DIGITAL LABEL PRINTING TECHNOLOGIES:
No one size fits all

These days label printers are spoilt for choice. On the analogue side of the fence are flexography, gravure, letterpress, offset, and screen printing, each with their own characteristics to help create labels that stand out on the shelves. Similarly, the digital side offers several technology options, all with specific attributes and features, making them more or less suitable for particular applications.

Perhaps because digital technologies are relatively new, compared with their analogue counterparts, their specificities are less well understood, and label producers and print buyers sometimes fail to see the wood for the trees, with all the dpi and picoliter specifications being used to convince them of the superior quality of this or that particular process. But dpi and picoliters do not tell the entire story. In a world with ever-shorter product life cycles, a proliferation of SKUs and a demand for increasingly eye-catching and sophisticated labels to win customers and fight counterfeiting, digital label production is arguably the best way forward to secure a profitable business. So it is important to understand the intricacies of the different digital technologies in order to choose the right one for each application.

The technologies discussed include those that are commercially available for professional label production: Dry toner and liquid toner electrophotography, and UV-curable inkjet, which are the most commonly used, and, for the sake of completeness, water-based inkjet.

1 DIGITAL IMAGING TECHNOLOGIES

1.1 Electrophotography

Electrophotography is the most mature and, with a market share of 85%, still the most popular digital printing technology used in de label market.

In the electrophotographic process, first, for each process color and spot color, a latent or invisible electrostatic image made up of dots is created onto the surface of a uniformly negatively charged photoconductor drum: The print head “writes” the image by shining light onto those areas where the image should be, leaving the areas that should remain empty, unexposed. In areas where the drum is exposed to light, the photoconductor layer becomes conductive, and the negative surface charge of the drum is reduced, depending on the amount of light used. The light source in the print head can be a laser, which is either on or off, or an LED array with a fixed number of LEDs, the light intensity of which can be modulated (see also Box 1). Lasers and LEDs provide extreme precision targeting.

In a subsequent step, the latent electrostatic image is developed by depositing negatively charged toner particles of the appropriate color onto the drum. These particles are only attracted to the exposed areas where the negative surface charge has been reduced (see above) and as a result, the latent image becomes visible. Note: The higher the amount of light used, the more the negative surface charge of the drum is reduced, and the more toner is deposited.

Finally, the image formed by the toner particles on the photoconductor drum is transferred to the substrate, directly or via an intermediate blanket.

The toner particle can be a dry powder particle or a solid particle dispersed in a liquid (see 2.2). In a dry toner electrophotographic process, once the image is electrostatically transferred to the substrate, the toner is fused by applying heat and pressure to fix the image. Heat causes the toner particles to melt and coagulate, forming a homogeneous, solid film adhered to the substrate. In a liquid toner electrophotographic system, the toner image is transferred by the carrier liquid to an intermediate heated blanket, where the toner particles coagulate and the carrier liquid evaporates, leaving a homogeneous film, which is then transferred to the substrate by transfusion.

Figure 1a
Dry toner

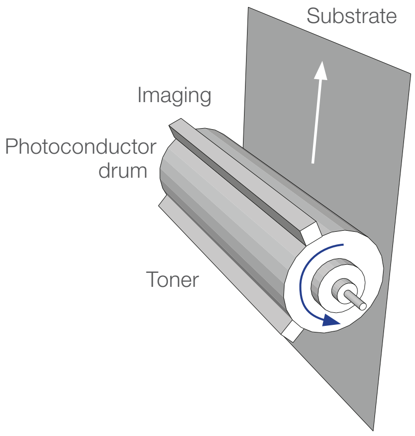
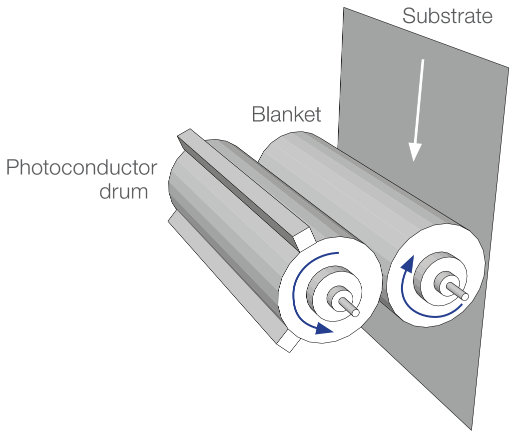


Figure 1b
Liquid toner



1.2 Inkjet

Of the digital imaging processes used for label printing, inkjet, with a market share of 15%, is the less established one.

The inkjet printing process essentially comes down to a print head ejecting droplets of ink of different colors directly onto the substrate to form the desired image, which sounds deceivingly simple.

The two main inkjet technologies are continuous inkjet, which forms the image by deflecting selected drops from a continuous flow of ink, and drop-on-demand (DOD) inkjet, which produces ink drops as needed to construct the image. Depending on the technology used to eject the ink, DOD inkjet is further divided into thermal and piezoelectric systems.

In this paper we will only consider the technology most commonly used for high-end label printing, i.e. DOD inkjet based on piezoelectric drop formation (UV-curable inkjet systems never use thermal print heads as the chemistry of the UV-curable ink is not stable at the temperatures required to operate these heads). We will further limit ourselves to the discussion of single-pass systems: In single-pass DOD inkjet presses, the print head remains in a fixed position and the image is built up in a single pass as the substrate is being transported underneath, in a direction perpendicular to the print head.

A print head is made up of an array of nozzles, each connected to small ink chambers that are in turn connected to an ink reservoir. These nozzles are typically arranged in several staggered rows, to accommodate the minimum required size of the ink chambers, while ensuring sufficient resolution (see Figure 2). The number of staggered nozzle rows depends on the print head architecture. In addition to these staggered nozzle rows, most single-pass systems also have separate rows of different print heads for each color.

Figure 2
A native resolution of 600 dpi (see Box 1) implies a nozzle distance of 40 µm, which is too small to accommodate the size of ink chambers capable of holding the volume of ink required to produce ink droplets of the desired size. By staggering different rows, the desired resolution can be achieved.

In piezoelectric DOD inkjet systems, the ink droplets are ejected through the nozzles by a pressure pulse generated by piezoelectric crystals in contact with the ink. When an electric field is applied, a piezoelectric crystal is deformed, which creates a pressure pulse in the ink chamber behind the nozzle, which in turn causes an ink droplet to be ejected from the nozzle onto the substrate. As the crystal returns to its original state, capillary action causes the ink to flow back into the nozzle, ready to produce the next drop. Without pressure pulse, the ink stays in the ink chamber, retained at the open nozzle by surface tension forces. Greyscale or multi-level print heads can generate ink drops of different sizes (see Box 1).

The inks used for label printing are UV-curable or water-based. In UV-curable inkjet systems, the printed image is cured by means of UV light, produced by a metal-doped (e.g. iron or gallium iodide) Mercury lamp or UV-LED. In water-based inkjet systems the image is dried by passing the substrate over heated plates or rolls and/or by blowing hot air. As a result, the water in the ink evaporates.

Figure 2 A
A nozzle

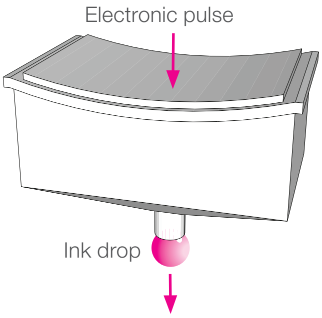


Figure 2 B
A row of nozzles

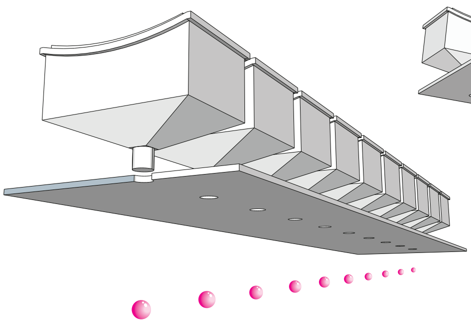
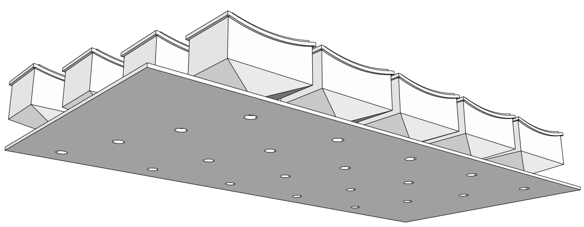


Figure 2 C
Array of nozzles



1.3 Electrophotography and inkjet imaging technologies compared

The outline of the different imaging technologies enables us to derive some of their strengths and weaknesses. While there are many, we limit the discussion to accurate dot placement, substrate conductivity and process reliability. While the text may seem skewed towards inkjet, this does not entail any value judgement. As inkjet is still the less established process in label printing, we felt it useful to discuss it in more detail.

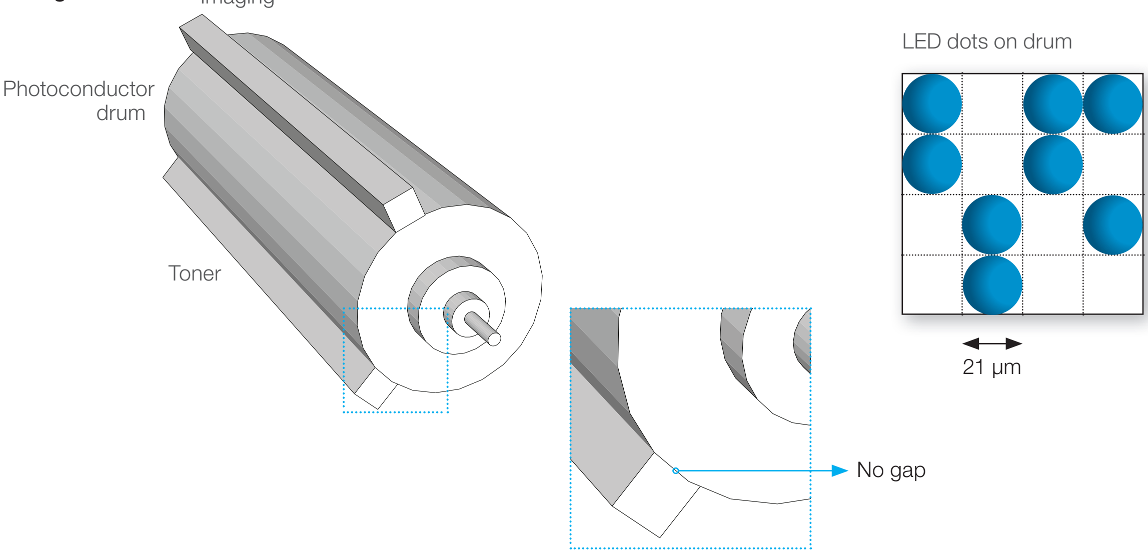
1.3.1 Dot positioning and dot size control

All digital printing systems print lines of dots, toner dots or ink dots, in a grid determined by the system's resolution and addressability (see Box 1). The more accurate these dots are generated, the more control you have over the reproduction of the original image. Ideally, the bitmap pixels sent to the press are printed exactly as intended (see Box 2). As far as dot positioning and dot size are concerned, the electrophotographic imaging process offers inherently better control than inkjet does.

1.3.1.1 Electrophotography: Accurate targeting, accurate transfer

By nature, lasers and LED arrays enable extremely precise placement of dots, the size of which can be derived from the resolution of the system (see Box 1). Moreover, these dots, making up the latent image, are also accurately developed as minuscule toner particles are attracted by a strong high-voltage electric field over a very short distance, of the order of a few microns, i.e. in virtually direct contact. And because there is also no speed difference between the photoconductor and the toner dispenser, there is no turbulence, which could otherwise cause the toner particles to deflect. Regardless of the specific technology used, the developed toner image is transferred to the substrate, again through direct contact, and again without any difference in speed between the components involved: In a dry toner electrophotographic process, the image is electrostatically transferred to the substrate in direct contact with the photoconductor, by applying an additional electrical field between the photoconductor and the substrate. In a liquid toner electrophotographic system, the image is first electrostatically transferred to a heated blanket, from where the molten image is transferred by transfusion.

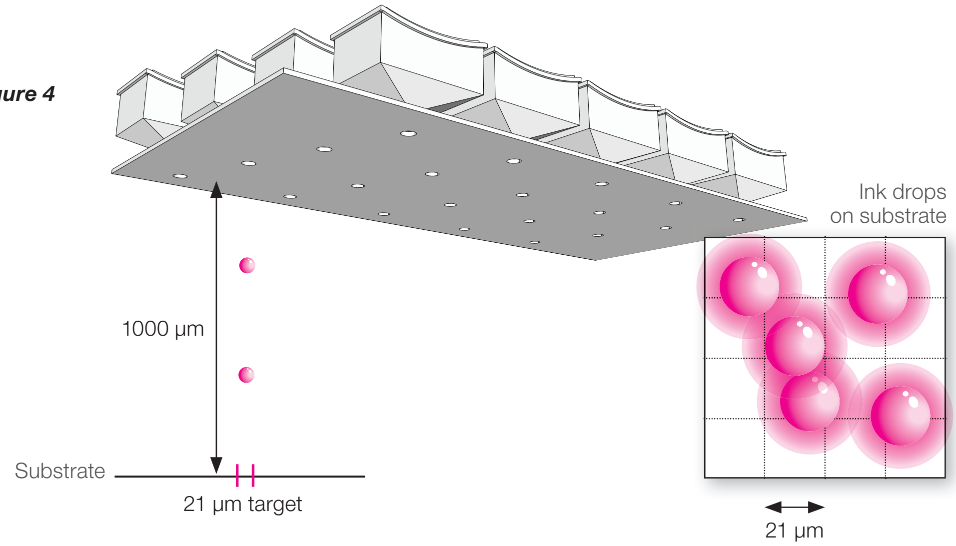
Figure 3



1.3.1.2 *Inkjet: Prone to dot positioning error*

For inkjet printing, the accuracy with which drops are jetted onto the substrate depends on several factors, including jet straightness and throw distance (the distance between the nozzle and the substrate), which is, depending on substrate thickness, about 200 times the distance traveled by toner particles in any electrophotographic system (i.e. 1000 µm on average). Obviously, the larger the distance, the larger the possible positioning error. Besides, as the head is fixed and the substrate moves, the air is dragged along with the substrate, which may result in turbulence, which in turn may deflect the ink drops, depending on their size and velocity (smaller or slower drops are more likely to be deflected than larger or faster ones). This effect is more pronounced the higher the speed of the substrate.

Figure 4



Also, the print head architecture with staggered nozzle rows (see 1.2) complicates accurate dot positioning. For example, in order to print a straight, uninterrupted line perpendicular to the substrate feed direction, the ink dots making up this single line are not jetted at the same time. Rather, the nozzles of the first nozzle row eject their drops, after which the nozzles in the second row eject theirs when the substrate has traveled the minute distance between the two rows, and so on for the other rows making up the print head. The position of the substrate is tracked by encoders, mounted at a certain distance from the print head, i.e. the locations of the encoder measurement and the nozzles do not coincide. In theory, these encoders could compensate for this distance, but in practice encoder errors are unavoidable: Label substrates are somewhat flexible. Fluctuations in tension control, which are inherent in motorized systems, inevitably lead to positioning errors as the stretch of the substrate at the location of the encoder measurement may differ from that at the location of the nozzle. And as this difference in stretch is unknown, it cannot be compensated. This encoder error has the effect illustrated in Figure 5.

Figure 5

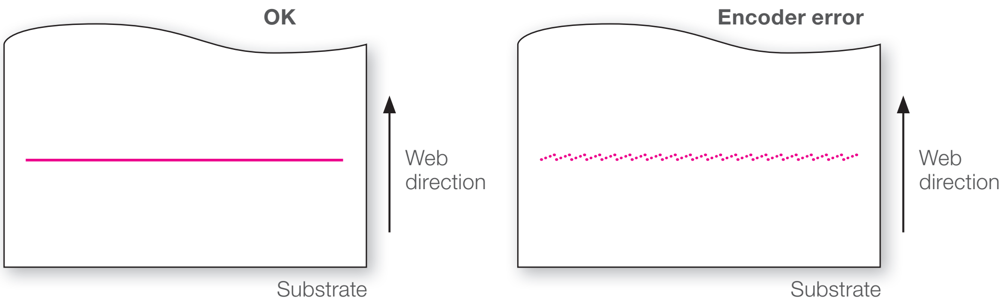
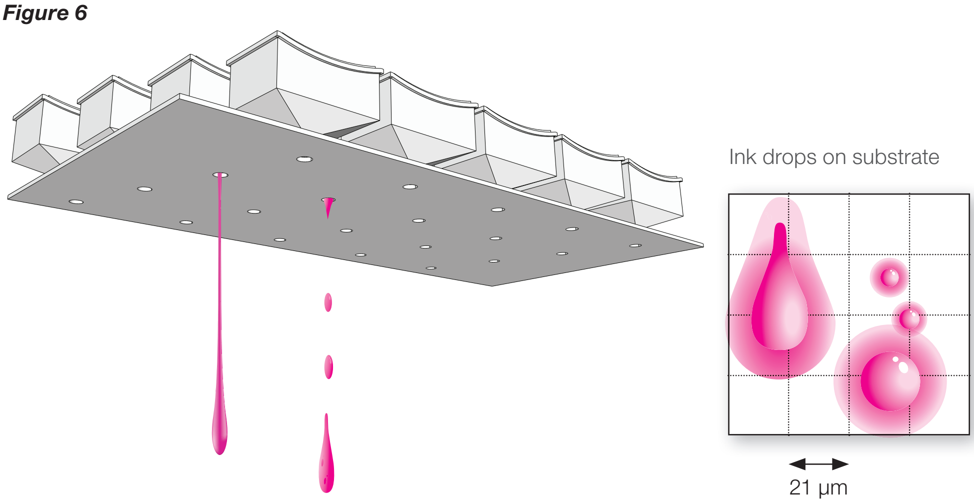


Figure 6



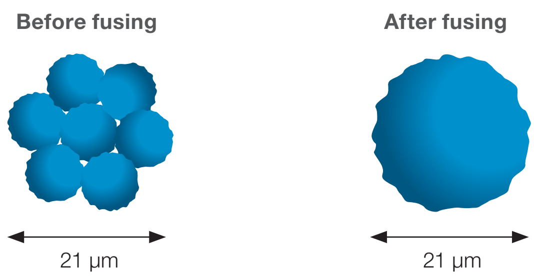
As a result of the above factors, the inkjet imaging process is inherently vulnerable to variations between the target location of a drop and its actual landing spot.

A common issue with inkjet printing, which further impacts dot positioning accuracy, is the formation of satellites. When an ink drop is ejected by a nozzle, it breaks off from the ink remaining in the ink chamber behind the nozzle. Ideally it moves towards the substrate as a single spherical drop. Looking in detail you will see that quite often the jet is made up of a head, containing the bulk of the ink, and a smaller tail. Depending on the surface tension of the drop, its viscosity and its inertia, the tail either merges with the head or breaks off, forming a satellite that drifts away from the main drop. Because these tails are small, they can be easily caught up in airflows, causing them to land elsewhere on the substrate, which is less of a problem in solids, but may be quite a quality issue in other areas (e.g. fine lines, small text). Drifting tails may also contaminate the nozzle plate or other parts of the system.

1.3.1.3 Dot sizes: The numbers tell the tale

In the electrophotographic process, there is very little dot gain, i.e. the size (and shape) of the printed dots remains constant, due to the high viscosity and chemical characteristics of the toner (see below, chapter 2). For a dry toner electrophotographic press with a resolution of 1200 dpi, i.e. a device dot size of 21 µm, this device dot is typically made up of 10 to 15 toner particles with a median size of 8 µm. On a liquid toner press with the same resolution and a median toner particle size of 2 µm, completely filling a device dot of 21 µm takes 60 to 80 toner particles.

Figure 7
Dry toner



As for inkjet, depending on ink composition and substrate characteristics, the size of the wetted surface of a dot generated by an ink drop may double or triple in time, e.g. on a paper substrate, a drop diameter of approximately 10 µm generated by a theoretical ink drop of 0.5 pL, at a resolution 1200 dpi, becomes about 15-20 µm. Note that today, however, no commercially available inkjet label press can jet drops as small as 0.5 pL. For water-based inkjet presses, the minimum drop size is 2 pL, for UV-curable inkjet presses the smallest possible drop has a volume of 5 pL (1 picoliter = 1 pL = 10^{-12} liter, i.e. one trillionth of a liter).

Figure 8
Inkjet

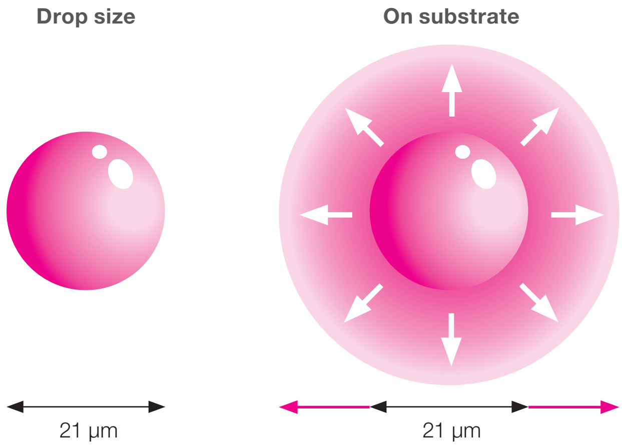


Table 1

	Ball diameter of particle or drop (µm)	Calculated volume of particle or drop[1] (pL)	Diameter of dot on substrate[2] (µm)
Liquid toner [3]	2	0.004	2-2.2
Dry toner [4]	8	0.268	8-10
Inkjet 2 pL	16	2.1	40-55
Inkjet 3 pL	18	3.1	50-65
Inkjet 5 pL	**22**	**5.6**	**60-80**
Inkjet 10 pL	26	9.2	75-100
Inkjet 20 pL	34	21	90-120

[1] Volume derived from perfect ball diameter (see column to the left)
[2] The final size on the substrate in case of inkjet is very much dependent upon the spreading of the drop when hitting the substrate. This spreading is influenced by the surface energy, the viscosity of the ink, the drop speed and the absorption capabilities of the material.
[3] Liquid toner particles have sizes in the range of 1.5-2 µm, which corresponds to a volume of 0.0005-0.004 pL.
[4] Dry toner particles have sizes in the range of 6-9 µm, which corresponds to a volume of 0.1-0.25 pL.

Table 1 shows how toner particle size, drop size and dot size on a substrate compare. As you can see, the ball diameter of the smallest possible ink drop is still 2 to 4 times bigger than that of the average dry toner particle and more than 10 times bigger than that of the average liquid toner particle. The volume of the smallest possible ink drop is even 500 times bigger than the volume of a liquid toner particle. The size of individual toner particles is not only smaller than that of a single ink drop, but of an altogether different order of magnitude.

1.3.2 Substrate conductivity

Dry toner electrophotographic processes are sensitive to the conductivity of the substrates used. For inkjet systems and for liquid toner electrophotographic processes relying on transfer to the substrate by transfusion, substrate conductivity is no issue whatsoever.

In electrostatic printing systems where the developed toner image is transferred directly from the photoconductor to the substrate, the transfer relies on electrostatic forces, in which case the electrical conductivity of the substrate is a crucial parameter. This electrostatic transfer is fast and should be homogeneous, i.e. the toner should be attracted with the same electrostatic force across the entire width of the substrate. Interference of the substrate with this electrical field should be minimal, which means the substrate should have homogeneous conductivity – not too high, not too low.

For paper substrates, the electrical conductivity is influenced by both the moisture content and thickness of the substrate, whereas for synthetic substrates only the thickness has an impact. To ensure optimal print quality, the substrate must hold the proper charge throughout the toner transfer phase. Controlling the moisture content is particularly important for paper substrates.

Note that the issue of substrate conductivity is not limited to dry toner digital electrophotography. Some gravure printing techniques use electrostatically charged ink to improve the transfer from the cylinder to the substrate. But as far as digital technologies are concerned, inkjet printing processes and liquid toner electrophotographic processes relying on transfer to the substrate by transfusion, do not have to control or monitor the conductivity of substrates, which is a plus.

1.3.3 Process reliability

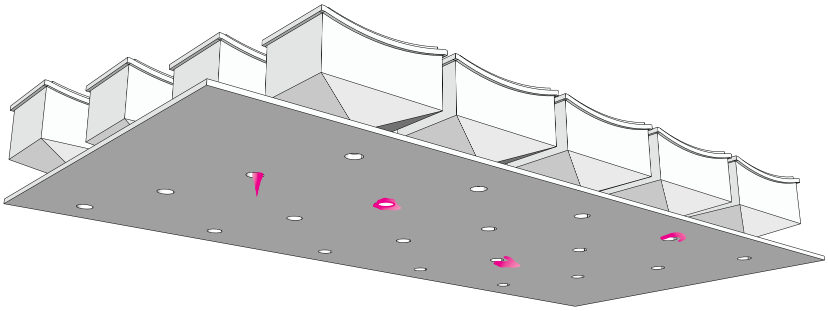
It is fair to say that, for the time being, the electrophotographic printing process is the more stable and intrinsically reliable of the two.

Although electrophotographic systems do have more components involved in the imaging, the process can be controlled to a greater extent, provided all components receive proper maintenance and servicing. Inkjet may seem simpler as far as the number of components involved, but almost the entire imaging process is concentrated in the print head. Any malfunction of this head has a direct impact on print quality. Let us have a brief look at one of the most important potential issues: Failing or deflecting nozzles.

If the ink does not leave the nozzle when instructed, no drop is formed where there should be one. Nozzles can fail for several reasons: As the nozzles are exposed to the environment, the more volatile components may evaporate at the nozzle opening, increasing the viscosity of the ink up to the point where it can no longer be ejected. A similar issue can arise due to sedimentation of heavy ink pigments (e.g. TiO_2 for white), clogging up the nozzle opening. Also, air bubbles in the ink may accumulate in the ink chamber behind the nozzle. Entrapped air bubbles lower the compressibility of the ink. The pressure pulse generated by the piezoelectric crystal will then fail to eject the ink from the nozzle. In order to prevent clogging and air bubble build-up, some print heads are equipped with a circulation system that keeps the ink in motion. To remove dissolved air, ink is also treated ultrasonically before it is sent to the print head.

The nozzle plate can also become contaminated by small drops of ink around the nozzle openings (e.g. from small satellites), which may affect the straightness of the jets. Deflected ink drops or "side shooters" are also caused by partial obstruction of the nozzle, internally or externally (e.g. by dust from the environment).

Figure 9



Precisely because DOD inkjets do not eject drops unless actuated, they are vulnerable to evaporation, especially of fast-drying inks, and nozzle clogging. The "open time" is the time that nozzles can be uncovered and idle before they will no longer print. This is an important parameter of both the print head and the inks, and should be taken into account. There are several ways to prevent clogging of idle nozzles, but the most effective ones require operator intervention, as does cleaning the nozzle plate, which is a very delicate procedure that should be carried out with the utmost care to avoid damage. Unfortunately, operator intervention means halting the production.

To prevent the risk of nozzles clogging by particles released from the substrate (e.g. paper fibers), it is recommended to use a substrate cleaning device. Electrophotographic systems are more forgiving in this respect, at least when printing on label stock.

While inkjet press manufacturers have developed several systems to detect and remediate or compensate for failing or deflecting nozzles, these systems have their limits. For the time being, inkjet is an inherently more vulnerable system.

2 TONER AND INKJET COMPOSITION AND CHARACTERISTICS

2.1 Dry toner

Dry toner is typically composed of:
- Pigment(s), the colorant(s) used to achieve the desired color
- Resin, mostly polyester, a high molecular weight organic polymer that is solid and brittle at room temperature. This resin surrounds the pigment particles and makes up the bulk of the toner.
- Filler(s), charge-controlling agents dispersed in the resin to either speed up or, if necessary, slow down the charging rate and maintain the charging properties of the toner and fusing aids
- Surface additives or external additives, to further improve the toner's properties
- Application-specific additives to achieve special properties and characteristics

Dry toner particles are relatively fine, in the range of 6 to 9 µm, with a median size of 8 µm.

As explained in 1.1, once the image is transferred to the substrate, heat is applied to fuse the toner to the substrate: Heat causes the toner particles to coagulate (i.e. the resin melts), forming a homogeneous, solid polyester film.

A single layer printed with dry toner has an average thickness of approximately 4 µm, but thicker layers can be achieved by adapting the amount of light to create the latent image (see 1.1), without any impact on productivity. This is typically done for opaque white layers.

2.2 Liquid toner

The liquid toner used in commercially available label presses is composed as follows:
- Pigment(s), the colorant(s) used to achieve the desired color
- Modified polyethylene resin with a low glass transition temperature, which makes it rubber-like at room temperature. During manufacturing, pigment is kneaded into the resin and the particles are reduced in size by tearing them apart, which causes the characteristic star shape of the toner particles.
- Carrier liquid, a mineral oil that is highly chemically compatible with the polyethylene resin, as a result of which it is partly dissolved inside the pigment-resin system, changing the viscoelastic properties of the resin so that it can be transferred/transfused in a molten phase to the final substrate
- Organic dispersants deposited onto the surface of the liquid toner particles in order to stabilize them and also to charge them (due to the incorporated metal salt complexes)
- Additives, additional molecules that are added to the carrier liquid to ensure the electrical neutrality of the toner system when a charged toner particle moves to the photoconductor drum

The toner particles in a liquid toner system are approximately 2 µm, i.e. much smaller than in dry toner.

As explained in 1.1, in the final step of the printing process, prior to the transfer of the image to the substrate, heat is applied. The toner melts and most of the carrier liquid evaporates. The toner particles coagulate, forming a homogeneous, flexible film on the substrate. After the image transfer, the evaporation process continues. Any residual carrier liquid should have evaporated within a few days, which brings the polyethylene polymer back to its normal state at room temperature.

A single layer printed with liquid toner has a thickness of about 1.5 µm.

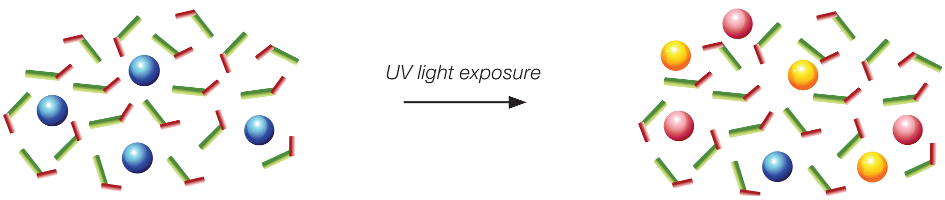
2.3 UV-curable ink

The typical UV-curable inkjet ink composition is as follows:

- Pigments milled down below 150 nm, stabilized with dispersing agents to keep the dispersion stable for a long time
- Carrier liquid, a reactive solvent, typically an acrylate, containing monomers (chemicals with a simple molecular structure that can combine with other similar molecules to form a polymer) and a cocktail of photoinitiators and synergists:
  - Monomers with monofunctional reactive vinyl groups, chosen from an extensive range of candidates to ensure good adhesion, flexibility, weatherability, smell, shrinkage etc.
  - Monomers with bifunctional reactive vinyl groups (acrylic or enol ether functions) to ensure effective curing
  - Photoinitiators and synergists to provide sensitivity to a range of wavelengths and to ensure good curing throughout the ink layer: At the substrate surface, in the bulk of the layer, and at the ink surface, where competition with oxygen is always a challenge as oxygen in the air slows the curing at the surface.
- Surfactants to control the static and dynamic surface tension of the inks, ensuring homogeneous drop formation (without the formation of satellites) and a good, fast and controlled wetting when the ink drop hits the substrate surface

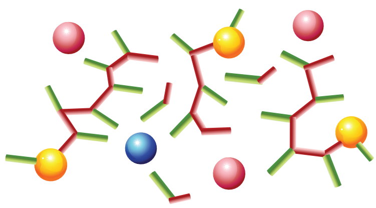
As explained in 1.2, under the influence of UV light, the ink is cured, i.e. the photoinitiators form free radicals that react, i.e. cross-link with other ink components, the monomers, to form a polymerized or cured film. The ink is dry when the cross-linking reaction is complete, i.e. when all components have been cross-linked.

Figure 10



Step 1 *- Unexposed ink (the lines symbolize the monomers where the red part is the reactive functional group, the blue parts are photoinitiator molecules)*

Step 2 *- The UV light hits the ink: the photoinitiators split in 2 free radical parts (the orange and red parts). Note that not all photoinitiators did split in radicals.*



Step 3 *- After UV light exposure, one of the radical parts started a cross-link reaction with the monomers resulting in a polymer where the red parts of the monomers are linked to each other. Unused photoinitiator (blue part), unlinked photoinitiator residus (red parts) and unreacted monomers are all potential candidates for migration.*

High-frequency jetting requires low-viscosity inks. Water-based inks offer the lowest viscosity possible (see 2.4). UV-curable inks have a higher viscosity, due to the chemical composition required for the curing. These inks, however, do have a 6 times lower viscosity than UV offset or UV flexo inks, which has several consequences as we will discuss further below (see 2.5).

A single layer printed with UV-curable ink has a thickness of 4 to 6 µm.

2.4 Water-based ink

The water-based inkjet inks used in commercially available label presses are generally composed as follows:

- An aqueous carrier medium, making up the bulk of the ink (60-90%)
- Pigment(s), the colorant(s) used to achieve the desired color, dispersed in the carrier
- Dispersing agents to stabilize the pigment dispersion over a long period of time
- Humectants to prevent the water from evaporating when the inkjet head is not covered or idle
- Surfactants to facilitate drop formation (without formation of satellites) and to improve the wetting of non-paper substrates
- Biocides to prevent biological growth
- Buffers to control the pH of the ink (CO_2 from the surrounding air dissolved in the ink affects the pH)
- Other additives, such as chelating agents, defoamers, and solublizers

Water-based inks offer the lowest viscosity possible and they are therefore best suited for high-frequency jetting. Low viscosity has, however, one drawback: Adequate dispersion of heavy particles, such as TiO_2 for white inks, is difficult to achieve.

After complete drying, a single layer printed with water-based ink typically has a thickness of 0.2 to 0.4 µm.

2.5 Different marking materials compared

Different marking materials, i.e. toner and ink, have different compositions and characteristics. For the sake of brevity, our discussion is limited to their interaction with label substrates, the look and feel and durability of printed matter, and the sustainability of the respective technologies.

2.5.1 Interaction with substrates

In our evaluation of the interaction of toner and inkjet with different substrates, we consider adhesion and pigment penetration. Adhesion determines if and how well the printed image stays fixed to the substrate. Pigment penetration indicates whether or not the toner or ink pigments penetrate the substrate. While adhesion should be maximized, pigment penetration is to be avoided as much as possible, for two reasons: (1) it has a negative impact on color depth, dot shape and size and (2) leads to inefficient use of pigments, i.e. more ink or toner is required to achieve the same color depth.

Table 2

	Dry toner EP	Liquid toner EP	UV-curable IJ	Water-based IJ
Paper substrate				
Adhesion	OK	OK, primer needed	OK, depending on porosity	OK
Pigment penetration	none	none	yes, primer needed	yes, primer needed
Synthetic substrate				
Adhesion	OK	OK, primer needed	OK, if substrate surface energy OK	OK, if polymer system present
Pigment penetration	none	none	none	none

Paper substrates
Due to the chemical affinity of dry toner systems for paper or paper coating, adhesion is good, no primer is needed. In dry and liquid toner, the pigment molecules are encapsulated in a high molecular weight polymer. These particles are too large to penetrate into the fibers of uncoated paper, let alone in those of coated paper. However, the polyethylene phase of liquid toner is less compatible with the chemical properties of paper or paper coating. Also, because the carrier liquid dissolved inside the resin system still needs to evaporate, adhesion is compromised. As a result, liquid toner, in contrast to dry toner, does require a primer, not to prevent pigment penetration, but to improve adhesion. (Note that, on natural papers, applying a uniform primer layer to ensure uniform adhesion is a challenge).

In order to ensure reliable jetting, inkjet inks have a low viscosity and the print heads are kept at a temperature of 45°C to maintain low viscosity (typically 4-17 mPa.s). The viscosity of UV-curable inkjet inks is about 6 times lower than that of commonly used UV flexo inks, so they can more readily penetrate the paper fiber, which is why a primer is needed to avoid pigment penetration. As far as adhesion is concerned, water-based inks can be applied without a primer: The components encapsulating the pigment particles are compatible with the chemical properties of paper or paper coating, but as said, to avoid penetration of the pigment (and dot gain) you would need a primer after all. For UV-curable inkjet the argumentation is somewhat different: For the ink to cure, the entire ink system needs to remain at the surface. Any ink penetrated into the substrate cannot be exposed to the UV light and therefore cannot be cured effectively. Releasing prints containing uncured substances is dangerous. Therefore, when printing on porous paper substrates, a primer should be used to ensure proper curing and adhesion.

Synthetic substrates
No pigments can penetrate synthetic substrates, so pigment penetration is not an issue for any of the marking materials discussed here.

Due to the chemical affinity of dry toner systems for synthetic substrates, adhesion is not an issue either. For liquid toner systems, however, adhesion is compromised as the carrier liquid dissolved inside the resin system still needs to evaporate. Therefore, a primer is needed.

The adhesion of UV-curable inkjet inks depends on the relative surface energy levels of the ink and the substrate. The higher the substrate's surface energy relative to that of the ink, the better the wettability. Good wettability is necessary to achieve good adhesion. Synthetic substrates typically have low surface energy levels so, for certain substrate-ink combinations, a primer or corona treatment increasing the substrate's surface energy is required to improve adhesion, which has an impact on gloss uniformity and image quality.

Synthetic substrates are impermeable to water. Water-based inks should adhere after evaporation of the water, which can be achieved in two ways: (1) By using inks containing polymers, so that the polymer film formed after evaporation of the water adheres well, or (2) by applying a polymer-based primer compatible with the ink pigments.

2.5.2 Look and feel

Depending on the application, functional or aesthetic considerations prevail. Without wanting to oversimplify things, we limit our overview to image quality, gloss impression, tactility and opacity.

Table 3

	Dry toner EP	Liquid toner EP	UV-curable IJ	Water-based IJ
Image quality (resolution)	1200 dpi	812 dpi	360 or 600 dpi	600 - 1200 dpi
Gloss impression on matte substrates	satin	satin	glossy[*]	matte
Tactility (3D texture)	medium	none	medium-high	none
Opacity				
White (single pass)	+++	++	++++	+
Other colors	+	++	+++	+++

[*]: Depending on the process, it is possible to achieve a more matte look.

Image quality

Image quality is a comprehensive concept and it would lead us too far to elaborate on all its aspects. From our discussion of accurate dot positioning and dot size control, it should be clear that dry and liquid toner electrophotography enable you to produce finer details than single-pass UV-curable and water-based inkjet for the same (native) resolution (see Boxes 1 and 2), in a more consistent and controllable process.

Gloss impression on matte substrates

The high viscosity of dry and liquid toner results in an average gloss (satin). The viscosity of UV-curable inkjet ink is such that the ink flows spontaneously, creating an extremely smooth surface with a high gloss. With or without a primer, water-based inks take on the gloss level of the substrate as the amount of ink remaining on the surface is insufficient to affect the gloss level.

Tactility (3D texture)

Whether or not you can achieve a 3D texture depends essentially on the thickness of the printed layer. UV-curable inkjet produces layers of on average 6 µm, offering medium to high texture. Dry toner layers are on average 4 µm thick, which is thick enough to offer some texture, albeit less than that of UV-curable inkjet inks (Note that white layers are often much thicker). Layers produced by liquid toner and water-based inkjet inks are too thin to feel any 3D effect.

Opacity

For white, the higher the opacity, the better. The opacity of a color is determined by (1) the concentration of pigments (pigment load) and (2) pigment particle size. Dry toner scores well on both accounts. White dry toner combines the highest pigment load with the largest particle size, offering white layers of an opacity that is generally higher than that of flexo white, in a single pass. The pigment particles in white liquid toner are of a similar size, but their concentration is lower, which results in a less opaque single layer (Note that, depending on the machine architecture, multiple layers of liquid toner can be laid down, one on top of the other, in order to achieve a better opacity. This does, however, reduce productivity).

For UV-curable inks used in single-pass high-frequency jetting systems, the pigment particle size should be small enough to avoid nozzle clogging. Also, the required viscosity of the inks does limit the maximum possible pigment load. However, inkjet inks are capable of achieving an opacity comparable to that of screen printing, (1) provided the print head features a low native resolution, producing a large-sized droplet (see Box 1), which is a disadvantage for design elements other than solids, and (2) at low printing speeds. Note that UV flexo inks tolerate a higher load because, as discussed, for these inks, low viscosity is not an issue. The viscosity of water-based inkjet inks being lower than that of UV-curable inks, the opacity achievable with a single layer of white ink is arguably lower as well.

For colors other than white, in contrast, the opacity should be as low as possible. The smaller the pigment particles and the lower the pigment load, the more transparent a color. Transparency also improves with layer thickness: the thinner the layer, the better.

2.5.3 Durability of the prints

Ideally, labels last as long as possible, on the shelves and in use. Depending on their intended use, prints should therefore be able to withstand scuffing and scratching, heat, water and chemicals.

Table 4

	Dry toner EP	Liquid toner EP	UV-curable IJ	Water-based IJ
Scuff and scratch resistance	moderate, UV varnish needed	moderate, UV varnish needed	OK	OK, less than UV-curable
Heat resistance	NOK, lamination needed	NOK, lamination needed	OK	OK
Water resistance	OK	OK	OK	primer-dependent
Chemical resistance	vulnerable, lamination needed	vulnerable, lamination needed	not vulnerable	not vulnerable

Scuff and scratch resistance

The lower the surface energy of a material, the higher its scuff and scratch resistance. The thicker a layer, the lower its scuff and scratch resistance. Based on layer thickness, you would expect dry toner and UV-curable inkjet ink to have the same score, but because layers of UV-curable inkjet ink have a lower surface energy than both dry and liquid toner layers, the latter two are more vulnerable to scratching. Adding a UV varnish to toner prints makes them as scuff and scratch resistant as UV-curable inkjet prints. Based on layer thickness, water-based inkjet are expected to have the highest score, but its layers are so thin that the scuff and scratch resistance of the underlying substrates comes into play.

Heat resistance

Dry toner and liquid toner images are polymers fused to the substrate, so when heated, they can melt again. Applying heat-resistant lamination remedies this issue. UV-curable and water-based inkjet inks are heat resistant: The polymers formed after the complete curing of UV-curable inkjet ink have a high melting point. In water-based inks, the concentration of polymers on the substrate surface is too low for the ink to melt and become sticky.

Water resistance

Water has no chemical affinity for the components in toners or UV-curable inkjet inks, hence their good water resistance. For water-based inkjet inks, the situation is as follows: In order to ensure proper dispersion of the pigments in the water-based carrier, these pigment particles are made hydrophilic by the adhesion of specially designed polymer molecules (dispersion agents), one side of which has a high affinity for the pigment, while the other is hydrophilic (e.g. deprotonated carboxylic groups increasing the polarity of the pigment particles and therefore their affinity for water). Making water-based ink labels water-resistant requires the use of a primer that reduces or suppresses the hydrophilic character of the pigments, e.g. a primer containing calcium salts.

Chemical resistance

Cross-linked systems are generally highly resistant to chemicals, which explains the performance of UV-curable inkjet inks compared to that of toner: The resins in toner are mostly not cross-linked. Applying chemically-resistant lamination remedies this issue. The chemical resistance of water-based inks is due to the fact that these inks do not contain any components with an affinity for chemical solvents.

2.5.4 Sustainability

The printing business, like any other industry, is under pressure to operate as sustainably as possible. How do the different technologies compare when it comes to the production of chemical waste, operator-friendliness and food compliancy?

Table 5

	Dry toner EP	Liquid toner EP	UV-curable IJ	Water-based IJ
Chemical waste	none	excess mineral oils	packaging, rinsing and flushing waste	none
Operator-friendliness	OK, ozone filter required	VOCs from carrier liquid, ozone filter required	OK, strong ozone filter required and UV light shielding (unless UV-LED)	VOCs from some humectants
Food compliancy	OK	OK after full evaporation and with specific barrier materials	difficult	OK, depending on type of humectants

Chemical waste

Dry toner electrophotography and water-based inkjet have one thing in common: They do not produce any dangerous chemical waste. By contrast, the bottles with ink residues, and the rinsings and flushings of the UV-curable inkjet process must be discarded safely, as indicated on the safety datasheets. As for liquid toner electrophotography: During the printing process, most of the carrier liquid is collected in the press and is disposed of as chemical waste, part of it evaporates into the production environment and part remains in the printed material from which it will eventually evaporate.

Operator-friendliness

All toner and UV-curable inkjet processes produce ozone during electrical discharge and curing, respectively. Ozone is a potentially toxic material, but it can be detected by smell at levels significantly below the safety threshold. Proper ozone filters mitigate any problem of smell or intoxication.
During operation of UV-curable inkjet systems, operators have to make sure they are shielded from UV exposure.
As far as volatile organic compounds (VOCs) are concerned: Unlike dry toner, liquid toner electrophotography produces VOCs as the carrier liquid evaporates. Water-based inkjet inks contain humectants, some of which qualify as VOCs.

Food compliancy

In a previous white paper we have discussed food compliancy at length, comparing dry toner and liquid toner electrophotography, and UV-curable inkjet. We have argued why, as far as migration (the transfer of substances from the packaging to the food) is concerned, dry toner electrophotography has an advantage over the other two technologies.

Water-based inkjet has a good starting position as the ink consists mainly of pigments that have no tendency to migrate and neither have the dispersing agents – very high molecular weight compounds. The only potential migrants present in water-based inkjet prints are humectants residing in the substrate prior to full evaporation.

In contrast to UV flexo and UV offset inks, it is difficult to formulate UV-curable inkjet inks in such a way that they too are food compliant. To ensure sufficiently low viscosity, the molecules used in UV-curable inkjet inks are smaller than those in UV flexo and UV offset inks, for which low viscosity is not a necessary requirement. The smaller the molecule, the more likely it will migrate. Moreover, for several reasons it is almost impossible to guarantee a 100% curing: The UV not reaching all the photoinitiator molecules because the layer is too thick, the pigment absorbing UV light and thus interfering with the curing, older lamps producing insufficient UV light, oxygen inhibition etc.

As a result, there are potential migrants present: Unreacted monomers, excess photoinitiator and photoinitiator fragments. UV flexo and UV offset inks typically include higher molecular weight oligomers or prepolymers with sufficient reactive groups to reduce the migration potential. Unfortunately, these increase the viscosity of the ink, which makes them unsuitable for use in high-frequency jetting systems. So far, only one molecule has been found fit for purpose: VEEA or 2-vinyloxyethoxyethylacrylate, which features two reactive groups and low viscosity. Most of the UV-curable inks for high-speed single-pass inkjet printing use this component. The presence of this component is, however, not sufficient for the ink to qualify as a low-migration ink. Working with polymeric photoinitiators is also an option, but this is more complex and expensive.

3 CONCLUSION

From this discussion it should be clear that there is no one-size-fits-all digital technology for label printing. Wine labels do not necessarily have to be chemically resistant, whereas for industrial and health & beauty labels it is a must. Pharmaceutical labels require extra fine print and food labels should be ... food safe. In short: The technology that fits best depends on the application.

With ever-shorter print runs, there are productivity gains to be had from automated workflows, which is exactly where digital printing comes into its own. As each technology has its own merits, ideally you should combine several, or all of them, in order to be able to make the most of their respective advantages and features. And the good news is: There are digital front-ends on the market that can control different press technologies, supporting customized and integrated workflows, thereby offering you a fully integrated production set-up.

RESOLUTION, ADDRESSABILITY AND BIT DEPTH

In an earlier white paper discussing the impact of device parameters on image quality, we have explained the concepts of resolution, addressability and bit depth for electrophotographic digital printing, concepts that we assume most readers are familiar with. Below we briefly discuss their inkjet equivalents. As there are no real industry standards, the meaning of these terms may differ slightly from one manufacturer to another. So, the definitions we provide here are for the sake of this paper only.

Resolution

We use the term resolution to refer to the number of discrete dots a print head can print within a fixed area, expressed in dpi (dots per inch).

For electrophotography, this number depends on the dot size. A system with a resolution of 1200 dpi places 1200 dots per inch with a size of 1/1200 inch, i.e. 21 µm. Resolution as we have defined it, is a hardware specification. For inkjet systems, this then corresponds to native or natural resolution, which is determined, not by the dot size, but by the number of nozzles per inch in a print head and, depending on the print head architecture, the position of the nozzle rows relative to each other. Native resolution is sometimes expressed in npi (nozzles per inch), but mostly in dpi.

The higher the resolution, the higher the level of detail that can be reproduced, e.g. fine text, guilloches and hairlines.

Example: An inkjet print head with 360 nozzles per inch, and two staggered rows in each print head, would have a native resolution of 2 x 360 dpi = 720 dpi. The highest native resolution currently available for single-pass inkjet label presses is 1200 dpi, but most inkjet printers typically have native resolutions lower than the resolution of electrophotographic systems.

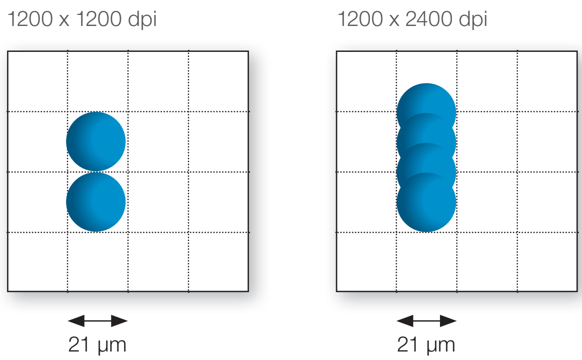
Addressability

We have defined addressability as the number of dots that can be printed within a specific grid. These dots can overlap.

Addressability is defined in two directions: (1) The direction perpendicular to the travel direction of the substrate and (2) the travel direction of the substrate. For LED-based electrophotography and for inkjet, addressability in the direction perpendicular to the substrate's feed direction is fixed, being determined by the number of LEDs and nozzles, respectively, and therefore equal to the resolution. In the other direction, the number of dots can be higher. For LED-based electrophotography, it depends on the pulse frequency of the LEDs. An addressability of 1200 x 3600 dpi means the LEDs pulse 3 times in the time required to process a line of 21 µm dots, i.e. each dot is being oversampled. For laser-based electrophotography, this oversampling can occur in both directions.

For single-pass inkjet, addressability is determined by the print head's jetting frequency, drop size and (maximum) substrate speed.

Figure 11



Bit depth

The bit depth determines the number of output levels or grey levels that can be printed.
Binary systems produce two grey levels. They print either "a dot" (ink or toner is deposited) or "no dot" (no ink or toner is deposited). Such systems are said to have a bit depth of one (2^1=2 grey levels, i.e. black or white). Systems with a bit depth of four, i.e. four bits per spot, bring the number of grey levels to 2^4=16.

Laser-based electrophotography and inkjet systems generating a single size of drop are examples of binary systems. In LED-based electrophotography systems, the light intensity can be modulated, producing more than one bit per spot and therefore more than two grey levels.

For inkjet, the number of grey levels is defined as the number of different drop sizes the print head can generate (incl. no drop). So, a print head producing 4 different drop sizes, e.g. 5 pL, 7 pL, 12 pL, and 18 pL, can generate 5 grey levels[1]. Inkjet print heads capable of generating variable drop sizes are called multi-level heads or greyscale heads. Nowadays, most high-end inkjet presses feature this type of print heads.

A higher number of grey levels can, to a certain extent, compensate for a lower native resolution, when it comes down to producing smooth tone transitions. As far as the reproduction of fine detail is concerned, however, there is no substitute for native resolution.

[1] *Note that, in practice, high-speed single-pass inkjet presses mostly use only up to 3 different drop sizes, i.e. 4 grey levels, even if more sizes are available.*

SCREENING

The outline of the working principles behind electrophotography and inkjet explain how marking material is deposited onto a substrate, but before the latent image can be developed by toner or any ink can be sprayed, several image processing steps have to be performed (calibration, color management, RIPping, ...). At least one step is common for all the technologies discussed: Screening.

Why screening?

Most printing systems cannot print continuous tone images as they can only deposit dots with a limited number of grey levels (see Box 1). The commonly accepted industry standard for high-quality reproduction of continuous tone images, offering sufficiently smooth gradations between any process color and white, is 2^8 = 256 grey levels (256 grey levels are indeed sufficient as the standard human observer cannot distinguish more than 200 shades).

This is why the RIP converts contone images to a bitmap with dots or pixels of 8 bits per process color. As the amount of information in such a bitmap is too large to handle, it is converted to a bitmap containing dots or pixels with fewer bits per color, i.e. 1 or 4, depending on the technology. This re-sampled bitmap is printed. The process used for the conversion is screening or halftoning, which basically transforms a continuous tone image into a series of halftone dots placed in a pattern. For a continuous tone color image, all colors are broken down into the four process colors (CMYK) and any spot colors, after which the screening process is applied to each. Screening relies on the limitations of the human eye, i.e. it cannot easily distinguish small dots that are closely spaced. The goal is to find a dot size such that, at normal reading distance, the human eye is being tricked into seeing these dots as a continuous tone.

AM versus FM screening

There are several different types of screening, but we will limit our discussion to two of them: Amplitude Modified (AM) screening and Frequency Modulated (FM) screening.

The AM screening is the "conventional" halftoning process, which arranges dots of different sizes in a grid, i.e. lines of equidistant dots. These screens are characterized by their screen ruling or line frequency, i.e. the distance between the lines, which is measured in lines per inch (lpi). To avoid image distortion caused by interference between screens, the screens of the different colors are rotated over a certain angle relative to each other, which results in the typical rosette pattern. The size of the dots is varied according to the tonal values that need to be represented, hence the name "amplitude modified". Smaller dots are used for the lighter tones, while larger overlapping ones represent darker areas.
An FM screen, or stochastic screen, uses dots of the same size and places them in a pseudo random pattern[2], which may vary from one type of FM screen to another. FM screens change the number of dots according to the desired tonal value, hence the name "frequency modulated". Darker tones are represented with more dots, lighter tones with fewer dots. Depending on the type of FM screen, the shape of the dots may differ and the halftone dots may be woven together in worm-like shapes.

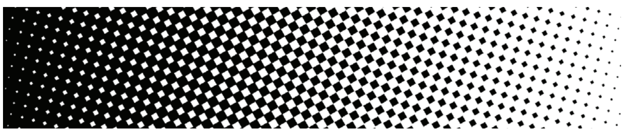
EP mostly uses AM

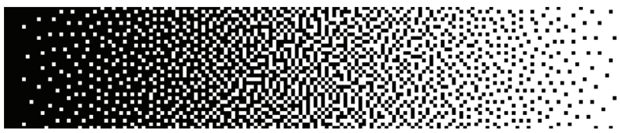
For historical reasons, electrophotography mainly uses AM screening, which was originally developed for conventional printing technologies and therefore widespread. It was translated to its digital equivalent, maintaining the same look and feel. As the resolution of the first digital printing technologies was insufficient for FM screening, electrophotography started off using AM screening.

When printing an AM halftone screen, the press will compose each halftone dot of multiple device dots, the size of which is determined by the print head's resolution (see Box 1). These device dots in turn are filled with many more toner particles (see 1.3.1.3).

IJ mostly uses FM

As explained in 1.3.1, inkjet, especially at high speeds, offers inherently less control over accurate dot positioning and dot size,





AM screening

+	especially suited for the reproduction of solids
+	achieves an offset look (some print buyers like the typical rosettes)
-	vulnerable to moiré effects
-	requires accurate control of the positioning of the individual imaging pixels

FM screening

+	random distribution eliminates patterns/artefacts, giving images a more natural look
+	no moiré, even when using more than four process colors
-	vulnerable to graininess in flat tints
-	more vulnerable to noise

two parameters that are essential for the reproduction of the rigid geometric pattern and fixed dot sizes of an AM screen.

Because it is difficult to control the exact landing spot and size of an ink drop on the substrate, it is difficult to accurately build up the AM halftone dots from multiple ink drops as these halftone dots, by definition, should have a defined (shape and) size at a precise location in the grid. Also, the staggered nozzle arrays in the print head may induce a pattern of their own, interfering with that of the AM screen. It is clear that FM screens, with their randomized halftone dots are much more forgiving.

Note: At lower speeds, dot positioning accuracy can be better controlled, opening up the possibility for AM screening. But these low speeds are not used for high-end label printing.

[2] *Truly random patterns might actually produce unwanted ones, so FM algorithms are specially developed to avoid this.*

ABOUT XEIKON

Xeikon, a division of Flint Group, is a long-standing leader and innovator in digital printing technology. Grounded in the principles of quality, flexibility and sustainability, Xeikon designs, develops and delivers web-fed digital color presses for label and packaging applications, document printing, and commercial printing. These presses utilise LED-array-based electrophotography, open workflow software and application-specific toners.

As an OEM supplier, Xeikon also designs and produces plate makers for newspaper printing applications. In addition, Xeikon manufactures basysPrint computer-to-conventional plate (CtCP) solutions for the commercial offset printing market. For the flexographic market, Xeikon offers digital platemaking systems under the ThermoFlexX brand name. ThermoFlexX systems provide high-resolution plate exposure combined with unique plate handling, flexibility and unmatched productivity .

In 2015, Xeikon joined Flint Group to create a new "Digital Printing Solutions" division for the leading global print consumables and solution provider to the packaging and print media industries. Flint Group develops and manufactures an extensive portfolio of printing consumables. These include a vast range of conventional and energy-curable inks and coatings, pressroom chemicals, printing plates and equipment, printing blankets and sleeves, and pigments and additives for use in inks and other colorant applications. Headquartered in Luxembourg, Flint Group employs some 7900 people. On a worldwide basis, the company is the number one or number two supplier in every major market segment it serves.

For more information about Xeikon, visit www.xeikon.com and for Flint Group, visit www.flintgrp.com

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