

Polyester Media Development for Inkjet Printers

A discussion of the mechanisms and ink/printer/media interactions that must be considered in the design of special media for a printer system, and of the methods available for optimizing them.

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The full capability of a printer system is best realized by printing on special media designed and developed to work on that specific printer system. HP special media include the CX JetSeries transparency film, the LX JetSeries transparency film, the LX JetSeries glossy paper, and the LX JetSeries single-matte inkjet polyester film. These special media are designed to give the best possible print quality for the printer system for which they were designed. In most cases, the media will operate over a range of products. The LX glossy paper and the LX transparency film both give optimum print quality performance on the HP PaintJet XL300, DeskJet 500C, DeskJet 550C, DeskJet 1200C, and DeskJet Portable printers. To ensure the highest possible print quality on all of these different printer platforms, various ink/printer/media interactions that occur while printing must be understood and accounted for in the printer, ink, and media design.

Polyester Substrates

Among the most common special media are the polyester-based materials. These include overhead transparency film, matte drafting film, and the bright white HP LX JetSeries glossy paper. All of these media are constructed on a base sheet made of biaxially oriented polyethylene terephthalate (PET).

Some of the factors that make polyester film a material of choice include its durability, thermal and hygroscopic stability, clarity, and stiffness. Along with all of these desirable attributes, a coated polyester substrate has several less-favorable properties that are not found in paper-based media, such as the base material's low absorptive capacity for aqueous inks.

Ink-Receptive Coating

The most obvious difference between paper-based materials and polyester film is that in a water-based ink system, the polyester film does not absorb any of the ink applied to the sheet. As shown in Fig. 1, the ink printed on the uncoated polyester sheet simply beads up on the surface. The identical pattern of ink applied to a coated polyester sheet retains the printed image.

The ink-receptive coating on the polyester film functions to absorb the ink, bind the free liquid of the ink vehicle until it can fully dry, cause the ink to spread into well-formed dots on the page, hold the colorant from the ink in place on the film, and provide outstanding image quality for both black and color. These are some of the properties that the development team will optimize during the design of any polyester film-based media.

Drying Time

The drying process on polyester film-based media is a two-fold mechanism, a combination of absorption by the ink-receptive coating and evaporation. The evaporation rate of the ink on a printed page can be estimated by printing the ink onto a sheet of an uncoated polyester film. With no ink-receptive coating on the film, all of the drying capacity must come from evaporative forces only. These forces are based on the surface area of the ink exposed to the air and the partial pressure of the ink vehicle.

When an uncoated polyester sheet is printed on a DeskJet 1200C printer and left to dry, an hour later it will still not be dry to the touch. This is because the nonvolatile components

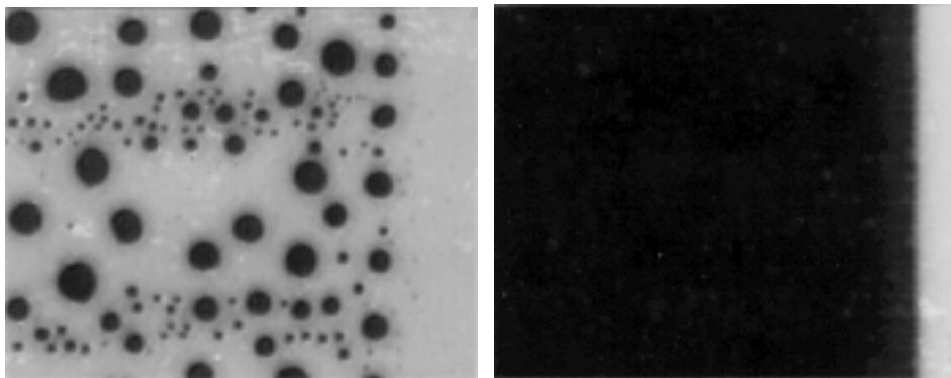


Fig. 1. Image printed on uncoated (left) and coated (right) polyester films.

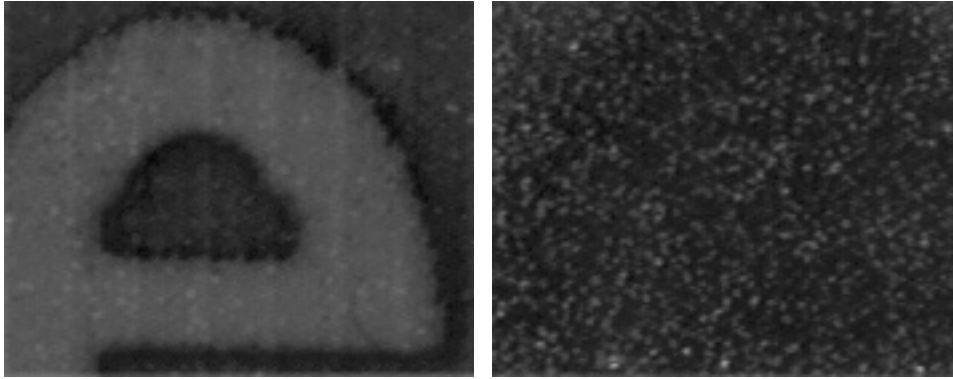


Fig. 2. Image printed on film with (left) and without (right) bleed fixing agents.

in the ink make the evaporative drying rate very low. By contrast, the ink applied to a coated sheet will be absorbed by the ink-receptive coating, and will be dry to the touch within a reasonable amount of time after printing. Achieving fast drying times while still maintaining the desired level of print quality is one of the most difficult aspects of polyester film development.

A typical inkjet printer will have a total ink flux applied to the sheet of approximately 30 to 40 g/m². The typical inkjet polyester film has an ink-receptive coating weight of 4 to 8 g/m². The ink-receptive coating must absorb and bind all of the ink applied to the sheet. While a greater amount of coating weight applied to the polyester base sheet would definitely improve the ability of the film coating to absorb the ink, additional problems develop such as image quality, curl, manufacturability of the film, and finished product cost.

Evaporation will eventually remove most of the excess volatile components of the ink. This will leave only the nonvolatile components from the ink to be absorbed by the coating. The inks used in the DeskJet 1200C have approximately 20 to 30 percent nonvolatile components. At full ink densities, there will be 6.9 to 9.2 g/m² of nonvolatile ink components remaining in the coating. Some of these nonvolatile components will act as humectants and hold additional moisture in the coating with them, making the total remaining mass of ink in the coating even higher. Depending on the environmental conditions, the humectant tendencies of the ink may also prevent the inks from fully drying on the film.

Bleed

Image bleed is another major development issue with polyester film-based media. The images shown in Fig. 2 depict two different ink-receptive coatings and two different levels of image bleed. The image coating without any bleed inhibitors shows a high level of bleed, allowing the colorant to diffuse through the coating medium freely. The film sample that does have bleed inhibitors incorporated in the coating retains the ink in the location where it was originally printed, making it a more robust printing system.

The ink-receptive coating is based upon combinations of water-absorptive polymers. These polymers act like highly viscous liquids on top of the polyester film. The viscosity of these liquids is very sensitive to dilution. As they absorb moisture either from a humid environment or from the ink printed on the sheet, the ink-receptive coating will act as if it has been diluted, and its viscosity will drop significantly. In

this less-viscous state, the colorants in the ink are able to diffuse more freely.

Colorant selection for the inks can have a significant impact on the ability of the ink-receptive coating to inhibit bleed. The size and mobility of colorants can range from molecular-sized dyes to large colorant particles that are orders of magnitude larger. A relatively small, easily mobile colorant particle will diffuse through the coating much more easily than a much larger colorant particle. Even the smallest, most mobile colorants can be immobilized somewhat by the use of a fixing agent in the coating. For example, large organic structures can bind the colorant, make the effective size of the colorant particle much larger, and make the colorant less mobile in the coating medium. Other fixing agents such as inorganic counterions dispersed within the coating will precipitate the colorants and make them less mobile in the coating medium.

Temperature also has a large effect on the bleed of an image on polyester films. This is evident if a sheet of polyester media is imaged at ambient conditions (23°C, 50% R.H.) and allowed to dry thoroughly. The imaged sheet can be placed into a moisture barrier such as a sheet-protector sleeve. If the imaged sheet in the sleeve is then moved to a high-temperature environment (35°C), the image will exhibit significantly more bleed than an identical image left at ambient conditions.

The effect of temperature is consistent with the Stokes-Einstein equation for liquid diffusivity:¹

$$D_{AB} = \frac{kT}{6\pi r\mu_B}$$

where D_{AB} is the diffusivity of the colorant A in the coating B, k is Boltzmann's constant, T is the absolute temperature in Kelvin, r is the effective hydrodynamic colorant particle radius, and μ_B is the viscosity of the coating. The observed effects of temperature, coating viscosity, and increased colorant particle size on the diffusivity of the coating are consistent with this relationship. Diffusivity is directly proportional to temperature and inversely proportional to the viscosity of the coating. Not so evident is an additional effect of temperature: the viscosity of the coating is strongly dependent on temperature. The viscosity of the coating can be estimated with the empirical Fox-Loshak correlation:²

$$\ln \mu_B = a + b/T(1+c)$$

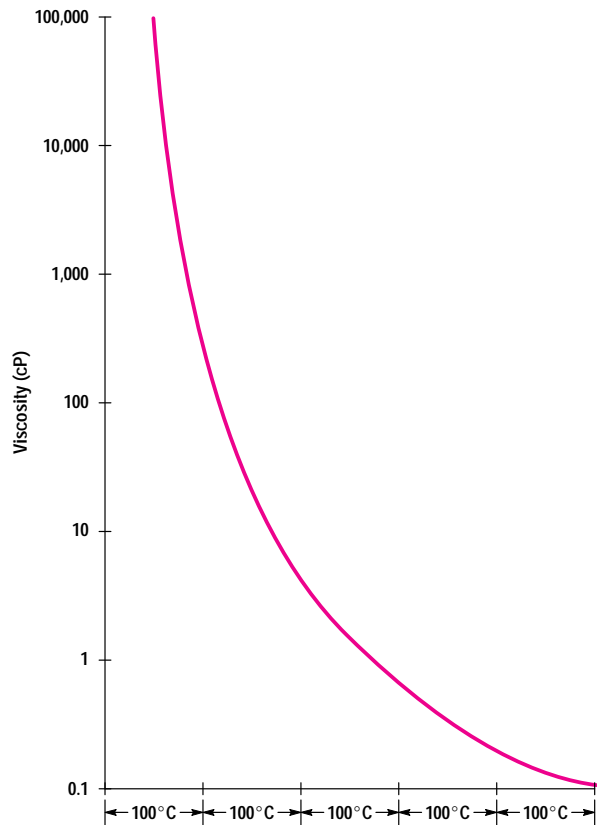


Fig. 3. Approximate temperature variation of liquid viscosity.³

where a, b, and c are physical constants (usually $c \approx 1$) for the particular polymers used in the coating. The chart in Fig. 3 shows the approximate relationship of temperature and liquid viscosity (in centipoise) for low temperatures (relative to the boiling point). The slope of the viscosity-temperature curve is very steep in the region of high-viscosity liquids ($> 10,000$ cP) like the polymers used in ink-receptive coatings. A small change in temperature of 12°C (from 23°C to 35°C) has a much larger effect on a high-viscosity liquid than on a low-viscosity liquid.

Dot Gain

On the other end of the spectrum from bleed is the issue of dot gain. In an effort to correct the problem of bleed, heavier coating weights or highly absorptive coatings are applied to the base film. The thicker or more absorptive coatings will significantly impact the ability of the ink to spread adequately

on the film, resulting in incomplete pattern fill and low image densities.

Fig. 4 shows the solid fill generated by a small-dot-size film coating. The optical density of the image printed with a small spot size (left) is 1.10, while the same area fill pattern with an optimized-dot-size film coating (right) has an optical density of 2.25. The ideal dot size for a dot matrix printer can be calculated based on the printer resolution. The ideal dot diameter in micrometers is:

$$\phi = 35921/R$$

where R is the printer resolution in dots per inch. This ideal dot size ensures that the dots in a field will have sufficient overlap to fill an area with 100% coverage. The ideal spot size for a 300-dpi printer is about 120 micrometers. As the dot density increases and approaches 100% area fill, the dots will interact with each other to generate a larger dot diameter than when measured as single dots. Therefore the dot size required to achieve complete fill is actually slightly smaller, and will vary depending on the dot growth of the individual coating.

The minimum dot size achievable for dithering purposes is directly related to the drop volume of the ink applied and the ink-to-film contact angle. Fig. 5 illustrates the effect of contact angle on the size of the spot generated with equal volumes of ink. The minimum image spot size is equal to the area of the ink drop in contact with the surface of the film. For a high contact angle ($\approx 90^\circ$) the minimum spot diameter can be calculated from the equation:

$$\phi = (6000V/\pi)^{1/3}$$

where V is the drop volume in picoliters. For a typical 300-dpi inkjet print cartridge that delivers around 100-picoliter drops, the minimum spot size would be about 58 micrometers, or about half the ideal dot size. Increasing the drop volume will increase the minimum dot size, making it closer to the ideal dot size. The problem with increasing the drop volume to increase the minimum dot size is that, because the relationship is cubic, a drop volume of 905 picoliters would be required to achieve the ideal dot size with no dot spread in the coating. This amount of ink would cause severe problems with drying time, blocking, and bleed, and would cause an uncounted number of problems on paper media.

This creates the dilemma of getting the drops to spread enough to form the ideal dot size without requiring large amounts of ink to do it. Compounding this problem are the

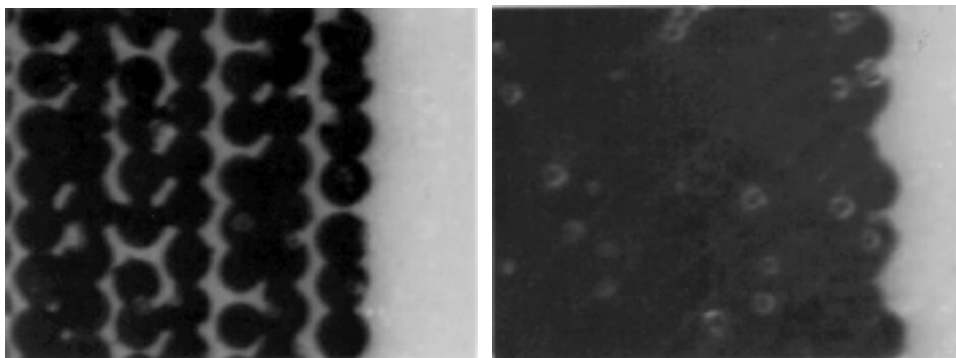


Fig. 4. Image printed with small spot size (left) and optimum spot size (right).

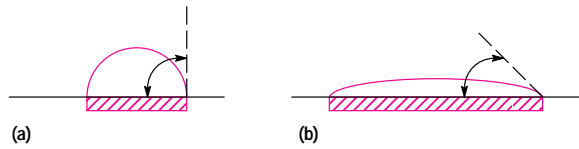


Fig. 5. Effect of contact angle on ink drop diameter on polyester media. (a) High contact angle (90°). (b) Low contact angle ($\approx 40^\circ$).

aspects of drying time and bleed. One method of generating dot spread is to promote ink spread through the coating. This will very often result in large amounts of bleed over time. The challenge is to design a coating that has enough dot spread to get sufficient ink coverage, and then have the spreading stop and stay fixed in place when the ideal dot size is achieved.

Even if the bleed can be controlled with very large dot spread, there are limits to the amount of dot spread that is desirable. If the dot size is too large, fine dithered patterns and individual dots can blend together. This has the effect of making a light gray scaled image blend together into solid, dark colors. The ability to halftone images is lost with very large dot sizes.

Blocking

The phenomenon of blocking is sometimes seen when an overhead transparency sheet is put into a sheet-protector sleeve. Blocking is defined as the localized sticking of the image to the sheet protector. Blocking will appear as blotchy areas on the image when projected. Overhead transparencies must be robust enough to survive storage in a sheet-protector sleeve. Sleeves are used by customers to protect the image from handling, or to facilitate storage in a binder. Most sleeves available on the market today are made of vapor-impermeable materials such as polyethylene, polypropylene, polyvinyl chloride, or polyester. The sleeves not only inhibit drying, but they also have a very smooth surface to promote clarity. If the ink on the coating is moist or tacky in any way, when the sheet is inserted into the sleeve the sleeve material will stick to sections of the imaged area of the transparency film and generate uneven blotchy patterns when projected.

To eliminate the blocking problem from a transparency system, there are several approaches that can be taken. The polymer coating on the film can be modified to be less tacky in the imaged areas, so the image will not stick to the sleeve. Coating composition and additives can be altered, but in many cases, other image properties such as bleed can or will be compromised.

Secondary top coatings can be applied to the film which will let the ink vehicle freely pass through to the bottom coating layer, which will absorb the ink and vehicle. This technique also may have adverse side effects of added drying time, image mottle, crystallization, or coating wrinkling.

Another method of improving the image blocking performance is to use mechanical spacers. Small particles can be dispersed in the coating that mechanically hold the sleeve away from intimate contact with the tacky film surface. The concentration and size of the particles used will depend on the extent of the tackiness of the coating used, and the physical appearance of the film. Small particles have a more

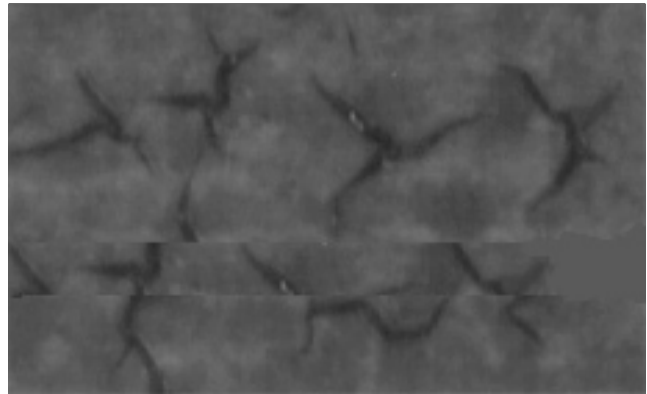


Fig. 6. Imaged film with wrinkles in the print area.

appealing texture on the film surface than do larger particles. Conversely, the small particles also need to be used in higher concentrations to be as effective as the larger particles. This will lead to higher levels of haze when the film is projected.

Wrinkling and Cracking

When the ink is absorbed, the coating will swell from the added volume of ink in the coating. This can add significant mechanical stresses to the coating layer as the ink/coating mixture dries. The swelled coating may be stretched to the point where it cannot recede back to its former dimensions. The resulting additional volume of the coating material forms folds and wrinkles in the imaged area. Fig. 6 shows an example of what wrinkling will do to an imaged area of film. The wrinkles will form darker lines in the imaged area. Not only does this generate severe print quality defects, but it also will impair the mechanical stability of the coating and allow it to peel off the base film. Many times, the wrinkling is on a much smaller scale than is visible to the naked eye, and simply appears as a high amount of haze in the imaged area.

Conversely, if the coating shrinks to a state much smaller than the original coating dimensions, cracks can appear in the imaged area as shown in Fig. 7. The addition of ink to the coating system can have several effects on the coating system. The ink vehicle can make the polymers in the coating less elastic, and the increased stresses from shrinkage will cause cracks in the imaged area. The ink may also change the amount of shrinkage that the polymers in the coating incur during drying, making

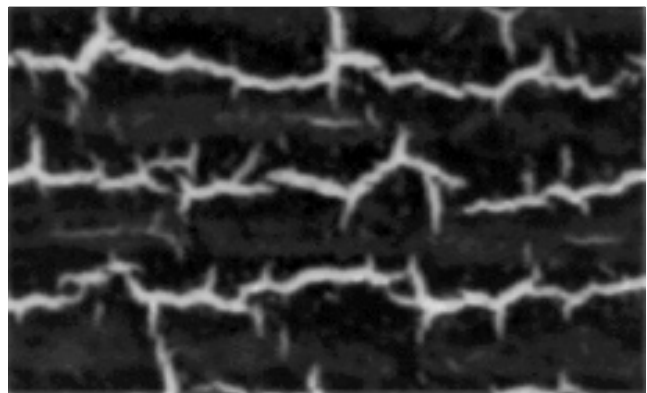


Fig. 7. Imaged film with cracked coating in the print area.

them shrink more than they can tolerate, which will also cause cracks to appear in the imaged areas.

Crystallization

One common problem associated with dye-based inks is that of dye crystallization. On a paper-based substrate, this phenomenon may never be noticed. It is best seen with transmitted light on an overhead projector. When printing on a coated polyester-based film, the dye molecules undergo a transition from a solvent system in the ink vehicle to a different solvent medium of the film coating. If the solubility of the dye in the coating solution is low, the dye can crystallize and generate undesired side effects. The crystallized dye will have a much higher light scattering effect than a dye that is not crystallized. The increased amount of light scattering will appear as haze on the projector. With several yellow dyes, for example, the crystallized dye will appear more brown when projected. The dye crystallization can be aggravated when fixing agents are used in the coating to reduce the amount of bleed.

Color Saturation

One of the main differences between paper printing and polyester film printing is in the end-use application. Images printed on paper or other opaque substrates are viewed directly with reflected light. In the case of transparency film, the images are almost always looked at with transmitted light and projected onto a white screen. The effect of the transmitted light and the magnification is that the image will tend to look more faded or washed out than the equivalent image printed on paper. To compensate for this, the print mode used in the printer to generate an image for transparency film uses more ink per unit area than for an equivalent image printed on paper. This can dramatically increase the drying time, the amount of bleed, blocking, wrinkling, cracking, and dye crystallization.

Heater Distortion

As printer speeds and resolutions have increased, heaters or dryers have been incorporated in the printer mechanism to speed the drying process and increase throughput. The problems faced by paper and film in an environment where printer-induced drying occurs are quite different. On an unheated paper sheet, the paper will want to swell and buckle when ink is applied. The heater in the product heats the paper and dries the ink quickly, preventing the ink from swelling the paper fibers.

In a polyester film-based product, the sheet will not cockle as a result of ink being applied, but it will cockle from distortion caused by the heater. The polyester base has a glass transition temperature of 73°C. When the film is heated above this point, the mechanical structure of the polyester is lost and the base film will wrinkle and warp. To avoid this, the printer does not heat an image printed on the transparency film as much as it does a paper image. The result is that the amount of ink drying is substantially less than the equivalent paper image. The additional ink required to solve the problem of color saturation on transparencies requires more ink to begin with, and the problems of drying time, bleed, and blocking are compounded.

Similar to the transparency film, the HP LX JetSeries glossy paper is also a polyester-based product. Instead of a clear

polyester base material, the HP LX JetSeries glossy paper has an opaque white polyester base sheet. The problem with the opaque white base sheet is the amount of heat that can be applied from the printer. The clear polyester base sheet absorbs very little infrared energy from the heater. Most of the heat energy is transmitted through the film and absorbed directly by the colored ink on the sheet. With the opaque white polyester sheet in the glossy paper, the base material absorbs all of the infrared energy from the heater, and the only heat energy that is absorbed by the ink on the page is from conductive heat transmission from the opaque white base sheet. The implication of this phenomenon is that the allowable heater setting for the opaque white polyester sheet is much lower than setting for even the clear polyester film. This makes drying time, bleed, and blocking even more of a problem for this base material.

Printer Mechanisms

Some of the considerations for compatibility with the printer mechanisms also put constraints on the polyester film-based media. Paper and polyester films have different mechanical handling problems and require different considerations in printer design. Polyester films need special adaptations or mechanisms that paper media do not need.

Scratches. Scratching is one of the most challenging aspects of handling polyester films in the media path of a printer. The smooth, clean surface of transparency films and the HP glossy paper will show scratches and scrapes from a poorly designed media path.

A simple burr on a piece of metal or plastic can put a scratch along the entire length of a sheet of film that will appear as a dark line when placed on an overhead projector, even in unimaged areas. A deep scratch can remove the ink-receptive coating from that area of film and leave a blank line through the image. A paper sheet will generally not show any print defects or material defects from these same conditions.

The media pick motion from the media tray can also leave scrapes on the image side of the film caused from the pressing force of the pick wheels during the sheet pick. On an overhead transparency, this can leave localized spots of high haze caused from minute scratches in the coating where the pick wheels make contact.

Sheet Feeding. Polyester film is often coated on only the image side, and the raw polyester is left on the back side. This can cause problems for both media pick and media advance accuracy. The uncoated polyester film is very smooth. When the printer attempts a media pick with a very smooth sheet, there can be a high frequency of missed picks or skewed sheets during the sheet feeding process. Having an uncoated back side of the polyester film can also induce media advance accuracy errors. If the film is too smooth, the main drive mechanism may not be able to advance the media without some degree of slippage. This will cause misregistration that leads to dark bands of overprinting in the imaged area. Many polyester films have a back side coating that may help these problems, but this only adds to the cost and complexity of manufacturing the film.

Curl. The method for holding down the media in the print zone also can affect the design of the polyester film-based

products. If the media is allowed to curl upward in the print zone, the printhead can crash into the media. The tear resistance of polyester films is well-known. Unlike paper, if the printhead crashes against the media, the polyester film will not tear, and may cause severe damage to the printhead or the printer itself. This very often will necessitate a back side coating on the film to balance the thermal and hygroscopic expansion of the image side coating. Similar to a thermostat, if a one-side-coated polyester film is heated or exposed to moisture, it will have differential rates of expansion and contraction that will cause the media to curl in one direction or the other. The back side coating is designed to match the front side coating for the degree of thermal and hygroscopic expansion so that the sheet will lie flat in all conditions.

The back side coating used for curl balance must also be designed to satisfy all of the other requirements for the print system. In the case of the transparency film, it must be clear, resist scratches, provide a good surface for sheet feeding, resist blocking to another imaged sheet, and perform its main function of providing curl control. In the case of the glossy paper, the back side coating must provide curl control and be resistant to image transfer when stacked on top of a previously imaged sheet. The back side coating must also have surface properties adequate for sheet feeding.

Pen and Ink Considerations

The ink is ultimately the only component that is added to the media to create the final image. Many of the ink-sensitive variables have already been discussed. Some of the other important considerations about the ink can have significant print quality consequences.

Colorants. Colorant selection is critical to the success of any media design project. The robustness of the colorants selected will greatly influence the media design. The tolerance to light exposure, the water solubility, the tendency towards dye crystallization, the pH sensitivity, and the color intensity of the colorants all have influences on the media design.

The amount of colorant loading in the ink also has similar contributions. A low colorant loading will require more ink to deliver the same amount of colorant to the sheet. Higher ink volumes create problems with drying time, bleed, and blocking. High dye loading allows for lower ink volumes, but the lower ink volumes increase the challenge of attaining high dot spread to generate the ideal dot size. The higher dye loading also increases the risk of dye crystallization.

The film coating must have a pH that is compatible with the colorants that are selected. There are some colorants that are stable in a low-pH environment, but they may lose their chromaticity in a basic environment. This would cause a base-sensitive colorant to fade prematurely if applied to a film coating that has a relatively high pH.

Inks. The physical properties of the ink must be carefully matched to the polyester film coatings to achieve a compatible printing system. The coating must have a surface tension that is compatible with the ink so that the ink does not bead up on the surface of the film, resulting in a mottled print image due to coalescence of the ink on the surface.

The film coating must also be compatible with the vehicle in the ink. The coating must be able to absorb the ink and

vehicle without dissolving in the ink vehicle. If the coating were soluble in the ink vehicle, heavy fill areas could dissolve the coating layer and disrupt the mechanical integrity of the film coating, making it very susceptible to scratching and smearing.

As mentioned earlier when discussing drying time, the percentage of nonvolatile components in the ink has a huge impact on the design of polyester films. If the ink does not eventually evaporate into the atmosphere, the coating must accommodate all of the remaining ink components. Since the total nonvolatile components in the ink can be equal to or greater than the total amount of coating, this is a major film design problem. The humectant aspect of the ink increases the total amount of ink that the coating must absorb. This is especially difficult when the printer system must operate in conditions of high temperature and high humidity. The amount of moisture in the air at ambient conditions (23°C, 50% R.H.) is about 60 grains per pound of dry air. At high temperature and high humidity (35°C, 80% R.H.) the amount of moisture in the air is about 220 grains per pound of dry air. This translates to a large increase in the amount of moisture contained in the film before any ink touches the page. The coating has a finite absorption capacity, and the more the coating is saturated with atmospheric moisture, the less ink it can absorb.

Multiple Product Compatibility

The customer viewpoint of polyester films is usually one of parity. One cannot look at a polyester film and determine if it is going to be compatible with a printer/ink system. The ideal polyester film solution is one that works on all HP ink-jet printers equally well. The number of printers and inks on the market today make this a nearly impossible challenge. There are printers such as the DeskJet 1200C with heaters incorporated in them to facilitate drying and promote high-quality, high-density images. There are also printers such as the DeskJet 550C that do not have a heater, but still produce stunning high-density black and color graphics. Each printer type has its own ink imaging system that places different demands on polyester film media.

Polyester film solutions that are designed to maximize the print quality for a highly water-based ink may not be able to satisfy the demands of an ink system that has a high level of nonvolatile components. If the ultimate print quality is to be maintained, the film designs must be tailored to match the printer/ink systems. Although the trend may be toward plain paper compatibility, that definitely does not apply to polyester film-based products. The cost of a single sheet of polyester film-based media requires that there be no compromises in the final output quality.

Conclusion

With the introduction of the HP DeskJet 1200C printer, plain paper printing in both black and color has reached new levels of quality. There is still an overall improvement that can be achieved by coupling the printer/ink system with a specially designed set of polyester films and coated paper such as the high-quality, high-density HP LX JetSeries transparency film or HP LX JetSeries glossy paper for high-quality photographic type imaging and presentation output. There will always be a demand for these media.

In the DeskJet 1200C system, the advances in the ink system that made high-quality plain paper color graphics possible presented a new set of challenges for the polyester film-based products. The high level of nonvolatile components in the ink made the already difficult task of controlling the drying time, bleed, and blocking on the film even more challenging. The requirement that this same film product also be backward-compatible with the existing HP 300-dpi inkjet printer family added to the design constraints.

Numerous challenges and design constraints must be addressed when developing any polyester-based film media. The technical achievement of the DeskJet 1200C polyester media set is the result of the teamwork and vision of several

teams dedicated to producing the highest-quality products. The DeskJet 1200C polyester film media set gives outstanding image quality on overhead transparencies and glossy paper not only on the DeskJet 1200C, but across all of the HP 300-dpi inkjet printer family.

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