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Thermal Coating Development for Impulse Drying*

W.J. Lenling, M.F. Smith, and D.I. Orloff

A plasma-sprayed coating has been developed for the heated surface of rolls used in a new energy-efficient paper drying process, known as "Impulse Drying," which could save the US paper industry an estimated $800 million annually in reduced energy costs. Because impulse drying rolls operate at substantially higher surface temperatures than conventional drying rolls, the thermal properties of the roll surface must be carefully tailored to control energy transfer to the paper and thus prevent sheet delamination or other undesirable effects. To meet this requirement, a plasma-sprayed thermal barrier coating has been developed to control thermal mass, heat transfer, and steam infiltration. A coated test platen significantly outperformed a comparable uncoated steel platen in preliminary experiments with a heavy-weight grade of paper on a laboratory-scale impulse drying simulator. Based on these results, the coating was then tested on the roll of a pilot-scale impulse dryer. Compared to conventional wet pressing, linerboard that was impulse dried with the coated test roll showed marked improvements in water removal as well as improved physical properties, such as density and specific elastic modulus. The successful prototype coating design has three plasma-sprayed layers that are deposited sequentially: a nickel alloy bond coat, a thick, 17% porous zirconia thermal barrier, and a thin, 5 to 7% porous zirconia top coat.

1. Introduction

THE pulp and paper industry is one of the largest industrial consumers of energy in the United States.[1-3] Based on an average of 35 MJ/kg (30 million Btu/ton) of paper produced and an annual production of 7×10^{10}kg (76 million tons) of paper, this industry consumes an estimated 2.4×10^{18} J (2.3 Quads) of energy annually. Drying is the largest single use of energy in the papermaking process and accounts for about one quarter of the total energy consumption. Therefore, even a modest improvement in drying efficiency can yield substantial energy and cost savings.

In conventional wet pressing and evaporative drying processes, a great deal of energy is required to heat and vaporize water. The impulse drying process takes advantage of a different water removal mechanism. In this process, a steam pulse propagates through the paper and expels much of the water in liquid form, thus saving a significant amount of energy that would normally be required to heat and vaporize that water. In typical impulse drying, wet paper is brought into contact with a press roll that has been heated to a temperature of 473 to 673 K (200 to 400 °C), and a peak pressure of 3 to 6 MPa (435 to 870 psi) is applied for 20 to 40 ms as the paper passes through the nip (i.e., the high-pressure "pinch" region) of a drying press. Under these conditions, water at or near the interface between the sheet and the heated roll surface flashes to steam. This steam layer grows and propagates through the sheet, displacing liquid water into a receiver, typically a press felt, that is in direct contact with the sheet on the side opposite the heated roll. It is estimated that wide-scale implementation of impulse drying could reduce paper drying costs in the US by at least 10%, a potential savings of roughly $800 million annually.

Although the basic principles and potential advantages of impulse drying have been known for some time, prior research[4-7] has shown that delamination of paper sheet subjected to impulse drying is a serious problem that must be solved before this process can be commercialized. The delamination problem was most apparent when drying heavy-weight paper grades, such as linerboard. This was extremely unfortunate, because these grades have the greatest potential for significant energy savings.

Researchers at the Institute of Paper Science and Technology (IPST) hypothesized that delamination is caused by the transfer of excess energy into the paper, with the result that water in the inner part of the sheet becomes superheated. Then, as the sheet leaves the nip and the applied pressure is rapidly released, the superheated water within the sheet flashes to steam, causing the sheet to delaminate. To test this hypothesis, IPST performed tests with a laboratory-scale impulse drying simulator (Fig. 1) using different materials to alter the heat input to the paper sheet.[8-10] Platens for the impulse drying simulator were made from the following materials: steel, aluminum, porous sintered stainless steel (two different densities), and a low thermal mass machinable ceramic. The steel and aluminum resulted in different heat fluxes to the paper sheet, but the effect on delamination was negligible. The porous stainless steel platens suppressed delamination, but venting of steam into the porous platen surface reduced the intensity of the steam pulse in the sheet, thus

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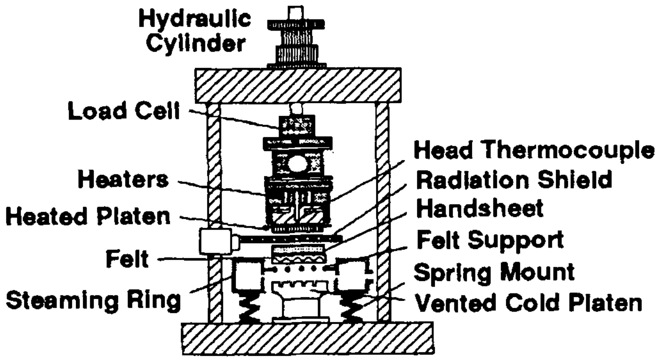

Fig. 1 Electrohydraulic press used to simulate wet pressing and impulse drying.

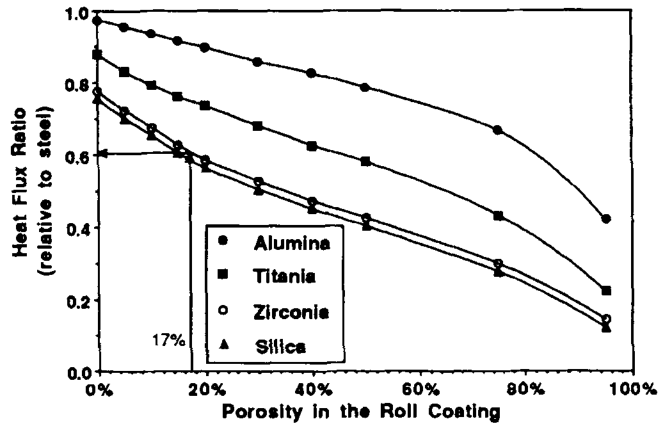

Fig. 2 Calculated heat flux into a paper sheet as a function of the porosity in the candidate coating material. These results are based on an initial roll temperature of 573 K (300 °C), and they have been normalized to the heat flux from an uncoated steel roll.

greatly decreasing the expulsion of liquid water into the felt and reducing drying efficiency. The machinable ceramic provided good water removal, and it also reduced delamination by limiting the transfer of excess energy to the sheet. Unfortunately, commercial drying rolls are quite large, typically on the order of 1.2 m (4 ft) in diameter by 6.1 m (20 ft) long, and it is not practical to produce such a roll from a monolithic ceramic material.

In view of the success of the ceramic platen tests at IPST, it was proposed that a plasma-sprayed ceramic coating on a conventional steel roll might provide a practical way to achieve the desired thermal properties and performance. With funding from the US Department of Energy, a joint research program to produce and test plasma-sprayed coatings for possible use on impulse drying rolls was initiated by the Institute of Paper Science and Technology, Thermal Spray Technologies (TST), and Sandia National Laboratories.

2. Materials Selection

The coating material should have a low thermal conductivity and a low heat capacity to minimize energy transfer to the paper sheet. Four common oxides—Al_2O_3, TiO_2, ZrO_2, and SiO_2—were selected for initial consideration on the basis of published thermal properties.[11] For a given coating material, the level of porosity in the coating also has a strong influence on the bulk thermal conductivity and bulk heat capacity of the coating. The heat flux into the paper sheet was calculated for each of the four candidate materials with various levels of porosity, and the results were normalized to the heat flux that would occur with a conventional, uncoated steel roll. The computed results in Fig. 2 show that the heat flux into the paper decreases in a nearly linear relationship as the porosity increases for each of the four candidate materials. Additional details concerning these calculations are presented in Ref 10.

Based on the results in Fig. 2, zirconia or silica would be the best choices to minimize the heat flux to the paper sheet. Zirconia was selected for further development for several reasons. Fine silica powder is a potential health hazard, and zirconia is much easier to plasma spray than silica. Also, because plasma-sprayed zirconia thermal barriers are used extensively for aircraft engines and other commercial applications, many different types of high-quality zirconia powders are tailored for plasma spraying. For this initial proof-of-concept study, an arc-fused/spray-dried, partially stabilized zirconia (PSZ) containing 8.0 wt% yttria, 1.7 wt% hafnia, and 0.4 wt% silica was selected. This material was chosen primarily because research has shown that arc-fused/spray-dried powders tend to produce more porous coatings than hollow spherical powder (HOSP) or fused and crushed materials.[12] Also, this particular spray powder, Zircoa Zirspra™ 9204, has performed well in other thermal barrier applications at Sandia and at TST. The particle size range of the zirconia powder was −100 to +44 µm.

3. Thermal Properties of Sprayed Zirconia

The specific heat and thermal diffusivity of the plasma-sprayed zirconia was measured as a function of temperature at the Properties Research Laboratory of West Lafayette, Indiana. These measurements were repeated for a series of sprayed samples with porosities ranging from 5% to nearly 20% by volume. The resulting data were used to predict the specific heat and thermal diffusivity for a theoretical full-density (0% porosity) plasma-sprayed material (Fig. 3).

A parameter called the "thermal mass," defined as the ratio of the thermal conductivity to the square root of the thermal diffusivity, is useful in considering potential surfacing materials for impulse drying. Thermal mass (K) can also be expressed as follows:

$$K = [\rho C_p \sqrt{\alpha}]_{\text{solid}} \frac{[1 - V]^{1/2}}{[1 + C'V]}$$

where ρ is density; C_p is specific heat; α is thermal diffusivity of the solid ceramic; V is the volume fraction of pores in the sprayed coating; and $C' = 8.52$ is a constant determined from the curve of the best fit to the measured data. As shown in Fig. 4, the thermal mass of a plasma sprayed PSZ coating decreases significantly with increasing porosity, but it is relatively insensitive to operating temperature up to at least 800 K (527 °C). In general, the ideal coating should have the lowest practi-

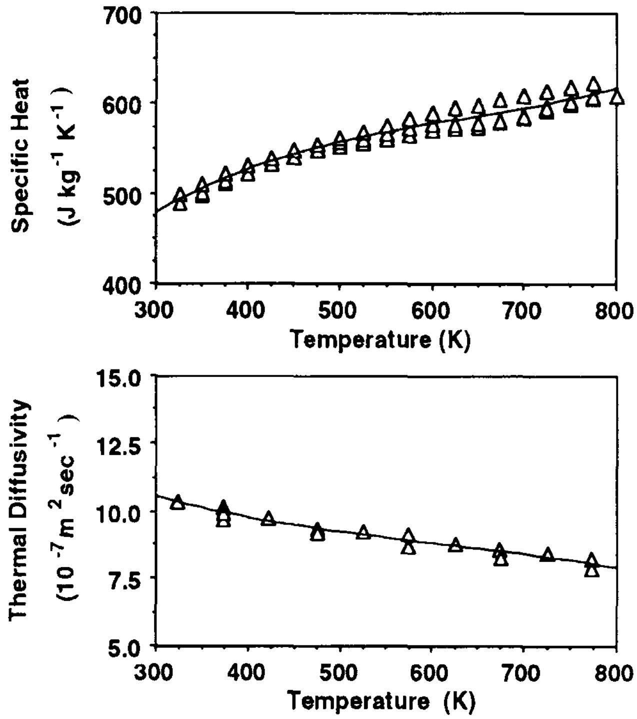

Fig. 3 Specific heat and thermal diffusivity versus temperature for a theoretical, full-density, plasma-sprayed 8 wt% yttria/1.7 wt% hafnia partially stabilized zirconia.

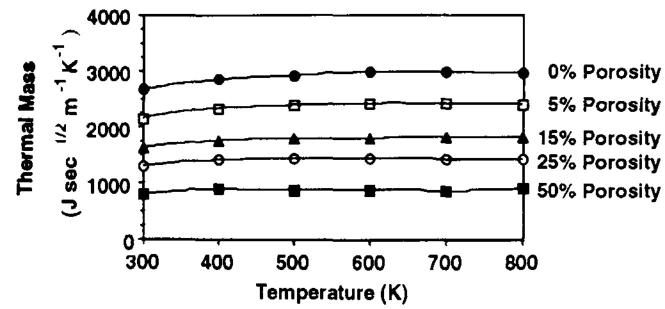

Fig. 4 Thermal mass of 8% yttria/1.7% hafnia PSZ as a function of porosity and temperature.

cal K value, which is consistent with the earlier statement that high porosity is desirable for the impulse drying roll coating.

4. Coating Design for Impulse Drying Tests

A porous zirconia coating sprayed directly onto a steel platen or roll would meet the basic requirement for a low thermal mass coating. However, practical factors, such as adhesion of the coating to the substrate and possible venting of steam into the porous coating, must also be considered. For these reasons, the test coating consisted of three layers that were plasma sprayed sequentially onto the test hardware—a metal alloy bond coat, a thick, porous PSZ thermal barrier, and a thin, relatively dense PSZ top coat.

4.1. *Bond Coating*

A Ni-6.5Al-6.0Mo (wt%) alloy with a –105 to +44 μm particle size distribution from Anval of Rutherford, New Jersey, was selected for the impulse drying application. This bond coating provided a tensile adhesion strength of ceramics to metals of typically 20 to 35 MPa (3 to 5 ksi) and could be sprayed at relatively high deposition rates of 0.08 mm (0.003 in.) per pass. A high deposition rate is attractive for the impulse drying application due to the exceptionally large surface area to be coated on an actual commercial drying roll. Surfaces of the test samples were cleaned and degreased with 1,1,1-trichloroethane and then grit blasted with 36-mesh aluminum oxide at a blasting pressure of 275 kPa (40 psi) before a final trichloroethane rinse. The bond coating was then applied to a thickness of 0.08 to 0.13 mm (0.003 to 0.005 in.) using the plasma spray parameters shown in Table 1.

Table 1 Plasma spray parameters

Process parameter	Ni-Al-Mo bond coat	17% porous zirconia	5 to 7% porous zirconia
Anode type	2083-119MI	2083-119MI	2083-165
Cathode type	1083A-120	1083A-120	1083A-129
Gas injector	1083A-121	1083A-121	2083-130
Arc gas and flow, L/min	Argon, 47	Argon, 47	Argon, 47
Auxiliary gas and flow, L/min	Helium, 20.5	Helium, 20.5	Helium, 20.5
Arc current, A	800	950	950
Arc voltage, V	37	38	37
Carrier gas, L/min	Argon, 5	Argon, 5	Argon, 5
Powder feed, g/min	39.9	44.5	44.5
Spray distance, cm	10	10	9
Traverse rate, cm/s	51	51	51

Note: All coatings were deposited with a Miller Thermal Technologies model SG-100 plasma gun.

4.2. *Porous Zirconia*

Although high porosity in the sprayed coating is desirable for impulse drying, there are practical limits to the porosity that can be produced in a sprayed coating. The upper limit of porosity that could be reproducibly achieved with a reasonable deposition efficiency was 17%, as determined by quantitative image analysis of the relative areas of solid ceramic and pores in polished metallographic sections. It is noteworthy that the procedure used for metallographic preparation of brittle coating materials, such as porous ceramics, can strongly influence the apparent porosity in a polished metallographic mount. An investigation of this problem and a detailed description of the procedure used to prepare the metallographic samples for this study have been presented previously.[13]

As shown in Fig. 2, a 17% porous zirconia coating should ideally result in a heat flux to the paper sheet that is approximately 60% of the heat flux from an uncoated steel roll operated at 573 K (300 °C). Therefore, even though a further increase in porosity might be desirable, the 17% porous coating still provides a significant potential reduction in energy transfer to the paper sheet. Using the spray parameters summarized in Table 1, a 0.38 mm (0.015 in.) thick layer of 17% porous zirconia was deposited over the Ni-Al-Mo bond coating on the steel test hardware.

4.3. *Top Coat*

The results described earlier for impulse drying simulator tests with porous stainless steel platens suggest that excessive escape of steam into a porous coating might reduce the intensity of the steam pulse propagating through the sheet, thus decreasing the expulsion of liquid from the sheet into the felt. To minimize steam infiltration into the coating, a thin, dense top coat was applied over the high-porosity zirconia. Initially, two different top coating materials were tried. One was the same zirconia spray powder that was used for the 17% porous zirconia layer, but the plasma spray parameters were adjusted (Table 1) to reduce the porosity in the deposited zirconia to approximately 5 to 7%. The dense zirconia top coat was kept relatively thin, with a final thickness of approximately 0.05 mm (0.002 in.) after the coating surface was diamond ground to a 1.01 µm R_a finish. Therefore, the overall bulk properties of the porous and dense layers of sprayed zirconia were still dominated by the much thicker layer of the 17% porous material. Microstructures representative of the nickel alloy bond coat, the 17% porous zirconia, and the 5 to 7% zirconia top coat are shown in Fig. 5.

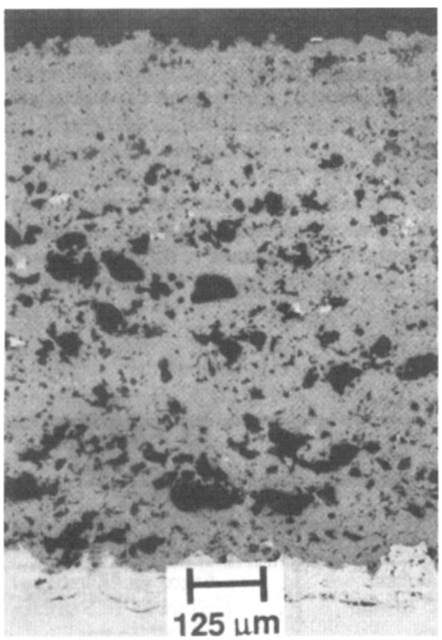

Fig. 5 Cross section of an as-deposited coating, showing typical microstructures of the porous and dense zirconia layers as well as the bond coat. Although these microstructures are representative, the zirconia layers in this photograph are somewhat thicker than the corresponding layers of the prototype test platen and roll.

As an alternative to the dense zirconia top coat, several experiments were also conducted with a thin layer of copper plasma sprayed over the porous zirconia. Because copper has a higher thermal conductivity and heat capacity than zirconia, the thin copper coat was tried to explore the effects of a more intense initial heat pulse. The copper top coat was kept as thin as possible, approximately 0.025 to 0.050 mm (0.001 to 0.002 in.) after finish grinding of the sprayed surface, in an effort to limit its thermal mass contribution. Nevertheless, the copper-coated test platen produced significant sheet delamination in laboratory-scale impulse drying tests. This experimental result is consistent with predictions of prior process modeling results that showed that a low thermal mass is needed to suppress paper delamination. Therefore, the test results are based on hardware surfaced with the 5 to 7% porous zirconia top coat.

5. Laboratory Simulator Tests

The impulse drying performance of the plasma-sprayed zirconia was initially tested by IPST using the same electrohydraulic simulator (Fig. 1) that was used for the earlier monolithic metal and ceramic platen experiments. The performance of a 127 mm (5 in.) diameter steel platen plasma sprayed with the multilayer coating was compared to that of an uncoated steel platen. The paper used for these experiments was a 205 g/m^2 single-ply linerboard, a heavy-weight paper grade that is highly susceptible to delamination. Linerboard handsheets were prepared and presteamed to a typical processing temperature of 358 K (85 °C) with 30% in-going solids. Experiments were run at peak pressures of 3.1, 4.8, and 6.2 MPa (450, 695, and 900 psi) with initial platen temperatures ranging from 358 to 773 K (85 to 500 °C). A high-temperature polymer release agent, Freekote™ 700 NC from Dexter Corporation, was applied to both the steel and PSZ-coated platens so that differences in release would not influence the results.

Water removal was quantified as a moisture ratio change (MRC), defined as follows:

$$\text{MRC} = \frac{\text{in-going weight} - \text{out-going weight}}{\text{oven dried weight}}$$

Table 2 Comparison of maximum initial platen temperature and moisture ratio change

Peak pressure, MPa	Evaluation method	Maximum temperature, (K)		Maximum MRC(a)	
		Steel	PSZ coated	Steel	PSZ coated
3.1	Visual	525	476	0.95	0.95
	Ultrasound	484	518	0.90	1.00
4.8	Visual	401	717	0.93	>1.20
	Ultrasound	350	717	0.88	>1.20
6.2	Visual	444	771	1.03	1.27
	Ultrasound	389	743	0.98	>1.25

(a) MRC is the "moisture ratio change." See text for details.

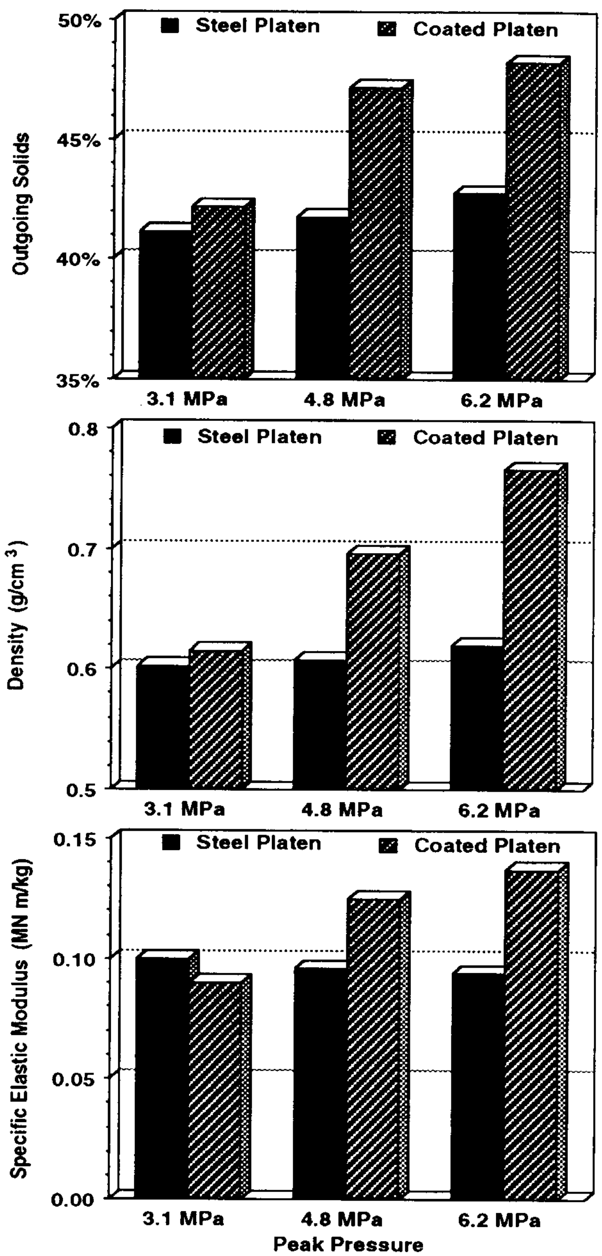

Fig. 6 Comparison of maximum out-going solids, soft platen density, and specific elastic modulus of impulse dried linerboard sheets in simulator tests with steel versus PSZ-coated platens.

A higher MRC value indicates better water removal. Impulse drying test results have shown that water removal increases as the platen is heated to higher temperatures before it is pressed against the test sheet.[9,10,14] However, the maximum initial temperature of the platen is limited by the onset of sheet delamination. In the laboratory simulator experiments, the onset of delamination with increasing initial platen temperature was determined by a careful visual examination and also by an out-of-plane ultrasonic test method. Table 2 compares the maximum temperature limits as determined by these two inspection methods and also shows the corresponding MRC values.

The results in Table 2 show that the performance of the plasma-sprayed test platen is very similar to the uncoated steel platen at the lowest peak pressure of 3.1 MPa. However, the operating temperature limits for the coated platen at 4.8 and 6.2 MPa are roughly twice as high as those for the uncoated platen, resulting in a significant increase in water removal with the coated platen.

Although water removal efficiency is important, enhanced sheet property development is also a major potential advantage of impulse drying. Once the operating temperature limits were defined, the platen materials were further compared in terms of maximum out-going solids, sheet density, and specific elastic modulus. Figure 6 shows a comparison of these results based on the most conservative temperature limits from Table 2. Values for out-going solids in Fig. 6 were computed as follows:

$$\%\ \text{out-going solids} = 100 \times \frac{\text{oven dried weight}}{\text{weight of fiber} + \text{weight of water}}$$

Consistent with the MRC values in Table 2, the results in Fig. 6 show little difference between the coated and uncoated platens at 3.1 MPa, but the coating afforded significant improvements in all of the measured properties at 4.8 and 6.2 MPa. The values shown in Table 2 were calculated averages of 50 tests per test parameter. The increased densities observed for the coated platen are consistent with the hypothesis that there was less flash vaporization deep within the sheet to cause fiber separation and a reduced density in the inner part of the sheet. The increased specific elastic modulus for the coated platen at 4.8 and 6.2 MPa further suggests a probable improvement in sheet strength, because the out-of-plane specific elastic modulus has been shown to be proportional to standard destructive strength tests.[9]

Energy use calculations based on the platen test results also showed that impulse drying with the coated test platen was more energy efficient than conventional wet pressing. For example, to remove the same amount of water that was removed by impulse drying using conventional wet pressing/evaporative drying requires 2257 kJ/kg. Impulse drying requires on 666 kJ/kg, less than one third of the energy consumed with the conventional process.

6. Evaluation of Coated Pilot-Scale Roll

Based on the encouraging results of the laboratory simulator tests, it was decided to test the prototype PSZ coating on an actual press roll. The objective was to determine whether a prototype ceramic-coated press roll could be used to impulse dry a heavy-weight paper grade without inducing sheet delamination. A test roll was plasma sprayed with the same multilayer coating that was used on the simulator platen. The coated roll was then diamond ground and installed on the first nip of a pilot-scale impulse dryer at IPST. As with the simulator test platens, Freekote™ release agent was applied to the roll surface to inhibit adherence of the sheet to the roll. The roll surface was radiantly heated with infrared heaters, and an infrared pyrometer was used to monitor the temperature of the roll surface just before it entered the nip. The pyrometer output was tied to a controller that adjusted the heaters to maintain a constant in-going surface temperature. The paper tested on the pilot impulse dryer was again a 205 g/m^2 linerboard made from an unbleached softwood kraft. To evaluate the potential benefits of impulse drying over single-felted wet pressing, drying experiments were conducted over a range of conditions, with in-going roll surface temperatures of 373 to 703 K (100 to 430 °C), in-going solids ranging from 30 to 45%, as well as 20 and 40 ms dwell times. The peak nip pressure was held constant at 6.2 MPa (900 psi), and the in-going sheet temperature was held at 373 K (100 °C).

An extensive discussion of the results of all of these experiments may be found in Ref 14. It was found that impulse drying with the ceramic-coated roll produced significant improvements in drying efficiency and also paper quality compared to conventional wet pressing technology. The best results were obtained with the longer (40 ms) dwell time and an in-going dryness of more than 40% solids. Under these conditions, the roll could be operated at surface temperatures of 644 K (371 °C) without sheet delamination, but evidence of delamination was observed at the next higher test temperature of 699 K (426 °C). With a 644 K (371 °C) in-going roll surface temperature and an in-going sheet dryness of 41% solids, an out-going dryness of 60% solids was observed. This is a significant improvement over the 54% out-going solids that can be achieved with conventional double-felted wet pressing methods. Other properties, such as specific elastic modulus, burst index, and STFI strength indices, were also improved by impulse drying with the ceramic-coated roll.

A comparison of results for comparable laboratory simulator and pilot roll experiments showed that the roll provided somewhat better water removal than the simulator. This slight additional improvement in performance is attributed to the fact that the simulator has no provision to automatically separate the water-laden press felt from the sheet upon depressurization, whereas the felt and sheet are automatically separated as they leave the nip of the pilot impulse dryer.

7. Summary

Both laboratory simulator and pilot-scale roll press experiments have shown that the prototype plasma-sprayed ceramic coating permits impulse drying of linerboard sheets at high surface temperatures without delamination. As a consequence, the amount of water removed by impulse drying was substantially more than can be removed by conventional methods. In addition, significant improvements were also observed in energy efficiency and in the physical properties of sheets impulse dried with the ceramic coating. Additional testing is currently in progress to further optimize the design of the coating and the drying parameters. Further information about recent work on this development program may be found in Ref 15 to 17. A full-scale test of a plasma spray coated roll on a commercial paper machine is anticipated before the end of 1995.

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