

# Dynamic Nip Pressure in a Flexographic CI-Printing Press

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**Keywords:** Printing, Dynamic pressure, Plate, Print quality

**Abstract:** The dynamic nip pressure in a flexographic printing press has been studied. The nip pressure was measured by means of thin load cells. The measurements were made in a running full-scale flexographic central impression cylinder press. The aim was to measure and estimate the dynamic nip pressure at different press speeds and different impressions, using different printing plate materials and to assess its consequence for print quality.

The printing trials were performed on a liquid packaging board with a regular water-based cyan ink. Dynamic nip measurements and ink transfer were studied in the same printing unit. Press speed and impressions were varied as well as the printing plate material.

The results showed that measured dynamic nip pressure was a good indicator of the average dynamic pressure during the press pulse in the nip. The dynamic pressure was affected only by the level of impression. Neither the plate material used nor the press speed influenced the measured dynamic nip pressure.

The print quality was evaluated as print density, dot gain and amount of ink transferred to the substrate. The print quality parameters were all affected by press speed, impression and type of printing plate. It was possible to record the dynamic nip pressure in the flexographic printing press using the arrangement with the thin load cells. The “soft” printing plate gave higher ink transfer, a higher print density and less dot gain than the “hard” printing plate.

## 1. Introduction

Flexography is a common print method in packaging printing. The main features of flexographic printing are the flexible printing plate and the low viscosity

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ink, which make it possible to print on different absorbent and non-absorbent substrates. The use of water-based (VOC-free) inks, which predominate on absorbent materials, makes the print method attractive in fields where legislation demands more environmental-friendly inks (Neumann, 2001).

Conventional printing involves physical contact between printing plate- ink and ink- substrate. The classic ink transfer equation, presented by Walker and Fetsko (1955), includes the parameters; printing smoothness ( $k$ ), ink immobilization ( $b$ ) and fraction of free ink transferred ( $f$ ). Walker and Fetsko investigated how these parameters were influenced by printing speed and printing pressure in printing on coated paper. They found that  $k$  increased with increasing pressure,  $b$  increased with increasing printing pressure and decreased with increasing printing speed and that  $f$  increased with decreasing printing speed. The fraction of free ink transferred was not affected directly by pressure, but the pressure influenced the mechanical properties of the stock and thus also the ink transfer. Mangin, Lyne, Page and De Grace (1981) used different curve fitting methods to compare, estimate and interpret various ink transfer equations. They found that the Walker and Fetsko equation was superior, and when introducing a fourth parameter according to Karttunen, its superiority increased. They also concluded that the equation said nothing about the paper factors which control the ink transfer process. Cozzens, S. L., Butto, A. M., Schaeffer, W. D. and Zettlemyer, A. C (1965) showed that ink transfer increased with increasing pressure and decreased with increasing printing speed. They also noticed that a low viscosity ink gave constant ink transfer at high printing speeds (300 m/min and 425 m/min), but that ink transfer increased with increasing pressure at given speed. The trend appeared to be due to an increase in ink immobilization. De Grace and Mangin (1984) reported that compressible, porous and rough substrates were affected by both printing pressure and speed. The ink transfer to compressible, rough and porous substrates increased with increasing impression. An increase in printing speed resulted in a decrease in ink transfer. Ink splitting and ink immobilization strongly affected print quality. De Grace and Mangin (1986) also investigated the cause of the asymmetric and symmetric splitting behavior of inks on non-porous substrates in the printing nip. They concluded that ink transfer equations must include a splitting factor which decreases with increasing amount of ink on the paper. They could not confirm that asymmetric splitting was controlled by either a temperature-induced or a shear-induced reduction in ink viscosity at the ink-substrate interface. Asperities on the substrate surface could not alone explain asymmetric splitting. It was concluded that an additional mechanism, called "air-entrainment", was required.

The contact pressure and dwell time in the printing nip depend on the impression and press speed. Increased impression leads to a higher contact pressure and a longer nip length. An increase in printing speed results in a shorter dwell time. A compressible layer on the roller, as is the case in flexographic printing, means that the nip length increases with increasing

impression due to the more compliant layers. The appearance of the press pulse at a given press speed shows both the peak pressure and the nip length, which are important factors affecting the ink transfer. The fundamental theory of contact mechanism, frictionless elastic half spaces in contact, described by Hertz is simple but powerful. Approximate values of nip length, peak pressure and pressure distribution can be obtained, but the validity of the results must be discussed considering the assumptions made in developing the theory. Hannah (1951) described the pressure profile for both thick and thin compliant layers with derived integral equations. Hannah concluded that roller diameter, elastic modulus and layer thickness were the most important parameters determining the relation between load and deformation for a steel roller with an elastic layer in contact with a second steel roller. Numerical modelling experiments have been performed by Lim, Bohan, Claypole, Gethin and Roylance (1996) to describe the appearance of the pressure pulse in the nip. Their non-Newtonian model to predict the elastohydrodynamic behavior in a soft rolling contact gave results which agreed well with experimental data. Srinivas and Zettlemoyer (1988) developed a model for flexographic printing which considered the viscoelastic behavior of the photopolymer plate and the ink hydrodynamics in the nip. They concluded that the model agreed well with experimental data. Keller (1991) used force transducers embedded in a metal roll to measure the nip pressure and time profiles in a calender nip for different roll temperatures, nip loads and speeds. He also investigated the effect of pressure on paper properties and showed that paper compression is more impulse-related than pressure-related at high temperatures, probably due the softening effect on paper fibers. Speed and pressure are much higher in calendering than in flexographic printing. The complex analysis of two rolling layered cylinders has to rely on numerical methods (Wiberg, 1999).

In the present study, the effect of printing plate material, press speed and impression on ink transfer were studied in a full-scale central impression (CI) flexographic printing press. The dynamic press pulse was measured with thin load cells. The printing plate materials had the same thickness but different in hardnesses. Printing trials were performed on liquid packaging board at three printing speeds and three impressions. Ink transfer was analysed with regard to reflectance, dot gain and absolute ink coverage.

## **2. Materials**

### 2.1 Substrate

An uncoated liquid packaging board, denoted LPB, was chosen as substrate for the printing trials. The liquid packaging board consisted of five layers, two strong outer layers for strength and bending stiffness and three middle layers giving the board thickness and bulkiness. The print side was a blend of bleached short/long fibre, the reverse side was unbleached long fibre and the middle

layers consisted of CTMP (Chemical ThermoMechanical Pulp), filler and reinforcement pulp. The substrate was internally sized. The following substrate properties were measured; grammage (SCAN-P6:75), surface roughness (SCAN-P21:67), thickness (SCAN-P7:96) and surface compressibility (SCAN-P76:95) (*Table 1*).

**Table 1. Substrate properties**

Substrate	Grammage [g/m <sup>2</sup> ]	Surface roughness Bendtsen [ml/min]	Thickness [10 <sup>-6</sup> m]	Surface compressibility PPS [%]
LPB	177	445	263	13.8

## 2.2 Ink

A commercial water-based cyan ink (Scanbrite, Sun Chemical, Stockholm) was used in the printing trials. Viscosity was determined at the press with Zahn cup #2. Ink viscosity was kept constant at 30 ( $\pm 1$ ) seconds and the ink temperature was 22 ( $\pm 1$ )°C. The dry solids content of the ink was 39 % and the ink density was 1079.5 kg/m<sup>3</sup>. The ink contained 50-55 % water and had a Cu-content of 34 g/kg (dry ink). The ink was transferred to the printing plate with a laser-engraved (60 degree, angular position in relation to the roller axis) ceramic anilox roll with a 120 lines/cm screen.

## 2.3 Printing plate, adhesive tape and sleeve

Two different printing plates, both sheet plates, were used in the printing trials, one “soft” and one “hard”. The soft printing plate was ACE (BASF) with a hardness of 64° shore A (according to DIN 53505). The “hard” printing plate was NOW (DuPont Cyrel) with a hardness of 75° shore A. Both printing plates had a thickness of 1.14 mm. The photopolymer exposed to UV radiation according to SLP straight light position, at Flexopartner (Sunne, Sweden). The layout consisted of solid tone areas and halftone areas at values of 50% with a 28 lines/cm screen. The “soft” and “hard” printing plates were mounted on a soft coat sleeve (Polywest Kunststofftechnik) using a 0.1 mm (TESA), double-sided adhesive tape. The printing plates were mounted with a microscope-controlled, one-piece plate mounter (DuPont Cyrel microflex). The soft coat sleeve top layer consists of a two-component cold-cross-linked polyurethane (polyol and isocyanate) system with an open cell system. The top-layer to inner sleeve gives a total thickness of approximately 37 mm. “Soft” and “hard” printing plates and sleeve were characterized with a Differential Scanning Calorimeter, DSC (DSC 2920 CE, TA Instruments, New Castle, DE) to give the  $T_g$  (glass transition temperature) (*Table 2*) using DSC standard cell, equilibrated at -120 °C and heated to 180 °C at a rate of 10 °C/min.

**Table 2. Glass transition temperatures ( $T_g$ ) for “soft” printing plate, “hard” printing plate and sleeve.**

Sample	$T_g$ [°C]	$T_g$ [°C]
“Soft” printing plate	-88.5	63.9
“Hard” printing plate	-53.3	65.3
Sleeve	-59.3	67.1

### 3. Methods

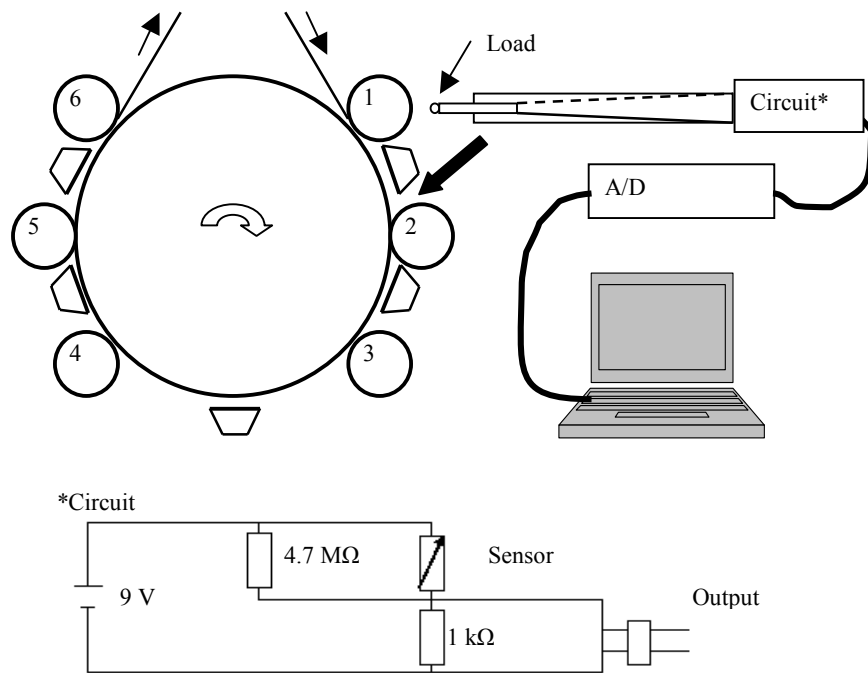
#### 3.1 Flexographic printing press

The printing trials were performed in a six-colour central impression cylinder press. The diameter of the impression cylinder was 0.9 meter. The printing press was equipped with five inner station air driers located between each of the six printing units and a final main dryer after the sixth printing unit. The air circulation was running during the experiments. Ink transfer was achieved with a chambered doctor blade, anilox roller, plate cylinder with attached printing plate and impression cylinder in printing unit 2.

The substrate was printed at three printing speeds (50, 100 and 150 m/min), and three impression settings (100, 200 and 300  $\mu\text{m}$ ) corresponding to three different printing pressures.

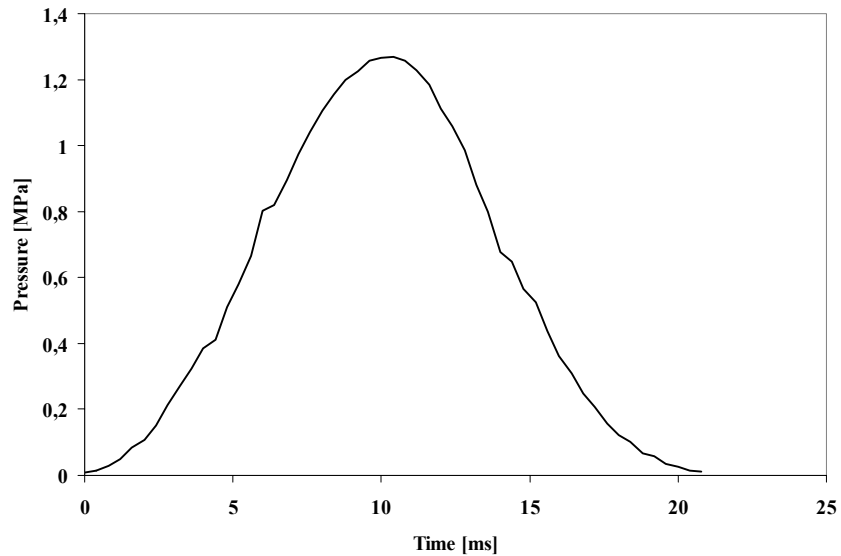
#### 3.2 Device for measuring dynamic nip pressure

The load cell, FlexiForce™ (PIAB Mätssystem AB, Sweden), had a diameter of 9.53 mm and a thickness of 0.10 mm. The precision of the load cell is 90-95 % and the linearity is 5 %. The load cell was attached to a strip and via conducting glue to an adhesive copper tape which united the strip to a circuit. With double-sided adhesive tape, the strip enabled the load cell to be picked up by the running web. The load cell was introduced into the nip between the board substrate and the printing plate cylinder. Measurements were made on the solid tone area of the printing plate. As soon as the load cell entered the nip, data collection started and the strip was detached from the circuit after passing through the nip. The potential difference at the output of the circuit depended on the resistance of the load cell. The potential difference was recorded using an A/D converter (model Daqbook 260, IOtech Inc., Cleveland U.S.). The data was collected at a speed of 2.5 scans per millisecond. The setup for these dynamic printing trials is shown in *Figure 1*.



**Figure 1. The set-up of instruments used when measuring the dynamic nip pressure.**

Data were further evaluated with a computer and the pressure was plotted versus elapsed time (*Figure 2*).



**Figure 2. Typical press pulse at a printing speed of 50 m/min, “soft” printing plate and impression of 200  $\mu\text{m}$ .**

Each measurement was repeated three times and the results showed good repeatability. The maximum nip pressure data showed good agreement with experimental pressure profile published by Mirle and Zettlemoyer (1988).

### 3.3 Platen press

The platen press experiments were performed with equipment from MTS, Material Testing System, using two plates ( $65 \times 65 \text{ mm}^2$ ). Pressure was applied with a hydraulic cylinder. The “hard” and “soft” printing plates and the sleeve had approximate E-moduli of 280 MPa, 420 MPa and 10 MPa, respectively, at a frequency of 100 Hz, which corresponds to a pulse time of 0.01 s with a haversine pulse.

### 3.4 Print evaluation

#### 3.4.1 Print density

The printed samples were evaluated considering optical print density with a Minolta spectrophotometer CM-3630 (Minolta Svenska AB, Sweden), with diffuse illumination and a zero degree viewing system. The instrument was calibrated in accordance with the provisions of ISO 2469. The reflectometer

measures in the wavelength range 360-740 nm with a resolution of 10 nm. In this study, only the reflectance factor values at 600 nm were used. This wavelength was chosen since there is a reflectance minimum at that point coinciding with an absorption maximum in the transmission spectrum of the cyan ink. The measurements were performed on printed samples with an opaque pad of the unprinted substrate as background. Optical print density was calculated using *Eqns. 1 and 2*.

### 3.4.2 Dot gain

The optical print density for halftone and solid tone patches were calculated from the reflectance factor values at 600 nm. Optical print density,  $D_V$  (full tone) and  $D_R$  (half-tone), is defined as:

$$D_V = \log\left(\frac{R_\infty}{R_V}\right) \quad [1]$$

$$D_R = \log\left(\frac{R_\infty}{R_R}\right) \quad [2]$$

where  $R_R$  is the reflectance values of the half-tones,  $R_\infty$  is the reflectance values of the unprinted substrate and  $R_V$  is the reflectance values of the half-tone. Dot gain was calculated for tone value 50 % and a 28 lines/cm screen using the Murray-Davies equation (Beier, 2001).

$$F_D [\%] = \left[ \frac{(1 - 10^{-D_R})}{(1 - 10^{-D_V})} \right] * 100\% \quad [3]$$

where  $F_D$  describes the optically effective area coverage in the print,  $D_R$  is the halftone density and  $D_V$  the solid tone density, whereas absolute dot gain in percent points can be calculated as:

$$Dot\ gain = F_D - F_{nom} \quad [4]$$

where  $F_{nom}$  is the nominal “tone value” of the negative film. This expression may be valid for the visual dot gain but is not a true representation of the physical dot gain. It gives a value only of the apparent area covered by the dots; the measurement is affected by the optical properties of the paper so that the filling-in appears greater than it actually is.

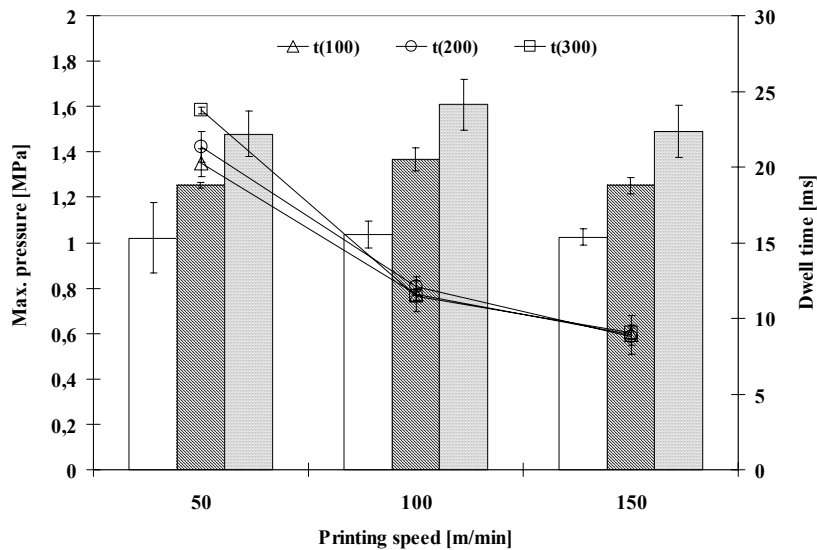
### 3.4.3 Ink transferred to the substrate

The amount of ink transferred to the substrate was assessed by analyzing the copper content of the printed samples. Printed samples with known weight were digested in concentrated nitric acid in a microwave oven. The copper content was determined by AAS (Atomic Absorption Spectroscopy) at a wavelength 324.8 nm and a slit width of 0.7 nm. The analysis was performed by Stora Enso Research Karlstad, Sweden.

## 4. Results

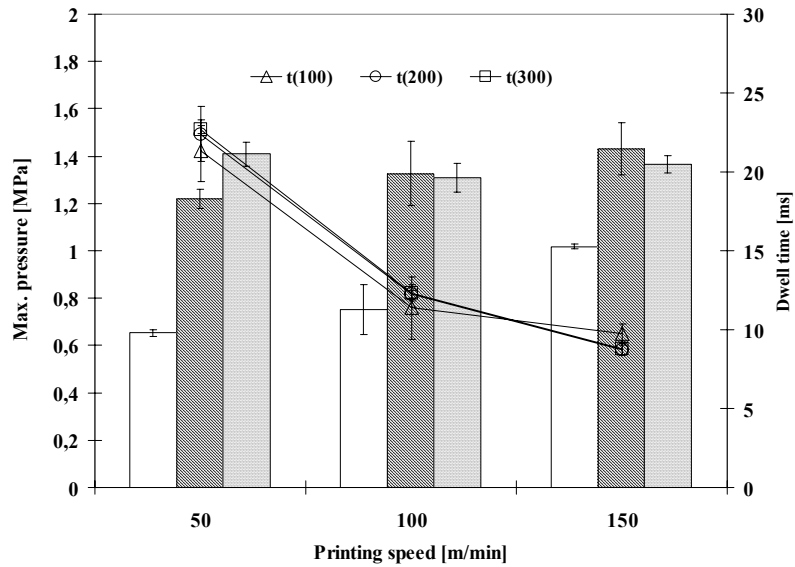
### 4.1 Pressure pulse

An increase in impression led to a higher dynamic nip pressure but neither press speed nor printing plate material had any significant influence on the maximum dynamic nip pressure. The dwell time decreased and the nip length increased with increasing web speed. *Figure 3* shows the maximum pressure and dwell time as a function of press speed for the “soft” printing plate.



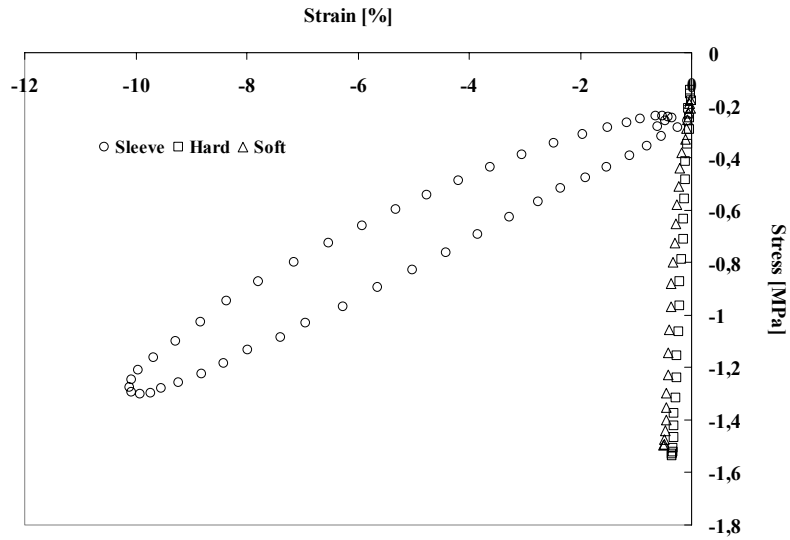
**Figure 3.** Maximum pressure, columns left-hand y-axis, and dwell time, lines right-hand y-axis, for “soft” printing plate at different printing speeds (50, 100 and 150 m/min) and different impressions (100  $\mu\text{m}$ , 200  $\mu\text{m}$  and 300  $\mu\text{m}$ ). Error bars indicate standard deviation.

The “soft” printing plate showed a clear relationship between impression and pressure with increasing impression. The “hard” printing plate showed a similar behavior, but it was less pronounced when the impression increased from 200 to 300  $\mu\text{m}$  (*Figure 4*).



**Figure 4.** Maximum pressure, columns left-hand y-axis, and dwell time, lines right-hand y-axis, for “hard” printing plate at different printing speeds (50, 100 and 150 m/min) and different impressions (100  $\mu\text{m}$  , 200  $\mu\text{m}$  , and 300  $\mu\text{m}$  ). Error bars indicate standard deviation.

Printing plates and sleeve were tested with regard to their material properties. *Figure 5* shows the MTS stress-strain relationship for the sleeve and for the “soft” and “hard” printing plates. The plates are considerably less compliant than the sleeve.

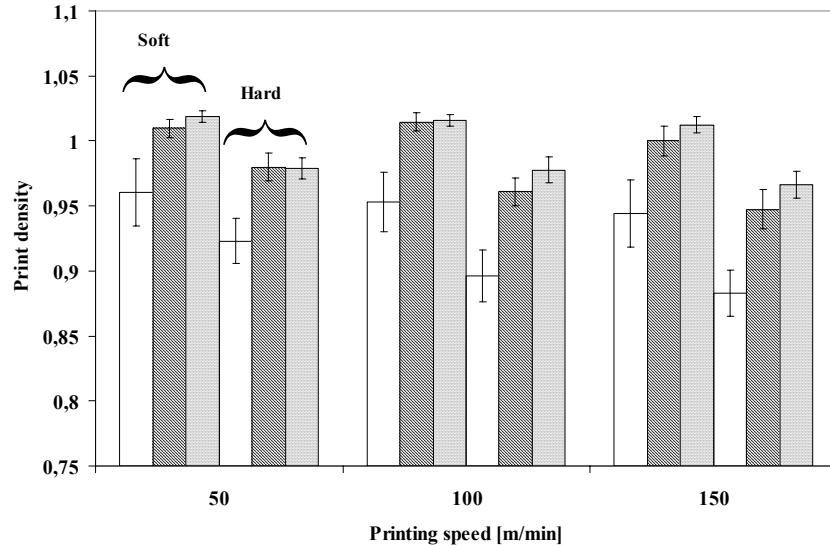


**Figure 5. Stress -strain curves for sleeve, “hard” printing plate and “soft” printing plate. Trials performed in a platen press using haversine pulse and a frequency of 100 Hz corresponding to a pulse time of 10 ms.**

## 4.2 Print evaluation

### 4.2.1 Print Density

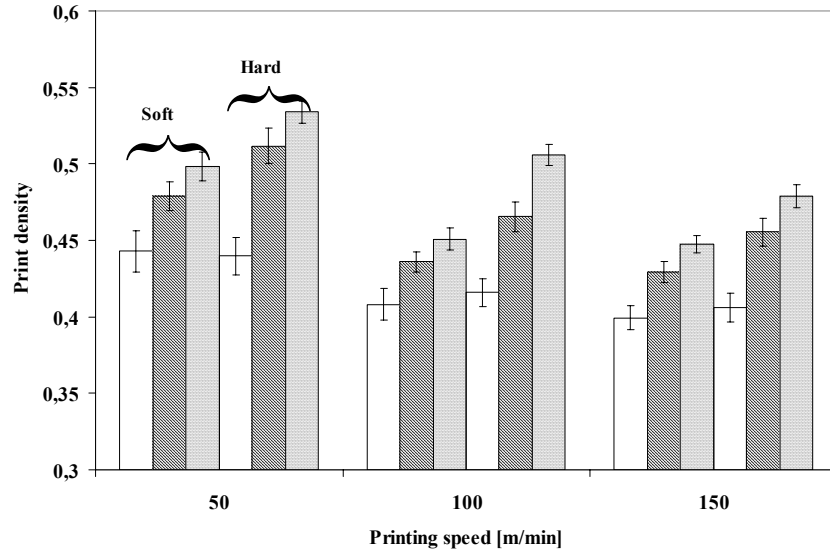
The print density was determined on fulltone and halftone areas on the printed samples. *Figure 6* shows the print density for the fulltone areas using “soft” and “hard” printing plates at different press speeds and impressions.



**Figure 6. Print density for solid tone using “soft” and “hard” printing plate at different printing speeds (50, 100 and 150 m/min) and different impressions (100  $\square$  , 200  $\square$  and 300  $\square$   $\mu\text{m}$ ). Error bars indicate standard deviation.**

The “soft” printing plate gave a higher print density than the “hard” printing plate, which may be explained by the fact that the “soft” printing plate had a higher flexibility and could therefore comply better with the surface roughness of the substrate. Both printing plates showed a slight decrease in print density with increasing press speed. This indicated that less ink was transferred to the substrate when the press speed was increased. A higher impression led to a higher print density. One interpretation could be that there was an increase in contact area between the ink-covered printing plate and substrate due to an increased compression of the plate. The steep increase in print density between 100 and 200  $\mu\text{m}$  was not repeated between 200 and 300  $\mu\text{m}$ . The printing plates reached their maximum deformation in these trials at about 300  $\mu\text{m}$ .

The same measurements were made on for halftone areas with a tone value of 50 % and 28 l/cm screen (Figure 7).



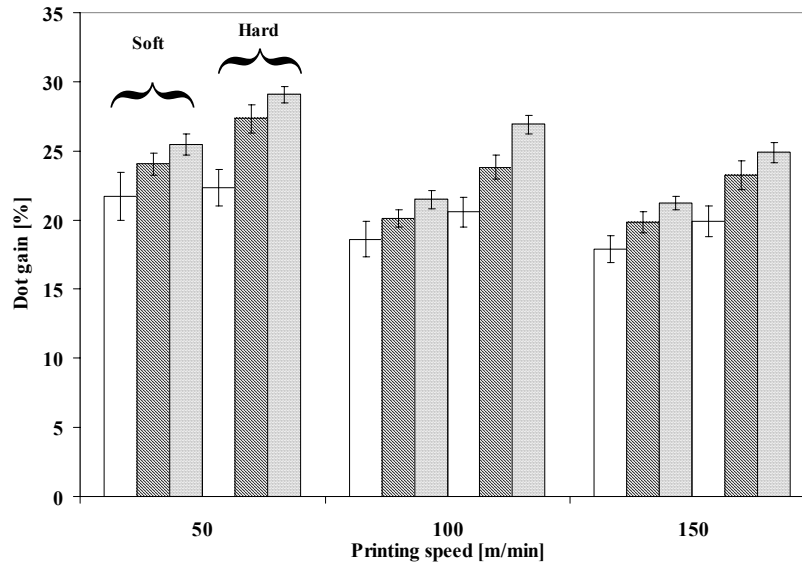
**Figure 7. Print density for halftone (tone value 50 % and screening 28 l/cm) using “soft” and “hard” printing plate at different printing speeds (50, 100 and 150 m/min) and different impressions (100  $\square$ , 200  $\square$  and 300  $\square$   $\mu$ m). Error bars indicate standard deviation.**

The “hard” printing gave higher print density than the “soft” printing plate. This was interpreted as a higher dot gain using the “hard” printing plate. There was a slight decrease in print density with increasing press speed, for both solid tone and half tone areas. Low pressure (100  $\mu$ m) gave a low print density and a low dot gain. As the pressure increased, the print density increased, and the dot gain was higher.

#### 4.2.2 Dot gain

Megat Ahmed, Gethin, Claypole and Roylance (1997) have reported that pressure, ink viscosity and initial ink thickness have an influence on dot gain. Dot gain increased with increasing film thickness and increased pressure, but decreased with increasing ink viscosity. Both ink thickness and ink viscosity were kept constant during the printing trials, but the ink viscosity is both temperature-dependent and shear-rate-dependent, so the ink viscosity decreases with increasing temperature and increasing press speed. This may lead to changes in ink viscosity which is not taken into account here.

*Figure 8* shows the dot gain for the “soft” and “hard” printing plate at different impressions and different press speeds.



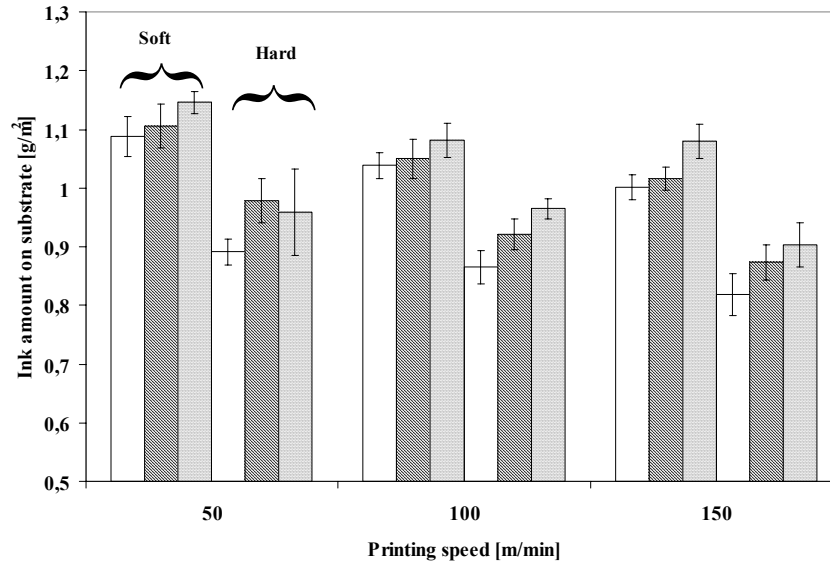
**Figure 8. Dot gain for halftone (tone value 50 % and screening 28 lines/cm) using “soft” and “hard” printing plate at different printing speeds (50, 100 and 150 m/min) and different impressions (100  $\square$  , 200  $\square$  and 300  $\square$   $\mu$ m). Error bars indicate standard deviation.**

The highest dot gain was seen at 50 m/min. Dot gain declined as the press speed increased to 100 and 150 m/min. At 50 m/min there was a long dwell time, the ink had time to spread on the substrate surface and this led to an increase in dot gain. An increase in the impressions affect the dot gain in a negative way since the dot gain increased with increasing impression. The “hard” printing plate showed the same tendencies as the “soft”, but generally gave a higher dot gain. The dot gain here is defined as the difference between dot area on the film negative and the printed dot area. The same film negative was used for the “soft” and “hard” plates. Small differences between “soft” and “hard” (up to circa 2 %) can be explained in terms of the platemaking process.

#### 4.2.3 Ink coverage

To understand whether the low print density depended on a low ink transfer or on an enhanced penetration of the ink into the porous substrate, printed samples were analysed with respect to copper content. A low copper content indicates a low ink transfer i.e. a low amount of ink on the substrate, whereas a high copper content should indicate an increased penetration of the ink. The results showed that the “soft” printing plate gave in general a higher amount of ink on the

substrate than the “hard” printing plate, concordant with the print density results, indicating a greater ink transfer using the “soft” printing plate. *Figure 9* shows the amount of ink on the printed samples as a function of press speed at different impressions using the “soft” and “hard” printing plates.



**Figure 9.** Dry ink amount on substrate using “soft” and “hard” printing plate at different printing speeds (50, 100 and 150 m/min) and at different impressions (100  $\square$  , 200  $\square$  and 300  $\square$   $\mu\text{m}$ ). Error bars indicate standard deviation.

The amount of ink on the substrate increased with increasing impression. A higher press speed had a negative influence on ink transfer for most of the printed samples, i.e. the amount of ink on the substrate decreased with increasing press speed.

## 5. Discussion

Printing involves the transfer of liquid ink to a substrate. The procedure requires dynamic mechanical contact between an ink-covered printing plate and a substrate. It also involves film splitting where ink viscosity, ink thickness and surface energetics are important, and paper properties such as porosity, smoothness and absorption come into play (Parker, 1976). Apart from the paper properties, where compressibility and surface topography govern the actual areas of contact between the substrate and the ink-covered printing plate, the

mechanical properties of the sleeve and the printing plate have a strong influence on the dynamic mechanical contact.

### 5.1 Platen press trials and dynamic press pulse

The platen press trials showed that the most compliant material was the sleeve, see Figure 5. It was therefore probable that the main deformation occurred in the sleeve. This was probably the reason for the small difference in dwell time between the “soft” and “hard” printing plates, see Figures 3-4. The nip length varied between 7 and 15 mm, depending on printing speed and impression. A higher printing speed and higher impression gave a longer nip length. Contributing factors were the small difference in hardness value between the printing plates and, of course, the resolution of the load cell. Another critical issue was the size of load cell. The nip length was small compared to the load cell diameter. This was only noticeable at a low speed (50 m/min), which meant that average pressure was measured over the actual nip length. The pressure measured by the load cell was then lower than the actual pressure, as only a part of the load cell was subjected to a load. This observation indicated that the dynamic pressure measurements performed at 50 m/min might be somewhat higher than those recorded in Figures 3 and 4. However using the assumption that the signal output from the load cell corresponds to the average stress,  $\sigma(t)$ , and approximating the press pulse as a sine wave:

$$\sigma(t) = \sigma_0 * \sin\left(\frac{\pi t}{t_p}\right) \quad [5]$$

where  $\sigma_0$  is the maximum pressure and  $t_p$  the pulse time ( $0 \leq t \leq t_p$ ), meant that the estimated error, when the nip length was less than or equal to the sensor diameter, was not greater than  $\sigma_0$  multiplied by a factor of  $\pi/2$ .

### 5.2 Implications for print quality

Even though the printing plates had only small differences in their mechanical properties, they differed in ink transfer, since the “soft” printing plate gave a higher ink transfer. This was indicated by a lower reflectance for the “soft” printing plate in the solid tone, see Figure 6. The dot gain was generally lower for the “soft” printing plate (Figure 8). This was contradictory because a higher ink film thickness normally led to a higher dot gain, as reported by Megat Ahmed, Gethin, Claypole and Roylance (1997) for offset printing. However the higher dot gain value obtained for the hard printing plate may be a consequence of the definition of dot gain (of Eqn. 3), since  $F_D$  is affected by the solid tone density in such way that a high value of  $D_V$  will result in a low value of  $F_D$ . It

may be difficult to compare samples with different print density for full tone areas.

## 6. Conclusion

It is possible to record the average dynamic pressure in a flexographic printing nip using thin load cells. Even though the differences in mechanical properties between the printing plates were small, they differed concerning ink transfer and print quality. The “soft” printing plate gave a higher print density in solid tone areas, a higher ink transfer and also a smaller dot gain than the “hard” printing plate. This may be explained by the higher compliance of the “soft” printing plate which may give an increased contact area between ink-covered printing plate and substrate.

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## Literature Cited

- Beier, W.  
(2001) Conventional Prepress. In H. Kipphan (Ed.), Handbook of Print Media (pp. 478). Berlin: Springer.
- Cozzens, S. L., Butto, A. M., Schaeffer, W. D. and Zettlemoyer, A. C.  
(1965) Ink penetration during high-speed printing of uncoated paper. In W. H. Banks (Ed.), Advances in Printing Science and Technology (pp. 1-23). London: Pergamon Press.
- De Grace, J. H. and Mangin, P. J.  
(1984) A mechanistic approach to ink transfer. Part I: Effects of substrate properties and press conditions. In W. H. Banks (Ed.), Advances in Printing Science and Technology (pp. 312-332). London: Pentech Press.
- De Grace, J. H. and Mangin, P. J.  
(1986) A mechanistic approach to ink transfer. Part II: The splitting behavior of inks in printing nips. Pulp and Paper Reports (PPR 603) (pp. 1-11). Pulp and Paper Research Institute of Canada.
- Hannah, M.  
(1951) Contact stress and deformation in a thin elastic layer. Quarterly Journal of Mechanics and Applied Mathematics (vol. 4, pp. 94-105). Oxford: Clarendon Press.
- Keller, S. F.  
(1991) Measurement of the pressure-time profile in a rolling calender nip. Paper presented at 77<sup>th</sup> Annual Meeting, Technical Section, held at Montreal, Canada, 31 Jan.-1 Feb. 1991. (pp. 89-96).

- Lim, C. H., Bohan, M. F. J., Claypole, T. C., Gethin, D. T. and Roylance, B. J.  
 (1996) A finite element investigation into a soft rolling contact supplied by a non-Newtonian ink. *Journal of Physics D: Applied Physics*, 29(7), 1894-1903
- Mangin, P. J., Lyne, M. B., Page, D. H. and De Grace, J. H.  
 (1981) Ink transfer equations – parameter estimation and interpretation. In W. H. Banks (Ed.), *Advances in Printing Science and Technology* (pp. 180-205). London: Pentech Press.
- Megat Ahmed, M. M. H., Gethin, D. T., Claypole, T. C. and Roylance, B. J.  
 (1997) A model for ink impression into a porous substrate. *Journal of Applied Physics*, 30(16), 2276-2264.
- Mirle, S. K. and Zettlemoyer, A. C.  
 (1988) Viscoelasticity of photopolymer plates and ink hydrodynamics in modeling flexographic printing. *Proceedings of the 6<sup>th</sup> International Conference of Mathematical Modelling* (vol.11, pp. 1162-1165). London: Pergamon Press.
- Neumann, R.  
 (2001) Packaging Printing Presses and Printing Systems. In H. Kipphan (Ed.), *Handbook of Print Media* (pp. 159). Berlin: Springer.
- Parker, J. F.  
 (1976) Fundamental paper properties in relation to printability. In F. Bolam (Ed.), *The fundamental properties of paper related to its uses* (vol. 2, pp. 517-542). London.
- Walker, W. C. and Fetsko, J. M.  
 (1955) A concept of ink transfer in printing. *American Ink Maker*, 33(12), 38-40, 42, 44, 69, 71.
- Wiberg, A.  
 (1999) Rolling Contact of a Paper Web between Layered Cylinders with Implications to Offset Printing, Licentiate Thesis (no. 66). Department of Solid Mechanics, Royal Institute of Technology, 1999). ISRN KTH/HFL/LA--66—SE.