MODELING WEB BEHAVIOUR IN PRINTING PRESS AND IN PRINTED ELECTRONICS

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ABSTRACT

VTT together with several companies in the printing value chain have studied web handling through the printing press. Studies have focused on the web tension formation mechanisms in printing which have an effect e.g. on color register problems, on web wandering and on web breaks in printing presses. Trials have been carried out on a printing press and in laboratory, and modeling of web tension through printing nips has been performed. Printing method used was heatset offset printing. Modeling work was carried out by finite element method (FEM). In the model, the printing press is considered to consist of an infeed unit and four printing units. Each printing unit consists of two rubber-covered cylinders (printing blankets) through which the paper web passes. The printing blankets were modeled as a triple-layer structure.

Results reveal how printing nips and paper properties have an effect on web tension in printing presses. The modeling results and experimental measurements correlated well. Results suggest that, between printing units, the feeding properties of printing blankets have a decisive effect on web tension. Printing blankets cause draw differences between printing units and the paper web reacts to these draws to a magnitude defined by its tensile stiffness.

In a case study, the modeling knowledge gained was applied to study plastic foils deformation in printed electronics. In printed electronics, the register accuracy requirements are much stricter than in traditional printing which makes great demands on the printing process and on web materials stability. In order to obtain a clearer impression of the web deformations in printed electronics a temperature-dependent plastic material model was developed and implemented in a finite element software. With the aid of the finite element code, a coupled thermal-stress problem, in which a plastic web is cyclically heated by dryers, was simulated. Experimental tests were carried out with a specially designed stress-strain apparatus (C-Impact).

Results obtained in the case study suggest that material properties should be taken into account when controlling web transport of printed electronics.

INTRODUCTION

The most important runnability disturbances in printing process are register errors, web breaks, web instability, wrinkles, dusting and linting. These phenomena are caused partly by paper and partly by the printing press and how the press is operated. Previous studies have shown, that web tension has an effect on web breaks, printed waste and a webs lateral movements [1,2]. Both too high web tension and too low web tension led to these problems.

VTT, together with the Finnish paper industry started to use finite element modeling (FEM) in the late 1990's to find out the reasons behind the typically convex shape of the cross-directional (CD) web tension profile in paper machines. Modeling revealed the formation mechanism of web tension profile in paper machines [3]. Figure 1 presents FE modeling results and web tension measurement results from this study.

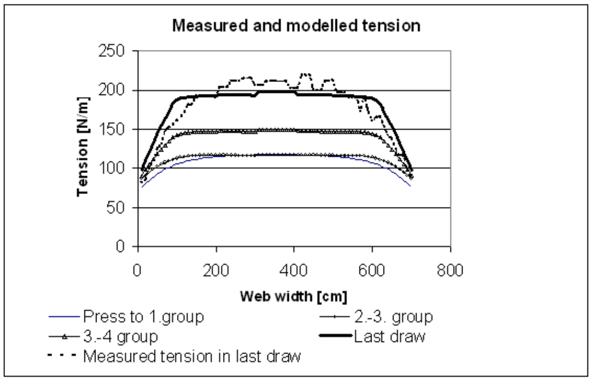


Figure 1 – Modeled and measured web tension profile in a paper machine. Web tension was modeled through a (100 m long) paper machine. The parameters used were web strains, draw lengths, moisture content of paper, shrinkage of paper web, tensile stiffnesses of the paper and the paper's Poisson value. Last draw curve represents the modeling result. Other curves are modeling results from different parts of the paper machine.

Subsequent to this study, FEM has been applied in printing press studies. For example, the effect of paper webs CD tension profile and paper webs fiber orientation (CD) on the webs lateral movements in printing have been studied [2,4]. Also webs deformation in the printing press has been studied and modeled [2].

Figure 2 presents the effect of fiber web orientation on web movement in a printing press [2]. Orientation was measured with L&W TSO-tester and paper position in press was measured with line scan cameras before and after printing units. Modeling was carried out with FEM. Modeling gave the same magnitude of web movement as measurements in a press.

The latest studies have concentrated on clarifying the web tension formation in the printing process; the focus has been on printing nips and their effect on the web tension formation, as in other parts of printing press web tension is mainly controlled by measurements and draws. Some results have already been reported [5]; the latest results are reported in this paper.

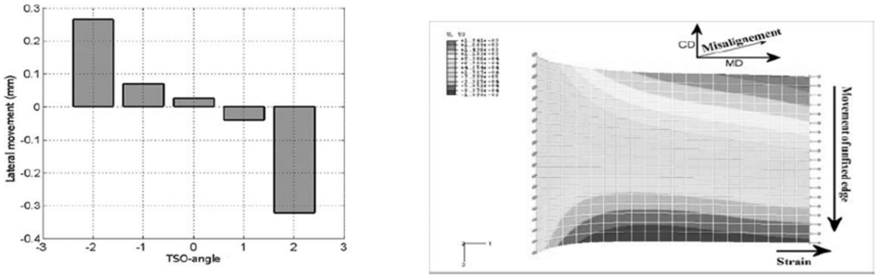


Figure 2 – The effect of the paper webs fiber orientation on web movement in a printing press (left). Negative and positive values in lateral movements represent different lateral directions.

The knowledge acquired in paper web studies can be exploited when studying roll-to-roll (r2r) printed electronics of plastic webs. The register accuracy in traditional printing between different colors/inks is about +- 50 µm because that is enough for human perception, which means that printing presses are designed to meet this criteria. In many applications in printed electronics, the register accuracy requirements are about 1 to 10 µm, which makes roll-to-roll (r2r) printed electronics very demanding. The first results of modeling, simulations and measurements of plastic webs are reported in this paper.

METHODS

Paper webs tension formation has been studied at VTT in earlier studies [1,2] . The previous study showed that printing blankets and printing nips can have a major effect on web tension formation [5]. A further study was carried out in which three different type of printing blankets were used. Results are reported in this paper. The goal was to clarify the effect of printing nips on web tension formation. This phenomenon was studied by finite element modeling and modeling results were verified by measurements in a printing press.

Knowledge acquired in modeling was implemented in a study where the deformation of plastic web in printed electronics was studied.

Measurements of Paper and Printing Blankets

To find out the influence of different paper, press and printing blanket properties on web tension formation a large test run was carried out in a printing press. A large number of paper and blanket tests were carried out in the laboratory. The results were utilized in modeling and simulations.

The aim of trials carried out in a press was to verify the effect of blankets with different feeding properties on web tension. In addition, the effect of paper properties was studied by using different paper grades. A trial run was performed on a heatset offset press (Albert-Frankenthal A 101). Measurements in the press included web tension measurements by weighing rollers between every printing unit and before and after printing units. The moisture content of papers was measured before and after printing units with IR-sensor. Nip load profiles of all printing nips were measured off-line by the Tekscan pressure sensor. Figure 3 presents the measurement set up in the press.

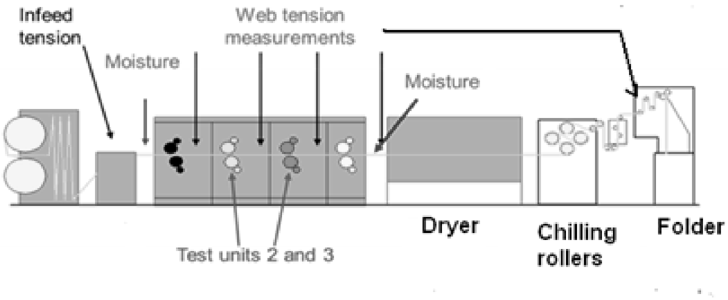


Figure 3 – Layout of the printing press. Web tension was measured before printing units (infeed). Additional weighing rollers were installed between printing units and after printing units. The pilot press has its own web tension measurement in the folder area. In trial runs the paper web width was 50 cm and the press speed was 5 m/s. The dryer temperature was 110° C (exit web temperature).

Printing blanket is a multi-layered structure, figure 4.

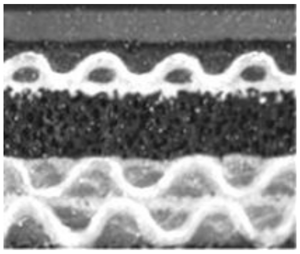


Figure 4 – A cross-section of a printing blanket. Total thickness was 1.96 mm.

The surface layer is rubber. Beneath it are layers of cotton fabrics and layers consisting of rubber and air.

By varying the materials used in different layers of the blanket, one can influence the feeding property of the blanket. According to the blanket manufacturers, blankets having positive feeding characteristics will feed more paper in the printing nip exit, which leads to a decrease in web tension. Blankets with a negative feeding property will feed less paper in the nip exit, which lead to web tension increase. The difference in feeding property is explained by the blanket manufacturers by the fact that negative feeding blankets have more air in the compressible layer of the blanket, Figure 5.

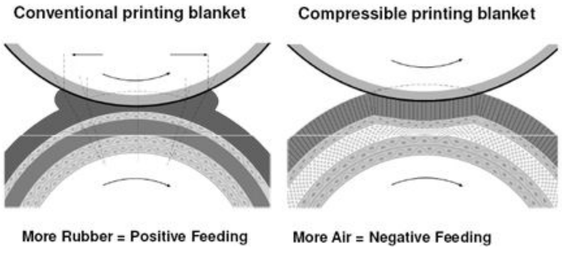


Figure 5 – Exaggerated figure of nip phenomena of different blanket types.

The effect of air in the blanket is illustrated in Figure 6. It can be seen that in case of rubber the Poisson effect (how material is deformed perpendicular to the applied load) is much bigger than the compressible foam-like structure.

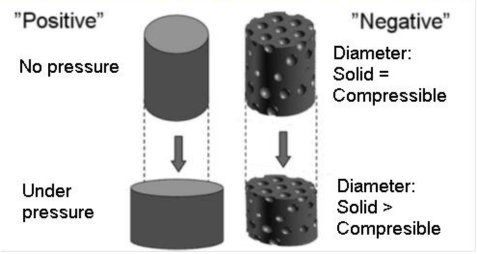


Figure 6 – The effect of material to deformation under pressure.

The feeding characteristics of a blanket can be measured in a specially designed rolling contact experiment [6]. The experimental setup consists of a rigid roller, which acts as the driver and a blanket cylinder, which is driven by contact friction, Figure 7. In the experiment, the angular velocities of the cylinders are measured. The feeding type can then be classified according to delta value, equation {1}.

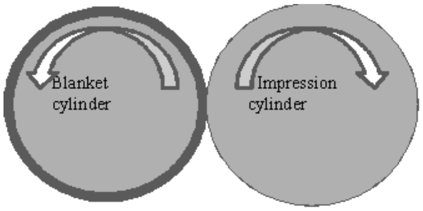


Figure 7 – Schematic view of the measurement of blanket feeding properties.

$$\delta = 1000 \cdot \left(1 - \frac{\omega_b}{\omega_r}\right) \qquad \{1\}$$

where ω_b and ω_r is the angular velocity of blanket and rigid cylinder, respectively. Delta values and corresponding feeding types are shown in Table 1.

Delta value	Feeding
… -2	Very negative
-2 … < -1	Negative
-1 … 0	Neutral
0 … < 1	Positive
1 …	Very positive

Table 1 – Delta values and feeding characteristics.

The printing speed and nip load also have an effect on the blanket's feeding property according to the blanket manufacturers. A higher press speed will lower the feeding value and an increase in nip load will increase the feeding value.

Three different blanket set ups were used in trials in the printing press, Table 2.

Printing unit	Blanket in 1st test run	Blanket in 2nd test run	Blanket in 3rd test run
1st printing unit	Neutral	Neutral	Neutral
2nd printing unit	Neutral	Positive	Negative
3rd printing unit	Neutral	Negative	Positive
4th printing unit	Neutral	Neutral	Neutral

Table 2 – Blankets feeding properties during trial runs in the printing press.

In this way, we could test every possible pair of blankets (feeding property) in successive printing units. It should be noted that normally printers do not mix blankets in this way. Nevertheless, it is quite possible that different printing nips have different nip loads, as printers do not normally measure nip loads.

Extensive laboratory studies were carried on printing materials (paper and blankets). These included the measurements of the blanket's feeding properties and paper measurements such as the paper's elastic modulus and creep.

Modeling of Paper Web and Printing Blankets

The effect of printing nips on web tension formation along an offset printing press was studied using the finite element method. The model was implemented in a commercial software ABAQUS. The two-dimensional finite element model consists of four printing units. Each printing unit consists of two rubber-covered cylinders, which the paper web passes through. The tension of the web was set to be constant before the first unit. The core of the blanket cylinders was considered to be rigid, and the blanket was considered to be firmly bonded to the rigid core. The paper web and rubber blankets were considered to be in a plane strain state. The friction between the surfaces in contact was modeled by the Coulombs friction law with a constant coefficient of friction. In all simulation cases, the radius of the cylinders was 100 mm and the thickness of the blanket 2 mm.

The material behavior of the web was assumed to follow the orthotropic linearly elastic constitutive law given by:

$$\begin{bmatrix} \varepsilon_x \\ \varepsilon_z \\ \varepsilon_{xz} \end{bmatrix} = \begin{bmatrix} \frac{1 - v_{xy} v_{yx}}{E_x} & \frac{\upsilon_{xz} - v_{xy} v_{yz}}{E_z} & 0 \\ \frac{v_{zx} - v_{zy} v_{yx}}{E_x} & \frac{1 - v_{zy} v_{yz}}{E_z} & 0 \\ 0 & 0 & \frac{1}{G_{xz}} \end{bmatrix} \begin{bmatrix} \sigma_x \\ \sigma_z \\ \sigma_{xz} \end{bmatrix}$$

where the x-direction, y-direction and z-direction denote machine (MD), cross machine (CD) and thickness direction, respectively.

The values of the Poisson's ratios were taken from the literature and are reported in Table 3 [8]. The elastic modulus in MD was obtained from the tensile test. The elastic modulus in MD is typically about 100 times greater than the modulus in the thickness direction. Therefore, the modulus in the thickness direction was determined from the relation $E_z = E_x/100$. The shear modulus was determined using the geometric mean approach

$$G_{xz} = \frac{\sqrt{E_x E_z}}{2\left(1+\sqrt{v_{xz} v_{zx}}\right)} \qquad \{3\}$$

Rolling contact is a well investigated area [7]. Rolling contact considering multilayered cylinders has been reported in the literature with a focus on the strains and stresses in the nip area [9,10,11]. The rubber blankets were represented as a three-layer structure, Figure 8. Surface and compressible layers were modeled as hyperelastic material whereas bottom fabric layer was modelled as linearly elastic material. The surface layer and the fabric layer were modelled as in reference [11]. For the compressible middle layer, the elastomeric foam material model was used. The strain energy function of the elastomeric material is given by:

$$U = \frac{2\mu}{\alpha^2}\left(\lambda_1^\alpha + \lambda_2^\alpha + \lambda_3^\alpha - 3 + \frac{1}{\beta}\left(\left(\lambda_1\lambda_2\lambda_3\right)^{-\alpha\beta} - 1\right)\right) \qquad \{4\}$$

where λ_i are the principal stretches and μ, β and α are material parameters. The parameter β determines the degree of compressibility and is related to initial Poisson ratio ν by the expression

$$\beta = \frac{v}{1-2v}$$

In the simulations values μ = 1.7 MPa and α = 0.37 were used. The value of ν depends on the feeding type of the blanket. For highly positive blankets, values close to 0.5 were used whereas for highly negative blankets values close to 0.0 were used.

ν_{xy}	ν_{xz}	ν_{yz}	ν_{yx}	ν_{zx}	ν_{zy}
0.32	1.52	1.84	0.15	0.008	0.021

Table 3 – Poisson’s ratios of paper

The actual simulation consists of three different steps. In the first step a tractive infeed tension is created. At this stage, the cylinders are not touching the paper web. In the second step, opposite printing cylinders are pressed together to generate nip. In the final step, printing process is activated by rotating cylinders with a prescribed angular velocity. The cylinders are rotated until a steady-state is attained.

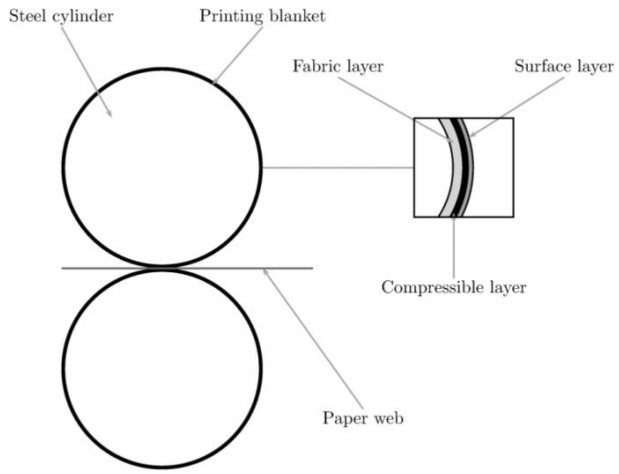


Figure 8 – The printing nip and different blanket layers used in modeling.

Measuring and Modelling of Plastic Web for Printed Electronics

VTT has developed a high speed stress-strain tester, named C-Impact. The C-Impact device will be presented in detail in a presentation held in this conference [12].

This device has normally been used when studying the effects of high straining speeds on paper web in a paper machine. Creep and relaxation tests can also be carried out with this device, as well as cyclic stress-strain tests. The temperature of tested samples can be controlled by using controllable thermo elements. The C-Impact was used to test and study the effect of stress and temperature to the web dimensions of plastic webs used in printed electronics. Web transport through a roll-to-roll printing press (Figure 9) was mimicked with C-Impact measurements.

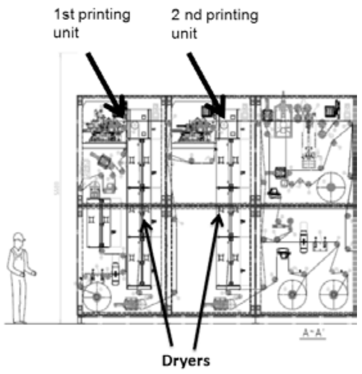


Figure 9 – Part of the roll to roll MAXI printing machine for printed electronics (VTT). MAXI was in an installation stage during this study.

Tests were carried out to on 75 µm thick polyethylene terephthalate (PET) foil, which was coated with aluminium or copper. Coating thickness was 60 nm.

In the finite element modeling an isotropic thermoplastic material model was used to describe deformations of the webs. The model is based on the von Mises yield criterion with isotropic hardening [13]. The material parameters were evaluated from tensile tests

(Figure 10) carried out at different temperatures (23 °C, 80 °C and 125 °C). The values obtained for the elastic modulus are given in Table 4. The Poisson ratio was assumed to be constant and in the simulations, a value of 0.35 was used for the ratio. In all cases, the yield point was close to 0.4 % (strain).

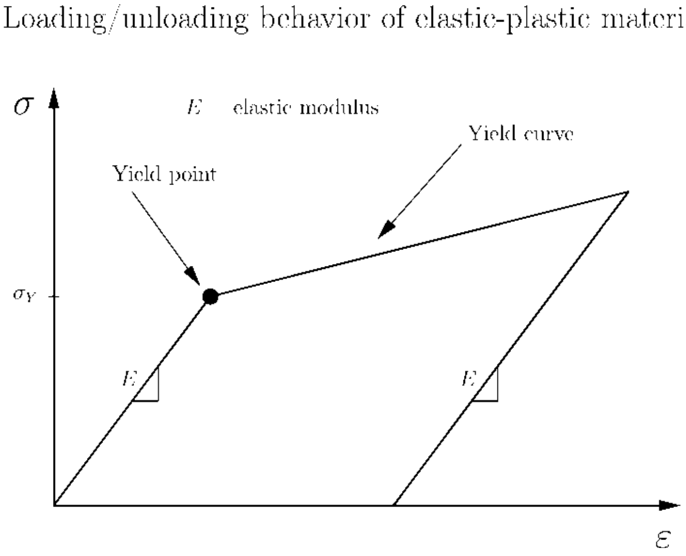

Loading/unloading behavior of elastic-plastic material

Figure 10 – Measuring principle for parameters needed in the mechanical part of the model; elastic modulus, Yield point where material behavior becomes plastic, plastic behavior (Yield curve).

E [GPa]	5.0	2.7	1.0
T [^{o}C]	23	80	125

Table 4 – Elastic modulus of PET foil at different temperatures

To model thermal-stress problems in which heat conduction occurs, thermal properties such as specific heat, thermal conductivity and heat transfer coefficient are needed. The values of the used thermal properties are given in Table 5.

Specific heat [kJ/kg/^{o}C]	Thermal conductivity [W/m/ ^{o}C]	Heat transfer coefficient [W/m^2/ ^{o}C]	Thermal expansion coefficient [10^{-6}/^{o}C]
1.3	0.14	30	38

Table 5 – Thermal properties

The effect of heating (heat conduction) on temperature and on mechanical material behaviour were solved simultaneously using finite element method (Abaqus).

RESULTS

Web Tension Formation in Heatset Offset Printing Press

The effect of press velocity and nip load on the blanket's feeding properties were measured in laboratory, Figure 11.

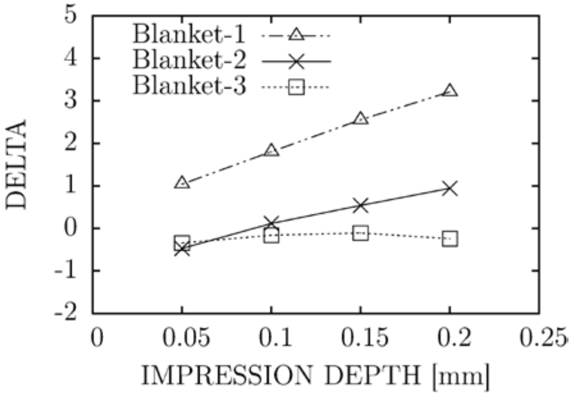
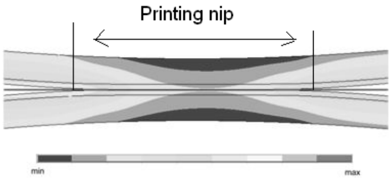
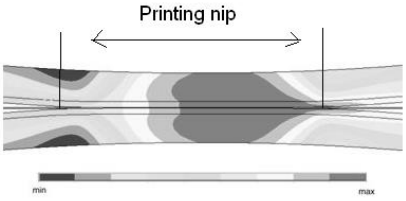


Figure 11 – Delta values as a function of impression depth when the speed is 5 m/s. Higher impression depth means higher nip load. Blanket 1 was the positive feeding blanket, blanket 2 was the neutral feeding blanket and blanket 3 the negative feeding blanket used in press trials.

As shown in Figure 11, Delta value is affected by the impression depth. Two of the three analyzed blankets tend to behave more positively as the impression depth increases. This is probably due to the blanket becoming less compressive under higher loads. This result is in line with earlier published results [9, 14, 15]. Impression depth in experiments carried out in the printing press was 0,15 mm in all printing nips.

Printing blankets and the printing nip were modelled as described in the methods chapter. Modeling results suggest that the different feeding properties of blankets give different velocity fields through the printing nip, Figure 12.





Web tensions in different parts of the printing press were measured in a trial run. Three blankets types were used in trials: neutral feeding blankets (n), negative feeding blankets (N) and positive feeding blankets (P). Three different blankets sets were used: n-n-n-n, n-P-N-n and n-N-P-n. Figure 13 presents result of the web tension measurements in the printing press.

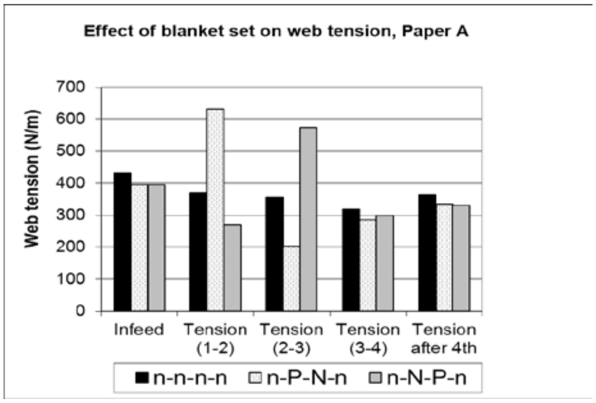


Figure 13 – Measured web tensions with three different blanket set-ups. Tension (1-2) means web tension measured between 1st and 2nd printing unit. n is a symbol for the neutral feeding blanket, N is a symbol for the negative feeding blanket and P is a symbol for the positive feeding blanket.

It can be seen that blankets feeding property had significant impact on web tensions between printing units.

Modeling results of the paper web suggest that blanket type has an effect on web speed before and after the printing nip. This means that the strain of the paper web between printing units is dependent on the blankets used. Figure 14 presents modelled strains (left side) as well as modelled and measured web tensions (right side) for blanket sets n-P-N-n (above) and n-N-P-n (bottom).

It can be seen that measurements and modeling results are well in line.

Different papers having e.g. different grammages and elastic moduli were used in the trial run. Results showed that the paper's elastic modulus defined the web tension level, Figure 15.

The same result was obtained between all units as web tension changed as a function of modeled strain and papers elastic modulus. These results suggest that web tension changes between printing units are caused by strain differences defined by the blankets. The magnitude of web tension change depends on the paper web's tensile stiffness.

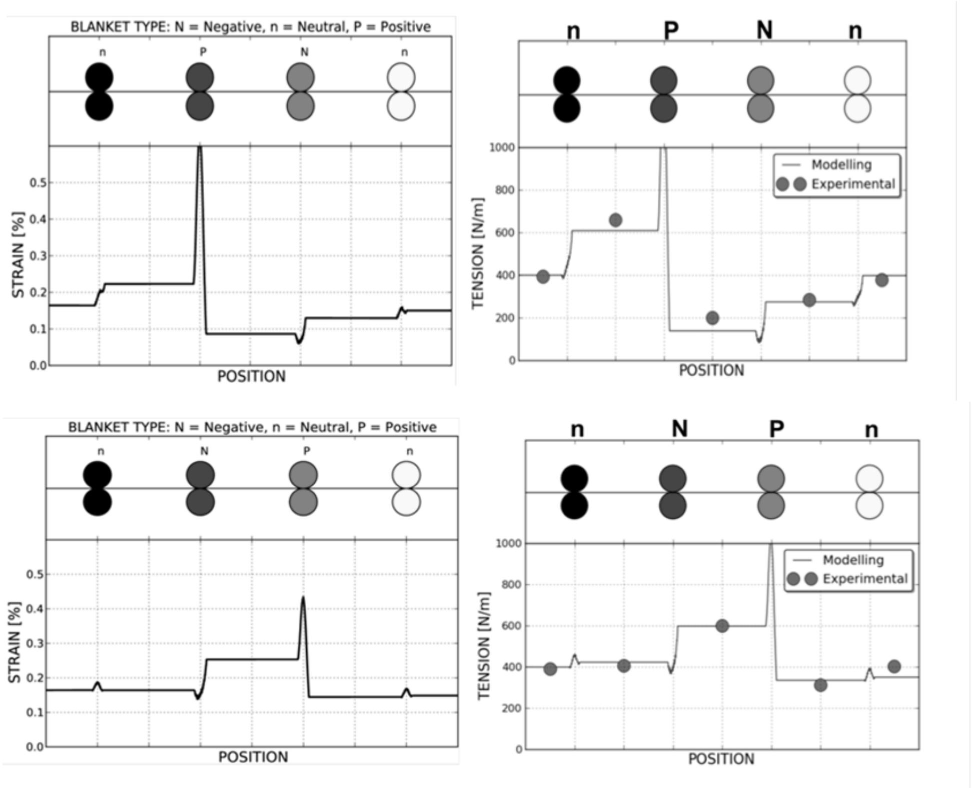


Figure 14 – Modeled strains of paper web through printing units left-hand side and modelled (solid line) and measured web tensions (dots) right-hand side. Blankets sets are marked above the figures, n-P-N-n above and n-N-P-n below.

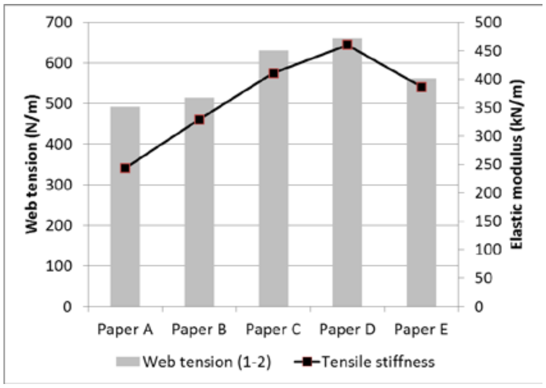


Figure 15 – The effect of papers elastic modulus on web tension measured in the press. Web tension measured between first and second printing unit when blanket set n-P-N-n was used.

A Case Study – Printed Electronics

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. In order to understand deformation mechanisms in a printed electronics application in which the printed media was PET foil, experimental laboratory tests and finite element modeling (described in methods) were carried out. Web inelasticity was studied by conducting temperature-dependent relaxation tests and uniaxial loading/unloading tests. In addition, cyclic heating tests were performed that mimic web behavior as the web goes through a series of dryers under load. The effects of heating (heat conduction) on temperature and on mechanical material behaviour were solved simultaneously using finite element method (Abaqus).

According to experimental results, the coated PET foil exhibits inelastic (plastic) material behavior only at elevated strain levels. Yield points were found to be approximately in 0.4 % strain at the temperatures used. As shown in Figure 16, straining the coated PET foil did not cause significant permanent plastic strains. In addition, it can be seen that the tensile stiffness decreased significantly as the temperature of the substrate increased. Modeling results correlated well with experimental results.

Figure 16 – Stress-strain curves of PET at different temperatures and modeling results.

It can be seen from the figure above that modeling correlated well with experimental measurements.

However, it can also be seen from Figure 16, that a hysteresis phenomenon takes place at all temperatures. This may cause strain differences in the web in the printing process and thus lead to register errors in printing.

Cyclic stress-strain and heating tests were carried out to mimic real life printed electronic process in a VTT MAXI press, which was at the installation stage during this study. In this press, a plastic web is pre tensioned to 300 N/m before the first printing unit. After this, the web goes through a dryer where the temperature is 125 °C and on to the second printing unit and again to a dryer. Web tension is kept constant throughout the process. The printing speed in MAXI is typically 3 m/min. Results revealed that heating induces significant thermal strains to the web, as shown in Figure 17.

It can be seen that modeling and measurements gave approximately the same strains when the web was heated, but laboratory measurements showed some irreversible strain after heating. A possible reason for this is that web tension was kept quite close to the yield point where materials plastic behavior begins. It is also possible that part of the thermal strains were irreversible. The model suggests that the thermal strains are the main cause of web expansion, as seen in Figure 17.

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 printing.

Results suggest that material parameters of substrates should be taken into account when controlling web transport in roll-to-roll printed electronics. Results suggest that one should know how the web materials respond to tension, draws and heat and further on how much the web deforms during the process to achieve the best possible register in printing. In traditional printing, register errors caused by web deformation are controlled by increasing printed image size from the first printing unit to the last. To make this kind of compensations one has to know the behavior of the printed substrate.

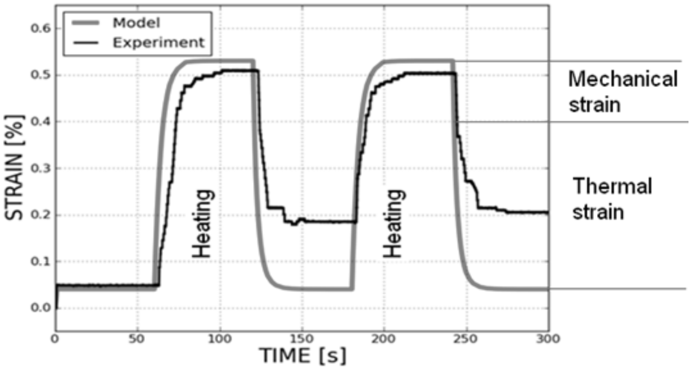


Figure 17 – Measuring and modeling results of web deformation in a cyclic test. Plastic web was pre-tensioned to 300 N/m; heating (125 °C) was applied to the sample for 60 seconds (the time the web is in the dryer) and the tension was kept at 300 N/m. Heating panels where then taken off and the sample cooled back to room temperature while the tension was kept at 300 N/m. After that, a similar interval was performed which mimicked printing from the second printing unit and drying. Proportions of thermal and mechanical strains are modeling results.

CONCLUSIONS

Studies carried out on an offset printing press suggest that web tension changes between printing units are caused by strain differences defined by printing blankets and nip properties. The magnitude of web tension change depends on the paper web’s elastic modulus. In practice, this means that a printer should know the feeding properties of used blankets and the elastic modulus of papers in order to be able to predict web behaviour between printing units. Also nip loads, as they have an effect on blankets feeding property, should be measured and the same nip load should be used in all printing nips to avoid runnability problems.

FE modeling was also used to study deformations in roll-to-roll printed electronics. Laboratory scale measurements and modelling in many ways gave the same results. However, some differences still exist and the strain mechanisms of PET foils during heating and cooling have to be studied in more detail in the laboratory and on printing presses.

Results obtained from the web deformation studies of PET webs suggest that the material parameters of the substrates should be taken into account when controlling web transport in roll-to-roll printed electronics. Results suggest that one should know how the web materials respond to tension, draws and heat, and further on how much the web deforms during the process in order to achieve the best possible register in printing.

VTT has recently installed a full-scale roll-to-roll printing machine for the manufacture of printed electronics. This flexible press is equipped with four different types of interchangeable printing units: flexographic, silk screen, rotogravure and slot die printing units. Further studies will be carried out at a production scale to determine the optimum way to achieve sufficient register accuracy with plastic webs. Studies concentrating on interaction mechanisms of substrate, ink and blanket will also be carried out.

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