Modern Approaches to the Forensic Analysis of Inkjet Printing – Physical and Chemical Examinations

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Documents submitted for forensic examination that have been printed by inkjet printers are becoming much more predominant. With the advent of this technology, there has been tremendous popularity amongst criminals to use inkjet printers and copiers to commit a variety of crimes such as counterfeiting, criminal record keeping, and extortion. In some instances, legitimate transactions such as contracts and wills later become the focus of a criminal investigation. This may prompt a suspect(s) to alter entries, generate new documents in an attempt to substantiate his case, or make false claims regarding the questioned document. Forensic document examiners can perform a variety of physical and chemical examinations that may help link multiple documents with each other or a suspect printer(s), ascertain if the document is legitimate with respect to date, or determine the make and model of the suspect machine. This article will provide a comprehensive discussion of modern approaches to the physical and chemical examination of documents produced by inkjet copiers and printers. In addition, some new ideas will be proposed to provide forensic document examiners (FDE) insight into the future of inkjet analyses.

Introduction

The examination of documents produced by nonimpact printing (NIP) technology has evolved significantly since Chester Carlson's discovery of the xerographic process in 1938. Inkjet printing and electrophotography are two of the most prevalent NIP technologies which create images without any mechanical impact with the paper. These systems are found in the home and office because they are capable of reproducing documents with rapid, high-quality output at affordable prices. Advances in speed and durability, decreases in prices, improvements in quality, and the popularity of digital photography have caused an increased demand for inkjet devices. A 2001 worldwide statistical publication reports that the narrow home/small office segment had an installed base of 130 million inkjet printers with estimated sales of 49 million units to be sold in the following year (Information Management Institute, 2002). This figure includes the number of inkjet printers in small office and home office (SOHO) markets. As a result, submissions of documents produced using inkjet technology to forensic laboratories-related activities are becoming more common. LaPorte and Ramotowski (2003) have discussed the rising incidence of counterfeiting currency and identity documents by means of inkjet copiers and printers. Furthermore, inkjet printing is used to counterfeit other materials (e.g., product labels and motor vehicle titles) and is often used to produce documents commonly submitted for forensic examination such as threatening letters, wills, contracts, and other documents associated with illegitimate business transactions.

When referring to inkjet office machines and the documents they produce, it is necessary for forensic examiners to envision more than a printer. Office machines utilizing inkjet technology include printers, copiers, and multifunctional "all-in-one" devices that print, copy, scan, and fax documents. Furthermore, using physical defect (e.g., trash marks) associations to make conclusions can be complex because defects associated with peripheral devices such as scanners and digital cameras can be incorporated into an electronic file and then printed by multiple users at multiple print stations. Horton (2000) showed that "photocopier-type defects from the scanner platen and internal components may also allow the correlation of a specific scanner to a printed result." An example of this can be found in the counterfeit production of documents such as driver identifications, travelers' checks, or money orders. The criminal production of counterfeit documents is sometimes multifaceted, whereby one party may be responsible for designing an electronic file that can be easily modified. Changeable features such as biographical information and photographs can be incorporated into a scanned and saved format. The criminal then may disperse the saved image to other criminals, who in turn print the final product on different printers. Therefore, significant repeating defects may be evidenced on documents produced by multiple sources due to defects that were generated while producing an original scanned image.

Depending on the nature of the criminal activity, forensic examiners may be requested to authenticate a questioned document, determine if two or more documents were produced from a common source, or ascertain the make and model of the office machine system(s) used to produce a questioned document(s). The Scientific Working Group for Document Examiners (SWGDOC) is currently attempting to formulate a guide for the examination of documents produced with liquid inkjet technology. It has been submitted for consideration to the American Standards for Testing and Materials (ASTM) and, although the 2003 standard has not received full approval at this time, it was recently balloted to ASTM members.

The objective of this paper is to provide a comprehensive discussion of modern approaches to the physical and chemical examination of documents produced by inkjet copiers and printers. Some new techniques and ideas will be presented to provide forensic document examiners (FDE) with insight into the future of inkjet analyses.

Historical Developments

William Thomson (Lord Kelvin) was knighted in 1866 for his work on transatlantic submarine cables from Ireland to Newfoundland. By 1867, Lord Kelvin had invented a process to electrostatically control the release of inkjet drops. To record and transmit a series of incoming signals, he designed and patented the Siphon recorder. The Siphon worked by jetting a continuous stream of ink while the paper, controlled by a drive signal, moved back and forth in a horizontal direction. Lord Kelvin, a genius and extraordinary inventor, was once quoted as saying (internet website, 2003), "Wireless [telegraphy] is all very well but I'd rather send a message by a boy on a pony!" Lord Kelvin did not envision the important repercussions of this invention on the developmental history of inkjet technology. It was not until nearly a century later (late 1940s) when C. W. Hansell (1950) from RCA invented a jet sprayer that ejected ink droplets as a result of pressure waves generated from an acoustic frequency applied to a piezoelectric disc. U.S. Patent 2,566,443 (1951) was issued for a recording mechanism invented by R. Elmqvist of Siemens-Elema, and the Mingograph was eventually released in 1952. Liquid ink, consisting of water, glycerin, dye, and a biocide, was dispersed through a capillary (Pond, 2000). Although these inventions were not classified as inkjet printers, they did establish the foundation and principles of inkjet technology.

Naiman (1962) developed a sudden stream printer that ejected an aqueous ink solution through a nozzle to produce dots on a substrate. Finally, in 1968, A.B. Dick used all the results from previous research and introduced "the first continuous inkjet-printing product" known as the Videojet 9600 teleprinter. Development of this product was abandoned until the late 1970s when Canon and Hewlett Packard (HP) independently began an intensive research and development program to investigate the thermal process of printing. In the mid-1960s, Richard Sweet devised a method to charge each individual drop, thereby allowing them to be selectively deflected. This theory was used to manufacture a printer using a piezoelectric vibrator. The ink was continuously ejected from multiple jets and droplets were selectively deflected to create an image. Inkjet technology was still slow, expensive, and messy, so Panasonic led the market with the production and refinement of dot matrix printers. There was a driving force in the market to replace dot matrix printers with more efficient, reliable, and quality printers, so virtually every major printer manufacturer invested in lengthy and mostly unsuccessful inkjet development programs. Companies worked feverishly, but it was not until 1981 that Canon demonstrated their Bubblejet™ concept which operates on the principle that ink is propelled from a nozzle when heat is applied to the inkjet head. In 1984, HP astonished the industry with the introduction of the ThinkJet™, a compact, thermal printer with a disposable ink supply. During the 1980s these two companies elevated the quality of inkjet printing, gaining widespread acceptance of their printers in offices and homes.

For the next decade, resources were committed to increasing the reliability and print quality of inkjet technology. The dynamic properties between the printhead, the ink, and the substrate were critical. Controlling the ink flow, preventing drying and clogging within the printhead, and placing the ink on the substrate efficiently and effectively were just a few considerations that needed to be solved. Nearing the end of the 1980s, Canon and Hewlett-Packard became adept at understanding and developing the necessary inkjet chemistry to produce reliable office machines capable of quality printing. The 1990s, followed by the new millennium, were times of vast improvement in color quality, speed, and reliability, as well as significant decreases in price. Many other companies have entered this proliferating market, but Canon, Epson, HP, and Lexmark have the majority of the worldwide market share of inkjet printers. Xerox manufactured inkjet printers beginning in 1999, but production ceased in 2001.

Inkjet Systems

Although inkjet technology is mostly found in the SOHO segment, its use in wide format and industrial applications is growing quickly. It is not the intention of this article to provide a detailed description of industrialized inkjet printers, but the FDE should be aware that these products may be the subject of a forensic examination. The basic operation of wide format and office machines using inkjet technology is the same, but there can be vast differences in their respective designs, the inks they utilize, and some of the substrates used. SOHO inkjet systems can deliver ink in different ways with the two most predominant being continuous and drop-on-demand (DOD). In continuous jet systems, a continuous stream of ink is broken into droplets. The droplets, which are uniform in size and volume (as low as 2 picoliters), are then charged and deflected allowing an image to be created while ink is removed and recycled. DOD systems are predominant in the SOHO, and operate on the principle that only the droplets of ink needed to create the desired image are emitted. DOD printers are typically designed to print on porous or absorbent surfaces. DOD printers are further classified by how the ink is ejected or forced from the nozzle onto the paper. These include thermal, piezoelectric, electrostatic, and acoustic, but the latter two are uncommon and thus will not be discussed. Understanding the fundamental differences between thermal and piezoelectric printers is essential for the FDE because these technologies dictate how the ink is dispersed onto a substrate. In effect, there will be differences in the print quality and ink chemistry, which can be a discriminating forensic attribute.

Thermal technology operates on the premise that high heat (>290°C) causes the ink to vaporize a bubble, which forces it to burst and emit a drop of ink from the nozzle. Canon has patented the term Bubblejet™ technology based on this concept, but other manufacturers use this technology including HP and Lexmark. Piezoelectric printers use an electrical voltage that causes a chamber composed of a piezoelectric material to deform. The deformation propels ink from the chamber, through a nozzle, and onto the substrate. Epson inkjet printers employ piezoelectric technology.

The one common aspect of these various classifications is that all inkjet printers utilize a printhead to emit ink droplets onto a substrate. As the paper is drawn through the printer, the printhead moves back-and-forth horizontally. Ink deposition is digitally controlled via the software and the firmware (within the printer), and is sprayed so that multiple gradients of dots accumulate to form an image with variable tones of color. Modern color printers typically print using at least four different colors—cyan (bluish green), magenta (reddish purple), yellow, and black (CMYK). Cyan, magenta, and yellow are defined as the primary subtractive colors such that when they are combined in equal proportions, black is created. When mixed in different ratios, they produce a full gamut of other colors. Figure 1 is a photomicrograph showing the colored dots used to create an image. Some manufactures offer additional colors such as light cyan, light magenta, and gray in order to extend the gamut of hues. As well, variations in black (e.g., dye-based black and pigment-based black), within the same printer, are becoming more common.

Doherty (1998) recognized the proliferation of inkjet printers utilized in criminal activities and attempted to classify them. She concluded that "many of the inks used in drop-on-demand thermal inkjet printers can be differentiated and dated by their physical and chemical properties." Since 1998, hundreds of new printers have been introduced to the market, and technological advancements have vastly improved the quality, speed, and design of inkjet machines.

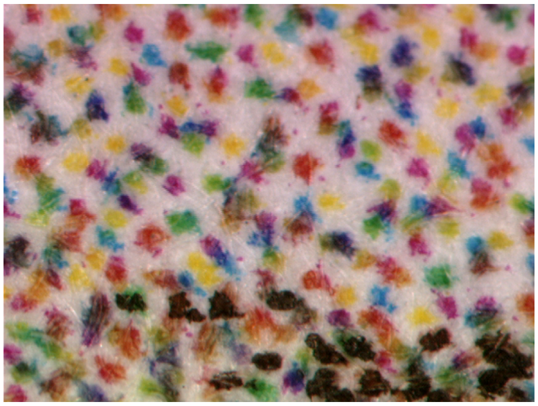

Figure 1. Photomicrograph showing the colored dots used to create an image.

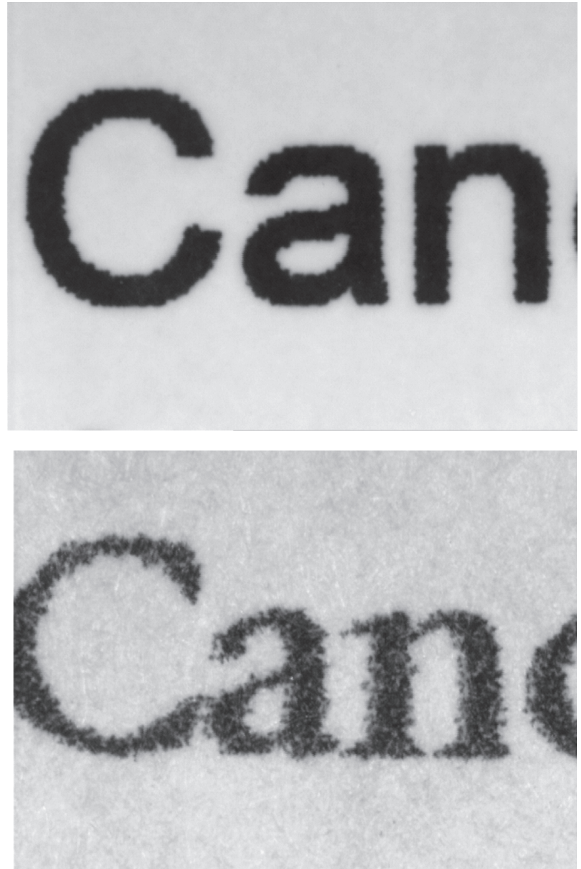

Figure 2. Shows the physical appearance of the same document printed on different substrates.

Physical Examinations of Inkjet Printing

The three most important attributes that affect the quality of inkjet printing include the substrate, printhead, and ink composition. Frost and Dekalb (2003) have presented a review of these three factors and their respective influences on print quality. Changes in any one of these can cause significant differences in the final printed product. The use of different substrates can have a dramatic influence on the appearance of printing. It is crucial for the FDE to be aware of this, especially in cases where comparisons are conducted on multiple documents consisting of different types of paper (e.g., glossy, bond, or inkjet copy paper). In these situations, it is difficult to make comparative physical evaluations due to remarkable microscopic and macroscopic distinctions when documents produced on different substrates are printed from the same device. Figure 2 shows the physical appearance of the same document printed on different substrates.

Differences in the printhead design and the ink composition are sometimes the most significant source of discriminating features when conducting forensic examinations. The resulting quality of an inkjet droplet, once it is ejected onto a substrate, is largely due to the chamber size, nozzle thickness, and the technology of a printhead. For example, in cases where a page substitution(s) is suspected, there may be differences detectable by microscopy in the print quality which may be attributable to design differences in the printhead. Figure 3 demonstrates black text printed on three different printers. In addition to the various printhead designs found from one manufacturer to the next, rapid technological advances in inkjet printing have resulted in dramatic changes within the same manufacturer. For example, Canon first implemented its Microfine Droplet™ technology in the BJC-8200C inkjet printer. By changing the design of the printhead, the bubble ejection process occurs differently, resulting in decreased dot size with improved stability and reliability of the ink. Another example of the radical changes that have been introduced by the same manufacturer is the development of the HP printhead architecture from 1985 to present. The ThinkJet, introduced in 1985, had 12 orifices and printed 96 dots per inch (dpi). With many changes in the interim, the DesignJet 1000 series, launched in 1999, contained 512 orifices and printed documents with the potential of 600 dpi.

Definitively associating two or more inkjet printed documents or associating a questioned document(s) with a suspect printer can be a formidable challenge for forensic document examiners. These examinations require the recognition and identification of individual characteristics associated with inkjet printers. Occasionally, repeating defects (e.g., occurrence of multiple printing breaks due to a defective printhead) may be present, allowing a FDE to reach a definitive conclusion. Parker (2002) showed that the presence of both class and individual flaws "enabled an association between the anonymous documents and the suspect inkjet printer." Instances where identification is possible are less common, and currently there are a limited number of protocols that can be used to definitively link a questioned document to a suspect printer. Indeed, this should not stall efforts to delve into modern approaches of document examination that attempt to solve this perplexing issue.

Although still a challenging task, physical examinations can be implemented as part of a procedure to confine a questioned document(s) to a manufacturer or family of printers, or to an era of printers. Such determinations are possible because of the revolutionary improvements that have been made in the design of these office machine systems in the past two decades. Physical printing characteristics and artifacts that are imparted by inkjet printing may be characteristic of a certain generation or class of printers. Also, they may potentially be used to determine if multiple documents are associated with each other or a suspect printer(s). To make forensic discriminations, there are a number of physical characteristics that the FDE should remember when microscopically examining an inkjet document: satellites, banding, bleeding, feathering, blooming, mottling or

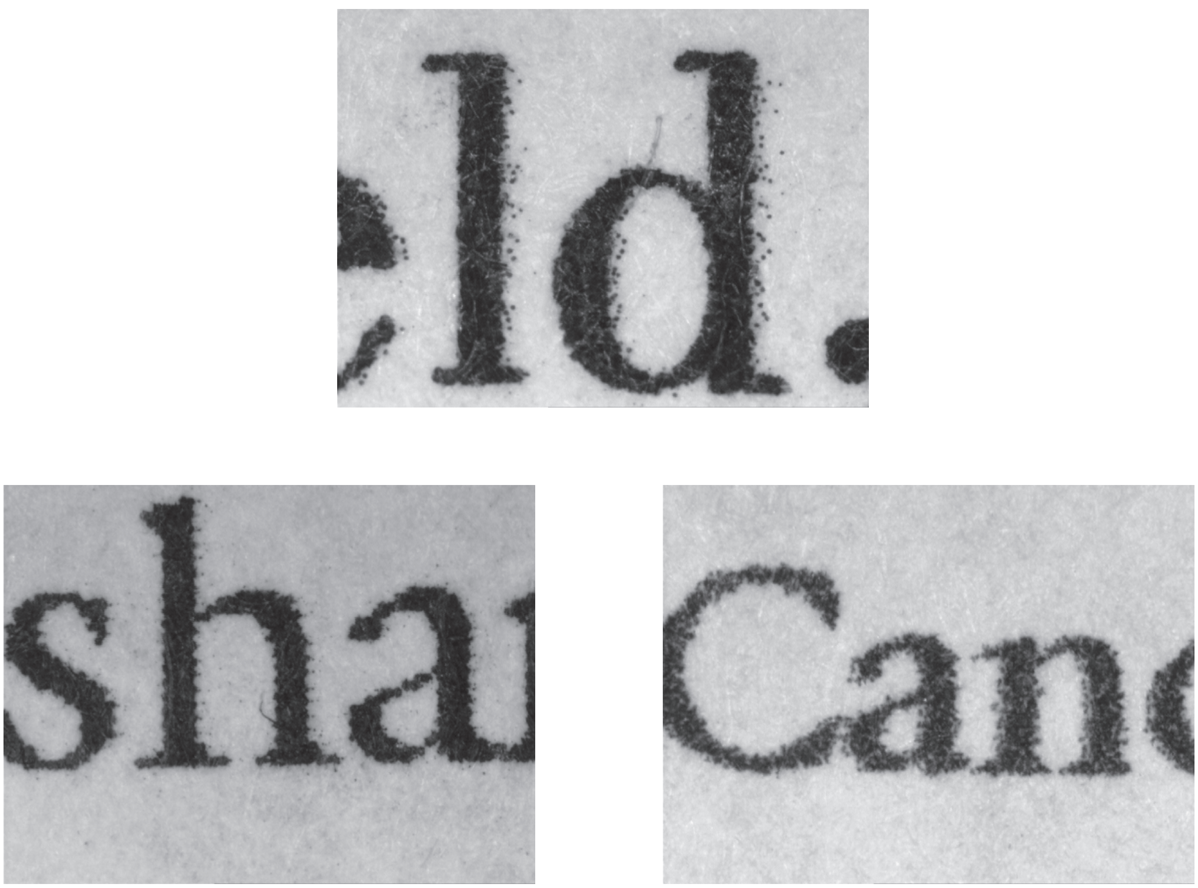

Figure 3. Black text printed on three different printers.

cockling, markings, and image quality. Each of these characteristics is discussed below.

Satellites

Satellites are tiny drops of ink that separate from the main drop as the ink is being ejected (see top image in Figure 3). Each drop of ink can have one or more satellite drops that follow it and/or land nearby (this terminology should not be confused with spatter, which occurs when an ink droplet hits the intended area with such force that it splashes onto an unintended area). Some satellites will land on other printed areas and never be observed. General observations indicate that they will gather at the edges of printed material. Looking at the position of the satellites on a questioned document can reveal the printhead directionality. Typically, when satellites are formed from the main drop, they land ahead of the main drop in the direction of the printhead. Thus, if satellites appear to the right of the printed area, it indicates the printhead was moving to the right. When satellites appear on one side of the print on every line then it can be delineated that the printer utilizes a unidirectional printhead. If satellites are positioned on opposite sides from line to line, then this is indicative of bidirectional printing. Oliver and Chen (2002) demonstrate a microscopic comparison of the same character printed on the same substrate by three different inkjet printers. There are easily distinguishable differences in the occurrence and position of the satellites

The absence of satellites over the entirety of a document is an important observation. Multi-pass printing occurs when the printhead prints over the same area several times to improve the print quality. The ultimate function of multi-pass printing is to mask those defects or artifacts which are evident to the human eye. When printing a document in the "best" mode setting (found in the printer settings menu), the printhead makes multiple passes. Also, the author has observed that inkjet printed documents from Epson printers have very few, if any, observable satellites. This may be due to piezoelectric technology, the printhead, the ink, or a combination of all three factors.

Banding and Lining

Banding is defined as uniform, or regularly occurring, density variations or voids in a given color. These appear along the axis of printhead movement and are evidenced by dark or light linear stripes that occur in the print areas (e.g., the absence of a CMYK component, or any combination, can result in dark or light areas). Lining is another term that is used to describe a missing area, or line of ink, due to a consistently missing jet and can be considered a form of banding. Both of these are more noticeable in image prints, but are also observed in text documents. The occurrence of banding and/or lining can be used as a characteristic to possibly link multiple documents to each other or to a printer(s). There should be sufficient occurrences, and the FDE should make accurate measurements of their distances from each other, how often they occur, and the extent to which they create void and/or dark lines. Using banding patterns as individual characteristics may be feasible in certain instances, but one should be aware that there are numerous possibilities to explain why they occur. These may include, but are not limited to: 1) a faulty nozzle; 2) a blocked or clogged nozzle from debris or dried ink; 3) manufacturing defects in the nozzle and/or; 4) disturbance in the electrical contact between the ink cartridge and the circuit. Briggs, et al. (2000) provides an excellent discussion about banding characterization and some of their work on quantitatively evaluating this problem. Moreover, the FDE must remember that these defects can be transitory. They may disappear if the cartridge is changed or the nozzle becomes unclogged. Therefore, it is very difficult to exclude that two or more documents originated from a common source (or from a suspect printer) if they exhibit different banding and/or lining patterns. Figure 4 depicts the occurrence of banding (left) and lining (right).

Bleeding, Blooming, and Feathering

Bleeding occurs when two or more different colored inks are side by side and the inks migrate into each other. Blooming results from the ink absorbing into the paper and diffusing further than the preferred dot size (the size and volume of an ink drop defined by the software). When ink is distributed and migrates along the paper fibers it can create a spider web effect referred to as wicking or feathering. The result is often poor print quality evident with the naked eye. The phenomenon occurs when ink incompatible with the substrate is used, when printing in fast mode, or when printing in unfavorable ambient conditions, i.e. high temperature and/or high humidity.

Mottling and Cockling

Mottling occurs when the print density or color of an image is uneven because of inaccurate dot assignment and/or dot density. The resulting appearance is often observed in heavily inked areas and follows undesirable patterns in the substrate. Cockling is detected in the paper and is characterized by wrinkling or puckering from the deposition of too much ink and/or nonuniform drying of the ink on the substrate. These occurrences are often found in documents printed by early models of inkjet printers (e.g., machines manufactured prior to 1995) or they may occur when the ink and substrate are not compatible.

Physical Markings

There are a number of mechanical components of a printer, such as star wheels and pinch rollers, which may cause microscopic or macroscopic marks on documents after they have been printed. LaPorte (2003) discussed the use of an electrostatic detection device (EDD) for developing latent images of striations and fine minutiae caused by rollers and other mechanical parts found on printers and copiers. In some instances, the developed markings were directly associated to various parts within the printer and/or copier. As well, broken or misaligned components can result in visible (e.g., paper tears) and latent individual defects so it is imperative that all examinations include a thorough inspection of the questioned document.

Image Quality

Assessing image quality by means of instrumentation appears to be promising for the field of forensic document examination. Previous reports have explored image quality analysis utilizing instrumentation commonly implemented by the manufacturing industry for quality control protocols (Fleming & Others, 2003; Forrest & Others, 1998; Oliver & Chen, 2002; Wolin, 2002). These devices measure several characteristics of the printing such as: dot size; the distance and angle between multiple dots; the circularity of dots; line width; line blurriness and raggedness; inter-color bleed; the size, distribution, and occurrence of voids; text quality; and the presence of satellites. These are just some examples of physical attributes of a printed document that can be tabulated and statistically analyzed. However, there may be limitations to this type of analysis when comparing documents produced on different substrates. Bandyopadhay (2001) studied the effect of paper properties on print quality and concluded that "the smoothness and absorption characteristics of paper, affects ink-paper interaction and finally the image quality." Studies in the forensic evaluation of print quality on various types of printers using different types of substrate are currently being conducted by the Canada Customs and Revenue Agency (CCRA) Laboratory (Gaudreau, 2002).

Optical Examination

After conducting a thorough physical examination of a questioned document, an optical assessment can sometimes be very beneficial. The use of an instrument such as the Video Spectral Comparator (VSC™) can be used to evaluate infrared reflectance (IRR) and infrared

Figure 4A.

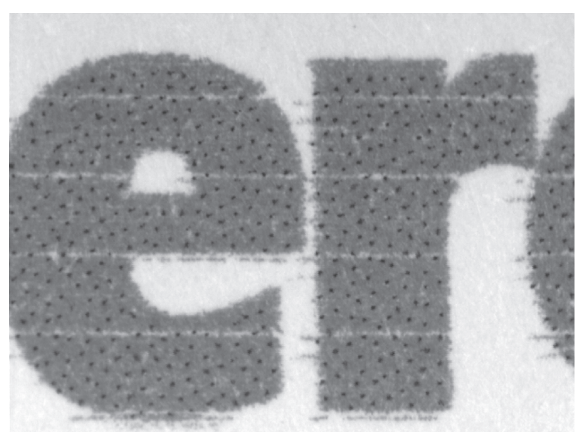

Figure 4B.

Figure 4. Depiction of the occurrence of banding (4A) and lining (4B).

luminescence (IRL) properties of inks. Black inkjet text documents are frequently submitted for forensic analysis and can sometimes be optically differentiated. Some inkjet inks are formulated using a dye-based black ink (e.g., some Epson and Canon models) that will exhibit different IRR and IRL properties than formulations of black ink that are pigment-based (e.g., carbon black), or composed with carbon black. Figure 5 demonstrates IRR and IRL differences that are readily apparent in some black jet inks. Also, by using filters of varying wavelengths, IRR and IRL measurements can be conducted on each of the CMY components. The FDE should exercise caution when making fluorescence and/or absorbance evaluations since inkjet inks may be quenched or enhanced on different types of paper. Optical examinations can sometimes demonstrate that two or more different inkjet formulations were used to prepare a document(s), but this does not necessarily mean that more than one printer was utilized. It is possible for a single printer to use more that one type of inkjet cartridge or for a cartridge to be refilled with ink of a different formulation or produced by a different manufacturer. Some companies, other than the original printer manufacturer, produce compatible cartridges and inks for aftermarket use that are chemically different since inkjet formulations are highly proprietary. Figure 6 shows spectrometer measurements using the VSC 2000 HR™ for three different black inks.

Chemical Examinations

The development of jet inks that work properly is a complex process. The developmental chemistry of jet inks and the physics necessary for efficient and effective dispersion of ink from printhead nozzles is far beyond the scope of this article. In fundamental terms, a well designed ink should have near photographic quality and must be able to withstand high heat, dry quickly so as not to smear, and be lightfast and water resistant. There is also an array of other necessities for proper ejection from the nozzle and the receipt of ink on the substrate. Manufacturers expend considerable resources on the research and development of inks. Understandably, they closely guard their ink formulations which allows inks to be discriminated based on differences in their composition. One widely accepted methodology for separating and identifying the various colorants (e.g., dyes) present in inks is thin layer chromatography (TLC). Pagano, et al. (2000) described methods of analyzing jet inks using different chromatographic systems. Furthermore, LaPorte and Ramotoski (2003) discussed how differences in the composition of color jet inks make it possible to compare ink from a questioned document with standards from a reference collection to identify the manufacturer. The United States Secret Service maintains the largest known collection of inkjet standards in the world. This collection is composed of printed documents and inkjet ink samples for hundreds of printers and copiers.

Rapid advances in the technological design of printers and copiers have been the consequence of greater demand for efficiency and print quality. As a result, manufacturers are continually improving inkjet formulations to meet the stringent demands on ink performance. Indeed, the significance of matching a questioned ink(s) to a known standard becomes even greater as new formulations are introduced to the market. The chemical analysis of inkjet inks often involves four colors, i.e., CMYK, which produce at least four different regions of colorants on a TLC plate. In some instances each color may contain more than one dye, ultimately producing a chromatogram with several points of comparison. Figure 7 depicts a thin layer chromatogram of 12 different printer inks that can be differentiated based on their respective composition of colorants.

TLC is only one chemical technique used for examining inkjet inks, but there has been very little research focusing on other methods of instrumental analyses. Mazella (1998) used diode array microspectrophotometry to measure the cyan and magenta components in the range of 380-760 nm on 70 different brands and models of inkjet printers. Doherty (1998) performed a battery of chemical tests that include water resistance, solubility, and TLC on inkjet printed documents.

Formulating an ink to create a high quality image is an obviously complex task. Inkjet inks for SOHO machines can have very complex formulations needed to create acceptable images. Inkjet ink manufacturers typically use acid, direct, and reactive dyes in their formulations. Acid dyes (e.g., azo, anthraquinone, triphenylmethane, azine, and xanthene) are water soluble, anionic dyes that have a wide gamut of hues. Direct dyes (e.g., phthalocyanines) have a variety of bright hues and some of them are fluorescent, as well as possessing relatively good lightfast and water resistance properties. More recently (i.e., the past 5-6 years), reactive dyes have been added to some

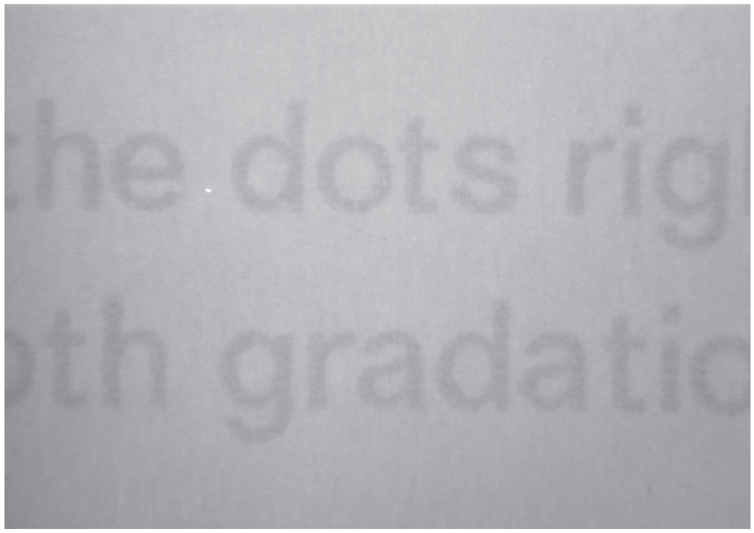

Figure 5A.

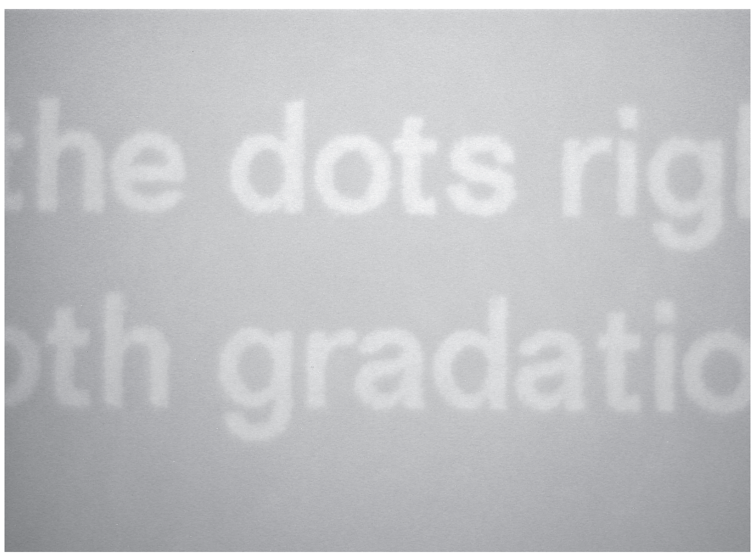

Figure 5B.

Figure 5. IRR and IRL differences that are readily apparent in some black jet inks.

formulations because they have desirable chromophores. This class of dyes link very strongly with cellulose fibers when heated and they are found in some magentas (Fabian, 2003 and Colour Index, 1971). Table 1 provides a summary of some of the ingredients found in jet inks and their respective purpose (Pond, 2000 and Fabian, 2003).

Forensic Analysis of Inkjet Technology – What's on the Horizon?

It has been emphasized throughout this paper that inkjet technology has rapidly evolved during the past two decades. Inkjet applications have easily surpassed expectations, but there is still room for improvement and refinements, making it a strong likelihood that this technology will continue to progress. Inkjet printing still lags behind the speed of laser printing. Moreover, inkjet printing is still limited to certain substrates, and there is trepidation regarding lightfastness and water resistance of some modern ink formulations. One of the main concerns of some inkjet manufacturers is ink bleed. This occurs when the process colors are placed on the substrate and bleed into each other prior to complete dryness. Pond (2000) states that one of the theoretical solutions to this phenomenon is to formulate jet inks such that the "chemical components of one ink are employed to affect the behavior of another ink." This may include the addition of certain compounds to some or all of the CMYK components to prohibit the color(s) from interacting once they are placed on the substrate. The need for improvements will likely result in the creation of new ink formulations and/or the development of new printhead designs.

The creation of more diverse ink formulations and products with varying print quality means there will be potentially more opportunity for greater forensic discrimination of a document(s) produced on an inkjet printer(s). Accordingly, physical and chemical techniques may evolve as well. It is difficult to conceive a single analytical test that will be applicable to questioned document examinations of inkjet printed material in all cases. For this reason, the FDE should develop a gamut of testing procedures to provide meaningful and accurate information to investigators and/or the courts.

Print quality analysis is a promising technique that is routinely utilized as a quality control procedure by inkjet manufacturers, but needs to be validated by the forensic community. Using a variety of statistical calculations and certain criteria to microscopically make evaluations, inkjet printing has a very sound foundation. Ideally, print quality analysis will be able to help the FDE identify the make and/or model of an office machine used to produce a document. Cases that involve page substitution(s) of a multi-paged document or those where several documents printed on the same substrate are believed to be produced by the same printer could be evaluated using this approach. Even if the results of such test are not definitive, this tactic should have some value as a preliminary or corroborative test. The International Organization for Standardization (ISO) issued ISO-13660, a print quality standard intended as a practical, objective means of describing basic image quality parameters and measurement methods for assessing digital print quality. The printing industry will use ISO-13660 for evaluating print quality (Briggs & others, 1999) and ultimately could be a tremendous help should quality tests be conducted by forensic laboratories.

With the addition of numerous organic and inorganic compounds other than dye components, one might expect to utilize additional analytical techniques. The following is a list of some of the instrumentation that has been utilized in limited studies at the United States Secret Service to evaluate inkjet printed material: Fourier transform-infrared spectrometry (FT-IR), gas chromatography/mass spectrometry (GC/MS), scanning electron microscopy-energy dispersive spectrometry (SEM-EDS), and inductively coupled plasma mass spectrometry (ICP-MS). Because inkjet ink is actively absorbed by some paper fibers and the composition of CMYK components varies dependant on the area of the image analyzed, FT-IR (dispersive and attenuated total reflectance) has not always been successful. Extracting the ink and subsequently performing an FT-IR analysis using a potassium bromide (KBr) pellet sample preparation method has revealed some limited success. Since the three process colors are usually found in combination on a document, it is sometimes difficult to directly analyze areas with adequate amounts of a single ink for characterization. Using a gas chromatograph (GC) coupled with a FT-IR might be a better tactic for separating and identifying the various chemical components. In theory, GC/MS should provide significant information regarding ink formulations, particularly if they contain organic compounds such as ethylenediaminetetra-acetic acid (EDTA),

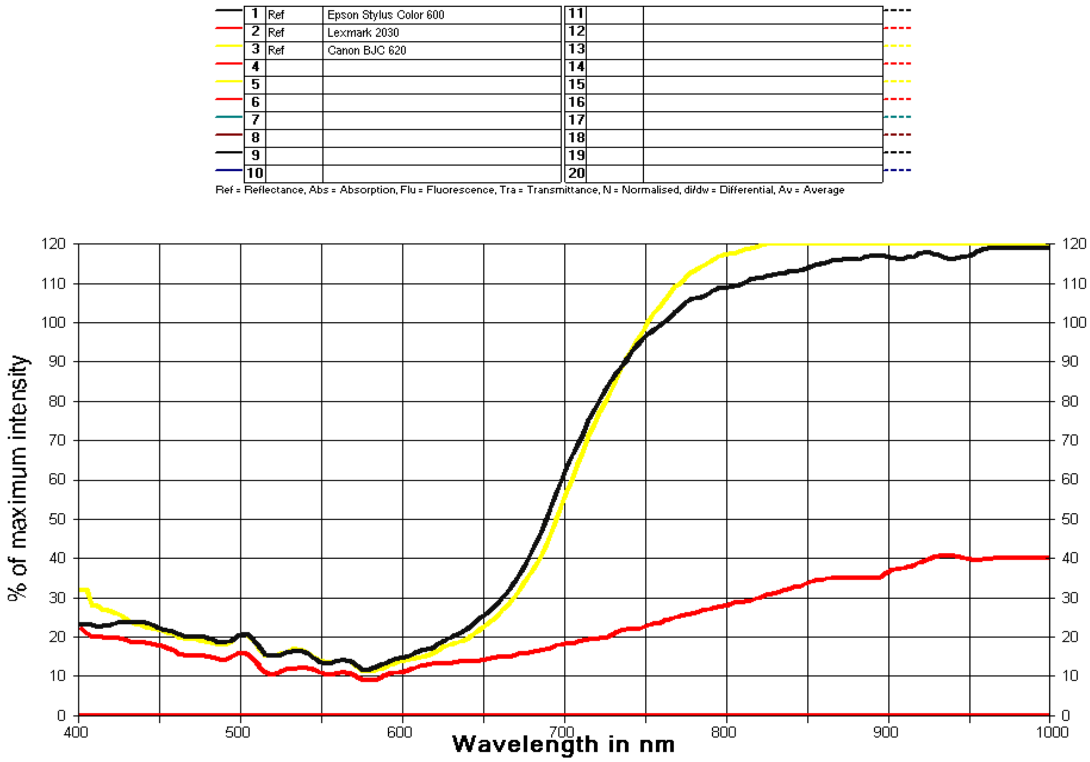

Figure 6. Shows spectrometer measurements using the VSC 2000 HRTM for three different black inks.

N-methyl pyrrolidone, glycols, and alcohols that may be present in a formulation. Preliminary studies indicate that some of these compounds are detectable and some differentiation can be achieved. The use of different extracting solvents and/or capillary columns may achieve significantly better results, but this remains to be investigated.

The elemental analysis of inorganic materials can be extremely beneficial when characterizing some materials. Inkjet manufacturers constantly strive for higher quality inks and it is likely that subtle changes in the elemental composition of these inks are taking place. As an example, HP has developed a patent for the addition of calcium and magnesium to their inkjet inks to prevent adjacent colors from precipitating together once they are on the substrate (Stoffel, 1992).). With a patent on this technology, this information can be used to identify HP ink (or any licensee). Further investigation will help reveal when these components were first added to their formulations so that one can utilize the information to determine if an inkjet document is legitimate with respect to the purported date. In theory, SEM-EDS is an appropriate technique; however, in practice, there has been limited success with the detection of inorganic materials and the characterization of inkjet inks. Presumably, the levels of detectable compounds may be too low. The United States Secret Service laboratory has experimented with inductively coupled plasma-mass spectrometry (ICP-MS), another reliable analytical tool to identify the elemental composition of unknown material. Equipped with a laser ablation unit, this instrument is capable of detecting low levels of elements with minimal destruction. Preliminary studies indicate that ICP-MS is capable of differentiating ink formulations based on their elemental profiles.

Some additional approaches that may be worthy of investigation are Raman spectroscopy and high pressure liquid chromatography coupled with mass spectrometry (LC-MS). Fluorescent papers and dyes may cause significant interference when conducting Raman analyses, but the chemical examination of black inks on nonfluorescent substrates may be more suitable. LC-MS should be a

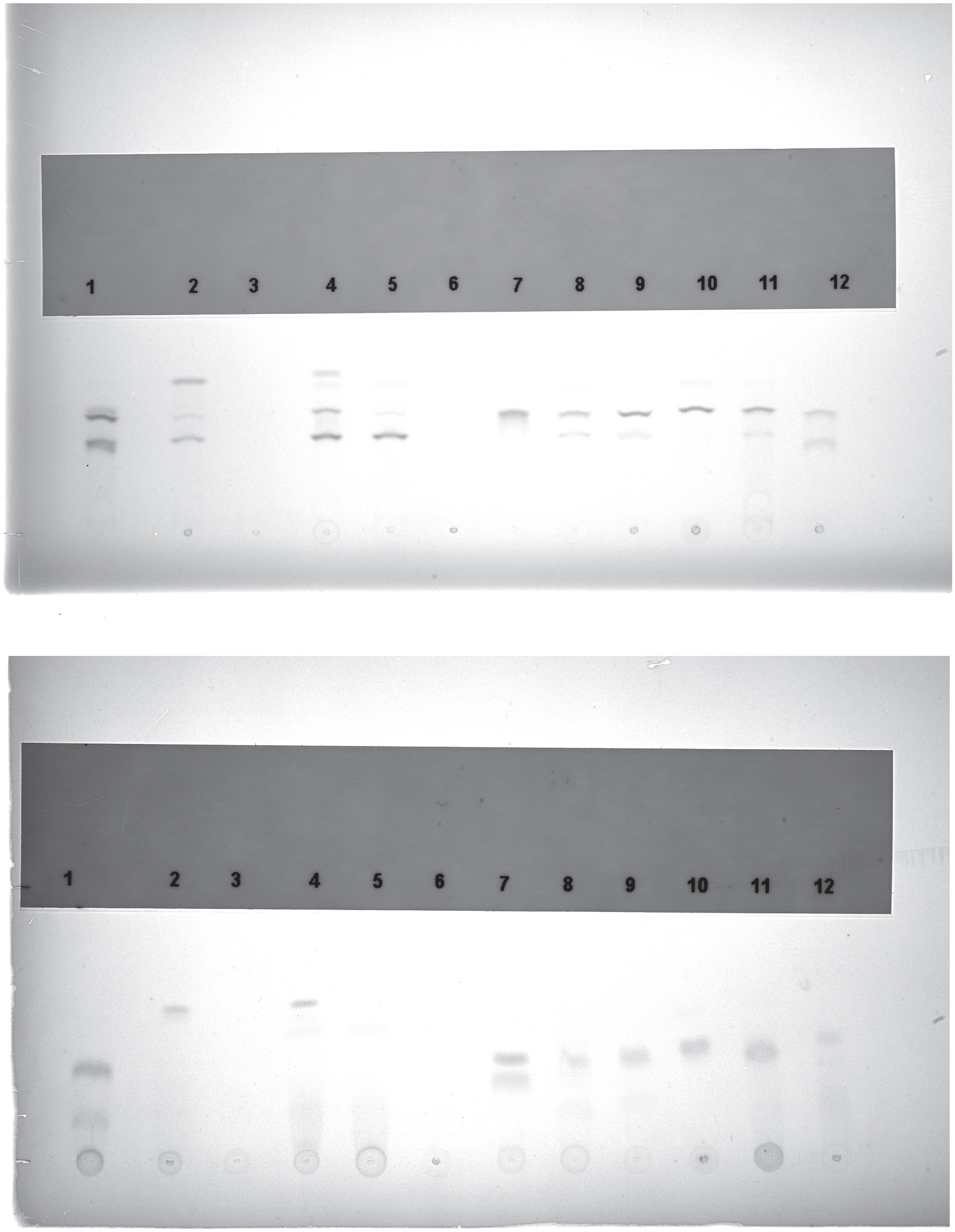

Figure 7. Thin layer chromatogram of 12 different printer inks that can be differentiated based on their respective composition of colorants.

Inkjet Ingredient	**Purpose**	**Composition** (wt %)
Colorant	Dyes and/or pigments that provide the desired color and aesthetic properties.	2-10
Solvent	Vehicle that dissolves or suspends the colorant (e.g., water, alcohol).	35-80
Humectant	Inhibits evaporation (e.g., diethylene glycol)	5-30
Surfactant	Lowers the surface tension of the ink to promote wetting, or even distribution of colorant solutions on substrate (e.g., Surfynol 465).	0.1-2.0
Penetrant	Allows ink to penetrate fibers and promote ambient drying (e.g., pentane-1,5-diol).	1-5
Viscosity Modifier	Added to increase viscosity and can be a humectant (e.g., long chain glycols).	1-5
Dye Solubilizer	Helps maintain dye solubility in the solvent because of evaporation in the nozzle(e.g., n-methyl pyrrolidone).	2-5
Dispersant	Maintains pigment suspensions (e.g., Derussol carbon black {Degussa}).	3-8
Fixative	Helps maintain image permanence and smear resistance (e.g., water soluble latex).	1-3
pH Buffer	Maintains overall pH to promote colorant stability in the vehicle (e.g., Trizma base {Aldrich Chemical}).	0.1-1.0
Chelation Agent	Used to complex metal ions (e.g., ethylenediaminetetra-acetic acid).	0.1-0.5
Biocide	Prevents and kills bacterial, yeast, and mold growth in aqueous inks (e.g., Dowicil {Dow Chemical}).	0.1-0..3
UV-blocker	Increaselight-fastness (e.g., Tinuvin 171 {Ciba-Giegy}).	1-5

Table 1. Some common ingredients found in inkjet formulations, their purpose, and approximate percentage of the total weight.

suitable methodology for separating and identifying various components of jet inks including dyes and other additives. Finally, one last technique for the analysis of inkjet inks may be chemical imaging, which is a nondestructive technique that provides chemical or spectroscopic information, of each image pixel in a digitally imaged area (Exline and others, 2003). It is a form of hyperspectral imaging which allows quantitative and qualitative data to be measured with accuracy and precision by using a spectrometer capable of spectral discrimination over a wide range of wavelengths (e.g., visible and near infrared).

Conclusion

The submission of documents produced by inkjet printers and copiers to forensic laboratories will undoubtedly increase in the years to come. This has necessitated developing a standard protocol for examining these documents. Recently the ASTM balloted its members concerning a standard which was developed by the Scientific Working Group for Document Examination (SWGDOC) for the examination of inkjet documents. Moreover, improvements in the quality and efficiency of inkjet printers has led to the evolution of new ink formulations and print characteristics which can be used as class characteristics to identify a model or group of printers. There is a pressing need for new methodologies that can be used to analyze inkjet documents produced by copiers and printers to help reduce the number of printers within a particular class and therefore increase the likelihood of greater forensic discrimination. Several new techniques that can be used when examining documents produced by inkjet office machines have been discussed and proposed. While these modern approaches will hopefully benefit the FDE, further studies and research must be conducted to determine the effectiveness of each method.

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