Web tension formation and web deformation in printing process

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Background

VTT, in association with several companies, has carried out in-depth studies of web handling in papermaking and in printing presses. These studies have examined, for example, issues related to paper web tension formation, web deformations and lateral movements of the paper web, which have an effect on production efficiency and printed quality in printing presses. The behavior of the paper web in the printing process is now reasonably well understood. The results presented herein concerning paper are mainly drawn from web offset printing studies. Methods used in studying paper webs can be applied when exploring web behavior in roll-to-roll printed electronics, where register accuracy requirements are much higher than in traditional printing.

Methods

Extensive trial runs have been carried out at a pilot scale and in commercial presses. Besides normal press measurements, on-line web tension, web moisture and web dimension measurements have been carried out. Offline measurements have included laboratory analysis of papers, printing blankets and printed sheets. Finite element modeling has been used for detailed simulations and studies of the interactions of the paper web and the printing press components and controls. We have also developed a simulation model that predicts the liquid absorption dynamics in paper materials, the resulting non-mechanical and inelastic deformation of a paper web (in machine direction (MD) and in cross direction (CD)) and their effect on web tension.

Web deformation and web tension formation

Web tension variation and web deformations can lead to production problems such as web breaks, printed waste and color register errors. Earlier studies have found that both too high or too low web tension can cause web breaks and that web tension variations lead to an increase in printed waste /1,2/. The paper web's tension in the printing press is dependent on a number of factors, but basically in the uniaxial case it can be expressed as follows /3/:

$T = E\varepsilon_{el}h = K\varepsilon_{el}$ (1), where $\varepsilon_{el} = \varepsilon_{tot} - \varepsilon_{in} - \varepsilon_{hyg} - \varepsilon_{temp}$ (2)

E is the elastic modulus of paper, h is the thickness and ε_{el} is the elastic strain; K is the tensile stiffness that is often used since thickness measurements are rather difficult with paper. The elastic strain is a part of the total strain ε_{tot} where ε_{in} is inelastic strain (due to creep or plasticity, for example), ε_{hyg} is the hydroexpansion of printed substrate and ε_{temp} is thermal strain. The total strain is controlled by the speed differences between different press components.

Deformation of the paper web

Liquid absorption into the web pore structure is a very fast process (of the order of milliseconds) whereas the absorption into fibers takes less than 1 s and the evening-out of moisture a few seconds for typical paper grades /4/. The most important of these mechanisms is fiber absorption /4/ as its time scale interacts strongly with that of the printing process (e.g., delay between printing units).

Absorption causes the swelling of fibers. The fiber network transfers the resulting stress effectively in a cross-machine direction along the web, which leads to rapid expansion of the web. At low moisture intake, the dynamical expansion of the web is an almost linear function of the moisture intake. However beyond 2 g/m^2 moisture intake, the response is highly nonlinear so that, e.g., the difference between CD expansion for 2 and 6 g/m2 can be only 50% or so (see Fig. 1, left side) /4/. The typical water amount transferred to the paper web in four-color offset printing is about 2.5 g/m^2 /5/. In the expansion curve, one can see quite a steep initial rise due to the wetting of the fiber walls and resulting swelling near the moistening surface. This is followed by a gradual further increase due to the diffusion of liquid within the fibers, which evens out the moisture in the paper. This process takes a few seconds. As long as moisture is unevenly distributed within the structure, there are very large stresses in the fiber network that cause inelastic deformations contributing to the expansion behavior. This is the reason for the nonlinearity of the expansion as a function of moisture intake /4/.

Applied web tension introduces additional effects on web expansion due to Poisson effects. Higher web tension suppresses CD expansion and enhances MD expansion.

Paper web widening (CD expansion) was measured in a newspaper press and a simulation model was used to facilitate analysis of widening (Fig. 1, right side). It was found that the paper's hydroexpansion (measured in laboratory) was the most important parameter affecting the widening. Widening caused cross-directional color register errors in the paper web.

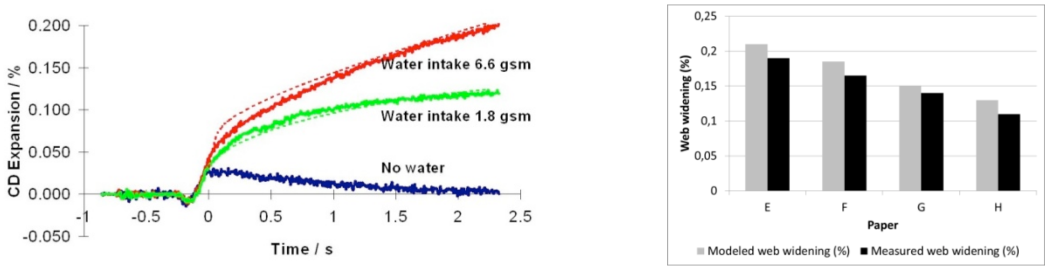


Figure 1. Left side: CD expansion of book paper measured in laboratory. **Right side:** Measured and modeled web widening of four papers from the 1st printing unit to the exit of the 4th printing unit.

Web tension

As indicated by Eqs. (1-2), web tension can be affected by hydroexpansion, inelastic deformations (creep/relaxation) and also changes in the elastic modulus due to changes in the moisture content or temperature of paper.

Several trial runs were carried out in a heatset press equipped with additional web tension measurement devices (Fig. 2, left side). Only the main results are presented herein. Web tension is controlled by adjusting the web tension level with the infeed unit. After the printing units, web tension is controlled by the draw from chilling rollers and draws in the folder area. The infeed control and succeeding draws define the web tension level before and after the printing units, as they have a direct effect on the elastic strain of the paper web. Paper webs react to these strains mainly according to their tensile stiffness values. Fig. 2, right side, presents the effect of the paper's tensile stiffness on web tension measured after the last printing unit. Tension change carried out in the infeed unit can also be seen between the printing units and after the printing units but draw changes carried out in chilling rollers have only a very small effect on the web tension between printing units.

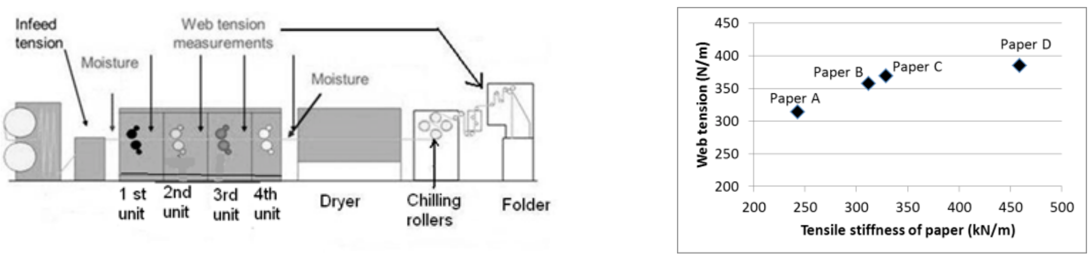


Figure 2. Left side: A heatset offset press with additional web tension measurements. **Right side:** Web tension after the last printing unit and the tensile stiffnesses (dry paper) of different paper grades. Paper grades were all wound onto the same reel and the control values in press were kept constant during these trials.

Between the first and the last printing unit, web tension formation is more complex and analysis of the tension formation has to be supported by means of finite element modeling. In particular, modeling was used to understand how stresses and strains build up in the printing nip area, as they cannot be measured on-line. Printing blankets were modeled as 3-layered structures by means of the finite element method using the Abaqus software. In trial runs in the press (Fig. 2, left side) printing blankets having neutral, negative and positive feeding properties were used. The feeding property of a blanket is mainly dependent on the compressibility of the inside layers of the printing blanket /6,7/. Due to feeding characteristics, negative blankets gave higher web tension values than the neutral and positive blankets; Fig. 3 (left side) presents measurement results with the negative and the neutral feeding blankets. The press speed and the nip pressure /6/ also have an effect on the feeding property of blankets, and ageing can also change this property. The reasons behind tension changes were studied by finite element modeling, and it was found that web tension changes are mainly caused by the strain changes occurring between printing nips because of different feeding properties. Fig. 3 (right side) presents the modeled strain and web tension and measured web tension. In this trial we mixed blankets so that the first printing unit had neutral (n), the second unit negative (N), the third unit positive (P) and the last unit neutral (n) blankets. We also used blanket set n-N-P-n with the same press controls; in this case, the web tension increased to 700 N/m between the 1st and 2nd unit and decreased to 200 N/m between the 2nd and 3rd unit. The modeling results also correlated well with the measurements. These trials were carried out with six paper grades, all of which reacted to these strains between printing units according to their tensile stiffnesses.

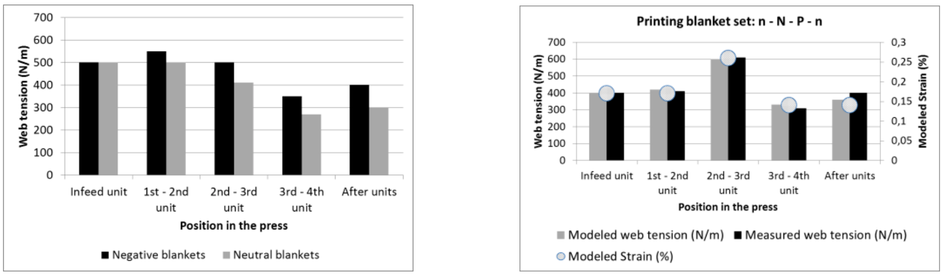


Figure 3. Left side: The web tension measurement results with different blanket types. **Right side**: Modeled strains (secondary y-axis, circles) and web tensions (columns) between printing units and measured web tensions, blanket set: n – N – P – n (see text above Fig. 3).

Fountain solution is applied to the paper web in the offset process, increasing the moisture content of the paper web in printing. Another printing process parameter affecting the rheology of paper is drying; the typical temperature of paper at the dryer exit is about 130 C^0 (heatset process). An increase in the moisture content or in the temperature decreases the tensile stiffness of paper and leads to a decrease in web tension /8/. Fig. 4 presents the effect of temperature and moisture on web tension in a trial run in a press. Increase in moisture content also increases the hydroexpansion of paper, which also decreases web tension. Drying of the paper web leads to higher shrinkage of the web in the machine (MD) and cross direction (CD); the role of shrinkage in web tension formation in the press is yet not clear, but is being studied in an ongoing project.

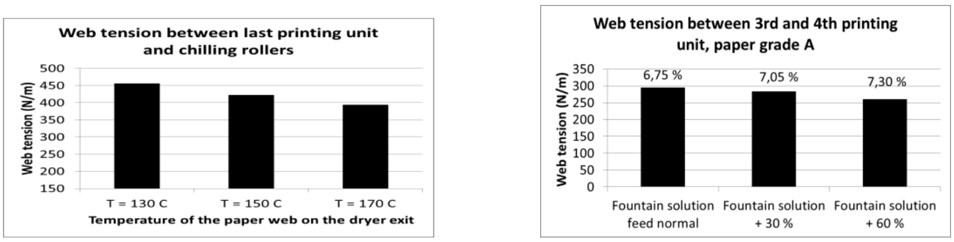
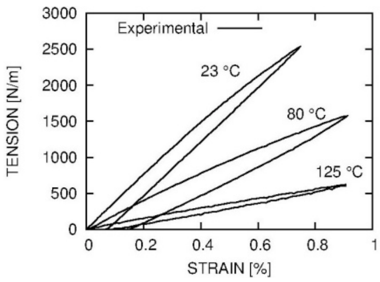


Figure 4. Left side: The effect of drying on web tension, tension measured between the last printing unit and chilling roller. **Right side:** The effect of fountain solution feed on web tension measured between the 3rd and 4th printing unit. The percentages refer to increases in the speed of fountain solution ductor rolls in all printing units. The values above the columns are the measured moisture content of the paper web after the 4th printing unit; the moisture content of unprinted papers was 6%. During these trials, the press speed, the infeed tension, and the draw from chilling rollers were kept constant.

Web deformations in printed electronics – a case study

As already indicated by Eqs. (1-2), web deformations depend on mechanical loading as well as on changes in internal variables such as moisture content and temperature. The dominant deformation mechanism depends on the properties of the printed media and on external loading conditions. To understand deformation mechanisms in a printed electronics application in which the printed media was coated PET foil, experimental laboratory tests were carried out. Web inelasticity was studied by conducting temperature-dependent relaxation tests and uniaxial loading/unloading tests. In addition, cyclic heating tests that mimic web behavior as the web goes through a series of dryers were performed.

According to experimental results, the coated PET foil exhibits inelastic (plastic) material behavior only at elevated strain levels. As shown in Fig. 5 (left side), straining the coated PET foil did not cause significant plastic strains. In addition, it can be seen that the tensile stiffness decreased significantly as the temperature of the substrate increased. Cyclic heating tests revealed that heating induces significant thermal strains to the web, as shown in Fig 5, right side.



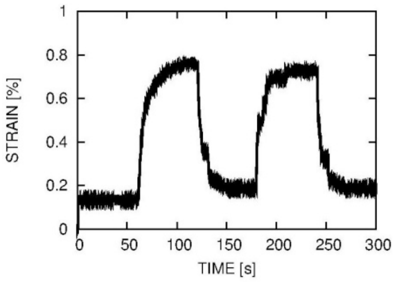


Figure 5. Left side: Tensile test of coated PET foil in different temperatures. **Right side:** Measured strain in a cyclic heating test where the foil is heated to 120 degrees for 60 seconds at times 60s and 180s. Web tension was kept constant during these trials.

The results suggest that at the normally used web tension levels (100-300 N/m) the mechanical deformation of the web is mostly elastic. Furthermore, most severe deformations occur when the web is dried. Drying decreases the tensile stiffness of the substrate, which can lead to web tension-related problems in production.

Conclusions

Extensive studies carried out in printing presses have revealed the key parameters affecting paper web tension and web deformations. Studies have focused on offset web printing, but the results can also be applied to other printing methods. Methods used in paper web-related studies can be used when studying roll-to-roll printing of electronics on, e.g., plastic webs. Results obtained in the case study suggest that material properties should be taken into account when controlling web transport of printed electronics. VTT has recently installed a full-scale roll-to-roll printing machine for the manufacturing of printed electronics. This flexible press is equipped with four printing units – flexographic, silk screen, rotogravure and slot die printing units – that can be used simultaneously. Further studies will be carried out at a production scale to determine the optimum way to achieve sufficient register accuracy with plastic webs.

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