Advances in Instrumented Defect Mapping Technology for Photoreceptors

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Abstract

Among the factors critical to print quality in electrophotography are defects on the photoreceptor. For the highest level of print quality, reliable quality control methods must be applied to ensure that the photoconductive coating is free of defects. In production environments today, the most commonly used method for examining photoreceptors for defects is visual inspection. The dominance of this method is due to the speed and sensitivity of the human vision system and its image processing and pattern recognition capabilities. However, the weaknesses of visual inspection — its subjectivity and inconsistency — are also well known. Hence, to improve product quality and reduce manufacturing costs, there is a critical need to develop instrumented defect detection methods suitable for production environments. This paper reviews the requirements for such methods and surveys the technologies available. In particular, recent advances in electrostatic mapping are discussed in detail. The capabilities and limitations of electrostatic mapping are examined critically, and opportunities for future development are discussed.

Introduction

Problem Definition

Defects on photoreceptors are among the most significant sources of print defects in electrophotography. In photoreceptor production, it is critical that defects be identified and that photoreceptors with unacceptable defects not be shipped to the customer.

Currently, the prevalent method of photoreceptor inspection is visual examination, which capitalizes on the high sensitivity and processing speed of the human vision system. The operator, examining a photoreceptor such as an OPC drum, makes an accept/reject decision based on experience or a pictorial catalogue of allowable and non-allowable defects. This is a 100% inspection process in which the entire photoreceptor surface is inspected for defects of all kinds. The process is quite taxing, demanding a great deal of experience and concentration. Operators capable of performing this type of inspection must be highly trained, and in a competitive business environment, ensuring a continuous supply of trained operators for the job is no easy task. Thus, there are obvious limits to the reliability and practicality of this method as an evaluation tool. Developing reliable, robust systems to automate photoreceptor inspection is highly desirable.

The objective of this paper is twofold. First, to review the state of the art in automated defect inspection. Second, to examine critically a defect detection technique that uses a non-contact surface potential probe for mapping the electrostatic field on the photoreceptor. The principle behind this method is examined and its advantages over other methods are demonstrated. The process window is discussed relative to sensitivity and speed requirements in a production environment. The limitations of the technique are also identified to highlight areas for further research and development.

Although most of the discussion in this paper applies not only to drums but to belt-type photoreceptors, and to both OPCs and inorganic photoreceptors, the results presented are from OPC drums only. For the sake of simplicity, we will use the term “drum” throughout this discussion.

Requirements for a Defect Detection System

The primary requirements for a drum defect detection system are: 1) sufficient sensitivity to pick up all significant defects (that is, defects that result in print defects) and 2) acceptable inspection throughput (that is, fast enough for production use). In addition, the system must be nondestructive, robust, and easy to use, calibrate and maintain. It must provide real-time input for quality control and process control. In addition, some form of robotic drum handling is required for truly automated inspection.

Sensitivity

Drum defects vary greatly in type and size. To determine the sensitivity requirements for a drum test system, we performed an experiment in which white pages were printed using a drum with a variety of known defects. A panel of judges was asked to examine the printed pages and pick out as many of the resulting black spots as they could see. Based on their responses, we estimated that the visual detection threshold is in the range of 100-200 µm. The sizes of the defects on the printed pages and the defects on the drum were then measured using an automated image analysis system set up as appropriate for each of these tasks. Figure 1 demonstrates the correlation between print defect size and drum defect size. The results suggest that on average print defects are about twice the size of the drum defects that produce them. The exact magnification factor ranges between about 1.5 and 3 and may depend on a number of physical factors and on the behavior of the various electrophotographic subsystems. For our study, we adopted a magnification factor of two. Based on the visual detection threshold of 100-200 µm, this put the sensitivity requirement for drum defect detection at 50-100 µm.

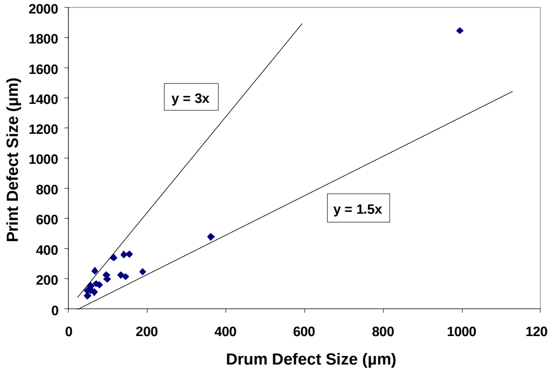

Figure 1. Correlation between print and drum defects

Review of Instrumented Drum Defect Detection Systems

As noted, a variety of techniques for detecting defects in drums has been reported in the literature. Figure 2 shows a classification system developed to facilitate systematic evaluation of the numerous instrumented methods available. Key criteria for evaluating these methods are: sensitivity to small defects (50-100 µm) that cause print defects, speed, ability to provide quantitative information for defect characterization, and practicality for production applications.

Instrumented methods for defect detection can be broadly grouped as microscopy or electrical/electrostatic methods. Microscopy includes: automated image analysis,[1,2] toner-image analysis,[3,4] and scanning electron microscopy.[5] Electrical and electrostatic methods can be classified as contact and non-contact methods. Contact methods usually involve the application of a biased voltage on the sample under test or on an electrode placed in contact with the sample. Examples include the charge injection method[6] and the gas discharge method.[7] In non-contact methods, a charge is applied to the sample and the charge level and charge distribution are subsequently examined. Non-contact methods include so-called electrostatic force microscopy[8,9] and measurements made with a capacitive-coupled probe. In the capacitive-coupled probe category, there are at least three variations: static charge measurement (usually with an electrometer),[10-15] dynamic current sensing,[16,17] and the surface potential probe method, [18-22] the subject of this study.

Automated Image Analysis

The purpose of the automated image analysis technique is to automate the visual inspection process using a computerized machine vision system. The drum is illuminated with a light source and monitored with an imaging sensor such as a CCD camera. Overall, the design requirement for such as system is that it be able to scan the drum surface at a resolution equivalent to 2400 dpi (approximately 10 µm per pixel) in order to get sufficient information on defect morphology and gray level. With this kind of system, the resolvable feature size is about 50 µm.

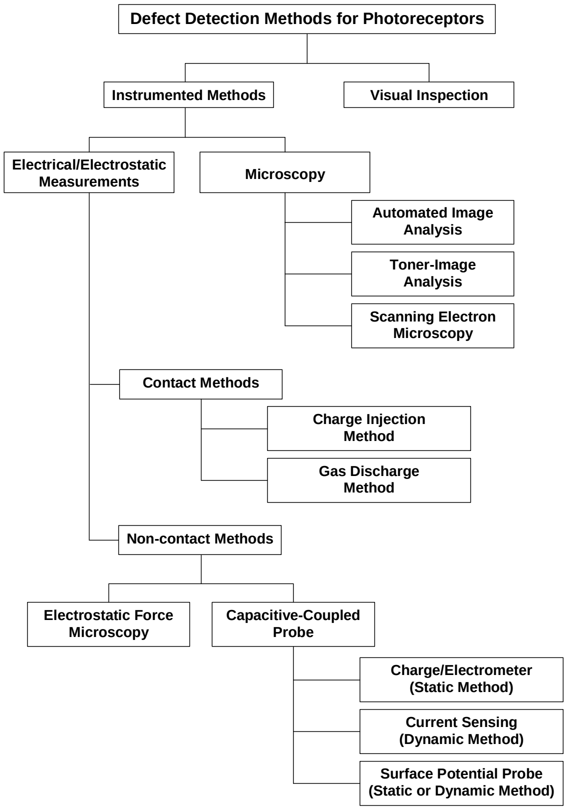

Figure 2. Classification of defect detection methods for photoreceptors

The data rate requirement for such a system is quite high. Springett[2] has estimated that in a large-scale production facility the image acquisition rate needed for an OPC drum 84 mm long is on the order of 0.25GHz, based on 2 seconds of image acquisition time and a single-channel inspection system. Clearly, other assumptions would result in different data acquisition rates. However, Springett's main point stands, namely, that use of an automated vision system for drum defect detection is not only a challenging optics design problem (considering the variety of possible defects), but also a difficult data processing problem (given throughput requirements in a production line).

Another critical factor in vision system-based defect detection is "training" the system to recognize a wide variety of defects, including dust, pinholes, scratches and other surface damage. Ideally, the training should be adaptive in order to accommodate changing production requirements. Figure 3 shows defective drums from an actual OPC production line, illustrating defects of a variety of sizes and shapes. A human operator would probably be able to make accept/reject decisions on these drums very quickly, picking up most of the large defects; but training an automated vision system to perform the same task would not be as easy.

Toner-Image Method

The toner-image method, developed by Lin et al.,[3,4] is similar to automated image analysis in principle, with one significant difference: here, the drum is installed in a simulated electrophotographic "printer" and subjected to charging, exposure and development to produce a toned image. When this has been done, image analysis similar to the method described above is performed using a line-scan CCD camera to pick up anomalies in the toned image indicating drum defects. Although simulation of the electrophotographic process appears to be a strong point in favor of this technique, having to install the drum in a printer and subject it to the complete charging and development process makes it very inconvenient for production use. Furthermore, the drum must be cleaned after testing, and the additional steps involved increase the likelihood of damage by mishandling. All in all, this method is not suitable for production use.

Scanning Electron Microscopy (SEM)

Scanning electron microscopy has been used as a research tool by Fritz et al.[5] for high resolution measurements (5 µm or less) of electrostatic fields on photoreceptors. While this method may have the highest resolution of any technique discussed here, it has many drawbacks as a production QC tool. For example, testing must be done in a vacuum. This occasions many problems, most notably in drum handling and the possibility of changes in charge distribution due to vacuum discharge.

Charge Injection Method

In the charge injection method, a small shielded electrode is brought into contact with the charged photoreceptor surface to measure any anomalous charge flow. The measurement is done with an instrument such as an electrometer after a bias voltage is applied to the photoreceptor. Popovic et al.[6] have demonstrated the use of this technique for detecting electrical defects on photoreceptors using a shielded stylus with an effective diameter of 85 µm. The photoreceptor is scanned in a stepwise fashion under computer control. The resolution claimed is "a few tens of µm." The method requires the use of a drop of silicone oil at the interface between the electrode and the drum to minimize arcing and ensure reproducibility of the measurement. The results suggest injection spots from the ground plane of the photoreceptor and an upper limit for the defect size, which can be estimated from the magnitude of the injection current. While this method is interesting and shows promise as a research tool, the use of a silicone oil coupling and the slow scan time (about 1 hour for a 6.4x6.4 mm^2 area) preclude the use of this technique for production.

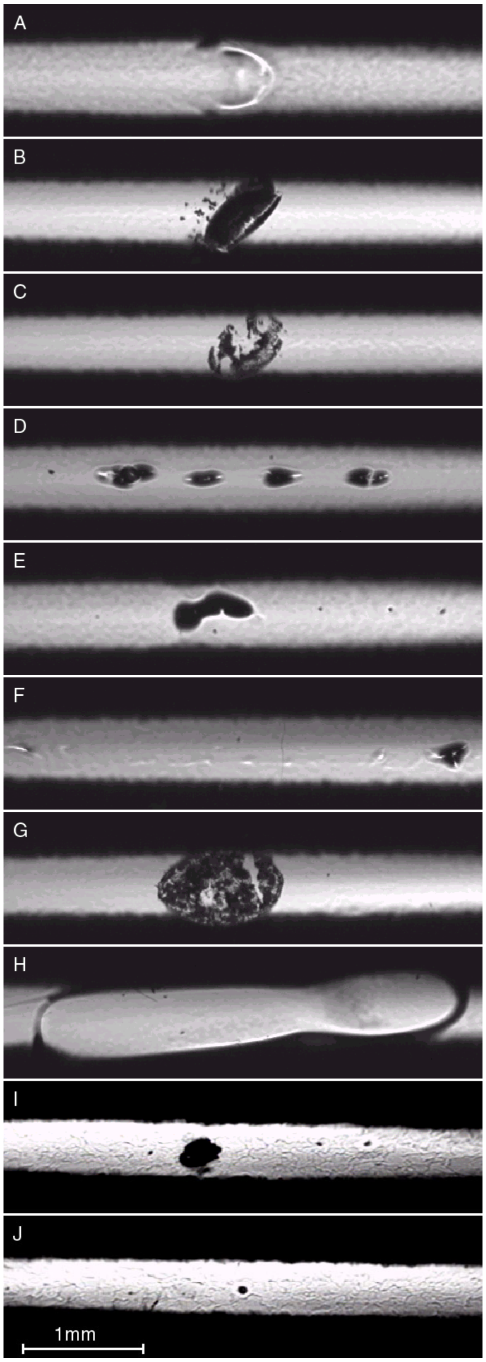

Figure 3. Examples of drum defects (images obtained by optical microscopy)

Gas Discharge Method

In the gas discharge method, a modified charge roller with no resistive top layer is used to charge an OPC drum. The basic concept is that pinhole defects in the OPC coating cause the charging current to spike when the pinhole faces the charge roller. This is due to gas discharge between the roller and the flawed OPC. The current surge can be detected by a number of methods including current sensing, a drop in resistance, or even the temporary overloading of the charge roller power supply resulting in an undercharged line on the OPC.[7] The method is simple and makes use of a well-known phenomenon in charge roller charging. However, it is a destructive method and is therefore not an ideal production QC tool.

Electrostatic Force Microscopy

Inoue[8] and Tani[9] have investigated the use of a miniature cantilever of nickel foil for measuring charge distribution on a dielectric film. Based on numerical analysis of the electrostatic force between the cantilever and the charged surface, the researchers proposed that this method should be able to provide high-sensitivity charge measurements with a spatial resolution of 10 µm. The analysis also demonstrated that the measurement is affected not only by the charge density, but also by thickness variation in the dielectric coating. Despite its potential as a high-resolution probe, further work is needed to demonstrate its practical potential for QC use.

Capacitive-coupled Probe Methods

In capacitive probe methods, a small metal electrode is placed in close proximity to a charged surface to pick up an induced charge. There are many implementations of this basic method (see Figure 2), exemplified by 1) static charge measurement, 2) dynamic measurement of induced current in a scanning mode and 3) static or dynamic measurement using surface potential.

In ***static charge measurement***, the induced charge on the sensing electrode is measured directly, typically with an electrometer. Yarmchuk et al.[10] have reported the successful application of this approach in achieving better than 10 µm spatial resolution in charge distribution measurements, with a system that closely approximates a printer or copier. The problem with this method is that in order to achieve the resolution claimed, the sensing electrode must be placed so that it is almost touching the charged surface – a requirement that may be acceptable in research but is highly undesirable in production. Similar high-resolution static-charge measurement methods were reported by Gerhard-Multhaupt et al.[11] and Singh et al.[12] Lin et al.[13-15] reported the development of a small (70x70 µm²) transparent capacitive probe for characterizing photoreceptors. As with Yarmchuk's work, however, the Gerhard-Multhaupt, Singh and Lin approaches all suffer from the need for careful control of the separation between the electrode and the charged surface.

In ***dynamic current sensing***, a small probe is placed in close proximity to the charged surface of the drum. As the probe scans the surface, a current is induced in the sensing electrode proportional to the capacitive coupling (*C*) and the rate of change of the voltage between the probe and the surface (*dV/dt*). This principle was adopted by Trek in a commercial photoreceptor test system.[16] The technique has some apparent advantages. For example, the induced current increases with scanning speed — the faster the scanning, the better the detection sensitivity, a highly desirable effect for optimizing both small defect detection and scan time. Unfortunately, this gain in sensitivity with increasing scan rate entails a cost. When the scanning speed increases, any variation in capacitance (*dC/dt*), for example, due to fluctuations in sensor-drum spacing are also proportionally amplified. To circumvent this problem, Pritchard[17] reported the use of a biased voltage on the photoreceptor substrate. While some success for noise reduction was reported, Pritchard concluded that "measurement of charge density variation on the surface of the drum has not provided adequate correlation to print defects."

The basic problem with dynamic current sensing is twofold: 1) noise introduced by variation in the capacitive coupling and 2) the low signal level resulting from using a small electrode to achieve high spatial resolution. The primary advantage of this technique is that it is non-contact and nondestructive. Use of a sensor array has been put forth[16] to minimize overall scan time. If the noise problem can be resolved, the technique has potential for high-speed production QC.

The ***surface potential probe method*** is an alternative to dynamic current sensing. It uses an electrostatic measurement technique in which a non-contact probe measures the surface potential on the charged surface of the photoreceptor. This approach has been discussed as Electrostatic Charge Decay (ECD) in several previous publications.[18-22] The surface potential probe is based on a well-known "field-nulling" principle that eliminates the problem of noise from gap variations in a capacitive-coupled measurement method. The induced voltage on the capacitive sensing element is modulated by an electromechanical chopper or by oscillatory motion of the element.[23] Using the difference between the modulated signal and the modulating reference signal as feedback information (the error in a closed-loop control system), the voltage on the sensing element is driven to the same potential as the surface under test. In this way, the field between the sensing element and the charged surface becomes zero, and the voltage on the sensor is read as the surface potential on the sample. With a zero field in the gap, the effect of any capacitance variation is eliminated from the measurement.

The surface potential probe method offers the very significant advantage of minimizing noise and gap dependence in the measurements. It does, however, have limitations, most notably:

1) The spatial resolution is limited by the size of the sensing element, which is typically on the order of 0.7 to 1.5 mm in diameter. Comparing the sensor size to the sensitivity requirement for drum defect detection (50-100 µm), this seems excessively large.
2) The use of an electromechanical chopper and the feedback principle imposes a limit on the dynamic response. The bandwidth is limited by the modulation frequency.

At first glance, these limitations seem at odds with the basic requirements of drum defect detection; yet commercial systems using the surface potential measurement principle for computer-controlled mapping of photoreceptors have been available for some time now and are clearly effective.[24] With these systems, drums are scanned to obtain full body maps of the charge and discharge voltage distribution as well as to detect defects in the size range of 100 µm. How is this possible?

Efficacy and Operating Window for Surface Potential Method of Defect Detection

To establish the validity of the surface potential probe technique for drum defect detection, a scanning system similar to those illustrated in Figure 4 is used to map a variety of drums with a variety of known defects. The system was instrumented to simulate a printer, complete with corona charging subsystem, exposure subsystem and surface potential probe. To put the practicality of this method to the test, an off-the-shelf probe with a relatively large sensing area (1.75 mm dia.) was used instead of the very small or custom probes used in other studies.

In this defect detection system, the primary operating variables are nominal drum voltage, scan speed and scan pitch. We will show that these variables can be used to minimize or overcome the apparent drawbacks of this technique, maximizing detection sensitivity and minimizing scan time.

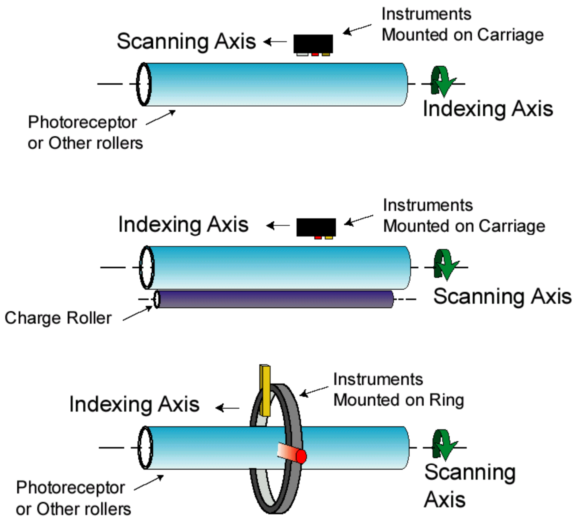

Figure 4. Schematic Diagram of Computer-controlled Scanners for Drum Defects

Effect of Nominal Drum Voltage

A nominal drum surface voltage is produced using a controlled charging device. The defect voltage depth is the difference between the nominal voltage and the voltage at the defect location.

Figure 5 shows the effect of nominal drum voltage on defect voltage depth for two pinhole defects in the coating of an OPC drum. The nominal drum voltage can be controlled by the high voltage or the current supplied to the corona charger. The most significant conclusions from this figure are:

1) The defect voltage depth is a function of the nominal drum voltage.
2) The voltage depth is substantial, even for defects in the 50-100 µm range (in contrast to the noise in the system, which is on the order of 2-3 volts).
3) The voltage depth increases with defect size, providing the basis for a defect sizing scheme.

These results are clearly contrary to the intuitive prediction that the large surface potential probe size should not be able to detect small defects in the 100 µm range. In fact, we have found such defects quite routinely. Evidently, the voltage depth and the distortion in the electrical field at the defect location are great enough that the relatively large probe can detect them readily. Furthermore, the voltage depth can be increased by judiciously increasing the nominal drum voltage. (Clearly, the drum voltage cannot be increased indefinitely: an upper limit is imposed by the breakdown voltage of the drum coating.)

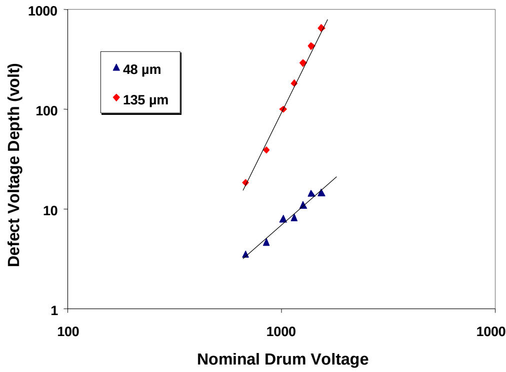

Figure 5. Effect of nominal drum voltage on defect voltage depth for defects of 2 sizes on a 30 mm dia. OPC (scan speed = 1 rps, scan pitch = 1 mm/rev).

Figure 6 shows an empirical correlation between the sensitivity of the detection system and the nominal drum voltage for the OPC drum type tested. Sensitivity here refers to the voltage depth per µm of defect size. The figure suggests a strong dependence of voltage depth on drum voltage. This plot, for example, shows the voltage depth increasing by a factor of 2.4 as the drum voltage increases from 800 to 1000 volts. The sensitivity curve is expected to be different for different types of defects.

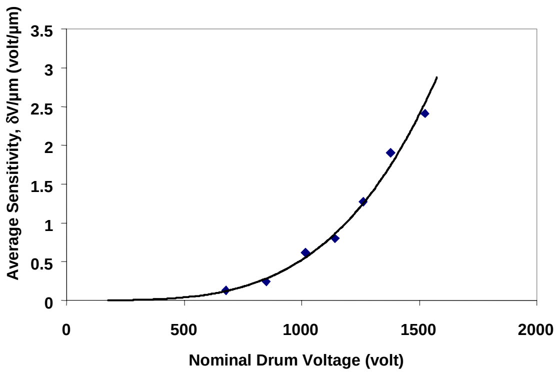

Figure 6. Effect of nominal drum voltage on defect detection sensitivity (data shown are averages of a range of defects 50-1000 µm in size; scan speed = 1 rps, scan pitch = 1 mm/rev)

Effect of Scan Speed

Scan speed is the relative speed of the drum surface and the probe. Scan speed is limited by the mechanical design of the system as well as by the dynamic response of the surface potential probe. The dynamic response of the probe used is better than 5 msec for a full-scale step input. The maximum scan speed for drum defect detection is estimated to be approximately 200-300 mm/sec.

Figure 7 shows the effect of scan speed on defect voltage depth for three pinhole defect sizes. Generally, defect voltage depth decreases with scan speed. The results suggest that at 300 mm/sec, the voltage depth is about 20 volts for a small (96 µm) defect. With a system noise level of 2-3 volts, this voltage depth is very detectable under the conditions in effect: 100% coverage (at a 1 mm/rev scan pitch), 80 seconds total scan time (at 3 rev/sec or 283 mm/s scan speed), and a nominal drum voltage of 1000 volts (well below the breakdown voltage of the specific OPC drum under test).

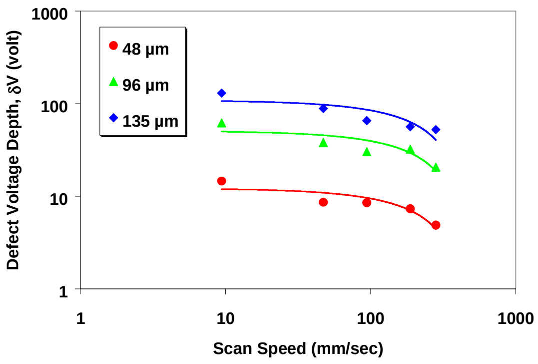

Figure 7. Effect of scan speed on defect voltage depth (nominal drum voltage = 1000 V, scan pitch = 1 mm/rev).

Effect of Scan Pitch

Scan pitch is the axial motion of the probe with each rotation of the drum. The scan pitch in the defect scanning system must be chosen to ensure 100% coverage of the drum surface in order to avoid missing any small defects or mis-characterizing large defects. The determining factor in choosing scan pitch is the size of the sensing element. Since a 1.75 mm dia. sensor was used in this study, a scan pitch less than 1.75 mm is a logical choice in a helical scanning mode. Figure 8 shows the defect voltage depth as a function of scan pitch for several defect sizes ranging from 48 to 135 µm. Not surprisingly, the defect voltage depth increases with finer scan pitch. From the point of view of detection sensitivity, decreasing the scan pitch seems desirable. The trade-off here is scan time – decreasing scan pitch increases the scan time. In this study, a scan pitch of 1 mm/rev was used in most experiments.

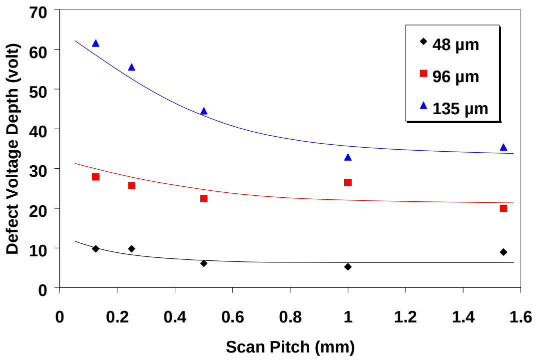

Figure 8. Effect of scan pitch on defect voltage depth (nominal drum voltage = 1000 V, scan speed = 1 rps).

Dependence of Scan Time on Scan Speed and Scan Pitch

Figure 9 summarizes the dependence of scan time on different scan speeds and scan pitches. The computations were for a 240 mm long OPC drum, with a single probe used in the measurement system.

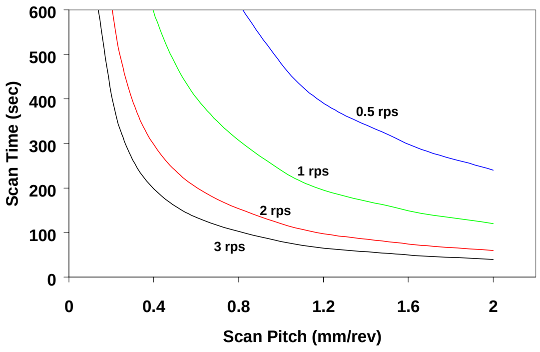

Figure 9. Scan time computed for a 240 mm long OPC for a single probe scanning system

From this plot, we can determine an appropriate combination of scan speed and scan pitch for a given application. For example, if we choose a scan pitch of 1.5 mm/rev to ensure 100% coverage, and if the maximum scan time allowed for the testing operation is 2 minutes, the scan speed should be about 2 rev/sec or higher (this is equivalent to a 283 mm/sec linear speed for a 30 mm dia. drum).

Defect Sizing

The surface potential method satisfies the primary requirement for a drum defect detection system: sufficient sensitivity to pick up all drum defects that result in print defects greater than 100 µm in size. Figure 10 shows the correlation between the voltage depth of detected drum defects and the sizes of the corresponding print defects. This correlation provides the means for characterizing defects and applying accept/reject criteria. For example, if we want to reject all print defects larger than 100 µm, the correlation in Figure 10 indicates a defect voltage depth threshold of 6 volts. Applying this threshold to the data in Figure 10, all but 2 of the defects are rejected. Defects B and C are accepted, even though they are of objectionable size. Upon careful inspection, they were found to be surface or near-surface defects, and indeed the sensitivity of the surface potential method to these types of defects is lower than its sensitivity to deeper defects such as pinholes.

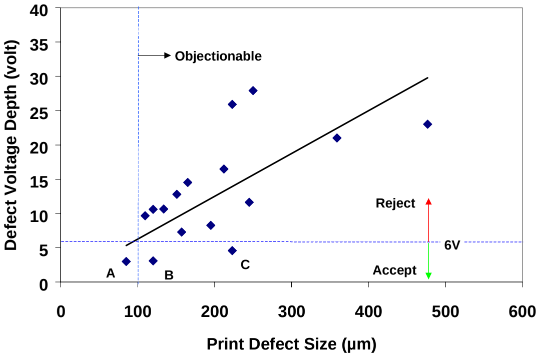

Figure 10. Correlation between defect voltage depth and the size of corresponding print defects on an OPC (nominal drum voltage = 1000 V, scan speed = 1 rps, scan pitch = 1 mm/rev).

It should be emphasized that despite the exceptions noted, the sensitivity of this method to small defects is remarkable, even with the off-the-shelf instrumentation used in this study. Furthermore, the defect voltage depth is only one of many metrics provided by the surface potential mapping method. For more detailed defect characterization, one may examine area, shape, and edge qualities of each defect in the surface potential map. It is also possible to map the surface potential after the drum has been exposed to a controlled amount of light energy, providing more detailed defect characterization and potentially revealing additional “discharge” defects that are not apparent in a charged drum.

Discussion

The primary requirements for a drum defect detection system for production QC can be summarized as follows:

- Sensitivity to drum defects that affect print quality.
- Reasonable scan time, permitting integration into the production line.
- Quantitative methods allowing assessment of defects for go/no-go decisions.
- Ease of use, maintenance and calibration; flexibility, “trainability” and robustness.

Examining alternatives to the prevailing practice of visual inspection for defect detection, we surveyed and critiqued many of the techniques reported in the literature, using the above criteria as guidelines. We found that most existing techniques are unsuitable for production use. The most promising appear to be automated image analysis and the surface potential probe technique.

Application of automated image analysis to drum defect detection in production environments appears to be in its infancy. The strengths of this technique are primarily in surface defect detection, but many issues remain to be resolved. These include optical design for maximizing detection accuracy and reliability, and how to handle the high data acquisition rate and the large volume of data in a high-resolution, high-throughput imaging system. Another issue is system “training.” Because of the large variety of defect types, an imaging system must have a high level of intelligence built in for signature analysis and defect characterization. More research is needed to develop the potential of this technique.

Another promising class of techniques is non-contact, capacitive-coupled probe techniques for charge, current, or surface potential measurement. The dynamic current sensing method has some inherent advantages in sensitivity and speed, but the need for tight control of the distance between the sensor and the surface under test poses as-yet unmet challenges for production use.

The surface potential probe, on the other hand, despite some apparent limitations in bandwidth and sensor size, has demonstrated high sensitivity for defect detection. Furthermore, the system designer can, within limits, increase the sensitivity by increasing the nominal drum voltage. In terms of scan time, the method has limits. For example, at a scan speed of up to about 300 mm/sec and a pitch of 1 mm/rev, the scan time for a 30 mm dia, 240 mm long OPC drum is about 80 sec. However, this need not be considered a fundamental limitation. We can imagine an eight-probe array in which measurements are made on the same drum in parallel, reducing scan time to about 10 seconds — not at all unreasonable for use in a production line. Combining the advantages of a well-proven technology, detection sensitivity, and the quantitative nature of the approach, the surface potential probe technique is a strong candidate for on-line defect detection. Further improvements in signal-to-noise, dynamic response and array technology will advance the technique for production use.

Defect sizing and characterization with the surface potential probe technique remain areas for improvement. On-going research is in progress at QEA using both theoretical modeling and experimental investigations to optimize the test system and the methodology for detailed characterization of defects.

Conclusions

1) Visual detection sensitivity to print defects is on the order of 100 to 200 µm. The magnification factor from drum defect to print defect is about 2 times. Based on these observations, the sensitivity required of a drum defect detection system is on the order of 50-100 µm.
2) The variety of real-world drum defects is very large, covering a broad range of sizes, shapes, and types. Visual inspection is the dominant technique used in photoreceptor production QC today. Due to its subjective and demanding nature, there is a recognized need for an instrumented inspection system.

3) A survey of the techniques reported in the literature suggested that automated image analysis and the surface potential probe method show the most promise. More R&D are needed to advance both techniques for reliable production use. The surface potential probe method in particular uses proven measurement instrumentation and is a leading candidate for production applications.
4) Using the surface potential probe technique, defects as small as about 100 µm can be detected readily. Research is in progress to optimize the detection reliability and the defect characterization methodology.

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Biography

Dr. Ming-Kai Tse founded QEA, Inc. in 1987. The company designs and manufactures automated quality control test systems for manufacturing and R&D applications in digital printing. Dr. Tse was a professor of Mechanical Engineering at the Massachusetts Institute of Technology between 1982 and 1989. At MIT he specialized in the areas of manufacturing, non-destructive testing, and quality engineering. Dr. Tse received his BS degree in Mechanical Engineering from Cornell University and his MS and PhD degrees, both in Mechanical Engineering, from MIT.