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Press Felts Coated with Electrospun Nanofibres

Abstract
Press felt specimens were coated with nanofibres using the electrospinning process. The coating weight of the nanofibre layer and the spinning distance were varied in order to study the homogeneity and coverage of the nanofibre web. The specimens were studied by scanning electron microscopy (SEM) and laser profilometry to understand how the nanofibre web attaches to the press felt, and how nanofibres improve the surface smoothness. The surface pore size, thickness, weight per unit area and air permeability of the specimens were measured. The surface smoothness improved and the air permeability decreased slightly. The adhesion of the nanofibre web to the press felt and the mechanical strength of the nanofibre web were poor. The study showed, however, that the combination of electrospinning and felt structures has the potential to enhance press felt performance.

Key words: *electrospinning, nanofibre, press felt, surface roughness, wet pressing.*

■ Introduction

Paper machine clothing (PMC) suppliers produce special textiles which are tailor-made to transfer, support and dewater paper webs on a papermaking line. Each PMC product is designed for a certain machine section and position. In particular, continuous press felts are subjected to mechanical stress in the wet pressing section for several weeks, where they go through over-lapping rollers (a nip) a million times. Their water handling capacity decreases and the risk of marking increases owing to the wear, compaction and contamination of the press felt [1]. The structure and material properties are key factors in reducing these unwanted phenomena in order to increase the life of press felt.

A press felt typically has a multilayer structure consisting of batt layers on the roll (underside) and paper side (upside), and a woven base fabric in the middle. The base fabric can vary from a woven single-layer to a multilayer structure. The other structures are laminated (two separated woven base fabrics) or non-woven (non-crimped yarn layers) structures. The raw materials of the yarn and staple fibres, the fibre fineness, and the amount and density of the filament can be different in the various press felt designs. The finest staple fibres are usually located on the paper side in the topmost batt layer to support wood fibres, improve retention, and minimise the risk of textile marking and rewetting. Below the topmost batt layer the staple fibres are slightly coarser, thereby increasing the mechanical strength and allowing rapid water removal from the press felt when the maximum pressure in the nip has been passed. Typical materials for press felt are synthetic polyamide poly-

mers, such as PA 6, PA 6.6 or PA 6.10, due to their good abrasion resistance and hydrophilic properties. The structure and materials for press-felt products are chosen according to the paper or board grade to be produced, and the press section configuration to be used [1 - 3].

Press felt designs have been developed to improve felt performance and properties, such as durability and dewatering, in the harsh papermaking process. The connection between the nip and press felt wear (ageing) has been studied using wet-pressing simulators [4, 5]. Nip simulation is a practical and time-saving test method for researching new raw materials and structures for press felts. The material properties of staple fibres and

yarns, such as the abrasion resistance, have been improved by blending and high-molecular-weight polymers in order to increase the life of press felts [6, 7]. Such structural properties as homogeneity on a microscopic scale and the void volume determine the pressure uniformity, compressibility and flow resistance of the press felt. The uniformity of the press felt structure as well as the surface topography and porosity were discussed in [8 - 10], in which their connection with energy consumption, marking and vibration problems was explored.

Examples of real life and research results reveal the current state of PMC research and development work (R&D). The aims of R&D work are to improve productivi-
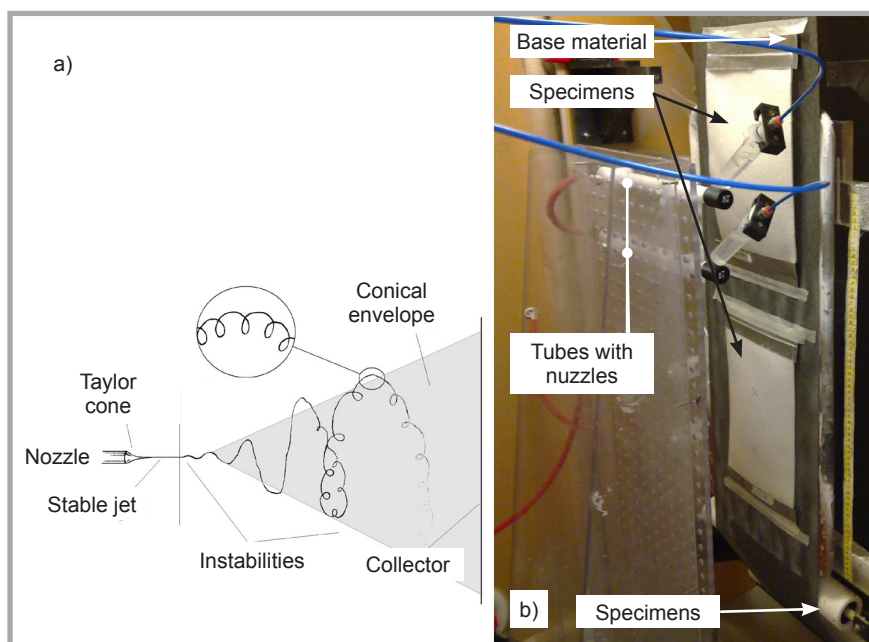

Figure 1. *Principle of the electrospinning process (a), from which can be seen the different phases of a jetting. Our electrospinning device is also shown (b) with a nozzle system (tubes containing 10 nozzles each), two press felt specimens, a dark nonwoven base material and a collector plate.*

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89

Specimen	Base fabric	Voltage, kV	Distance, mm	Amount of nanofibre, g/m^2
A1	double-layer	30	150	1.0
A2	double-layer	30	150	0.25
A3	double-layer	30	150	0.5
A4	double-layer	30	150	0.75
A5	double-layer	10	50	0.5
A6	double-layer	20	100	0.5
A7	double-layer	40	200	0.5
B	double-layer	30	150	1.0
C	laminated	30	150	1.0
D	single-layer	30	150	1.0
E	single-layer	30	150	1.0

ty as well as the properties of current materials and press-felt structures. The work is challenging and complex because of the varied end uses and large number of different press felt structures. Totally innovative and new PMC products are rarely mentioned in the literature.

Electrospinning of nanofibres

Non-woven nanofibres are typically used in technical textiles, such as air filters and sound absorption materials, and in biomedical applications due to the improved capacities of end-use [11, 12]. In air filtration, especially, the use of nanofibres enhances separation efficiency without increasing the weight, because as the number of fibres increases, their diameter decreases [13]. Thin nanofibre layers can have a dramatic impact on filtration efficiency for small particles (diam. below 0.5 μm) without a large increase in the pressure drop [14]. Typically an electrospinning device (*Figure 1.a*) consists of a collector, a high-voltage power supply, a metallic needle and a syringe. An electric field is generated between the needle and the collector with a positive or negative charge. The collector is earthed, or has an opposite charge to that of the needle. The electrical forces attract the solution towards the collector, and jetting occurs from the Taylor cone. After a short stable stage, instabilities start to bend the jet, which eventually leads to 3-D looping within the conical envelope. Secondary and tertiary looping can also occur before the jet reaches the collector. The process thus produces thin polymer-based fibres using an electrostatic field. Electrospinning parameters such as the polymer concentration, polymer flow, spinning voltage and the distance all have an impact on the nanofibre diameter and porosity of nonwoven materials [15 - 17].

The purpose of this study was to modify a press felt structure using the electrospinning method. We assumed that nanoscale fibres on the surface of the press felt would improve its surface smoothness and other properties affecting papermaking parameters, such as retention and the risk of paper fibre penetration. We were aware of the poor adhesion between nanofibres and the press felt surface, as well as the poor mechanical properties of the nanofibres.

Press felt specimens were coated with electrospun fibres by varying the nanofibre amount. The surface topology and pore size distribution were studied in order to evaluate the impact of nanofibres on the surface smoothness. The impact of nanofibres on other felt properties was evaluated using air permeability measurements.

Experimental

Materials

The press felt specimens (A - E) consisted of several types of woven base fabric, which had a single-layer, double-layer or laminated structure, as well as batt layers on both sides of the base fabric(s) (*Table 1*). Carded and pre-needled batt layers were formed from 3-D curled staple fibres, whose fineness varied between 11 - 44 dtex. The batt layers and woven base fabrics were connected by punch-needling. Specimens A - C were commercial press felts, and specimens D and E were prepared in the Fibre Materials Science laboratory. The preparation of the specimens is reported in [4]. Specimens A were used in the experiments with varying electrospinning parameters, and specimens B - E were for comparison. The size of the specimens was about 90 × 100 mm (A2 - A7) or 210 × 297 mm (A1, B-E). The thickness of the specimens varied from 3.43 to 4.30 mm and

the weight per unit area - from 960 to 1710 g/m^2; these values were related to the felt designs. The cross-sectional structure of a press felt specimen is shown in *Figure 2*.

The polymer for electrospinning was a PA 6 of high molecular weight (Ultramid B5 Natur) from BASF. According to gel permeation chromatography (GPC) analysis, the molecular weights, Mn and Mw, were around 86,000 and 198,000, respectively. The formic acid used (98%) was from Merck.

Cellulose-based nonwoven material was used as a base material in the electrospinning. The press felt sheet specimens were attached to the continuous base material.

Electrospinning

Before electrospinning, a polymer solution was prepared by dissolving the PA 6 in formic acid. The viscosity of the polymer solution was approximately 1,500 cP (measured using a Brookfield DV-II+ viscometer), and its polymer concentration was about 12 wt%. Additionally, the end-taped felt specimens were wetted on their paper sides by spraying before the electrospinning process, which made the specimens more conductive, allowing the electrospinning coating process to take place with these thick, porous specimens. Finally, the wet specimens were quickly attached to the dark base material with tapes.

The continuous electrospinning equipment (*Figure 1.b*) consisted of a multi-nozzle system, a nonwoven base material, a collector plate, and a voltage source (Simco Chargemaster BP 50). The parameters of the electrospinning process were based on previous electrospinning trials [18]. We used two plastic tubes, each of which had 10 nozzles pointing in a horizontal direction - the inner diameter of each nozzle being 0.4 mm. The strength of the electric field was kept constant at 2 kV/cm, while the spinning voltage varied from 10 to 40 kV, and the spinning distance - from 50 to 200 mm. The velocity of the base material was adjusted according to the targeted amount of PA 6 nanofibre web. The parameters used in the calculations were the solution consumption, the concentration and density of the solution, and the width of the electrospinning zone. The amount of nanofibre produced in one electrospin-

ning cycle was 0.125 g/m² or 0.250 g/m², and the total amount was achieved by repeated cycles. After the electrospinning process, the specimens were heat-treated by ironing to improve the adhesion of the nanofibre coating. The temperature was about 100 °C, and the ironing time was 2 minutes. All the experiments were performed at room temperature.

■ Characterisation

Scanning electron microscopy (SEM) figures were used to observe the attachment and quality of the nanofibre webs, Philips XL-30 equipment, for SEM imaging of the webs, and a Zeiss ULTRAplus was used for imaging electrospun fibres. Before the SEM imaging, the press felt specimens were gold sputtered. The weight per unit area, thickness (M 034A, SDL International Ltd.) and air permeability (L13, Karl Schöder K.G.) of the felt specimens were measured under standard conditions. The humidity was $65 \pm 5\%$ RH and the temperature 20 ± 2 °C. Parallel measurements were not performed due to the small specimen size.

The topography of the four press felt specimens was measured by µScan (NanoFocus Inc.) at VTT (Espoo, Finland) using a confocal sensor. The area measured was approximately 45×45 mm for each of the specimens, which were attached to the metal background plate. The measuring accuracy was 20 points/mm - 810,000 points for each measurement. After topographical measurement irregularities, such as the buckling of the specimen, were filtered from the data, then RMS (root mean square, i.e. standard deviation) values were calculated.

The diameter of the nanofibres and the surface pore size of the four specimens were estimated from the SEM figures using an ImageTool program. The fibre diameter was calculated from 120 measure-
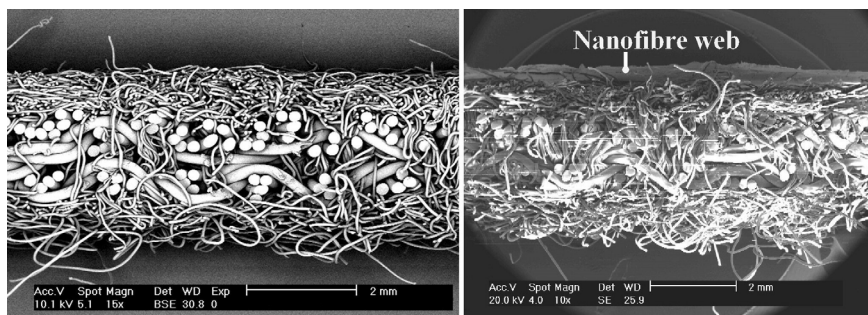

Figure 2. Cross-sectional figures of specimen C without (15× left) and with (10× right) an electrospun nanofibre web.
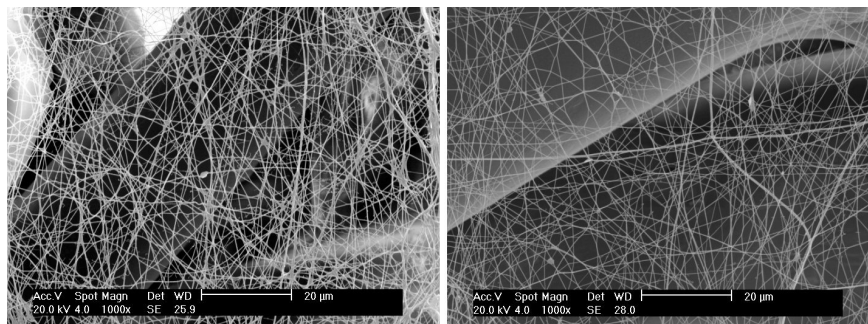

Figure 3. Specimen C coated with a nanofibre web of 1 g/m² (left) and specimen A2 coated with a nanofibre web of 0.25 g/m² (right). In both cases the spinning distance was 150 mm (1,000×).

ments of individual fibres (10,000× and 20,000×). In the measurements of the surface pore size, the circumference of holes was outlined, and then the program automatically measured and calculated the area of holes in the nano- and non-woven webs. The average was calculated from 675 measurements of individual holes (1,000×) in the nanofibre webs, as well as from 240 measurements of individual holes (75×) in the non-woven webs.

■ Results and discussion

The nanofibre webs attached to the press felt specimens are shown in *Figures 2 - 4*. Images were taken of cross-sections and the paper side, shown at several different magnifications.

Based on the SEM figures, we observed that the PA 6 nanofibre web was only attached to some of the uppermost staple fibres. Nanofibres were randomly placed and formed a thin 3-D web. Several contact points were between nanofibres, and some drops and holes had appeared in the web (*Figures 2* and *4*). It also seemed that single nanofibres were axially stretched, and their diameter varied. The increased amount of the nanofibre web raised the number of contact points between the nanofibre web and staple fibres (*Figure 3*). Unwanted holes were generated randomly with smaller fibre quantities; however, several electrospinning cycles smoothed the surface. Moreover, the thicker nanofibre layers seemed to have more durable nanofibre webs. The solution drops in-
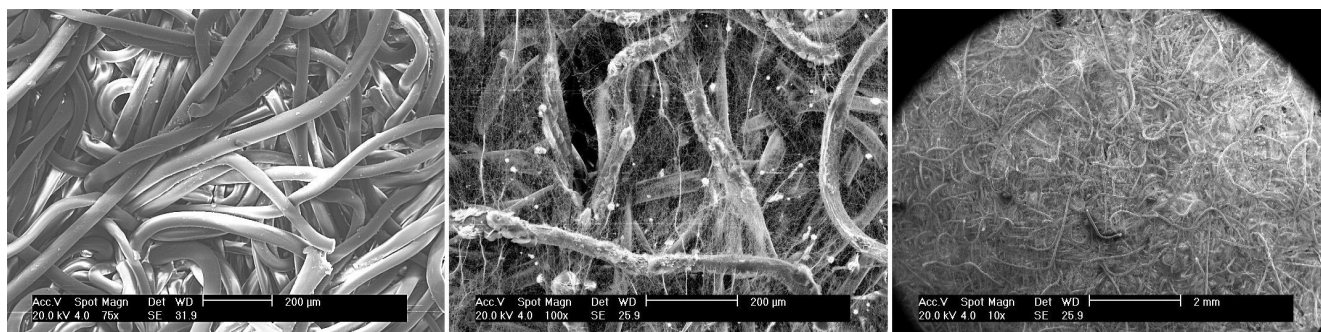

Figure 4. Paper side of the uncoated (75× left) and nanofibre coated specimen C (100× middle and 10× right).
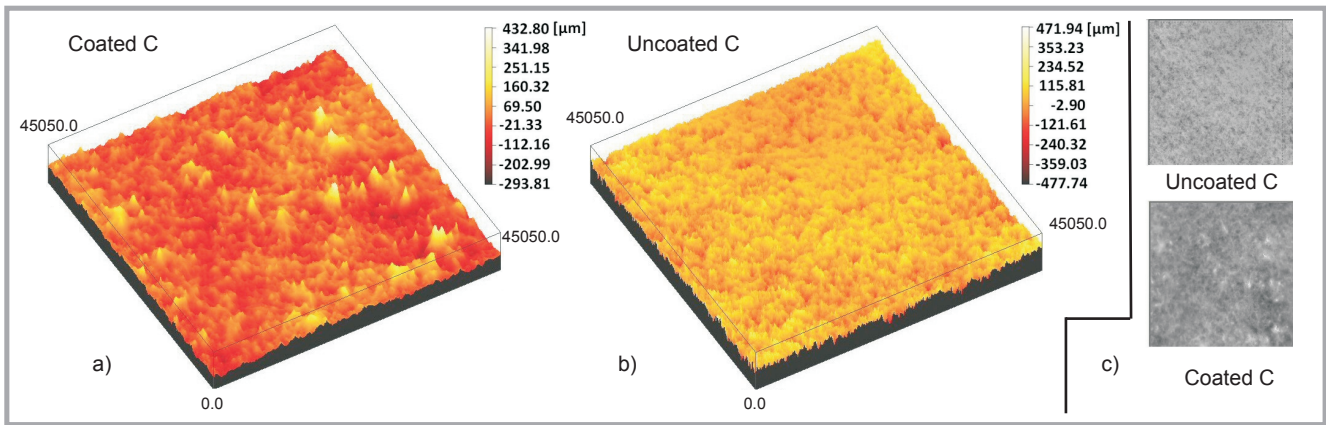
Figure 5. *Surface topography of the C specimens with (a) and without (b) an electrospun nanofibre web, and photographs of both specimens (c) from their paper side.*

dicated that the electrospinning process was not operating perfectly.

Surface topography measurements were conducted on specimens B and C with and without an electrospun fibre coating. The specimens were visually checked to ensure they were undamaged and were scanned on their paper side by a laser profilometer. In *Figure 5*, the 3-D measuring plots of the C specimens are shown, in which light (maximum) and dark (minimum) colours indicate the variation in topography: -294 - 433 µm and -478 - 472 µm for C specimen with and without a nanofibre coating, respectively. The better surface smoothness of coated C specimen is obvious.

Figure 5.c shows photographs of both specimens from the paper side; the appearance of the coated C specimen has less contrast, indicating a smoother surface due to the nanofibre web. The needling tracks are more obvious in the photograph of the C specimen without nanofibres; the tracks run diagonally from upper left to lower right. Needling tracks were also observed in the B specimen without nanofibres (not shown here).

The roughness values of the B and C specimens with and without electrospinning are presented in *Tables 2* and *3*. The minimum and maximum values of the topography with their difference (range) and standard deviation (RMS-value) are

shown in *Table 2*. *Table 3* presents RMS-roughness values in certain wavelength bands (2 - 4,096 µm), the smaller values indicating smoother surfaces. Electrospinning clearly improves the surface smoothness of these press felts.

Based on area measurements from the SEM figures and calculations from the ImageTool program, the diameter of the nanofibres was determined as about 147 ± 35 nm. The surface pore size distribution was mainly in the range 0.1 - 1 µm^2 for the coated B and 0.1 - 1.5 µm^2 for the coated C specimen. The average surface pore size was about 6,700 µm^2 for the uncoated B and C specimens. The values of the surface pore size varied widely from under 1,000 µm² to over 15,000 µm². The level of the surface pore size between the coated and uncoated specimens was thus very different.

The thickness, weight per unit area and air permeability of the press felt specimens were measured before and after electrospinning. Based on the measurements, the changes in thickness and weight per unit area were found to be insignificant; the coating either increased these values not at all or only by a few percentage at most. The air permeability decreased slightly after electrospinning (*Figure 6*); the decrease was significant when the quantity of nanofibre was 1 g/m^2.

The spinning distance varied with specimens A5 - A7. However, it seemed that the spinning distance did not have a significant effect on air permeability, whose variation was dependent on the quality of the press felt.

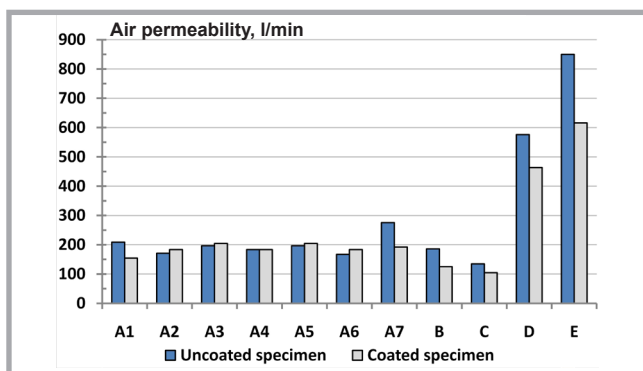After the tests, we concluded that 1 g/m^2 of nanofibre at a distance of 150 mm and

Table 2. *Minimum and maximum roughness values, range values and standard deviation values of specimens B and C with and without an electrospun nanofibre web.*

Roughness, µm	Uncoated B	Coated B	Uncoated C	Coated C
Minimal value	-392.93	-235.75	-477.74	-239.81
Maximal value	611.34	430.64	471.94	432.79
Range	1004.27	666.39	949.68	672.61
Standard deviation	69.97	49.50	69.73	50.85

Table 3. *Roughness values of specimens B and C at different wavelength bands with and without an electrospun nanofibre web.*

Band, µm	RMS-roughness in µm at different wavelength bands, µm			
	Uncoated B	Coated B	Uncoated C	Coated C
2 - 4	4.04	1.35	4.64	1.88
4 - 8	5.47	1.72	6.20	2.38
8 - 16	7.14	2.09	7.84	2.85
16 - 32	8.70	2.45	9.53	3.41
32 - 64	10.97	2.64	12.21	3.68
64 - 128	13.77	2.56	15.92	3.52
128 - 256	15.22	2.20	17.59	2.97
256 - 512	14.94	2.31	17.00	2.81
512 - 1024	13.78	3.29	16.07	3.50
1024 - 2048	13.23	5.67	15.33	5.48
2048 - 4096	13.52	9.20	16.02	8.90

voltage of 30 kV gives the best results for press felt performance with respect to surface smoothness and pore size. To define an optimal nanofiber web for certain felt designs requires its own specific test.

■ **Further research propositions**

Before the commercial utilisation of electrospinning with press felts, some key problems concerning adhesion, durability and manufacturing need to be overcome.

There are several possibilities for increasing the adhesion between the coating and the substrate, such as plasma and corona treatments, and the grafting of the polymer. The mechanical durability of the nanofibre web can be enhanced by the following methods: one solution is to locate the nanofibre web between batt layers on the paper side, in which a very thin batt layer is placed on top of the nanofibre web to protect it from mechanical forces and stresses. The disadvantage of this is that the nanofibre web does not improve the smoothness of the paper; however, the retention and sheet dewatering might be improved. Moreover, the preparation method - needle-punching may not be a suitable way to connect the batt and nanofibre layers due to the tearing of needles during the felt making. Another solution is to use elastic polymers in the solution, since the nanofibre layer is usually damaged when substrate fibres move relative to one another. If the nanofibre layer is elastic, it can tolerate larger movement of substrate fibres without exceeding its strain limits. In such cases, the impact of these polymers on the properties of nanofibres, on the electrospinnability of the solution and on the electrospinning process itself requires extra attention.

In summary, present felt manufacturing technology requires innovative ideas and progressive modifications in order to integrate the electrospinning process into PMC production with high-performance specifications.

■ **Conclusions**

We combined the electrospinning technique with press felt structures to achieve enhanced properties for technical textiles. We observed that the nanofibre web improves the surface smoothness of press felts, at the same time reducing the air permeability. A coating of 1 g/m^2 of nanofibres decreased the air permeability and improved the homogeneity of the nanofibre web. The latter parameter indicates better sheet dewatering. Moreover, the needling pattern was eliminated on the paper side, resulting in a lower risk of marking and paper fibre penetration. The surface pore size and its distribution were clearly smaller with coated specimens than with uncoated ones. Thus our assumption concerning better retention and paper fibre support is justified, but it requires further testing. Our assumption that the attachment of a nanofibre web to a press felt surface would be too loose despite heat treatment (ironing), proved to be true. One reason for this was that the nanofibres were only laid down horizontally with no vertical nanofibres to connect the nanofibre web to the lower staple fibres of the specimens.

Though further research is required, our study showed that a nanofibre coating has the potential to improve press felt performance.

Acknowledgment

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