Improved Ink Jet In Situ Visualization Strategies

Sandrine Allaman and Guido Desie*
Ardeje, Valence, France
*** Agfa-Gevaert N.V., Mortsel Belgium***

Abstract

In the last years, printhead, ink and printer manufacturers designed, developed and proposed improved ink jet systems having higher resolutions and smaller droplet sizes. Further optimization of these systems requires more sophisticated print quality tools and in situ visualization tools. As a consequence, print quality and metrology ink jet tools manufacturers have to anticipate and give capabilities to measure these smaller dots and smaller fast moving droplets. Compared to the traditional stroboscopic techniques, nowadays, two alternative ways are used for image capture: photodiode based systems as commercially available from Xennia and pseudo-cinematographic techniques as commercially available from Ardeje.

In this article, the experimental visualization of the dynamics of droplet formation and impact is investigated for various inks and various Drop On Demand (DOD) ink jet printing processes.

The drop ejection devices used are based on printhead modules, electronic boards and hydraulic parts to generate controlled droplets with variations in droplet volumes and velocities.

The visualization methods used are based on high-speed cinematography and proprietary phase controlled ultra-sharp snap shots of the drop formation and impact processes. Different possibilities of high-speed cameras, coupled with lens and optics have been combined with specific illumination sources, to observe droplet behaviour at different steps of the Drop On Demand printing process. Advantages and disadvantages of the different possibilities are discussed in terms of the target applications, being merely related to the actual droplet sizes, and droplet speeds. Both practical and fundamental limitations are discussed for the different in situ visualization strategies.

Introduction

In the printing world, Drop on Demand ink jet has gained a lot of attention for printing digital documents. Good image quality can be achieved by using a rather cheap apparatus for a wide variety of substrates, ranging from impervious surfaces to absorbing papers. However, to obtain the optimal quality, ink, media and jetting characteristics have to be adjusted.

The final image quality that can be obtained via an ink jet process is not only related to the final stage of an impacting drop. In fact, in a first step the droplet is ejected through the nozzle, it can reach a spherical shape during flight, before impinging the substrate and interacting with it. The fluid flow associated with drop formation and impinging substrates is rather complicated because of the extreme deformations of the surface droplet occurring at very short time scales. When droplet velocity is low, the surface tension has a strong influence on its behavior, whereas it has been shown that compressibility effects influence the droplet behavior at higher droplet velocities.[1]

The methods used to observe droplet behaviors were initiated by Worthington[2] who investigated the footprint left by drops after their impact on glass surfaces. More recently, Pierron and Schlemer have developed an automated print quality optimization apparatus,[3] which allows users to follow the drop from the exit of the nozzle to drop impact. It allows characterizing the performance of printheads in terms of drop sizes, optical density, color gamut and uniformity and so on.

In order to study the interaction of ink jet droplets with receivers a methodology is required that enables the visualization of droplets of a size of about 40 µm diameter at a speed of about 10 m/s, fired at a repetition frequency of about 10 kHz.

The simplest type of apparatus would therefore need a significant optical enlargement and a capturing possibility of the imaging system of about 1 million frames per second with an exposure time of less than a microsecond and a capturing buffer for hundreds of milliseconds. Unfortunately such a system does not exist!

However, several categories of ink jet visualization tools exist, based on true real time fast video capturing but at much lower speeds, pseudo cinematographic techniques based upon triggered exposure systems and based upon triggered capture systems.

The objective set in this work is to evaluate the different strategies applied in the visualization techniques in drop on demand ink jet printing, as listed below:

(1) The evaluation of dot / image quality via commercial measurement tools.
(2) The evaluation of the drop formation process via a stroboscopic method.
(3) The implementation of the methodology developed with short exposures times to evaluate the behavior of an

individual droplet during its flight, the impact and the spreading on substrates.

Therefore, to quantify aspects of ink jet printing, different visualization techniques are presented and the advantages and the drawbacks of the methodology used are discussed.

A wide range of experiments were done and evaluated in this work. Specific tools used for optimizing visualization of small objects were used at each step in the ink / head and ink/media interactions studies.

Dot Quality Control

In order to control the quality of several droplets, a band of paper is printed via an ink jet process and drops are analyzed via commercial software (KDY, ImageXpert, QEA) coupled with a standard camera allowing to capture and analyze the printed dot on various locations of the substrate.[5] This method typically uses an identification of the threshold to separate dots from the background (threshold @50% or @60% of contrast). It also has the possibility to ignore non-majority objects by manually clicking on them or by automatically choosing the range from min to max of the objects. The measurement of the remaining majority objects can be the following: area, diameter, roundness, unsharpness, mean and standard deviation.

For a deeper study of the ink jet quality parameters, other measurements allow the identification of line transitions: the raggedness that represents the deviation of the actual contour to the best fitting line, line width or bleeding that gives a distance between corresponding positions on two contours (mean and standard deviation).

This method allows to evaluate the quality of several printed dots of a wide range of substrates but allows also to determine if dots are missing during printing.

The quality and the quantity of droplets are analyzed in a static phase: several seconds or minutes after the impact phase. In this case, there is no information on the dynamic nature of the droplets such as the droplet filament propagation,[6] impact and spreading,[5] that define the final shape of the dot. In fact, the goal is to determine relationships with ink and printhead, and ink and print media.

Droplet Dynamics

Stroboscopic Technique

To allow the study of dynamic droplet behaviour, real in-situ experimental techniques have been developed by different companies such as Xennia's VisionJet, iTi's Dropwatcher or Ardeje's PQOA. These techniques allow to follow the drop from the exit of the nozzle to drop impact, by using a stroboscopic method. Such systems have a comprehensive set of built-in electronics, optical and mechanical hardware which allows to take very high magnification computer controlled photographs at different times and at different locations. To complete the system, commercially available printheads were added and controlled via ejection devices.

To check an entire head, a precise translation of the head from one nozzle to another in front of the static image acquisition system is implemented.

Depending on the configuration, the analysis system uses one, or more, CCD (CMOS) cameras. Standard speed (25 images/sec) is available with a frame grabber, which acquires images with adjustable magnification, according to the target object.

The electronic stroboscopic illumination control includes two types of illumination sources: a laser diode and a high luminosity LED. The laser diode allows longer distance of work between the object and the illumination source. For shadowgraphy images a higher power diffused light is required. The electronic device allows delivering regularly spaced flashes.

This stroboscopic method is useful to characterize the jet such as droplet break up, ligament behaviour and satellite formation, and droplet measurement studies: volume and velocity.

This stroboscopic technique gives images containing an average on several detected objects during the capture; the obtained images are a superposition of objects appearing during the acquisition time of the camera.

Pseudocinematographic Technique

Using external triggering electronics, multiple shots taken at different times of multiple droplets can be combined into a movie according to the pseudo-cinematographic technique. The drawback of this method is the limited time resolution that does not allow the detection of faster phenomena, which may happen within this time frame.

To improve the visualization of faster moving phenomena, the pseudo-cinematographic technique can be implemented using cameras based on short-shutter time CCD or CMOS capture.

Droplet Formation

In real ink jet printing configurations as available in the industry, droplets coming out of a printhead and impacting the substrate at a speed from 5 to 12 m/s, have a long filament, which may be broken up into satellites. A typical example of a Spectra printhead used with UV Sunjet black ink at an ejection temperature of 50°C is shown in figure 1. The Spectra printhead has multiple nozzle's (128 orifices with a radius of 38µm) in a piezo configuration. It operates under back pressure at maximum frequency of 20 kHz. In normal condition of use, the ejection gives one main drop followed by one or more satellites. In this work, the waveforms used were optimized in order to obtain a single droplet at impact and a high velocity.

To capture the droplet motion, a camera from PCO SensiCam was used with high luminosity LED to create pseudo cinematographic movies. This camera has a resolution of 1376 x 1040 pixels. The CCD sensor records for each pixel the light information as 12 Bit. This camera has a very short interframing time of 500 ns, a shortest exposure time of 500 ns, and a maximum frame rate of 10 frames per second at full CCD resolution. This technique is extremely useful for ultra-short processes such as inertial spreading of small drops.

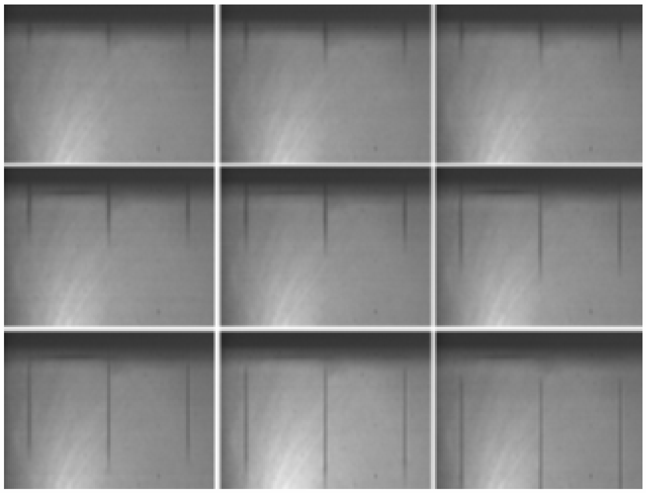

Figure 1. Visualization of drop formation at the nozzle plate of a SE-128 Spectra printhead (3 nozzles)

Figure 1 shows the evolution of three drops ejected in a row, with a delay time of 50µs (step 20µs). The LED-exposure time for each image is fixed at 20 µs and the applied waveform was block-shaped at 120V during 15 µs. The distance between two nozzles is around 508µm and it appears that filaments are so long that it will require more than 2 mm to become one single droplet. It can be noticed that the filaments look equal and are stable. However, the contrast of these images is not so good to measure the droplet size; only the filament diameter could be measured: 21.6µm. Therefore, this figure shows the difficulty to observe real ink jet droplet at high speed.

In order to have a better view on the droplet formation, the waveform was changed (the voltage was set to 80V – 15 µs) and the optical enlargement was increased to have two droplets in a single image. The results are shown in figure 2 (LED-exposure time 2 µs). For both droplets the velocity was around 1 m/s. A lower droplet speed gave a better definition of the acquired images and the contrast allowed to do more accurate measurements:

- For the left droplet, a filament is separated from the main drop, before to join it, at around a distance of 1mm from the nozzle plate. The volume of the main drop is 12,9 pl (drop diameter 29.1 µm) and its satellite volume is 3 pl (drop diameter 16 µm).
- For the right droplet, the filament joins the main drop earlier and has a volume of 16 pl (drop diameter: 31.8 µm)

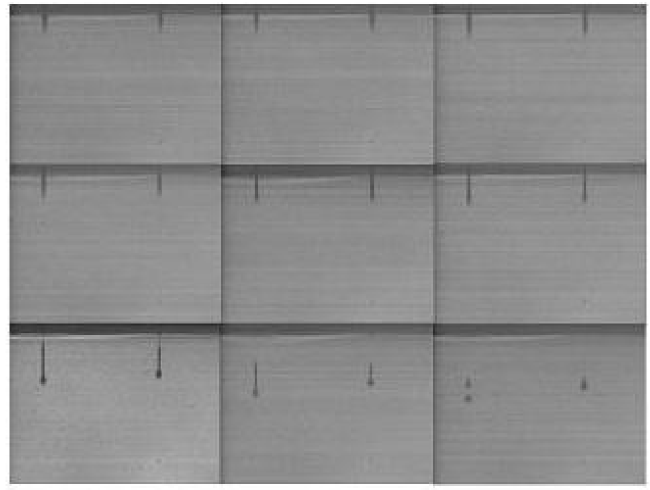

Figure 2. Visualization of drop formation at the nozzle plate of a SE-128 Spectra printhead (2 nozzles)

The evolution of one single droplet ejected by a SE Spectra printhead is represented in figure 3, where the delay time (in microseconds) is indicated on each picture (672 x 1040 pixels). The waveform applied is the same as for the experiment shown in figure 2. The exposure / shutter time of the camera was fixed to 2µs, and a continuous illumination was used. A lower shutter time gave less contrast between the background and the detected object but the drop outline seemed to be more precise, allowing to measure a droplet volume of around 9.6 pl for a drop diameter of 21 µm.

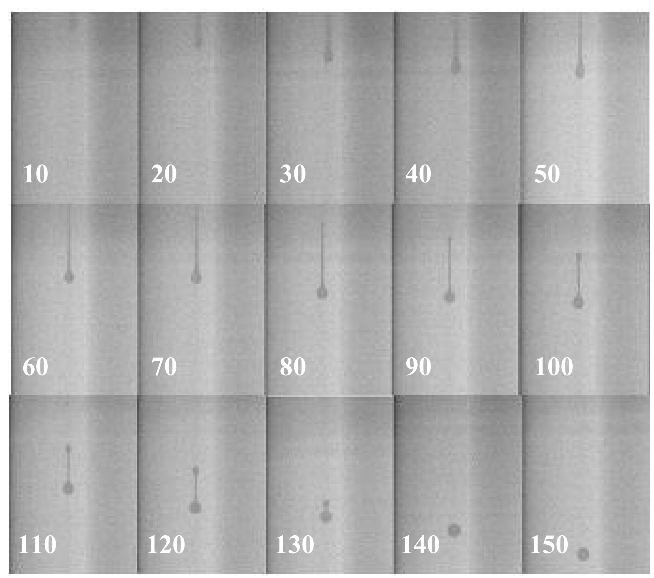

Figure 3. Visualization of drop formation at the nozzle plate of a SE-128 Spectra printhead (1 nozzle)

Small Droplets: Limitations

The observations made above, show difficulties to observe real fast moving droplets during the printing process. It has been shown that it was possible to see flying objects with enough contrast in certain conditions: specific waveforms to eject droplet at low speed combined with optics and lenses to zoom on small objects and high illumination controlled sources. Therefore, using the Spectra printhead, droplet sizes of around 10pl, acquired at a shutter speed of 2 µs, could be measured dynamically. To get a better contrast and droplet outline with such small volumes, it is necessary to decrease the shutter time and increase the light intensity without too much blurriness on the picture.

To determine the limitations new experiments were done using an IJT printhead and Agfa Sherpa water based ink. This print head is a multi-nozzle version designed for a wide range of industrial and commercial printing applications. The head is designed on shear mode technology, like the Sprectra head, and comprises 64 nozzles with dimensions of 60x60µm. The droplet volume, generated by this head, can vary between 80pl to 240pl. Built-in heating elements allow to work at a maximum temperature of 50°C. A high voltage fire pulse with controlled slew rates is necessary to actuate the piezoelectric transducer for each channel which may operate at a maximum frequency of 6 kHz.

The waveform was set at a voltage of 65V and a frequency of 1000Hz. The droplet volume was around 110 pl and its velocity 3,7 m/s.

The droplet formation study of such droplets gave enough contrast at 2µs shutter time to allow comparisons with strategies used to visualize small and fast droplets with Spectra devices. In this condition, it did take about 120µs to from the drop, then this drop oscillated during 200µs before having a stable shape during its flight. At that moment, the droplet was observed and captured at different shutter times. An example is given in figure 4, where the exposure/shutter times are indicated on the pictures. In the first picture, at a shutter time of 1µs, the outline of the droplet is not so clear: there is a variation of 4 pixels in the measurement. While, at an acquisition time of 400ns, this same line seems to be more continuous, so that analysis could be done even if the grey level between the droplet and the background was much closer.

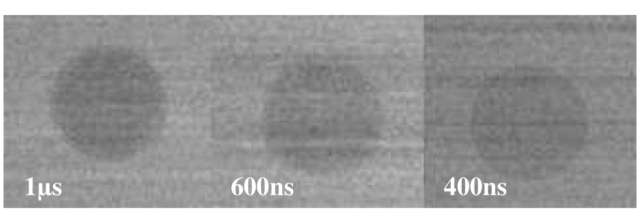

Figure 4. Exposure Time Variation for a flying 110pl droplet

Different tests have been involved in order to detect objects at low shutter time by combining different light sources. Unfortunately, it was not possible to isolate a droplet clearly from the background if an exposure time below 400ns was used.

As shown above, in-situ visualization experiments of small droplets jetted from a Spectra printhead gave measured volumes (10-15pl) that are smaller than the volume supposed to be created (25-35pl). Both the waveform used to isolate perfectly spherical droplets and some over-exposure of this drop might lead to smaller values.

Using a 100pl ink jet droplet, it is easier to observe its fast behaviour with the camera based on short shutter time and high illumination sources. The advantages of this technique could allow to evaluate the volume of an individual droplet and its velocity thanks to dual-exposure shot measurements using a Sensicam short shutter-time camera. Using the scaling rules to relate the properties of these larger droplets to the properties of smaller droplets, it is possible to give an accurate estimate on the droplet formation dynamics of very small droplets.

Droplet Impact

As described elsewhere,[5] the droplet impact process can be separated into different phases such as inertial spreading and imbibition phases. For color ink jet printing, color mixing and droplet coalescence studies have to be considered too.

Techniques used to observe the drop impact, drop imbibition or drop coalescence were based on high speed video methods or pseudo-cinematography methods with short shutter time capture for fast moving phenomena.

Inertial Spreading Phase

An example of a drop impingement picture is shown in figure 5, where indicated values on each picture are the time (in microseconds) after drop contact with the substrate. The droplet, generated by the IJT printhead, had a droplet diameter of 65 µm and its impact speed was 1m/s. The exposure time was fixed at 3µs. The obtained images had enough contrast to make measurements and studies such as dynamic drop diameter, height and contact angle.[7] The low impact speed allowed acquiring several pictures at controlled delays. It can be noted that the impacted droplet takes different forms before reaching a static equilibrium condition.

Droplet Coalescence

For color ink jet printing many tiny ink droplets of different colors are interacting with each other. A more detailed study on the coalescence of multiple droplets is described elsewhere,[8] but the results of such an analysis are shown in figure 6.

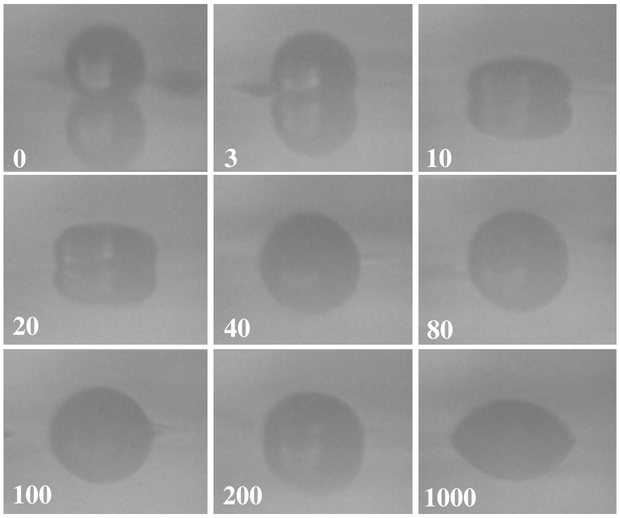

Figure 5. Experimental results of impact and spreading behavior during the inertial phase (pseudo-cinematography)

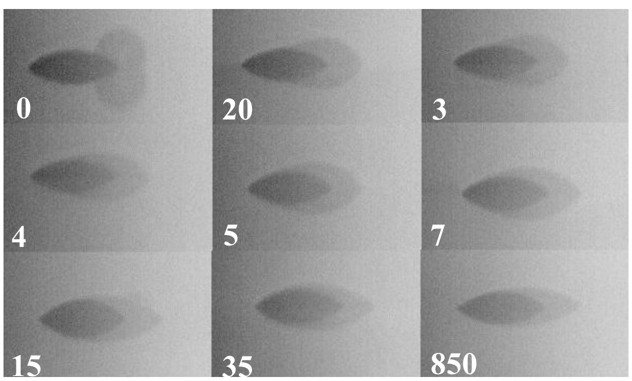

Figure 6. Experimental results of coalescence study (pseudo-cinematography)

A droplet was jetted on the substrate and remained there till an equilibrium condition was reached: this was typically a few ms. Then a second droplet was jetted on top or very close to the first one and the evolution of both droplets was followed using the technique of pseudo-cinematography. Because of the very short time scales (as indicated in figure 6 in µs) a dual exposure technique has been used to compensate for small deviations in droplet speed or timing. This is the main cause of the density difference between the 2 droplets in figure 6.

Absorption Phase

After a certain period of time, a droplet reaches an equilibrium condition, typically within 2ms, determining the final shape of the liquid on top of the receiving substrate prior to penetration or absorption into the receivers. Experiments regarding the absorption phase were done using an HP500 printhead and Agfa dye or pigment based inks.[9] Droplets with a volume of about 70pl were created and ejected at a velocity varying between 5 to 12 m/s.

Visualization techniques regarding this absorption process were done using a high speed camera HG2000, from Kodak. This camera was used to capture images of 512x356 pixels at a frame rate of 1000 fps. The exposure time was set to the minimum, 23µs. An example of photographs taken with this camera is shown on figure 7, where:

- on the left, a dye based ink disappears into the substrate, 2ms between two images
- on the right, a pigment-based ink droplet disappears slower into a paper, because of the ink characteristics.[9]

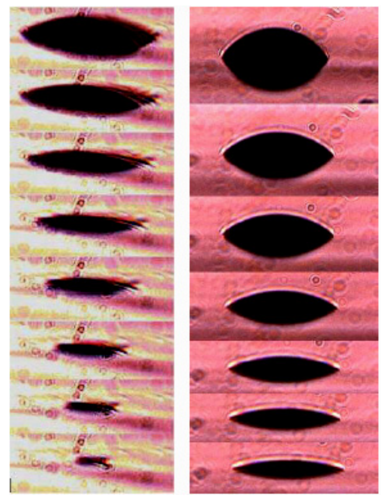

Figure 7. Experimental results of imbibition phase

The advantage of this high speed video technique is that it is not necessary to have a perfect reproducibility from one experiment to another. The drawback of this method is the limited time resolution of 1 ms for transients, which mean that all phenomena, which may happen within this time frame, cannot be detected.

Final Improved Experimental Set-Up

As shown in this article an in-situ visualization methodology to study the ink jet printing process has to tackle multiple phases: the drop formation process , the droplet flight path, the droplet impact and spreading phases, the droplet-droplet interactions. For this purpose a universal tool was built. The basic set-up, the "Print Quality Optimization Apparatus", which has been designed previously,[3] shown in figure 8, is based on an optical system an image acquisition part, a motion control part, a media support part, and an ink jet head control system. These systems are synchronized via electronic boards and software. This apparatus can be fitted with commercially available printhead, having single or multiple nozzles.

To perform the control of the head, a high mechanical support is required, based on microstep motors with encoders controlled by embedded software.

Depending upon the requirements, this apparatus can use one, two, or three standard CCD cameras, or can be adapted for high speed cameras working in the mode of pseudocinematography or high speed video.

The electronic stroboscopic illumination device allows delivering regularly spaced flashes of 100ns.

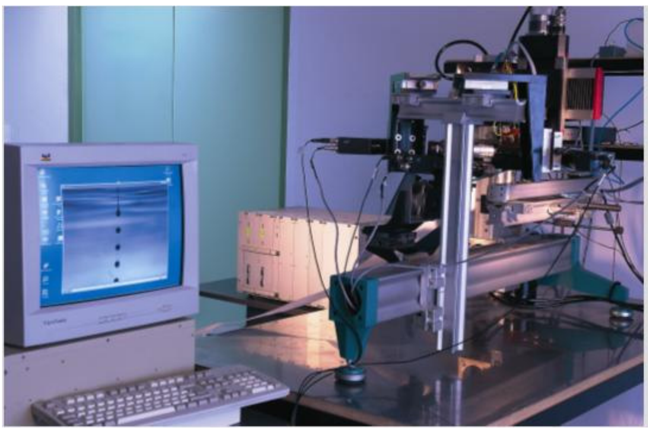

Figure 8. Global overview of the Print Quality Optimization Apparatus

Conclusions

In this work, visualization techniques used to study different steps of the ink jet printing have been presented.

Commercially available softwares coupled with cameras allow to easily evaluate the dot-quality in a static phase, but are limited for transient behaviors.

The evaluation of flying droplets is done by using a stroboscopic method based on controlled pulsed light. This method gives good results to study the droplet formation out of a printhead. These results quantify drops in terms of volume, velocity, satellite formation or filament behavior.

Studies of droplet formation for smaller droplets and studies of droplet impact dynamics upon a receiver require the pseudo-cinematographic method based on short-shutter time CCD capture and sufficient spatial resolution (e.g. PCO Sensicam).

Once the droplet impinging upon a substrate is in an equilibrium condition, the study of the absorption phase can be done using high speed video techniques at 1000 fps and a moderate exposure time (e.g. Kodak HG2000).

These strategies, described in the article allow following the dynamics of the ink during the entire ink jet process. However, the techniques seem to be limited when the size of the droplets become much smaller than 10 pl. Techniques need to be improved in this domain.

References

1. M. Rein, *Fluids Dynamics Research*, 12, 61 (1993)
2. A.M. Worthington, *Proc R.Soc. London*, 25, 261 (1876)
3. P. Pierron and C. Schlemer, Proc. IS&T, DPP2001, 203, (2001)
4. G. Desie, S. Allaman, O. Lievens, K. Anthonissen and A. Soucemarianadin, Proc. IS&T, NIP18, 306 (2002)
5. S. Allaman, G. Desie and A. Soucemariandin, Proc. 11th IPGAC, II5, (2002)
6. B. Lopez, D. Vadillo, P. Pierron and A. Soucemarianadin, Proc. IS&T, NIP18, (2002)
7. S. Allaman et al., *Mécaniques et Industries,* 4, 443 (2003)
8. G. Desie et al., paper #132 to be presented on NIP 20
9. G. Desie et al., Proc. IS&T, NIP19, 209 (2003)

Acknowledgments

The authors are indebted to the French and Belgian government (IWT-MNRT) for partial financial support of this work through projects PROFIJET and PRODIJ Σ!2911 and to the EC for partial financial support via project IMAGE-IN. The ink jet team of Agfa is acknowledged for their help in developing the visualization set-up.

Biography

Sandrine Allaman got a doctoral thesis in technology (DRT) in 2003, at the Université Joseph Fourier and the Agfa R&D laboratories where she was particularly involved in the study of physical properties of film materials. Now, she is a research engineer at Ardeje, a company involved in architecture and development of non impact printing processes. She is an author of several papers in the area of ink-jet printing. E-mail: allaman@ardeje.com