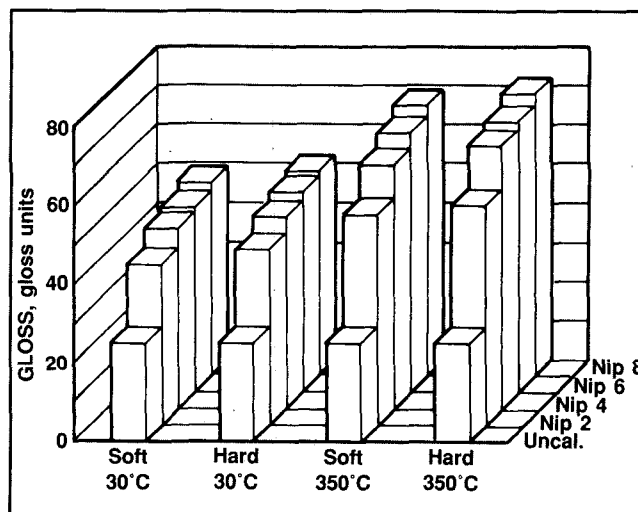
Evidently, a certain minimum pressure is necessary to make a sheet that is uniform in appearance. Early work that we did indicated that this pressure was about 30 MPa (4300 psi). Because this pressure depends on the paper uniformity, its elastic modulus, temperature, moisture, and so forth, such a generalization may not relate to a particular grade.

The irregularities of the sheet surface affect the properties of the sheet in two different ways. First, on a microscopic scale and low roughness level, the irregularities are responsible for the specular gloss. Second, at the size of fiber

1. Uniformity of gloss for both sides of the sheet



2. Improvement in gloss with multiple nips (915 m/min and 175 kN/m)



flocks and shives, the irregularities determine the smoothness as measured by air-leak methods. The calender will change these irregularities to different extents.

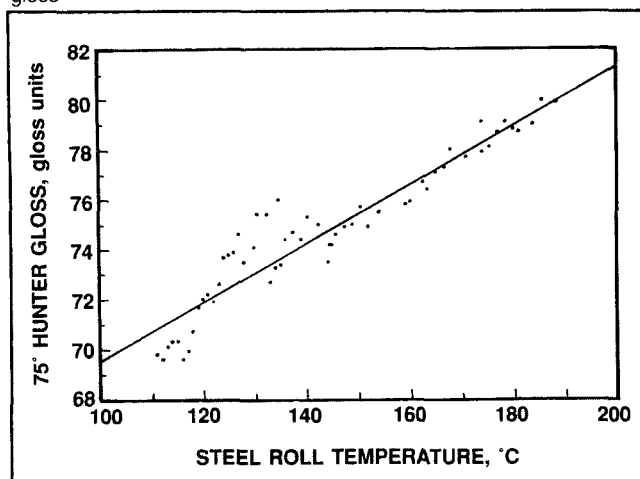
For coated papers, the coating composition can affect the gloss levels without corresponding changes in smoothness (2). The amount of coating drastically affects both the maximum gloss attainable and its final smoothness. For low coating weights of 7.5–13 g/m² (5–9 lb book), fibers extend to the surface of the coating, making surface response sensitive. For coating weights above 18 g/m² (12 lb), little effect is observed.

Compression limits

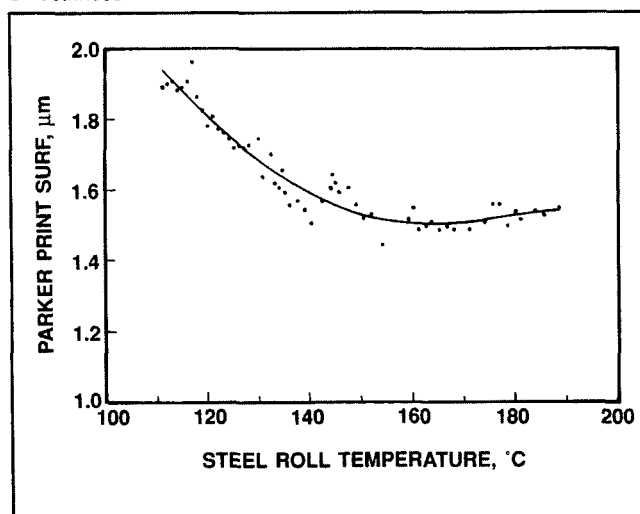
Another factor in the nonuniformity of paper is that, at some particular load, all of the fibers in the network touch, and the elastic modulus increases dramatically. This occurrence naturally takes place first in the flocks, which causes much of the mottle that we see.

In Crotogino's equation for calendering (3–6), the

3. Hot roll calendering, showing the temperature of the steel roll vs. gloss



4. Hot roll calendering, showing temperature vs. Parker Print Surf smoothness



compacting of the sheet, especially of the flocks, is represented by the upper limit of applicability of his equation. In simplified form, the relationship is:

$$e = A + u B_i \quad (2)$$

where

- e = the relative compression of the paper defined as the change in bulk or thickness divided by the original sheet bulk or thickness
- u = the nip intensity factor related to speed, pressure, and temperature in the nip
- A = a constant, different for each grade of paper
- B_i = the sheet bulk before calendering.

Because relative compression, e , contains the bulk of the sheet, the equation is a quadratic equation and has two solution limits. This equation can be solved for the determinant involving the final bulk (or thickness):

$$B_f = (1 - A) / 4u \quad (3)$$

This equation gives the final bulk at and above the upper initial bulk limit. The calendering equation is defined only when

$$B_i \leq (1 - A) / 2u \quad (4)$$

The lower limit on nip intensity (and bulk) is given by

$$B_i \leq -A/u \quad (5)$$

This lower limit represents a region of loading where the calender is not imparting enough stress to produce permanent deformation of the sheet ($B_i = B_f$). It corresponds to loading the sheet below its elastic limit. No useful work on the sheet is done.

Although this equation was developed for machine calendering, it qualitatively describes what happens in the paper, regardless of how the sheet is compressed. Notice that this equation is normally applied to the average sheet compression, not just the flocks. In reality, we would reach this limit in the flocks first. If there were sufficient moisture present, increased bonding would occur, and blackening would result. (Blackening is really a matter of the sheet becoming transparent and giving the appearance of being dark or black.)

Notice also that the amount of change in bulk is proportional to the bulk of the sheet going into the calender. In multiple-nip calenders, the largest changes will occur in the first nips. Therefore, the first nip (steel side) should be applied to the rougher surface of the uncalendered paper. The successive decrease in surface improvement is illustrated in Fig. 2, showing gloss and smoothness development in multiple nips.

Properties that affect cellulose

In practice, there are two major factors that affect the plasticity of the cellulose: temperature and moisture content. Ernst Back and others have made measurements of softening and the glass transition temperature of cellulose under various moisture conditions (7-12). The glass transition temperature is the point where the cellulose and other wood polymers begin to flow, even at low pressures. In paper containing groundwood, the lignin (with its lower glass transition temperature) will also flow. Therefore, a permanent deformation of the fiber occurs in those parts of the sheet raised above its glass transition temperature. This deformation will be in addition to the creep that has occurred previously in the nip. When the web is treated to high temperature, its swelling properties with moisture are permanently changed to some degree (13).

The high-temperature calendering process is complex in several ways:

1. Because of the molecular weight distribution, the glass transition occurs over a wide temperature range.
2. There will generally be a temperature gradient, with parts of the sheet being in the transition range and most of the sheet being below this range.
3. The flow, or creep, properties change nonuniformly

with temperature, resulting in a highly viscous solid (glass) that flows slowly with time.

4. Because the fibers contain moisture, their moisture content will change as the water diffuses in the nip.
5. This same moisture will evaporate rapidly as the paper leaves the nip, resulting in a cooling of the sheet.

Temperature effects—thermofinishing

Because of the range of change of properties and of the temperature gradients, the resultant sheet properties develop quite uniformly to their maximum potential values. **Figure 3** shows the result of hot temperature calendering of a lightweight coated printing paper using a resilient backing roll. No sudden inflection of the gloss produced is encountered up to a temperature as high as 30°C above the predicted glass transition temperature.

The smoothness follows a similar trend up to the point that further compaction of the cooler inner part reaches its limit. This is seen in **Fig. 4**.

Any time we use high temperatures on the iron roll, a temperature gradient will be established. "Hot calendering" is a term used to refer to any of the processes using a hot metal roll (usually at or above the glass transition temperature of the paper). The physical properties will be variable through the sheet in hot calendering. The deformation of the sheet will depend on both its local temperature and its moisture content when the load is applied. (It is not necessary to have all iron rolls to get temperature-gradient calendering effects.) Many calender manufacturers have proposed the use of hot calendering on new installations (14–27).

The basic principle of hot calendering is that the cooler resilient fibers in the center of the sheet do not deform as much as the hotter outside fibers. This temperature gradient permits a smoothing of the outer part of the paper with a minimal deformation through the rest of the sheet. Therefore, hot calender nips require less pressure to obtain the same gloss and smoothness. Keeping the paper in the nip too long may let the heat penetrate through the sheet, destroying the advantage of the temperature gradient. The result of the temperature-gradient calendering is a final sheet with better smoothness and gloss at the same or higher bulk. Photomicrographs by Crotogino (28) indicate that the high deformation seems to be limited to the outer fiber layer (5–10 μm) when temperatures of 200°C and moistures around 6% are used to calender newsprint under a temperature gradient. Similar profiles result from hot calendering with a soft roll.

In a recent paper, Vreeland *et al.* (29) describe a process in which a so-called "sub-stratum" is heated to or above the glass transition temperature to improve smoothness and gloss. This technique is simply a variation of temperature-gradient calendering using a soft backing roll. They propose an equation that can be used by the operator to limit heating to that necessary to soften the outermost fibers. This calculation takes into consideration the incoming sheet moisture, temperature, and the time in the nip (speed and nip width) to find the required drum surface temperature.

When one runs a series of different calendering conditions on the same calender unit at a single temperature, there is a fixed relationship between the smoothness,

gloss, and the bulk of the sheet. Plots of gloss against bulk or smoothness (by an air leak method such as Parker Print Surf) fall on a single curve. However, the operation of a hot calender can produce papers with a higher gloss relative to the smoothness generated. The result is a flatter sheet of paper.

Moisture effects

Because the moisture content affects both the elastic modulus and the gloss transition temperature, the control of moisture is extremely important. The disadvantages of running high moisture to the calender are:

1. Moisture variations across the web are evident.
2. Excess moisture must be removed.
3. Blackening occurs much more easily.

The considerations pertaining to temperature suggest that a moisture gradient within the sheet can also produce a gradient of elastic, flow, or creep properties, resulting in density gradients in the paper. Moisture gradient calendering can be achieved either with steam showers or with water mist sprays (30–32). The advantage of the steam is that it will establish both a temperature and a moisture gradient in the sheet. The disadvantage of steam is that it easily leads to picking or dusting. These advantages of steam are apparent in the application of some of the newer steam showers described in the related literature (30, 33–37).

Summary

In summary, the final properties of a calendered sheet can be controlled by the pressure applied, the roll type and roll hardness, the time in the nip, the roll temperatures, and the moisture of the sheet (and its uniformity). These factors all control the deformation within the sheet which, in turn, relates to the contact of the paper surface to the calender roll. This contact replicates the roll surface. When the pressure is relieved in the nip, the paper partially recovers from its deformation, producing a new paper surface. □

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