Print gloss development on a model substrate

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ABSTRACT

Print gloss of ink films was continuously recorded using a laser detector mounted on a laboratory print tester. Experimental variables were printing speed and the thickness of the ink film. Both variables had a strong influence on the results, with high speeds and thick layers of ink producing a film that levels rapidly and then slows down, ultimately producing a lower print gloss than that obtained at lower speeds and ink levels. These experimental results agree qualitatively with calculated results from a model that predicts the extent of ink leveling for a given substrate roughness, initial thickness of the ink layer, ink surface tension, and ink viscosity. The model shows that the wavelength of defects in the printed surface is a critical parameter, with long-wavelength defects having slower leveling rates. Apparently, these long-wavelength defects are introduced when printing at high speeds with thick ink films. However, extremely thin ink films also can reduce the leveling rate if there is not enough fluid to fill up the surface roughness.

Application:

Experimental results record the dynamics of print gloss and compare with model predictions obtained over a range of printing speeds and ink film thicknesses.

PRINT GLOSS IS ONE OF THE MOST important aspects of a printed surface. High gloss gives the print the appearance of high clarity, quality, and image resolution. However, a fundamental understanding of the factors that influence print gloss is not reported in the literature. Even though the final print gloss is routinely measured, there have been no measurements reported on the evolution of print gloss in time. This work is an attempt to quantify the leveling rate of ink films through a theoretical model and to measure how print gloss changed in time immediately following a printing nip.

Print gloss depends on the refractive index and the degree of smoothness of the printed surface. Because most inks have similar refractive index, differences in ink gloss are caused in large part by the degree of surface smoothness. The degree of smoothness, in turn, depends on a number of parameters such as the amount of ink, the speed of printing, the rheology of the ink, the smoothness of the substrate, and the porosity of the substrate. There have been some attempts to separate the effects of these different parameters on ink gloss, but a clear understanding is still lacking. As Zang and Aspler *(1)* point out, some printers are concerned only with the gloss of the substrate (roughness), while others are concerned with the rate of ink setting as a factor that determines print gloss.

Aspler and Lepoutre *(2)* and Fetsko and Zettlemoyer *(3)* reviewed several aspects of printing and print gloss. Generally, ink gloss increases with increasing ink film thickness. Some exceptions to this are noted by Fetsko and Zettlemoyer *(3)* with regard to high-gloss coated grades. Ink gloss increases with increasing substrate gloss at low ink levels but does not depend on substrate gloss at high ink levels *(1)*. Increasing printing speed tends to decrease gloss at high ink levels but increases gloss at low ink levels *(4)*. The roughness of the ink film immediately following printing should affect the final ink film roughness and gloss.

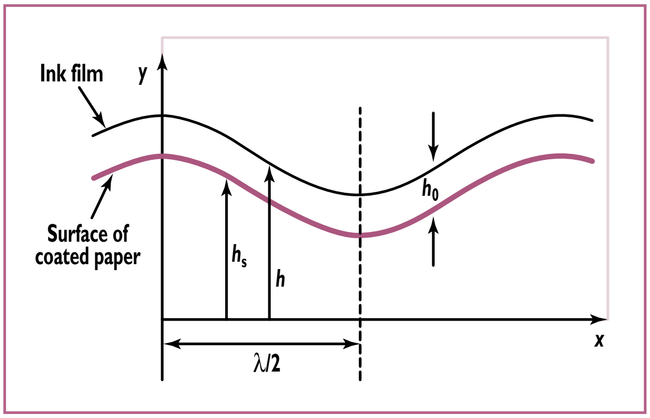
Oittinen *(5)* suggests that coated paper roughness can be split up into macroroughness (from the base sheet) and microroughness (from the coating). A high-gloss sheet must have no macroroughness, and the degree of gloss is limited by the degree of microroughness. As ink thickness is increased, surface voids caused by microroughness are filled, resulting in a higher gloss print. This will not be the case with extremely high-gloss sheets, where the roughness of the ink may be greater than the microroughness of the paper.

We propose here a model to describe the leveling of an ink film on a rough substrate. The model points out the importance of the disturbance wavelength on leveling rate. The model shows two different regions of behavior between low ink levels and high ink levels.

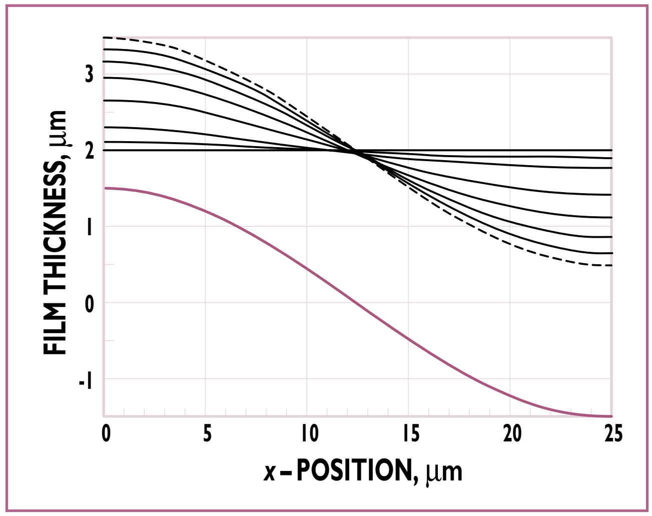
Experiments were conducted to measure ink gloss as a function of time, starting at 0.1 s after the nip. The influence of printing speed and ink film thickness on the rate of gloss development was quantified for inks printed on a plastic film.

MODEL DEVELOPMENT

The model proposed here is an extension of the "long-wave analysis"



1. Thin film leveling on a rough substrate



2. Model results showing predicted profile of a 2-µm ink film on a rough substrate at time = 0 (dashed line) and after 0.2, 0.5, 1, 2, 5, 10, and 20 s. The thick curve at the bottom is the substrate surface. (Roughness amplitude = 1.5 µm; roughness wavelength = 50 µm; ink viscosity = 50 Pa·s; surface tension = 40 mN/m.)

of Kheshgi and Scriven *(6)* for the leveling of a fluid layer in response to surface-tension forces on a level surface. For the film thicknesses and viscosities involved in printing, gravity can be shown to have no effect. A number of assumptions need to be made in a model of this type: ink is a Newtonian fluid, there is no drying or absorption of ink solvents, and the ink acts as a continuous fluid.

Figure 1 shows the initial film profile and substrate roughness. The film is depicted here as uniform in thickness, and the substrate roughness is modeled as a sinusoidal function, but any film shape and any substrate shape can be studied with the model. The substrate profile is h_s; h is the ink film profile; the film thickness is h_0; and the wavelength of the substrate roughness is λ. Another assumption, which should be valid for ink films, is that the wavelength is much greater than the ink film thickness. For thin films, the x and y momentum terms of the Navier–Stokes equations become

$$\partial P/\partial x = \mu[(\partial^2 v_x)/\partial y^2] \qquad (1)$$

$$\partial P/\partial y = 0 \qquad (2)$$

where

P = pressure
μ = viscosity
v_x = velocity in the x direction.

Equations 1 and 2 are valid for a thin Newtonian fluid with a wave number $k = 2\pi\lambda/h_0 < 1.0$ *(7)*. These equations show that the local pressure is not a function of the y position. Therefore, the x-momentum equation can be integrated to obtain the form of the velocity profile with a no-slip condition at $y = h_s$ and the no-shear condition at the film height $y = h$.

Any curvature at the ink surface creates a local pressure, relative to atmospheric pressure, and is given by Eq. 3 *(8)*.

$$P = -\gamma\partial^2 h/\partial x^2 \qquad (3)$$

where

γ = surface tension of the ink.

Conservation of mass gives the following relationship between the film motion and the velocity field:

$$\partial h/\partial t = -\partial/\partial x[\int_{h_s}^{h} v_x\, dy] \qquad (4)$$

When Eq. 3 is inserted into the velocity field and this velocity field is inserted into Eq. 4, an evolution equation is obtained for the film profile in time (t):

$$\partial h/\partial t = (-\gamma/3\mu)\ \{[(\partial^4 h/\partial x^4)(h-h_s)^3] + [(3\partial^3 h/\partial x^3)(h-h_s)^2(\partial h/\partial x)]\} \qquad (5)$$

Equation 5 is the working equation of the model and is solved with standard finite-difference techniques. Given any initial film profile, h, any surface shape or profile, h_s, and the fluid viscosity and surface tension, the model predicts the film profile in time. Most of the results will be limited to a sinusoidal surface profile with a uniform ink film, as depicted in Fig. 1.

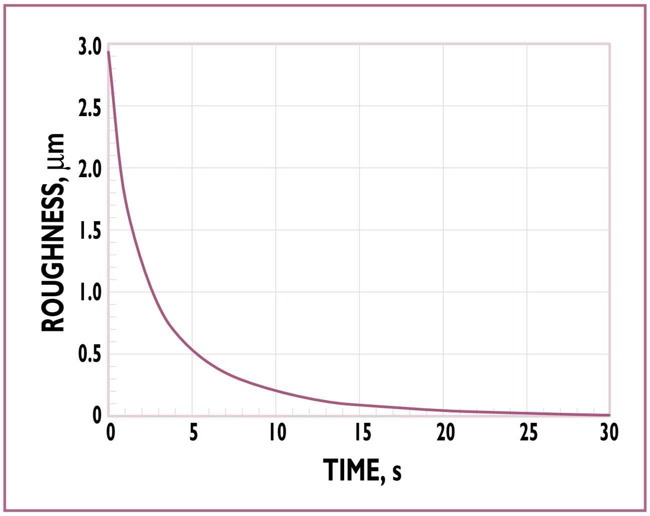
Linear analysis of Eq. 5 gives the same results as in Kheshgi and Scriven *(6)*:

$$h = h_0 + [\varepsilon \cos(2\pi x/\lambda) \exp(-\alpha t)] \qquad (6)$$

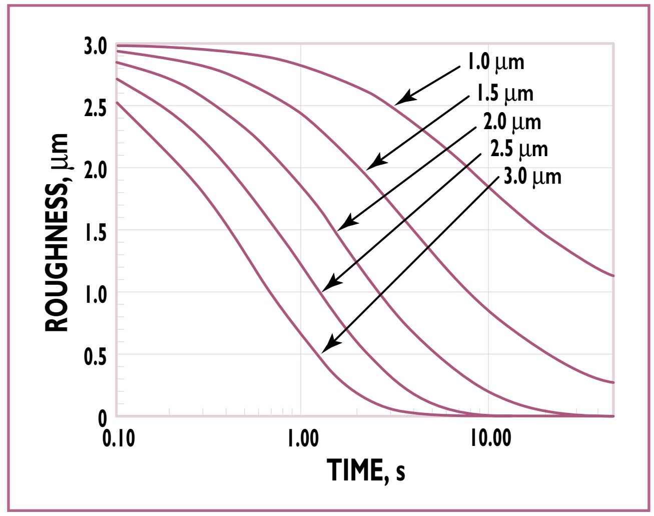
where the exponent factor, α, is:

$$\alpha = (16/3)\gamma\pi^4(h_0^3/\mu\lambda^4) \qquad (7)$$

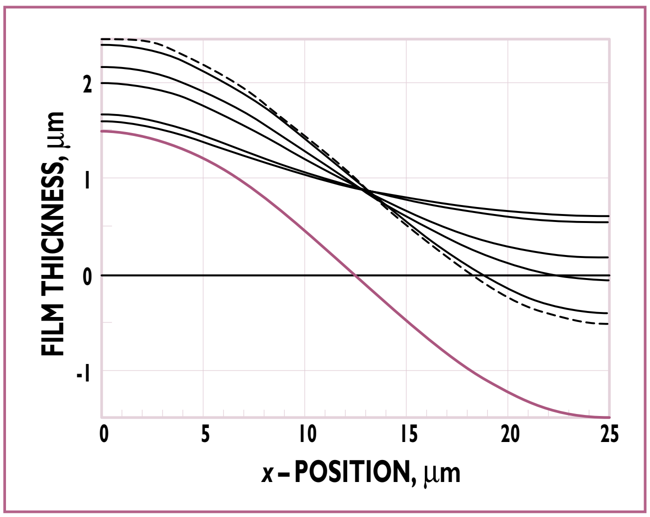
This shows that the leveling rate should be of an exponential form, with the rate constant proportional to the viscosity and surface tension.



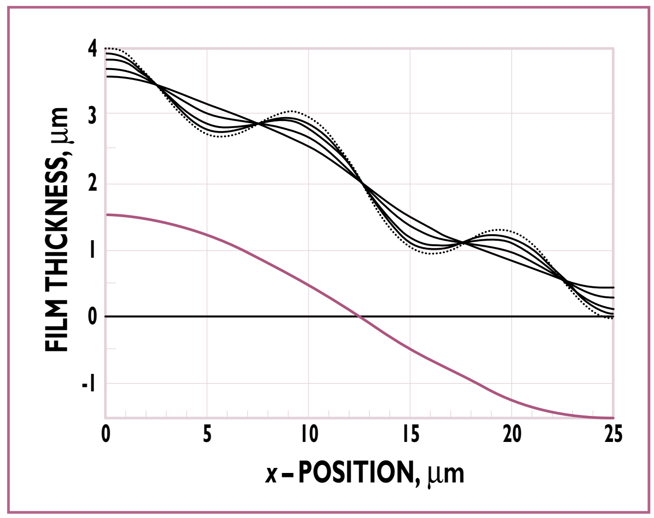
3. Model results showing predicted change in film roughness as a function of time for a 2-µm film leveling on a rough substrate (substrate and fluid conditions as listed in Fig. 2)



4. Model results showing predicted change in film roughness as a function of log time for thin films (1–3 µm) leveling on a rough substrate (substrate and fluid conditions as listed in Fig. 2)



5. Model results showing predicted profile of a 1-µm ink film on a rough substrate at time = 0 (dashed line) and after 1, 5, 10, 50, and 100 s. The thick curve at the bottom is the substrate surface. (Substrate and fluid conditions as listed in Fig. 2.) Ink leveling is inhibited by the thin layer formed on the high region of the substrate.



6. Model results showing predicted profile of a 2-µm ink film at time = 0 (dashed line) and after 0.01, 0.02, 0.05, and 0.1 s for a film with a disturbance of two wavelengths. The thick curve at the bottom is the substrate surface. (Substrate and fluid conditions as listed in Fig. 2.) The fine-scale disturbance levels rapidly to produce a film with a long-scale disturbance.

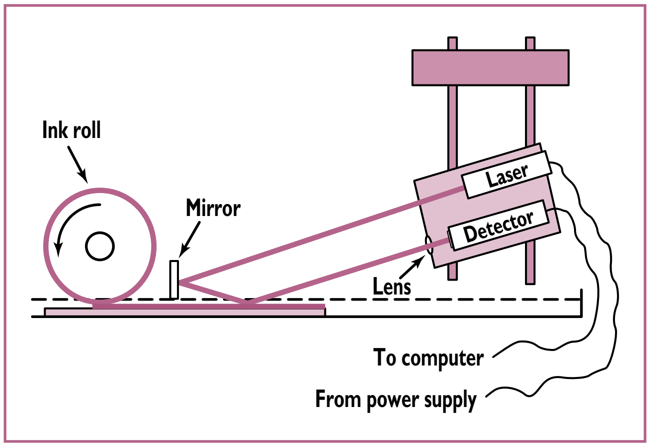
The leveling rate also depends on the third power of film thickness and the fourth power of the wavelength.

MODEL RESULTS

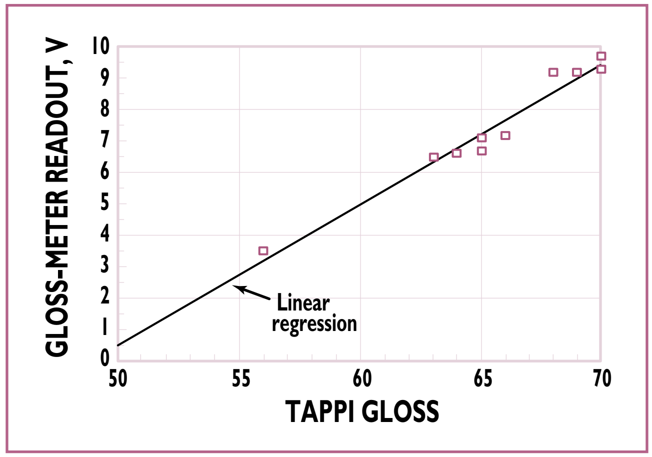
Figure 2 shows the ink film profiles for a substrate with a roughness amplitude of 1.5 µm and a roughness wavelength of 50 µm. The ink viscosity and surface tension are 50 Pa·s and 40 mN/m, respectively. The broken line represents the initial ink film shape with an initial thickness of 2 µm. The final profile is the nearly horizontal line that is obtained after 20 s of leveling. The curvature of the initial film creates a high-pressure region at the high point of the substrate. This high pressure drives fluid to the low-pressure region, where the film curvature has reversed sign.

If roughness is defined as the difference in height between the highest and lowest points, **Fig. 3** shows the change in roughness in time for the case in Fig. 2. When the curvatures of the film are high, there is a rapid leveling. As the film becomes uniform, the leveling rate slows down.

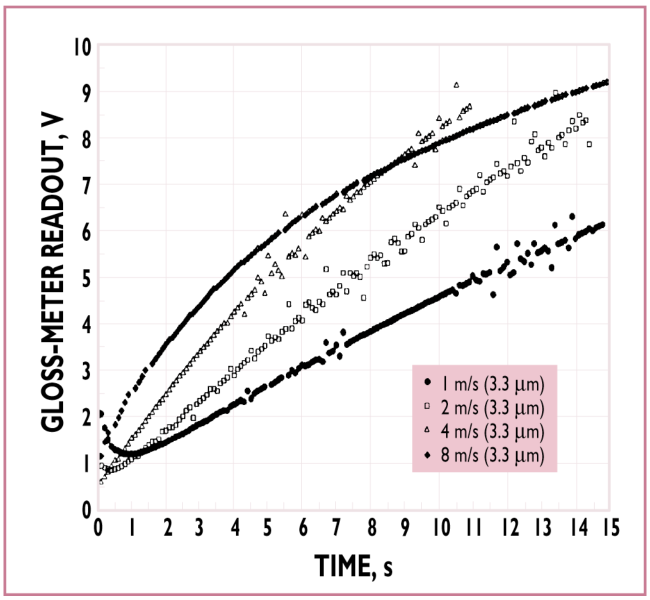
Figure 4 shows the influence of film thickness on the rate of leveling for the same conditions as in Fig. 2, but for a range of initial ink film thicknesses. Note that the time axis



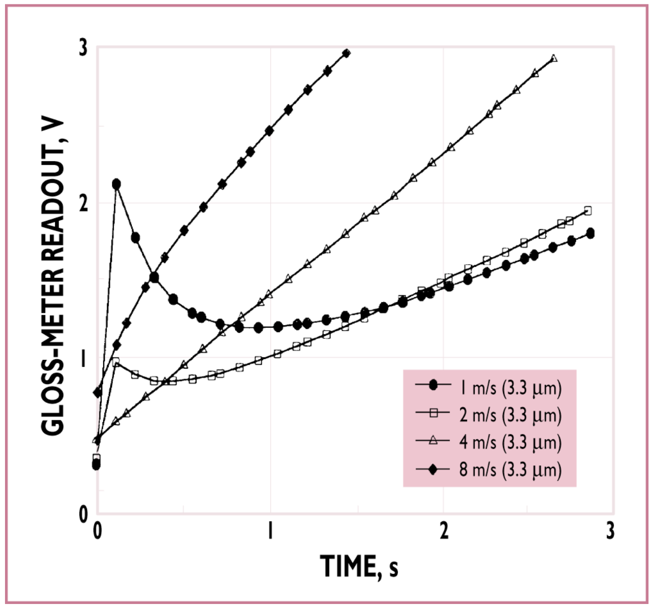
7. Schematic of experimental setup. The laser sends a beam of light that reflects off a mirror and then off the sample to the detector, which converts the light intensity to a voltage signal. The sample moves through the print nip and stops 100 mm from the nip, where gloss is recorded continuously every 0.1 s.



8. Voltage readings from the gloss meter as a function of TAPPI gloss (data for three different coated papers)



9. Voltage readings from the gloss meter as a function of time for 3.3-µm ink films (quick-set offset ink) printed at 1–8 m/s on Mylar. Each curve is an average of at least three prints.



10. Closeup of results in Fig. 9 showing behavior during the first 3 s after printing. Each curve represents a single print.

is a log scale. The initial roughness for each curve is equal to the substrate roughness of 3 µm. As expected, the thicker films level more rapidly. However, at low film thicknesses, another factor becomes important: At long times, the film thinning rate slows more than expected. This behavior is caused by the substrate roughness. The film cannot drain off the top surfaces of the roughness because of the no-slip condition at the substrate. The film never can become uniform because there is not enough ink to fill the void. When this occurs, the low portion of the ink film raises more than the high portion lowers, producing an effect not shown with linear analysis. This behavior is illustrated in **Fig. 5**, with an ink thickness of 1 µm on the same substrate as in Fig. 2. When there is some region with a thin layer of fluid, the entire leveling process is slowed.

The model does verify the trends shown in the linear-analysis predictions of Eq. 7. Viscosity and surface tension have a first-order effect on leveling rate. Film thickness has only an approximate third-order effect on leveling rate because of the nonlinear effect illustrated in Fig. 5.

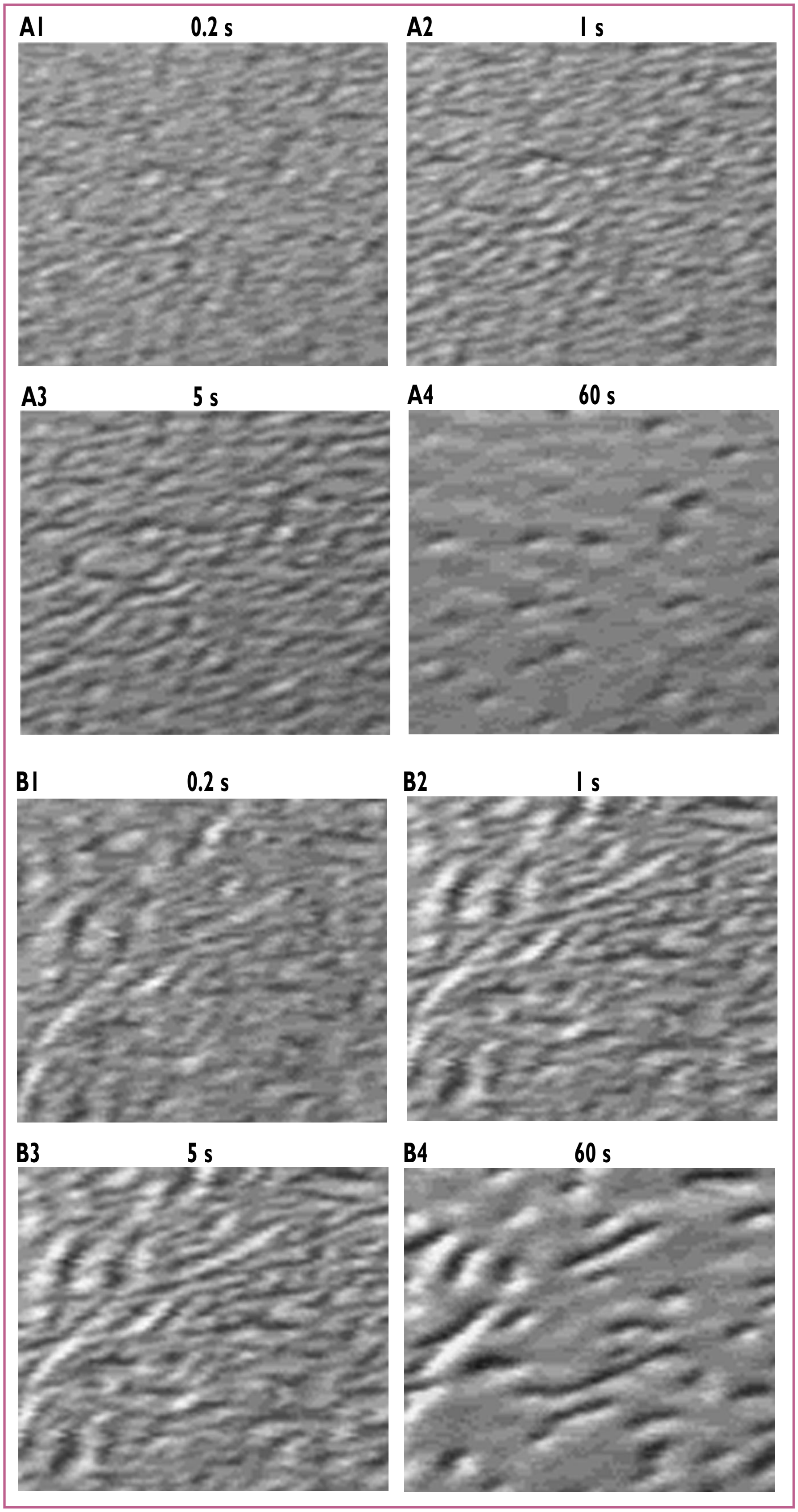
An important point is that the leveling-rate exponential factor is a function of wavelength to the fourth power. This indicates that film nonuniformities that occur on a short-wavelength scale will level quickly. Defects with long wavelengths will take much time to level. Thus it is critical to avoid defects of long wavelength during the printing process. Defects with a fine length scale should heal within a short amount of time.

Figure 6 shows the results for a uniform film, as in Fig. 1, with a small-wavelength thickness variation imposed upon the uniform film. The variation has a wavelength of 20 μm and a height of 0.5 μm. These small-wavelength disturbances quickly level, and we obtain the same shape as in Fig. 2. This demonstrates the importance of disturbance wavelength on leveling rate.

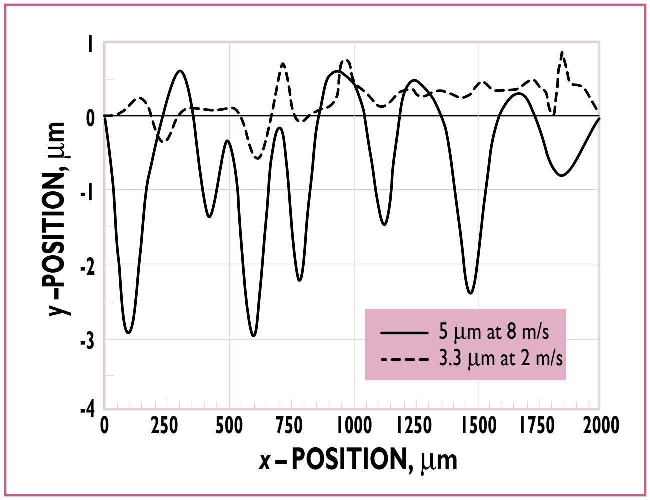
Even though the model has a number of assumptions that are not valid (such as constant ink viscosity after printing), the model does provide a starting point for future work and accounts for the influence of different variables such as defect wavelength. We are able to include the effect of increasing viscosity as solvent leaves the ink layer. Future work could include the influence of shear-thinning or viscoelastic behavior in the framework of this model.

EXPERIMENTAL

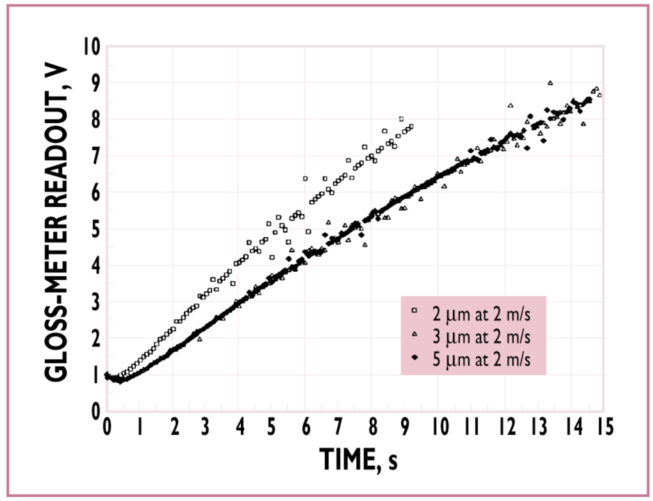
Figure 7 is a schematic of the experimental setup. A laser light source (675 nm, 1.0 mW, M38,920, Edmund Scientific) and detector are mounted at a 75° angle from the vertical at the end of a laboratory print tester (KRK). The light reflects from a mirror to the sample and then back to a 0.090-in. x 0.090-in. light detector (OPT201, Burr–Brown). A lens in front of the detector captures more of the light reflected from the film. The voltage signal from the light



11. Video images of quick-set offset ink printed on Mylar. Frames A1–A4: 3.3-μm ink film printed at 2 m/s; Frames B1–B4: 5-μm ink film printed at 8 m/s. Frames 1–4 in each series show printed surfaces after 0.2, 1, 5, and 60 s. Each frame depicts an area approximately 1.5 mm x 1.5 mm.



12. Measured profiles of dry ink films printed under the same conditions as Fig. 11



13. Voltage readings from the gloss meter as a function of time for ink films (quick-set offset ink) printed at 2 m/s on Mylar. Each curve is an average of at least three prints.

detector is collected and stored in a computer. The size of the light spot on the sample can be adjusted. We found that if the spots were too small, the results were not reproducible because of gloss variation along the sample, even when printing on plastic films. A spot size of 5 mm proved to be large enough to give reproducible results.

Printed samples were obtained as follows: A typical quick-set offset ink (Capiplus III process cyan, Flint Ink Inc.) was applied to the inking rolls. A substrate sample was then mounted on the moving member and printed with a layer of ink. At the onset of each test, the operator activated the computer to collect data. The sample stopped within 0.1 s after the printing nip, and the gloss was recorded in time. The gloss therefore was known 0.1 s after printing. The gloss value was then sampled continuously every 0.1 s.

The data were examined to determine the first deviation from the steady value seen before the sample entered the gloss detection area. This time was recorded as time equal to zero. The gloss value at this initial time may not be a true measure of the sample gloss because the sample is moving. However, within 0.1 s, the sample is stopped, and thereafter the gloss meter is measuring the same spot on the sample.

The amount of ink transferred was determined by weighing the inking roll before and after printing. There is some deviation between runs. However, a repeatable average was obtained by averaging four runs together.

The absolute value of gloss in the device was subject to error. However, paper samples with different gloss values, when placed at the location of measurement, gave the results in **Fig. 8**. The voltage range (0–10 V) seems to cover the TAPPI gloss range of 50–70. Because of questions with regard to gloss measurement, the values are reported here in terms of the measured voltage. We did not attempt to convert voltage to absolute gloss values. However, Fig. 8 could be used as a calibration curve to convert voltage to gloss.

Figure 9 shows the results for printing a 3.3-µm ink film on a plastic film (Mylar) at various speeds. Each line represents an average of at least three runs. The scatter in the data is due to the averaging method. (Results for identical conditions varied up to 20%.) **Figure 10** shows the same conditions during the initial 3 s. The curves in Fig. 10 have not been averaged, with each curve representing a single print. Figures 9 and 10 show two unexpected results:

1. At lower speeds (<4 m/s), the gloss first decreases before it starts to increase.
2. At higher speeds (>4 m/s), the gloss increases rapidly at short times and then slows down, with the gloss of the intermediate speeds ultimately equalling or surpassing that obtained at the highest speed of 8 m/s (Fig. 9).

For the 1-m/s and 2-m/s printing speeds, the decrease in gloss occurs for about 0.8 s and 0.4 s, respectively. This indicates that the ink film actually roughens in time initially at the low printing speeds.

A video camera was set up to view the ink film at short times. The images clearly indicate an ink film surface with many more defects as the printing speed increases. At high speeds, the fine features (<100 µm)

KEYWORDS

Equations, film, gloss, high velocity, ink, lasers, models, optical properties, parameters, print quality, properties, roughness, substrates, surface properties, velocity, wave lengths.

seem to level out quickly, and the surface is left with large-scale features (0.5 mm) that level slowly. This explains the results of the high printing speeds: more defects with a wide range of length scales are produced at high printing speeds. The fine-scale defects level rapidly, creating a rapid increase in gloss. However, the large-scale features persist and cause a low gloss of the print.

At low speeds, the video does seem to capture a roughening of the ink film. The cause of this is unclear to us at the present time. This could be a viscoelastic response of the ink film to the ink split, although it is not clear why this should be more evident at a lower printing speed compared with the high printing speeds. Whatever the cause, the decrease in gloss detected by the gloss meter is seen visually by the video as fine-features roughening during the first 0.5 s after the nip.

Figure 11 shows images captured by video. Frames A1–A4 show the leveling of a 3.3-µm film printed on Mylar at 2 m/s. It appears that the film roughens between frame A1 taken at 0.2 s and frame A2 taken at 1 s. Frames A3 and A4 show further leveling of the film at 5 s and 60 s. Frames B1–B4 show that larger defects are formed at higher ink film thickness and faster speed (5 µm film printed at 8 m/s). At 1 min, this film has a rougher surface with more defects than the thin film printed at slow speed. The defect sizes are expected to scale with the filament size right after the printing nip, as shown by figures in Hayashi and Amari *(9)*.

Profiles were taken of dry films using a stylus profilometer (TENCOR Alpha-Step 200). ***Figure 12*** shows profile measurements of dry films produced under the same conditions as Fig. 11. The profilometer gives an unexpected result that verifies the video images: Instead of a number of "hills" that did not level from filaments, there are a number of "holes" in the ink film that scale with the ink film thickness. The printing speed at 8 m/s produced more of these holes than the printing at 2 m/s. The relationship between ink filaments formed at the nip exit and these holes is not clear at present. However, the formation of filaments after the nip must cause ink to be pulled away from other regions.

Figure 13 shows the results for different ink film thicknesses printed at 2 m/s on the plastic film. The thin ink films give a rapid increase in gloss and a larger final gloss value. These results are the opposite of the initial expectation that thicker ink films should level more rapidly than thin films. However, this must be related to the length scale of the initial disturbances. High ink levels move the ink-split location farther from the nip and produce larger filaments [e.g., De Grace *et al. (10)* and Zang *et al. (11)*]. These larger filaments produce large features on the Mylar film that level more slowly. The video images of these cases confirm this mechanism. These results follow the results of Zang and Aspler *(1)* with regard to the influence of ink level on final gloss.

DISCUSSION

We cannot quantitatively compare the model predictions with the experimental results because the initial disturbances have a wide range of wavelengths and shapes. If the initial shape of a certain region could be obtained, then a quantitative comparison would be possible. However, the heights of the ink at various positions are difficult to estimate from the video. In addition, the cases reported here have enough ink to fill the roughness of the Mylar film, so the influence of substrate roughness is not seen. Nevertheless, the model results do explain the experimental results in qualitative terms, and the time scales predicted in the model agree with the time scales we observe for leveling.

For the case with the high ink levels and high printing speeds, a surface with many defects with a wide range of length scales is produced. The small length-scale defects level rapidly, producing a rapid increase in gloss. This is seen in the fine-scale features in Fig. 11 (B1 compared with B2). However, the large-scale features apparent in Frame B2 persist to long times, as seen in Frames B3 and B4. The rapid increase in gloss followed by the slow increase in gloss—as measured by the laser detector—confirms this behavior. Finally, this behavior is predicted by the model, as seen in Fig. 6, which shows that the fine-scale features level quickly, while large-scale features level slowly.

The same results are seen in Fig. 11 for the A series. Even though the ink film is thinner in series A than series B, the leveling rate of the fine-scale defects is about the same as series B. Therefore, the dependence of leveling on the defect wavelength or length scale is more important than the ink film thickness. This behavior is the major result of the model. For the experiments that compare different ink film thicknesses, the model would predict that the thick ink films would level more rapidly than the thin ink films. However, the size of the defects was not the same for the different ink film thicknesses. Again, the length scale of the defect dominates the rate of leveling compared with the ink film thickness.

In addition to these observations, the holes or pits in the final ink layer—as seen in the video images and by the stylus—agree with the model physics. In Fig. 5, leveling rates decrease rapidly when there is a thin film region in the domain. If the film split after the nip produces some regions of very thin film, these would be expected to persist according to the model. This seems to be the reason why the holes in the film do not heal, although other surface forces may be important.

CONCLUSIONS

A novel technique for recording changes in printed gloss right after the printing nip is described. High-magnification video images on the same time scale were used to interpret the results.

The technique shows that print gloss generally increases in time after printing. The increase in print gloss occurs as defects in the ink layer level out in response to the effects of surface tension. However, the length scale of the initial defects was found to be a critical parameter in the extent of leveling achieved over time. High printing speeds and high ink film thicknesses produce many defects with a wide range of length scales. The fine-scale defects level rapidly, while the large-scale defects level slowly. This leads to a rapid increase in gloss at short times—but a lower gloss at long times—compared with the gloss obtained at slower printing speeds with thinner ink films. Thick ink films produce large-scale defects that level slowly.

A model is presented to describe the dynamics of ink film leveling based on the geometry of the system (substrate roughness, ink layer thickness) and the ink film properties (viscosity and surface tension). The proposed model qualitatively predicts the leveling behavior of the ink film that was observed after printing. **TJ**

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NOMENCLATURE

h = film profile
h_0 = average film thickness
h_s = substrate profile
k = wave number
P = pressure
t = time
v_x = velocity in the x direction
x = Cartesian coordinate
y = Cartesian coordinate
α = leveling-rate factor
γ = surface tension
ε = initial disturbance amplitude
λ = wavelength
μ = viscosity