Deformation of paper fibers in the supercalender nip

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Previous ways of examining the permanent and elastic deformations of fibers in the sheet as they pass through the supercalender nip were too simple or mathematically complicated. They did not provide a comprehensive explanation to understand important events on a microscopic scale. This paper focuses on a fibrous mat with its inevitable fiber clumps and void fractions. It introduces the idea of flow, the driving forces that cause flow, and the effects of sheet compaction and surface finishing.

Roundtable discussions on the supercalendering of paper include many familiar topics. Participants exchange views about a proper program of preventive maintenance; the proper time to refill rolls; the best combination of speed, loading pressure, and moisture level; and the preferences for trailing blade coaters compared to roll coaters. These roundtable discussions never discuss what is happening to the fibers in the sheet as they pass through the finishing nip.

Why is there no discussion of this important topic? It is the culmination of all the efforts to apply the finest coating on the best possible base sheet by pressing between the most accurate, widest, and fastest calender rolls. The probable reason is that people are simply not familiar with what is occurring in that tiny zone.

It is difficult to gain familiarity with the effect of the finishing nip on paper fibers and coating. Direct observation is difficult or impossible. The sheet passes between a filled roll and a chilled iron roll at a very fast speed. The dwell in the narrow zone of high pressure only lasts a tiny fraction of a millisecond. The rolls are hard and impervious to light. No optical equipment can come close enough to focus on the web edge to resolve single fibers. Even if one could see the web edge effects, it would be hard to convince others that what is happening in the central regions of the web is similar to the occurrences on the outer edge.

Being unable to view the effect directly, one must take the next best alternative. This involves information retrieval from the literature and discussions with experts. These experts are the authors of the published information. Their explanations of events in the nip fall into two categories. There are highly mathematical treatises using complex formulas. These provide carefully graphed lines that fall convincingly on empirical data predicting the observed behavior of some variables. Other explanations try to teach by parable and analogy what might be happening. Although some stories may be easy to remember and relate, the explanations are far from rigorous. Sometimes they are inaccurate. My stories fall into this category, and I apologize profusely for sending any would-be disciples down the path armed with a poorly drafted set of gospels.

Flow of fibrous materials

I previously announced that the answer to the mystery of the nip lay in careful consideration of Von Mises' stresses *(1)*. Although this is a true statement, the publication was faulty because it immediately launched into more easily understood examples. The examples detailed how Von Mises' stresses could cause deformation and flow in materials that behaved as solids. The analogies were to pressing butter into a butter mold or the flow of metal into a forging die. This transgression invited criticism, since everyone knows that paper is a fibrous mat containing many voids or air space.

Figure 1 reproduced from my earlier publication verifies that I had drawn a fibrous web containing substantial void volumes before finishing. Finishing reduced these voids and the volume of the sheet. Visualization of this behavior taking place in the nip occurred as early as 1970 when the original artwork was drawn. The facts were available then *(2)*.

The critics pounced on their prey, however. Reaction was swift and pointed. One paper listed 61 references and contained 14 pages of graphs and charts *(3)*. Some of this ammunition aimed at a statement not in my publication. Critics thought I said there would be no permanent change in the volume of the paper web going through the nip.

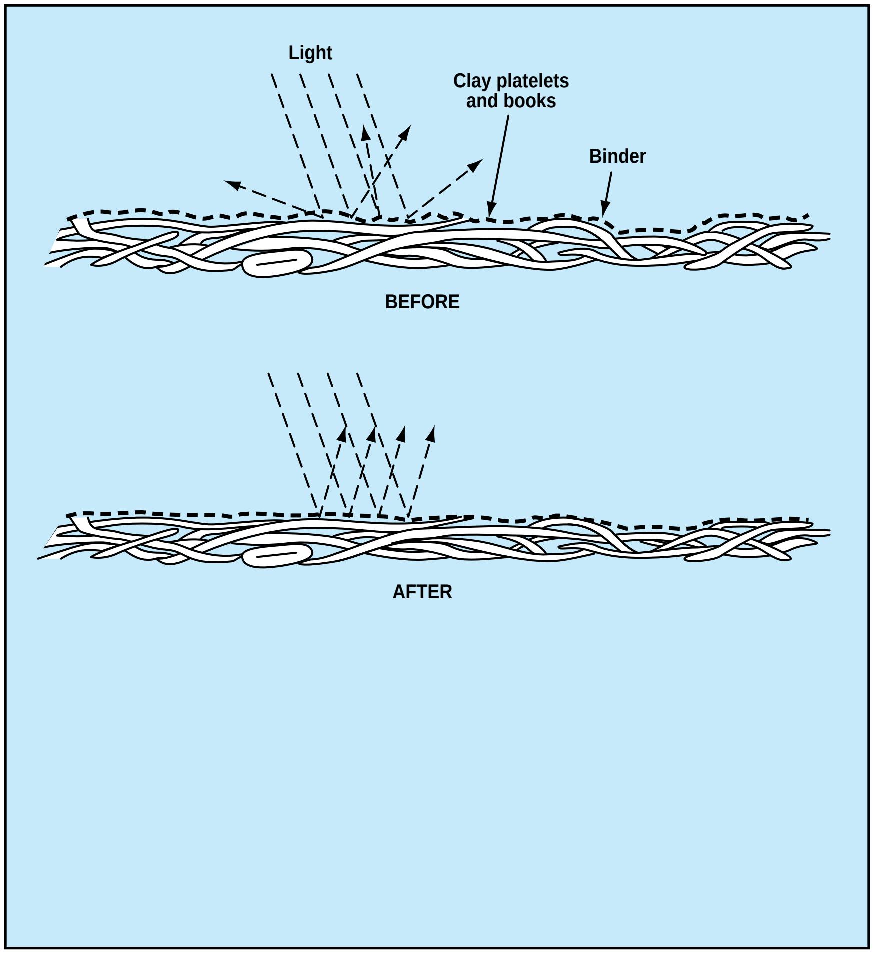
A point to defend is a statement I made that Von Mises' equivalent stress values and octahedral shear stress values—they are interchangeable for a uniform material—are the basis for coloring stress contour plots. Color scales like thermometer scales represent scalar quantities. One number equals one intensity. Stresses at any point in a body are second-order tensors requiring nine coefficients written in a three-by-three array to describe them. It is therefore not possible to assign a color to stresses unless transformed into a "how close are we to failure" scale. The square root of the sum of the squared differences of the three principal stresses is the most popular way to make the conversion. Although there may be others, it does not really matter to the inside cell wall of a tube of cellulose undergoing nip-loaded squeezing.

How can one combine cellular structure, distortion, flow, and pressure into one concept? The secret is in the "tweens." Cartoon animators originated this term in the early days of hand-drawn movie cartoons. The master artists used their valuable time to draw only the key frames in animation. Their assistants filled frames in between—the "tweens"—to create smooth motion.

Knowing where a point on an object is when motion begins and where it is when motion ends, one can position the point at all the intermediate intervals by splitting the motion into the "tween" frames. This involves moving the point slightly between each frame. For two points originally side-by-side with the second point not traveling as far during the total interval, the dots for the second point will advance a shorter distance in each "tween" than the first points do.

If the two points were on a solid—even if that solid were only a cellulose cell wall—then the fact that one point gets ahead of the other in time will generate a bending or distortion in the cell wall or a flow of the solid cellulose wall material due to shear stresses. The net result of distortion, flow, or a combination of both will depend on how the animator positions all the other points in the solid with time. The size of step taken by one point from a given "tween" to the next one and the direction of that step movement can be a displacement vector. Since the time between successive frames is usually a fixed and regular interval, this vector is also a velocity vector. Without becoming too technical, let me simply say that examining velocity vectors for groups of points tells what the resultant motion is doing to the body. It may be translating, rotating, or bending it or causing flow—plastic deformation.

1. Sheet before and after supercalendering showing fibers, voids, and densification or volume change

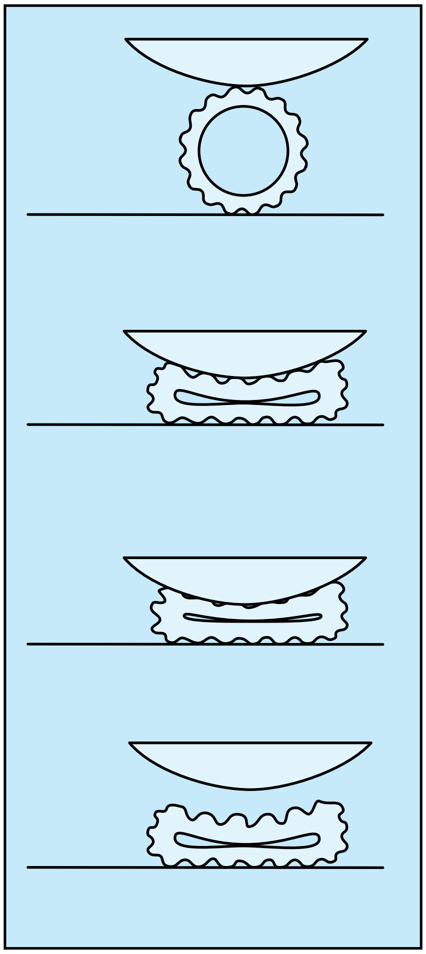


A demonstration using pasta

Our earlier approach gave examples illustrating points by analogy. To continue this, consider the following demonstration one might conduct in the kitchen. The purpose of the demonstration is to clarify the complicated physics of the real situation using an improved model. The model is a partially cooked tube of rigatoni. It now includes a void volume—the hole in the pasta. A tubular piece of pasta simulates an unbroken paper fiber. The fact that it is partially cooked makes it resemble more closely the cellulose that comprises the tube wall of the paper fiber. This assumes that the cellulose contains sufficient moisture to lower its glass transition temperature to our operating range.

Figure 2 illustrates the four key frames necessary to map the continuous motion as a spoon bowl approaches the pasta tube, pushes it closed against a plate, deforms the central portion, then recedes from contact. The intermediate frames drawn for this situation would show many different velocities for points within the material. These would show that flow was occurring particularly at the sharp bend radii when the pressure is highest

2. Key sequential frames when compressing a piece of rigatoni to illustrate fiber compression and flow



in the penultimate drawing.

Can two-dimensional flow really apply to a case where paper fibers cross at random angles to each other in the sheet? Yes, if one considers that the forces urging flow and displacement are strongest in selected directions. It is possible to select a direction to "go with the flow." The direction will change over a short space within a distance of approximately one fiber width. The motion of deformation—otherwise known as flow—will follow the path of least resistance. The pressure at various points will also depend on how many fibers and how much void space exists. Pressure in solids subjected to external forces is slightly more complicated than the pressure of a fluid in a pipeline. The latter are hydrostatic pressures. They distribute equally in all directions. The occurrence of hydrostatic pressure at various points in the web is rare. The reason is that flow occurs with the increase of hydrostatic pressure. If the z-axis—or vertical pressure—is strong, it will generate flow in the machine direction (MD) and cross direction (CD). The relatively weak paper fibers, binders, and coating cannot resist these high pressures. This is particularly true when void spaces exist into which those materials can move. It is a matter of local effective modulus or stiffness in different spatial directions. This couples with the fact that the substrate is a composite of paper fibers—whole and fragmented—containing air space or voids.

Because of the void spaces, the increase of pressure in the MD and CD directions is much smaller than expected, and it is discontinuous. As the pressure starts to increase in a direction perpendicular to the roll force (perpendicular to the z-direction), some flow starts locally and diminishes the pressure. What about the locations where many fibers cross each other to form a substantial resistance to the pressure? These locations are floc centers. Web defects occur there. A large floc center will carry more than the normal share of nip pressure reducing some load from adjoining areas. This is the place in the web where there might be substantial hydrostatic pressures. After pushing the material from the floc center in every direction until blocked against further flow, the cellulose and hemicellulose in that zone will become a gelatinous, translucent mass. The onset of that condition is web blackening or web mottle. One reduces nip loading or sheet moisture whenever this becomes objectionable. Making a more uniform sheet also helps to improve the formation. The cellulose does not change color, it merely loses its ability to scatter light from many surfaces that previously gave it a snowy white appearance. It is similar to compressing snow into black ice.

Building a sheet model

It is possible to continue using the partly cooked—not quite *al dente*—rigatoni to build a sheet model. One can drop the noodles onto a cookie sheet to a depth of five or six noodles in average height. It would be more realistic if rigatoni were not cut so short but were ten times longer to achieve the proper entanglement. Fibers of 15,000 μm width will form a sheet approximately 70,000 μm thick. This would simulate a paper web 70 μm thick providing a scale factor of 1000. Keeping that in mind, one can seek a section of roller with a 300–400-meter radius to simulate the rolling nip. This would be very difficult to find and even harder to move into the kitchen. One can, however, use a strip of 12 mm thick acrylic plastic 2 meters long. Fasten a turnbuckle between the two ends and adjust it so the center bows out 2 mm more than the ends. This will provide a good image of the scale of the "rolling" nip by placing one end of the strip on the floor, lowering it into the pasta, and rocking the 2-mm bow across the tray. If the plastic is clear, it is even possible to see what is happening inside the transparent nip. I do not recommend trying this, but it is a visualization exercise that might make what happens to paper fibers in their passage through the finishing nip a little bit more comprehensible.

Conclusions

In their high speed passage through the finishing nip, paper fibers experience highly unbalanced stresses. The stresses are very low in directions perpendicular to the z-axis or through-sheet axis. They are very high along the z-axis. This provides conditions for plastic yielding in the tubular cell wall structure. The tubes collapse. Cellulose can flow in the MD and CD until it spills off most of the z-axis pressure or encounters some resistance. The stresses are far from being hydrostatic—equal in all directions. They only contain a small hydrostatic component when resistance to flow increases. This is particularly true over floc centers in the sheet. All this occurs with no substantial

MD elongation of the sheet and only a very small percentage growth in CD. Fly rolls or bowed spreader rolls between nips can compensate for this. The volume of the sheet reduces almost as much as the thickness decreases in the nip. Contrary to criticism, I never disputed or denied this point. Von Mises' equivalent stress is still important to the onset of yielding of the cellulose tube walls and the cellulose strips crossing each other at fiber bonds. One can consider tube walls and fibrils as solids, although the cellulose molecules are directionally oriented within them. The resulting difference in critical yield strength along different axes of the fibers is much less important than the fact that empty space surrounds the fibers on many sides including the insides of hollow tubes.

Paper behaves like paper. It does not behave like composite materials made of many layers of strong fibers pointing in precise directions and held in place by an impregnating matrix. For those materials, it is possible to describe the moduli for each layer in every direction. Paper has no rigidizing matrix. It does have an entangled layer structure and contains fibers of random diameters, lengths, thicknesses, and structure. After covering with coatings and clays, paper is more an aggregate than a reinforced structure. Coatings and clays simply go along for the ride through the calendering nip, although they may couple more z-axis pressure into the paper fibers. The binders in the coatings can flow similar to the cellulose in the paper fibers. TJ

Literature cited

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