A method to produce paperboard with a lightweight low-density coating

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ABSTRACT: In this work, a method is described in which a coating layer is produced that consists of a network of bubble-shaped air-filled voids within the coating. This is accomplished by instantaneously flash-drying all the water in the coating as it exits the application nip. The nip is formed between a polished chrome drum and a deformable press roll. The combination of the drum temperature, nip pressure, and nip width allow for sufficient energy to be transferred to the coating to completely flash-dry the coating material. The pressure within the nip is sufficient to allow the coating to superheat within the nip, then flash boil as it exits the nip. This boiling effect and resulting expansion are constrained by the roll surface, resulting in a coated surface that mirrors the polished chrome surface. The coating immobilizes while in the process of boiling, which preserves the bubble structure. With a coat weight of 5 g/m^2, a flat, smooth surface is produced. This process was scaled up to a mill production machine layout and run at speeds as high as 450 m/min.

Application: This work was fundamental and developmental. It did not have a specific application in mind, as we were developing a new method. In light of current trends toward lightweight and functional barrier coatings, this technology may provide an avenue to pursue both.

In this work, a method is described in which a coating layer is produced that consists of a network of bubble-shaped air-filled voids within the coating. This process was discovered as part of a project intended to make cast coated paper at faster line speeds. Cast coated paper is made at slow speeds, typically well less than 50 m/min, with the coated surface held tightly against a large, polished drum during drying, which gives a flat, smooth surface with a mirror-like finish.

One of the early experiments produced a very unique result that caused the project team to redirect their efforts. Initially, a laboratory-scale apparatus was constructed that could consistently produce the desired effect, and process and formulation development continued for about a year. At that point, it was decided to scale up the process in a pilot plant to assess its commercial feasibility. The scale up did not go smoothly, and the project team was forced to take a step back and establish the underlying fundamentals of the process to ultimately succeed. The process of converting from an empirical approach to a fundamental approach was time consuming, and at times arduous, which is difficult to capture in this manuscript.

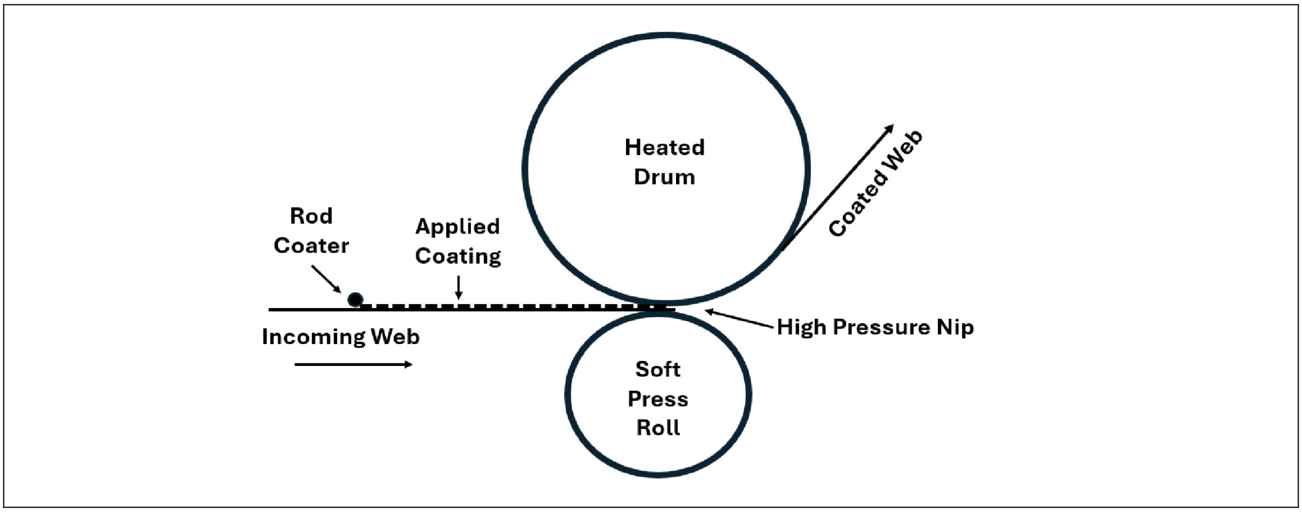
It is important to emphasize that this was not a project that started with a fundamental principle and built-up from there. Instead, it was a product development project with an empirical beginning that ultimately led the team to the fundamental aspects of this unique discovery. The story will be told from back-to-front starting with the final result, then explain the underlying fundamentals.

METHODS AND MATERIALS

The bulk of this work was conducted using uncoated solid bleached sulfate (SBS) paperboard with base sheet calipers ranging from 0.3 to 0.38 mm (12 to 15 point). Solid unbleached sulfate (SUS) paperboard was also used to demonstrate its viability in this process. The coating process was a rod coater applying a starch-based coating, which was then brought into contact with a hot polished drum under pressure (**Fig. 1**). This was a process development project, so a wide range of operating conditions were evaluated, including the following:

- Machine speed: 15–450 m/min
- Coating formulation: The most commonly used formulation was an ethylated starch solution with 25%–30% solids containing 4% glyoxal crosslinker, 20% glycerol, and 3% vegetable oil-based lubricant (all percentages based on dry starch).
- Coat weight: A range from 5–15 g/m^2
- Applicator roll: rubber roll, 30 Shore D hardness
- Applicator roll nip pressure: 3.45 MPa
- Heated drum surface: tungsten carbide surface ground to a 2-µm finish
- Heated drum temperature: surface temperature 240°C

The resulting coated paperboard surface smoothness was measured as Parker Print Surf and Sheffield smoothness according to TAPPI Standard Test Methods T 555 "Roughness of paper and paperboard (Print-surf method)" and T 538 "Roughness of paper and paperboard (Sheffield meth-



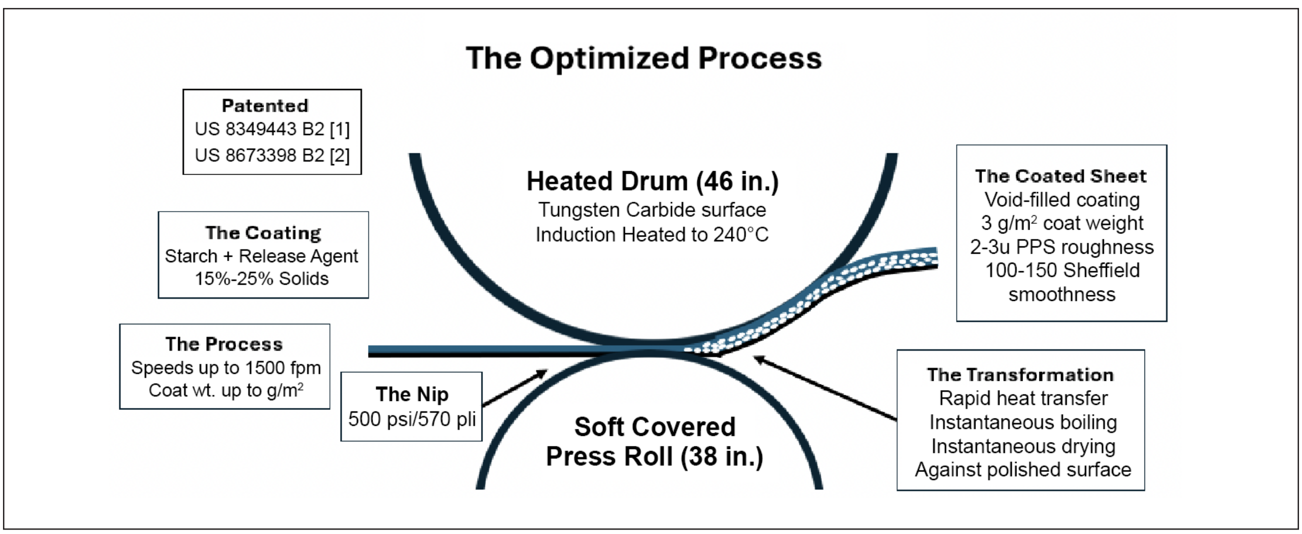
1. Schematic of the coating and forming process.

od)," respectively. Further surface analysis was also conducted using light and scanning electron microscope (SEM).

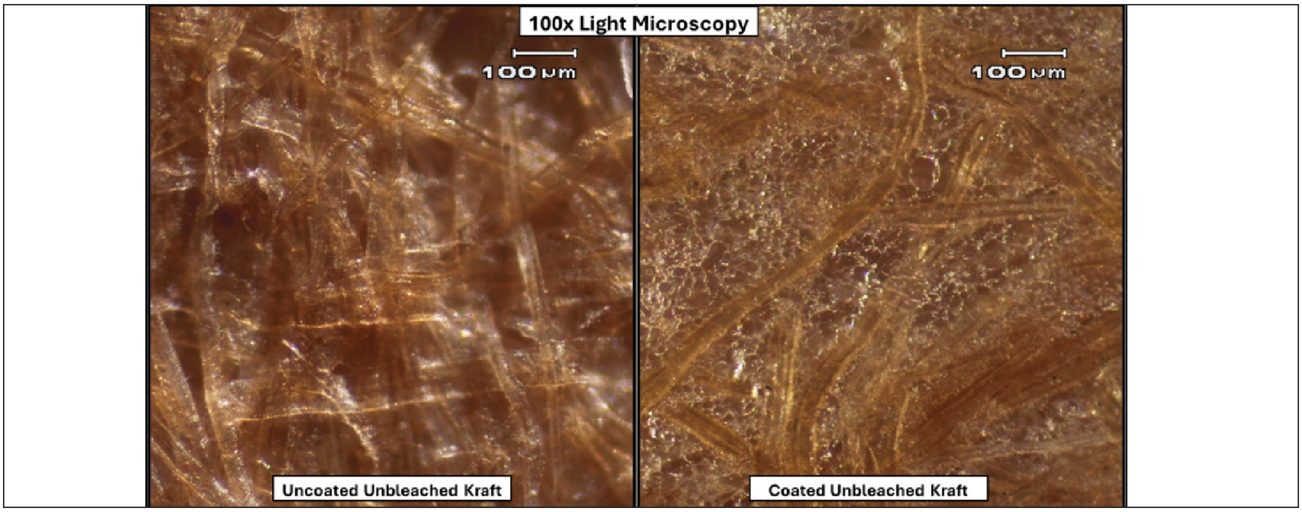
RESULTS AND DISCUSSION

The Process

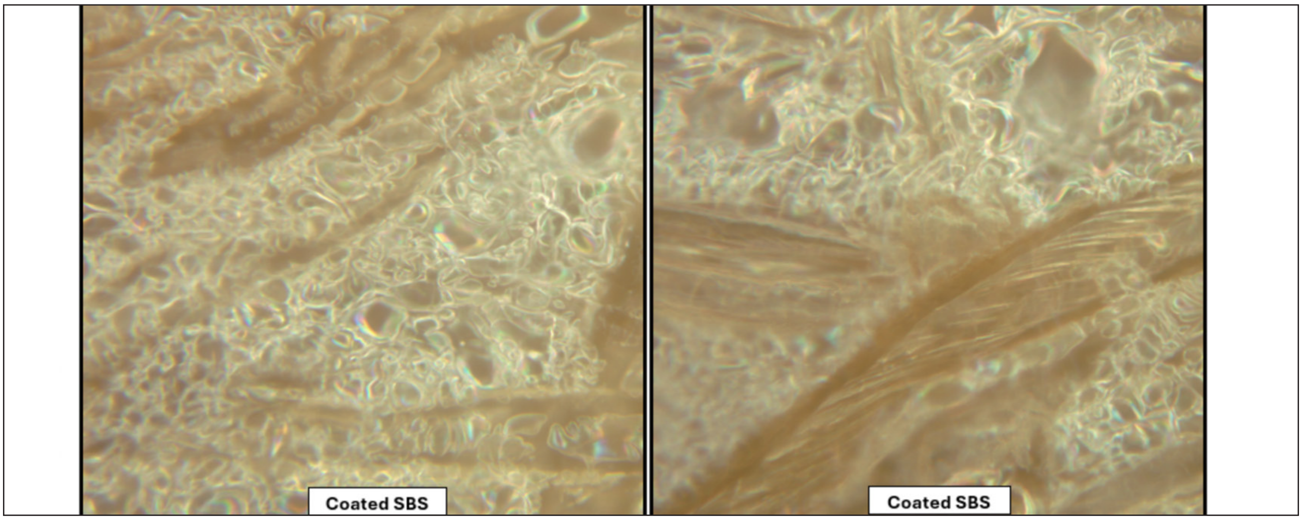
The process as described and resulting product were patented. The details can be found in patents US8349443B2 [1] and US8673398B2 [2]. A wide variety of coating formulations were evaluated, which will be presented later, but in its simplest form, the process is depicted in **Fig. 2**. A simple coating consisting of starch, a vegetable oil-based release agent, and a crosslinker was applied to the paperboard surface prior to reaching the ingoing nip. Coat weights as high as 15 g/m² were successfully run at slow speeds, but the work suggested 5 g/m² (dry) to be sufficient for complete base sheet coverage. The preferred coating solids was about 25% but can be lowered to accommodate longer dwell times before entering the nip. The process was demonstrated at speeds as high as 450 m/min, but most of the work was conducted at 240 m/min. The nip forms between a heated steel drum with a polished surface and a deformable press roll. Temperature and pressure were adjusted to accommodate the line speed and coat weight, but at 240 m/min, the drum temperature was 240°C and the press roll pressure was 3.45 MPa. The drum was heated by induction heating. In the nip, enough energy was transferred to the coating to completely evaporate the water in the coating. The combination of temperature, pressure, and nip width allows the coating to superheat to accept sufficient energy. Upon release of the pressure as the coated substrate exits the nip, the coating flash dried and expanded due to boiling while being held against the polished surface. The resulting coating had a voluminous structure due to the coating being immobilized while boiling as a result of the elevated drum temperature. The coating surface mirrored the smoothness of the polished drum, which had a ground surface roughness of 2 µm.



2. An overview of the final process.



3. 100x microscopic images of untreated (left) and treated solid unbleached kraft board showing bubbles in the coating (right).



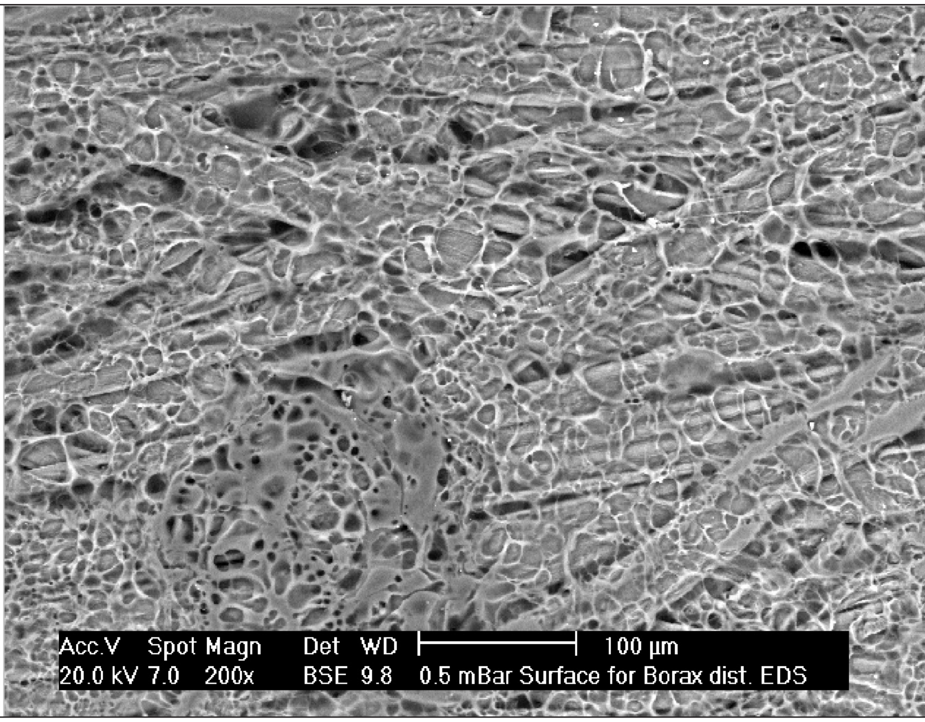
4. 800x scanning electron microscope (SEM) images of treated solid bleached sulfate (SBS) board.

The Product

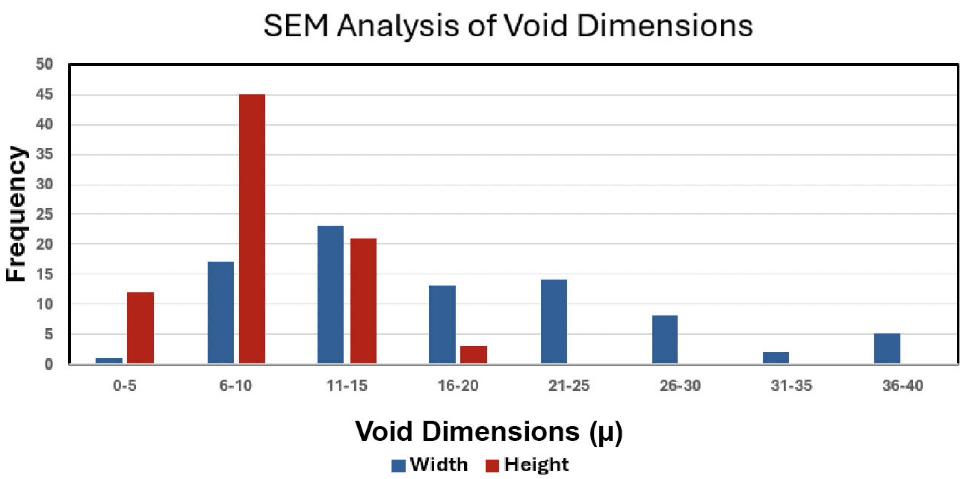
The surface structure of the coating can be seen clearly with a light microscope as shown in **Fig. 3**. Most of the work was conducted using SBS paperboard, but the process worked just as well with SUS paperboard. The images in Fig. 3 are shown on unbleached board, which makes the bubble structure easier to see due to the contrast between the coating and the darker substrate. These images were captured using a standard light microscope at 100x. The left of the two images is the board surface prior to treatment and the right is after treatment. The bubbles contained in the coating can be clearly seen. Additionally, it is clear that the roughness of the board has been filled and the surface fibers have been covered. **Figure 4** shows images of treated SBS at considerably higher magnification. For these images, an SEM was used. At this higher magnification, we can see that there is a wide distribution of bubble size and that some of the bubbles are very small.

Characterizing the size distribution of voids within the coating

To determine the size distribution of the bubbles, an SEM in backscatter mode was used, which made the edges of the bubbles stand out. Using a combination of surface scans (**Fig. 5**) and cross-sections, the size distribution of the bubbles could be determined (**Fig. 6**). We found that the height of the bubbles was considerably smaller than the width and had a much narrower distribution. The project team discussed this observation and believed this was related to the coating being more constrained in the *z*-direction than in the *x-y* direction. Bubble heights ranged from 5–15 μ with an average of about 10 μ. Bubble widths were widely distributed from 5–40 μ with an average of about 20 μ. This process was unique in its ability to create bubbles of 10 μ or less. Bubbles this size are very difficult to create, even in foams, and are generally very unstable.



5. An SEM image of a treated board surface using backscatter imaging.



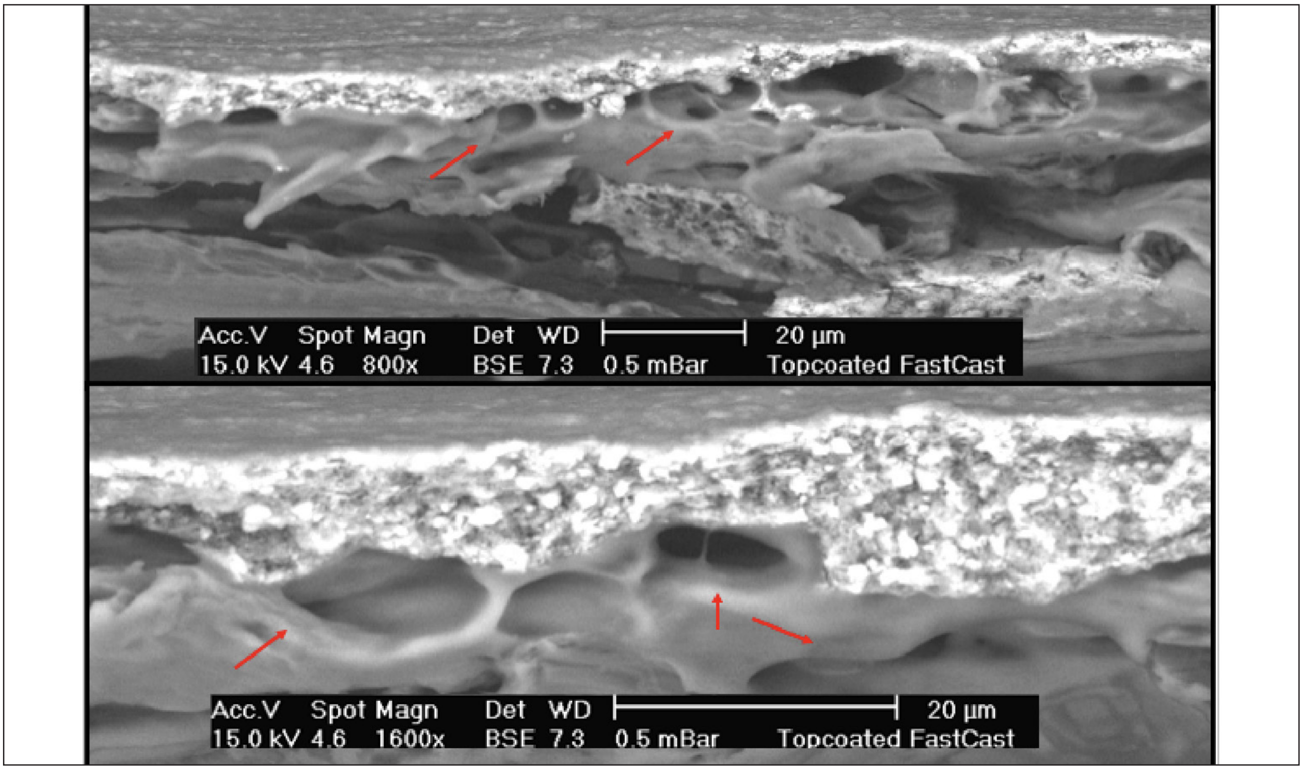
6. An SEM analysis of internal void dimensions.

Potential product applications

This work was conducted as a product development project in an industrial research environment, so academic rigor was not a priority. The team explored a wide range of potential commercial product applications, so many experiments were conducted to determine the robustness of the coated surface and potential end-use applications. Other soluble polymers were also evaluated, such as carboxymethylcellulose and polyvinyl alcohol, but the increase of viscosity, due to crosslinker addition, was prohibitive. One method was discovered to circumvent the viscosity issue by spraying the crosslinker onto the surface after coating application, but prior to the nip. The resulting coating structure was comparable to the starch-based coatings. Successful experiments were conducted by adding glycerol to starch as a plasticizer to alter the flexibility of the coating layer. It was found that flexibility (lower stiffness) could be improved by adding 15%–30% plasticizer, and a lack of visible cracking of the coating was also observed.

Results confirmed the process for speeds ranging from 15 to 450 m/min, and coat weights from 5–15 g/m^2 for non-pigmented coatings. The project team was also able to successfully apply pigmented coatings with pigment-to-starch ratios as high as 50:50 on a dry weight basis. These coatings resulted in higher coat weights.

Further work was carried out with samples created using



7. The SEM micrographs of top-coated low-density board.

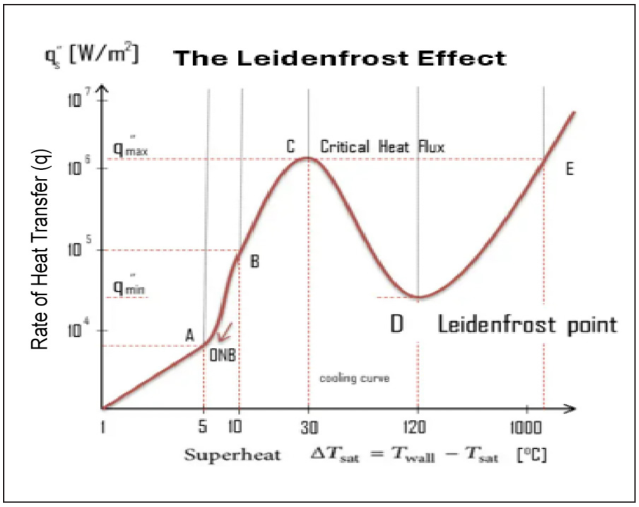
this process. A successful prototype was printed using a four-color sheetfed offset press. This prototype contained 20% glycerol based on starch. A metalized coating was then applied to this same coated paperboard. The metalized paperboard demonstrated that the flatness of the surface would be sufficient to make an acceptable metalized product. Both of these experiments were conducted as proof-of-concept but not pursued further.

Once the process was optimized, additional work concentrated on using the surface as a base coat for typical double-coated grades. This work progressed as far as the preparation of engineering drawings for a production-scale process. However, the work was discontinued due to the development of an alternative technology that was simpler and less capital-intensive to implement. This alternate technology is considered a trade secret and will not be discussed further.

Figure 7 shows SEM micrographs at two different magnifications of top coated samples of the low-density coatings. These samples were freeze-fractured, as opposed to conventional microtoming. The “bubbled” structure and relative volume of the basecoat in contrast to the conventional top coating structure can be clearly seen in these images

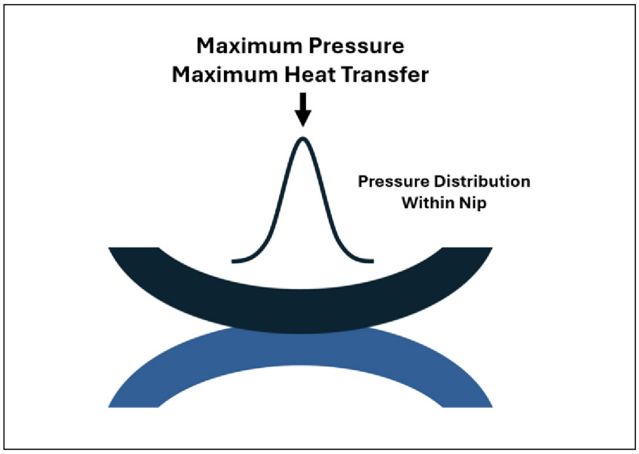
The Fundamentals

As stated in the introduction, this work was originally conceived as a high-speed cast coating process, and the web initially wrapped a substantial portion of the heated drum. It was discovered that the most important process effect occurs within the nip between the two rolls. Making the process work required a precise balance of nip width, nip pressure, and dwell time in the nip. Optimizing these parameters allowed the transfer of enough energy to completely dry the coating by the time the coated substrate exited the nip.



8. The Leidenfrost effect describes the rate of heat transfer as a function of the temperature difference between a heated surface and water [3].

A key discovery was that it was possible to overheat the drum surface. Heat transfer to water is a very nonlinear process, as shown in **Fig. 8**. This graph shows heat transfer to water, at atmospheric conditions, as a function of the



9. Diagram of the proposed pressure distribution within the nip.

temperature difference between the heated surface and the water. If the difference is too large, the steam vapor produced provides an insulating layer that prevents heat transfer. This phenomenon, called the Leidenfrost Effect, is what causes a water droplet to dance on a hot griddle. As the temperature difference increases, a point of maximum heat transfer is reached, beyond which heat transfer rapidly decreases and reaches a secondary minimum. The shape and location of this curve changes with pressure. Because of this relationship, experiments were run to empirically determine the optimum surface temperature for the nip pressures used in the developed process.

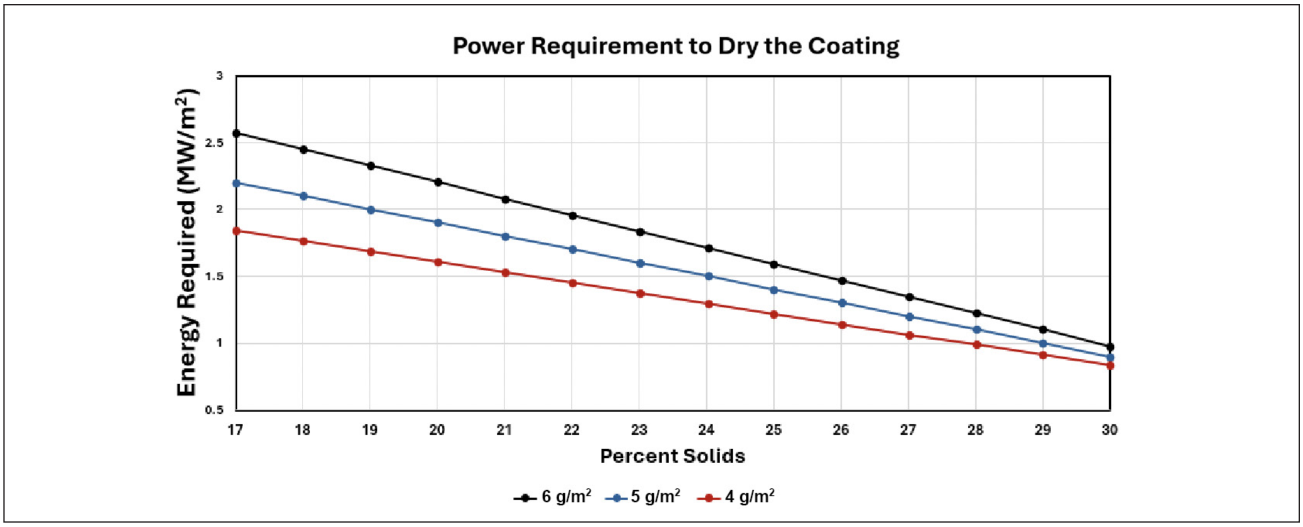
Based on this model of heat transfer, we developed a working model of the process occurring within the nip. The combination of nip width, nip pressure, and rapid heat transfer creates a large, narrow pressure distribution within the nip that results in superheating the water in the coating (**Fig. 9**). This superheating effect causes the coating to flash boil and dry in the outgoing side of the nip. The coating rapidly expands and then immobilizes, preserving the boiling structure in the dried coating. The optimized process balances coat weight, nip pressure, nip width, and surface temperature. Once a target coat weight (approximately 10 g/m^2) was set, for any given line speed, the drum temperature could be adjusted and pressure determined to obtain the necessary heat transfer and dwell time. A speed of 250 m/min was determined to be a manageable line speed for the apparatus we had constructed. A resilient press roll with a 30 Shore D hardness led to an optimum surface temperature of about 240°C at a nip pressure of 3.45 MPa. With this configuration, the project team could consistently produce the desired effect.

The energy required to evaporate the water in the coating can be calculated at varying coat weight as shown in **Fig. 10**. These values were consistent with the energy being supplied to the heated drum.

CONCLUSIONS

In conclusion, this research has successfully demonstrated a high-speed cast coating process that achieves a robust and effective coating. The process involves applying a basic coating, consisting of starch, a vegetable oil-based release agent, and a crosslinker, to the board surface before it reaches the ingoing nip. The project team's findings revealed that the entire process effect of producing a low-density and smooth coating occurs within the nip between the two rolls. By empirically determining the optimum surface temperature for the nip pressures used, a working model of the process could be developed. This model highlights the importance of the combination of nip width, nip pressure, and rapid heat transfer in creating a large, narrow pressure distribution that superheats the water in the coating, causing it to flash boil and dry on the outgoing side of the nip.

The resulting coating structure is voluminous and mirrors the smoothness of the polished drum surface. The process was demonstrated at various speeds and coat weights and successfully applied pigmented coatings. For



10. Power requirements to completely evaporate the water in a coating.

starch-based coating, plasticizers were used to alter the flexibility of the coating layer. Additionally, prototypes were printed, and metallized coatings were applied as proof-of-concept, showing the potential for commercial product applications.

Although the project was discontinued in favor of a simpler and less capital-intensive alternative technology, the insights gained from this research provided a solid foundation for future developments in high-speed cast coating processes. The optimized process parameters and the understanding of heat transfer dynamics within the nip could be valuable for advancing coating technologies and exploring new applications. **TJ**

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About this journal

ABOUT THE AUTHORS

We studied this topic to help in developing lightweight, low-density solid bleached sulfate (SBS) paperboard grades. The most difficult aspect of this work was scaling the technology to production scale. We eventually discovered a unique method for drying coatings and creating a unique coating structure, and it was interesting to see how everything occurs within the high-pressure portion of the nip. Mills might consider this study in their efforts to produce low-density grades.

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