

Media Optimization for Solid Ink Printing Systems

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Abstract

While solid ink printing is often considered to be substantially media independent, there are several important media-based parameters which must be carefully optimized to achieve the best performance. The following paper covers the media and print process parameters critical for optimal print quality and durability in solid ink printing systems. Although the offset solid ink printing architecture is the prime focus of the paper, some attention is given to the direct printing solid ink architecture. Relationships between print engine, controller, ink, and receiver media are discussed, and examples of their effects are given. The effects of print process variables on solid ink hard copy are covered, including such topics as media preheating, transfer drum temperature, and transfer drum nip loading. Relevant media parameters are discussed, including caliper, compliance, surface morphology, and ink adhesion promoting coatings. Experimental results are presented in terms of print quality and durability response variables; methods for the quantification of these variables are discussed as well.

Introduction

Within the past few years, solid ink printing has risen from niche markets to become a key player in the graphic arts proofing, networked color printing, and, most recently, the wide format color electronic printing market. The success of this technology stems largely from its combination of ink jet printing with inks relying on solidification rather than colorant vehicle evaporation to achieve image fixation. The key advantages of the technology driving its success are speed, ease-of-use, print quality, color consistency, low cost per copy, and media flexibility. The latter trait, media flexibility, or the ability of solid ink printers to yield high image quality on a wide range of substrates, is the focus of this paper.

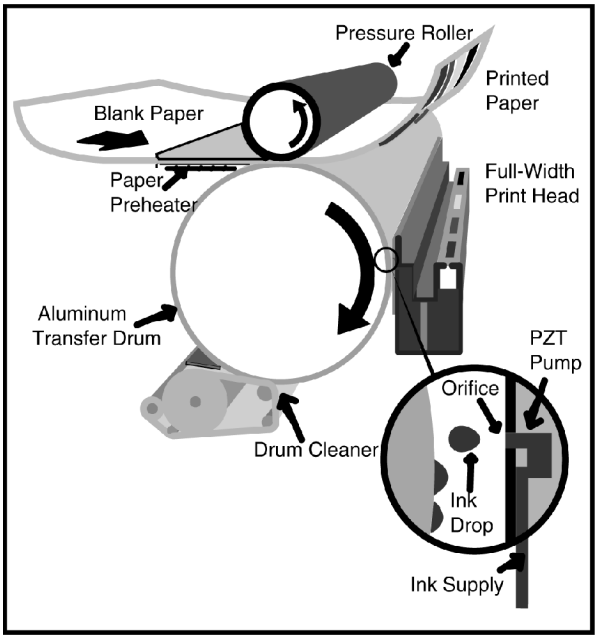

Figure 1: The offset solid ink printing process found in the Tektronix Phaser® 350 color printer.

Material properties of the ink and the print processing steps within the printer are the prime reasons solid ink printers are well known for their media flexibility. The inks used are low molecular weight polymers which are extremely fluid liquids at jetting temperature and flexible solids at room temperature.

Over a temperature range between solid and liquid phases, they are rubbery, or ductile, allowing further physical processing of the ink following deposition onto a substrate.

Physical processing of the deposited ink image is accomplished via one of two methods in commercial products. The Tektronix Phaser® 600 wide format color printer uses a *direct* solid ink architecture, where ink is ejected from a printhead directly onto the receiver media in conventional ink jet fashion. Following deposition of the ink onto the receiver media, image durability is increased through use of a pressure roller which may be assisted by a moderate amount of heat. The Phaser® 350 desktop color printer uses an *offset* solid ink architecture, where ink is first deposited onto an intermediate drum coated with a thin layer of a proprietary fluid. Following deposition of the complete image onto the intermediate surface, the image is transferred onto the receiver media. Transfer is accomplished by a combination of heat and pressure, with heat being applied to the media prior to its passing through a nip formed by a pressure roller and the intermediate drum. Figure 1 illustrates the offset solid ink printing process. A detailed study of the offset solid ink printing process is given by Snyder, et al., 1997. This paper focuses on media requirements for the offset solid ink printing technique.

Media Requirements for the Offset Solid Ink Print Process

Solid ink printing has a well deserved reputation of having excellent media flexibility. It is a true "plain paper" imaging process in that common copier papers can be used to produce vibrant color documents with excellent text and fine line detail. This being said, for truly optimal image quality and durability of both reflection prints and overhead projection transparency films, media parameters do play a critical role. Indeed, the offset solid ink printing process is capable of printing on a wide variety of receiver media; however, optimization of both the printing process and media are required to achieve the best results.

Optimization of the Print Process

As receiver material is but one piece of the solid ink printing system, optimization involves analysis not only of the media, but also of the printer. Similar to other nonimpact printing technologies, the components of the solid ink printing system can be divided into printer hardware, the hardware controller, ink, and the receiver material. Each component can be broken down further into parameters relevant to the response variable in study. In order to better understand the role of each component parameter relevant to image quality and durability, techniques of experimental design were employed to optimize system performance for desired materials.

Due to the overwhelming number of variables within the printing system, the technique employed to develop receiver materials and corresponding print modes was to hold either the print process or receiver material variables constant while varying the other component variables. Once the optimal setpoints had been determined in this manner, additional experimental designs were completed in which both print process and material parameters were varied. In all cases, the experimental designs chosen were of central composite construction, having an additional series of "star" points outside the traditional factorial box. This type of experimentation is covered in great depth by Heilberger, 1989.

Input variables were dictated by the print process. Response variables, on the other hand, were determined based on customer interaction and marketing studies. Once an understanding of the qualities important to solid ink customers had been achieved, metrics were devised to quantify these attributes. Generally, the relevant attributes related either to image view quality or image durability. In turn, we will discuss the effects of various system components on our image durability and view quality response variables.

Parameters Affecting Durability

As illustrated in Figure 1, the receiver media passes through a preheater prior to the transfer nip. Transfer is facilitated by high pressure and the heat supplied to the media and ink by the preheater and the transfer drum, respectively. Transfer from the drum to the receiver is further assisted by the use of a proprietary fluid insulating the ink from the drum. Transfer of ink from the drum to the receiver affects both durability (the degree to which the ink adheres to the receiver) and image quality (the percentage of ink transferred from the drum to the receiver). The primary print process factors governing durability and image quality are media preheater temperature, drum temperature, nip dwell time (or the velocity at which the receiver material moves through the transfer nip), and nip pressure. Of these four, the first three are the only ones that can be altered from print to print, as nip pressure is factory preset. For this reason, in optimizing the print process of an existing printer to accept a new media type, it is unrealistic to vary nip

pressure, as an alteration of this parameter would most likely be to the detriment of performance on other media types. Temperatures and velocities, on the other hand, are set via software. For this reason, print process optimization parameters were limited to drum and preheater temperature and transfer velocity.

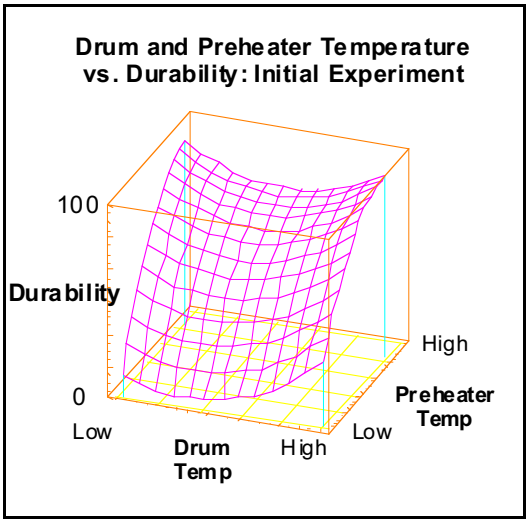

Figure 2: Response surface of durability as a function of drum and preheater temperature. Drum temperature range is within 40°-70°C; preheat temperature range is within 50°-100°C.

Figure 2 presents a graph of preheat and drum temperature as a function of durability for an overhead transparency material. Durability was measured using a proprietary technique that quantifies the degree to which the ink adheres to the transparency film. In this measurement system, a score of 100 is perfect and 0 is total failure; the limit of customer acceptance is 85. Note the strong dependence of durability on preheater temperature and the relative insignificance of drum temperature. Based on this information, it was decided to center a new series of experiments around the lower drum temperature and high preheater temperature. The goal of this second series of experiments was to gain a better understanding of the effects at high preheater temperature. Figure 3 presents the results of these experiments, which represent an expansion of the rear left corner of the graph in Figure 2 (note the x and y axes have been exchanged). With the increased resolution afforded by the graph of Figure 3, it can be seen that the effect of increased preheater temperature does diminish at high drum temperatures and that high drum temperatures can compensate for lower preheater temperatures over a small range. If the only response variable of concern was durability, a lower preheater temperature and higher drum temperature (on the scale of Figure 3) would be selected as the optimum setpoints. Of course, selecting final print process setpoints at this point would have been premature if not foolish.

Given printer setpoints obtained by the methods described above, focus can be turned to the receiver media. Although the offset solid ink printing process places fewer constraints on the receiver media than competing technologies, quality can be improved with specially designed materials. To this end, significant effort has been spent developing both overhead transparency films and papers for solid ink printers.

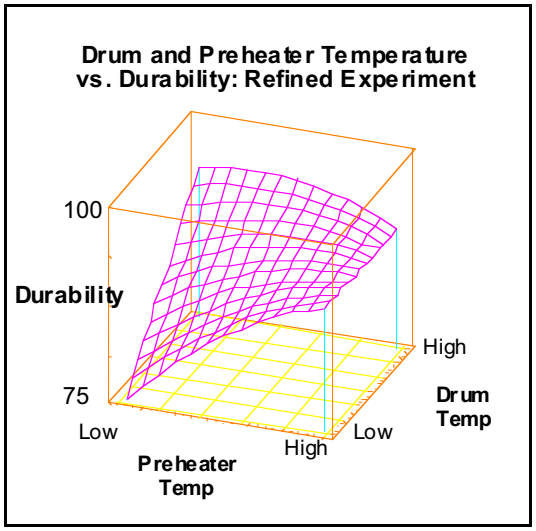

Figure 3: Refined response surface of durability as a function of preheater and drum temperature.

Figure 4 presents SEM images of two coated poly(ethylene terephthalate) (PET) films that were developed for use in solid ink printers. The images are of printed areas where ink has been removed using a proprietary method. The darker material in the upper half of each image is ink that has remained attached to the coated PET film, which is the lighter material in the lower half of each image. Both images are magnified such that one ink droplet is about 20 mm in diameter. Note in the upper image, where adhesion has failed and ink has been removed, the coated surface of the receiver media has been affected by the ink droplets, conforming to their convex shape. This compliant coating greatly improves adhesion of the ink to the receiver material. On the other hand, the lower image represents a material that was coated with a non-compliant material. On the durability scale presented earlier, the upper material would rank in the nineties where the lower would rank in the twenties. It is theorized that both the increased contact area as well as a favorable chemical interaction

between the ink and receiver coating promote the high durability of the upper material.

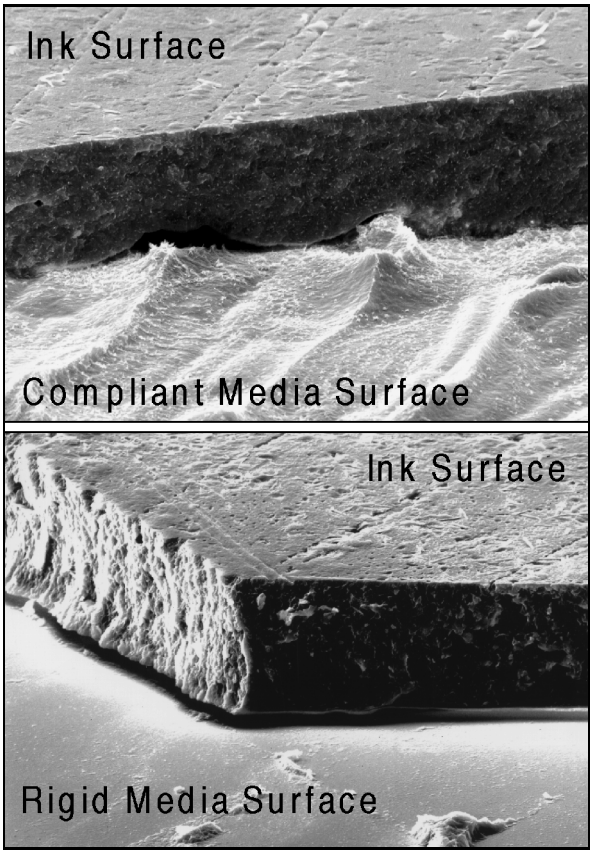

Figure 4: SEM images of two printed coated films. The darker material is ink; the lighter material is the receiver material. Ink has been removed to reveal the receiver material surface once hidden by a layer of ink. Magnification is 300x.

Not only is the coating material of great importance to print durability, but also the thickness at which it is applied to the PET substrate. Referring back to Figure 1, note that the receiver media is heated before the transfer step. In the current product, this heat is applied from the side of the media opposite the image receptive coating. According to fundamental laws of heat transfer, the temperature achieved by the image receptive media surface decreases inversely with the material thickness. Further, as discussed above, nip temperature has a very strong effect on image durability. Therefore, it becomes apparent that receiver media thickness, including image receptive layer coating weight, plays a role in image durability. Figure 5 presents the relationship, the linearity of which is characteristic of conduction heat transfer over small temperature ranges. Coating weight differences as little as 10% may affect durability to a perceptible extent, depending on the coating material.

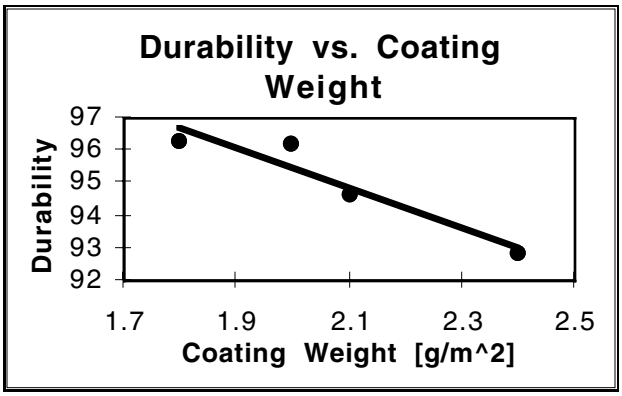

Figure 5: Relationship between durability and coating weight for PET film coated with an image receptive layer.

As illustrated by Figure 4, given chemical compatibility of the ink and receiver materials, increased contact area greatly aids image durability. Non-coated papers, such as those marketed for office copiers, have high surface area relative to the film materials just discussed and therefore generally yield prints of acceptable durability. The topography of such papers, even those that have been supercalendered, with exposed paper fibers, fiber knots, and voids between fibers, presents an excellent surface with which the ductile ink can mechanically interlock. Because the viscosity of the ink rises tremendously on a millisecond time scale following image transfer, there is no *wicking* along paper fibers as is so common with liquid ink jet. Figure 6 presents a topographical map of a single solid ink droplet printed onto a common office paper. Note the circularity of the dot and the general lack of influence of paper fibers on the dot.

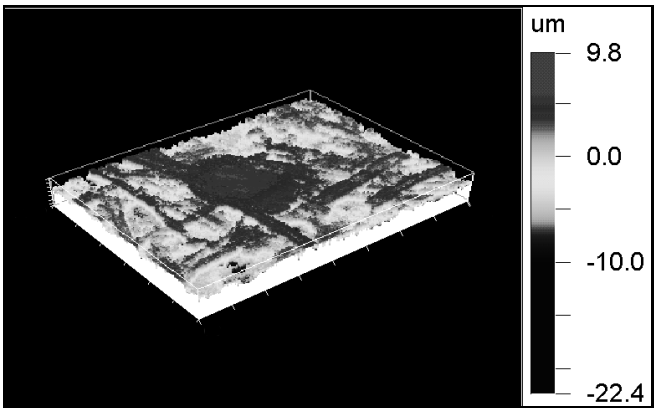

Figure 6: Three-dimensional topographic map of single ink droplet printed on copier paper (courtesy Wyko Corporation).

In the case of smooth, heavy weight papers commonly perceived as being of high quality, durability begins to become a variable worth monitoring. These papers may or may not be coated, but definitely have been supercalendered at minimum. Durability tends to decrease with such papers for reasons discussed above. Namely, the more smooth the surface, the less the potential for mechanical fixation of the ink to the surface. Of course, this relationship with roughness continues until a point, beyond which, sufficient contact between ink and receiver is not made, and durability begins to suffer. Also, as in the lower sample presented in Figure 4, the less compliant the media, the less the contact area between the ink and receiver. Compressibility, governed by the paper's density, certainly plays an important role in the determination of contact area between ink and receiver. Lastly, as discussed above, there is a dependence of durability on receiver media thickness, due to the manner in which the media is heated prior to image transfer.

In order to quantify the effects of the above parameters, a measurement system was developed to precisely scratch a printed sample and digitally record the amount of ink removed. The system computes a *scratch index*, equaling the ink area removed for any given print, stylus, force applied, and scratch length. Figure 7 presents the relationship between thickness, or caliper (as measured in terms of basis weight), and scratch index. Note the trend toward decreased durability (more ink removed) with increased basis weight, in support of the above stated thickness relationship. Even so, for all but the most demanding applications, all of the samples plotted in Figure 7 are of acceptable durability.

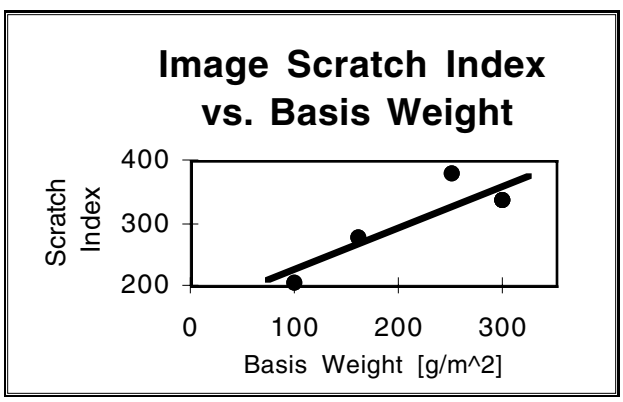

Figure 7: Image scratch index as a function of basis weight for four papers of equivalent construction.

In Figure 8, results of paper surface roughness experimentation show that surface roughness aids durability to a point, beyond which it begins to decrease. Of course, the exact shape of the curve presented is not known with statistical certainty; however, it is certain that the relationship is not linear. Durability suffers on very smooth papers for reasons stated earlier. For very rough papers (above 4.0 µm RMS roughness), durability suffers because the ink cools too quickly to conform to the highly irregular paper surface. As roughness continues to increase, durability continues to decrease due to decreased contact area between the ink and media. Again, over the range presented in Figure 8, as in Figure 7, durability is acceptable, although the differences are certainly perceptible.

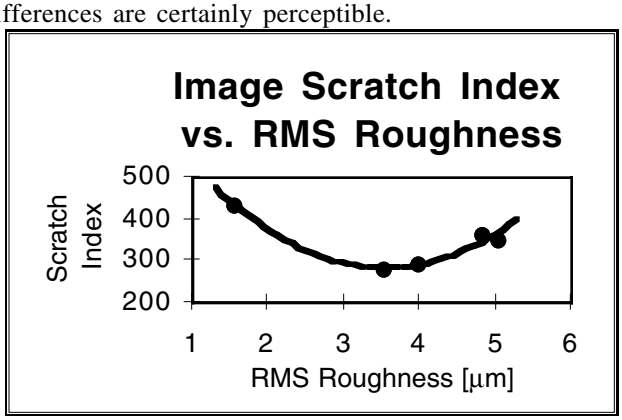

Figure 8: Image scratch index as a function of RMS surface roughness for five papers of equivalent basis weight. Root-mean-square (RMS) paper roughness was measured with Mitutoyo Surftest SV-502 Surface Texture Measuring System.

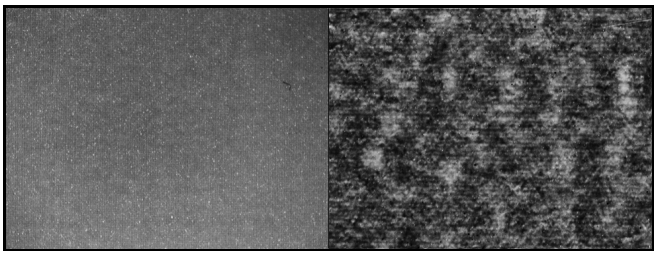

Figure 9: Magnified images (10x) of solid printed areas on two papers. The paper on the right has poor formation.

Parameters Affecting View Quality

Of course, there is more to an optimum print than high durability. For example, if a receiver material was selected on the basis of durability alone, there would be no guarantee that prints made using the media appeared as in the left-hand side of Figure 10. The image represents a solid area fill made with a paper having low floc size variation, or good *formation*. The image of the solid area fill on the right was made with a paper having poor formation. Although beyond the scope of this paper, it is worth pointing out that there are methods of

quantifying formation prior to imaging (Korol, 1997).

Further, if a print were made at the setpoints suggested in the opening section, it would be painfully obvious that this fantastic durability was achieved at the cost of image quality. With drum temperatures as high as those suggested by the graphs presented, the ink on the drum would actually cohesively fail during transfer, leaving half of the ink thickness behind on the drum. In areas of high ink coverage, the ink may be so fluid as to flow down the printed page during transfer. In order to avoid problems such as these, setpoints must of course be chosen such that preheater temperature and drum temperature is maximized for durability without adversely affecting image quality.

Shifting back to our coated PET example, given images having acceptable durability, it was desired to maximize projected view quality. One of the key issues with solid ink technology over the years has been its inability to yield highly chromatic overhead transparencies. Because the mass of the ink remains largely on the surface of the receiver material, if it is not substantially flattened, it forms a lens, scattering light away from the collector lens of the overhead transparency projector. Light scattered away from the collector lens is not projected onto the viewing screen and appears gray. In the case of color transparencies, this scattering results in achromatic images.

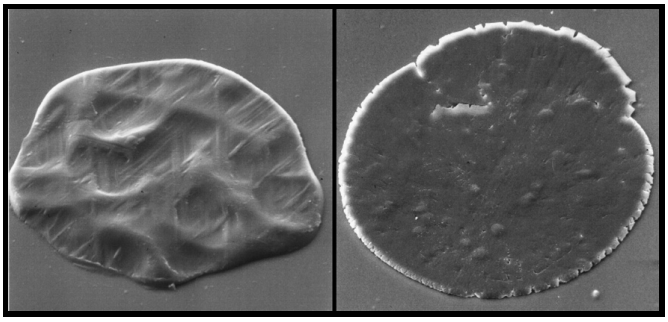

Figure 10: SEM images of single ink droplets on overhead transparency film. The droplet on the left was made using direct solid ink technology (Tektronix Phaser® 300X); the droplet on the right was made using offset solid ink technology (Tektronix Phaser® 350).

The offset solid ink architecture largely eliminates the light scattering problem, as the ink droplets are substantially flattened by the high transfer nip pressure. Figure 10 presents scanning electron microscope (SEM) images of ink droplets printed on overhead transparency film with direct solid ink (left) and offset solid ink (right) technology. These images show qualitatively the differences in height of the ink droplets. Note the relative flatness of the offset solid ink droplet. The texture of the ink droplet on the left was imparted by the surface of the pressure roller. Even with these improvements over the direct approach, chromaticity of overhead transparencies can be further improved by optimization of the print process.

The amount of diffraction was quantified directly with a BYK-Gardner Haze-Gard Plus hazemeter. Haze is defined by ASTM D 1003 as *that percentage of transmitted light which in passing through a specimen deviates from the incident beam by more than 2.5° on the average*. The lower the haze, the less the scatter, the higher the chromaticity of the projected transparency, and the higher the view quality. In order to simplify analysis, a single haze measurement was made at 80% yellow digital tint in the majority of experiments. Figure 11 presents the results of a series of experiments conducted to determine the effects of preheater and drum temperature on haze. From the graph, it can be seen that both drum and preheat temperatures have a significant effect on haze. Note once again that if this were the only relevant measure of performance, the optimal setpoints would be minimum drum and maximum preheat temperatures.

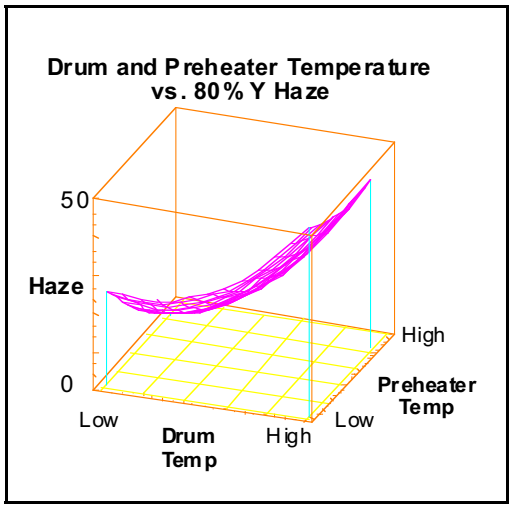

Figure 11: Response surface of Gardner Haze as a function of preheater and drum temperature. Temperature ranges are as in Figure 3.

The findings presented above may seem counter-intuitive -- if the flattest possible dots are desired, why then would drum temperature not be maximized? Actually, there are a couple of forces at work. On the one hand, warmer drum temperatures aid flattening of the ink droplets. On the other hand, warmer drum

temperatures decrease the cohesive forces within the ink. With cohesive forces decreased, the adhesive forces between the ink and the fluid on the transfer drum are of a significance great enough to cause tearing of the ink away from the drum. The roughly torn ink surface droplets lead to hazy overhead transparencies.

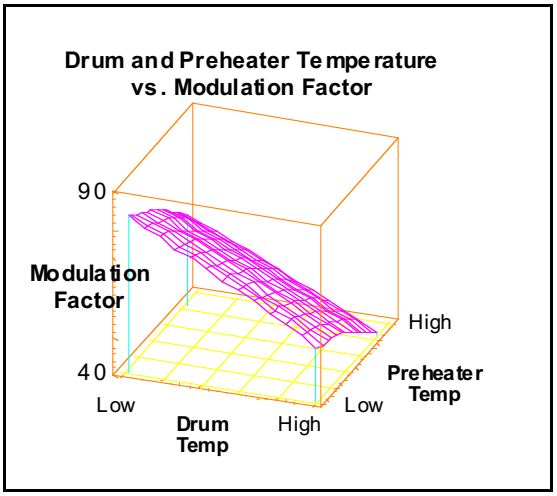

Figure 12: Response surface of Modulation Factor as a function of preheater and drum temperature. Temperature ranges are as in Figure 3.

In the evaluation of overhead transparency images, not only is color quality critical, but also resolution of fine detail. In order to quantify detail, the well known Modulation Transfer Function (MTF) (Dainty et. al, 1974) was employed. To simplify analysis, the modulation factor of a green image was computed at a single frequency. This frequency was chosen based on its relevance to the finest detail typically reproduced on overhead transparency material: 12 point text. The color was chosen due to the eye's peak sensitivity to green, and detailed secondary colors (those comprised of two ink layers) are difficult to reproduce with solid ink technology. While not providing as much detail as the MTF, this single frequency modulation factor was found quite useful in the optimization of print process parameters for transparency printing. Figure 12 presents the response surface corresponding to the effects of drum and preheater temperature on the modulation factor. Modulation factor decreases directly with image quality. Note that as preheater and drum temperature increase, image quality (as measured with modulation factor) decreases. The ductile ink, softer at higher temperatures, tends to spread or flow more than at lower temperatures, decreasing modulation.

Conclusion

Of the digital color printing technologies, solid ink is perhaps the most flexible in terms of receiver media requirements. Even so, several parameters within both the printer and the media must be carefully optimized to achieve the best image durability and view quality. Of the print process variables, the two of greatest importance are preheater and drum temperature, given that ink formulation and image transfer nip loading are essentially fixed for all media types. Of these variables, preheater temperature has the greatest effect on durability while drum temperature has the greatest effect on view quality, especially with respect to overhead transparency performance. Ideally, image receptive coatings not only have a chemical affinity for the ink, but also exhibit compliance to the convex ink droplets during the transfer process in order to maximize contact area between the ink and receiver. This idea carries over to conventional papers, where surface roughness plays an important role in final image durability. Additionally, the receiver material with the best performance will be of uniform thickness and compliance while promoting conductive heating of the image receptive coating from the back-side of the media. As many of these requirements are at odds with one another, the optimal choice is of course a supreme compromise where each variable is set as close to its optimal level without adversely affecting the response of all other variables.

Acknowledgments

The authors would like to thank Joyce Carone of Tektronix for providing the SEM images, Elizabeth Byström of the Wyko Corporation for generating the micro-topographic maps with the Wyko Rough Surface Tester, and Rolf Mueller of Tektronix for supporting this research.

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