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Testing and Implementation of Direct Imaging and Direct Jetting of Solder Mask

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Abstract

Printed circuit board manufacturers are continually challenged to fabricate denser solder mask patterns with smaller features to accommodate advanced electronic components. This trend is motivating manufacturers to adopt novel methods to achieve the required solder mask designs. One such method is direct imaging, which utilizes a controlled light source to directly expose the design image onto photosensitive solder mask material. Another method, termed herein direct jetting, uses inkjet printing to direct deposit jettable solder mask ink onto the circuit surface per the designed pattern. Both methods enable manufacturers to achieve fine solder mask features and circuit design registration with tight tolerances. The implementation of these methods in production requires testing and parameter setup as prerequisites, to ensure that the quality criteria are met, and the production process remains robust. This paper details the recommended steps to carry out such testing, included dedicated test vehicle designs that reduce the time and production resources required, while providing valuable data critical to defining process parameters and capabilities. The derived data is analyzed and compared with predefined performance criteria requirements to determine the optimal parameters that should be implemented in actual production.

Introduction

Solder mask (SM) is a permanent polymeric coating that is applied over the outer layer of circuitry on printed circuit boards (PCBs) to protect and insulate features that do not require soldering access. Its other main purpose is to prevent the shorting of adjacent component leads due to solder bridging. Areas on the outer layers that are intended for subsequent component soldering are selectively cleared from solder mask through the PCB fabrication flow. Materials originally used for solder mask came from the printing industry, such as thermally curable or UV curable inks; they were selectively applied onto the surface of the PCB via screen printing using a patterned screen. [1] To accommodate the ever-increasing density of PCB circuitry and registration requirements, photoimageable solder mask materials were developed and introduced to fabricators in the last quarter of the twentieth century.

Today, liquid photoimageable solder mask (LPISM) is the most common form of SM used in the PCB industry. It is applied to coat the outer layer of the PCB panel by various methods, including screen printing, curtain coating and spray coating. The coated SM is thermally dried to evaporate the solvents and allow handling. It is then imaged by selective exposure to UV light to create the required pattern. The traditional method of imaging LPISM uses imaged film (i.e., “artwork”) that is registered to the PCB, followed by flood exposer using a near UV light source, such as a mercury vapor lamp. The SM is developed to remove it from those areas that were not exposed to UV light and do not require the SM coating. Thermal curing is implemented to complete the polymerization cross linking and attain the SM’s final resistance properties.

As the density of the electronic components assembled on PCBs increased, so too did the size and registration requirements of the SM pattern feature. PCB fabricators found it increasingly difficult to successfully manufacture and register ever shrinking features using conventional imaging techniques. PCB manufacturers faced additional technical challenges in retaining small, imaged SM features on the board surface. This is mainly due to the strain applied on the SM layer by the high temperature of lead-free soldering and extended developing cycles needed to clear SM ink from high aspect ratio holes.

At the turn of the century, direct imaging (DI) equipment was developed as a way to image photosensitive materials used in the PCB industry. DI machines use an illumination source (e.g., laser or light emitting diodes) and a controlled optical mechanism to selectively expose only those areas on the surface that require photopolymerization. Initially, such equipment was used primarily for photoresist exposure, due to the low power and narrow spectral range inherent to early systems. However, as DI systems evolved and SM materials were modified to be more compatible with the output spectral range, manufacturers realized the benefits of DI exposure for SM imaging. [2] The most beneficial feature of DI of solder mask is the ability to accurately scale and register the SM pattern to each individual panel within a production batch. This intrinsic feature of DI technology dramatically reduces the scrap and rework rate that is common when using fixed-scale film for imaging tight tolerance SM features. [3] Additional advantages of DI are: (1) high resolution imaging, which allows definition of fine solder dams and openings; (2) general process compatibly, which requires little or no change in the process parameters of the pre and post exposure steps; (3) cost reduction through elimination of imaged film materials and process equipment; (4) independence from operator skill because there is no need for extensive operator training to manually register film to the outer layer circuitry and many systems can be integrated with automated loading and unloading of panels; (5) modified SM inks that are tuned to the common spectral output of DI systems to reduce the exposure time and increase the resolution (i.e., sidewall quality and adhesion). Given all of these benefits, it is clear why there is an accelerated adoption of DI within the SM departments of PCB fabricators worldwide. (Figure 1)

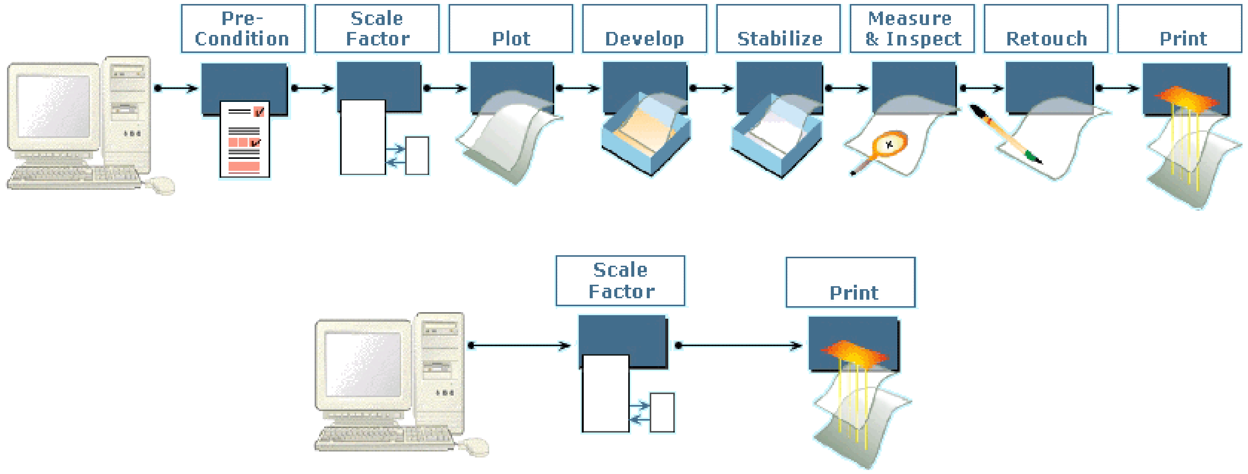

Figure 1 - Picture of Film Preparation vs. DI

PCB production has primarily used inkjet systems for nomenclature markings for over a decade. In recent years, inkjet equipment manufacturers and SM ink producers invested heavily in developing inkjet platforms to print SM directly onto the panel surface. With inkjet printing of solder mask, termed herein “direct jetting” (DJ), the SM ink is applied on the outer surface of the PCB according to the designed image. No material is applied other than the desired SM pattern, which eliminates the need for superfluous SM to be removed in later steps, a common practice with conventional photolithography. This process achieves true additive manufacturing in the SM application. The paradigm shift in the manufacturing concept dramatically decreases the process steps required for complete SM implementation, reduced to only three main steps: surface preparation, DJ and curing. Compared to the photolithographic based method that includes at least twice as many steps (surface preparation, coating, drying, exposure, developing and curing), the DJ method of applying SM is greatly simplified. (Figure 2) This in turn yields the benefits of: (1) reduced material usage; (2) reduction in capital equipment and process variables; (3) an eco-friendly process; and (4) no need to wash out SM in thru holes which also strains adhesion of fine features. Although DJ technology does not currently offer the same image resolution as DI, it does encompass the main advantages of scaling and registering the SM image design to each individual panel.

As DI and DJ technologies gain more acceptance for SM application [4], testing methods are devised to capture relevant quality data that can be translated into implementable process parameters. This article will discuss some of the test methods that the author has used successfully and found advantageous for PCB process engineers during the exploration and implementation stages of DI and DJ.

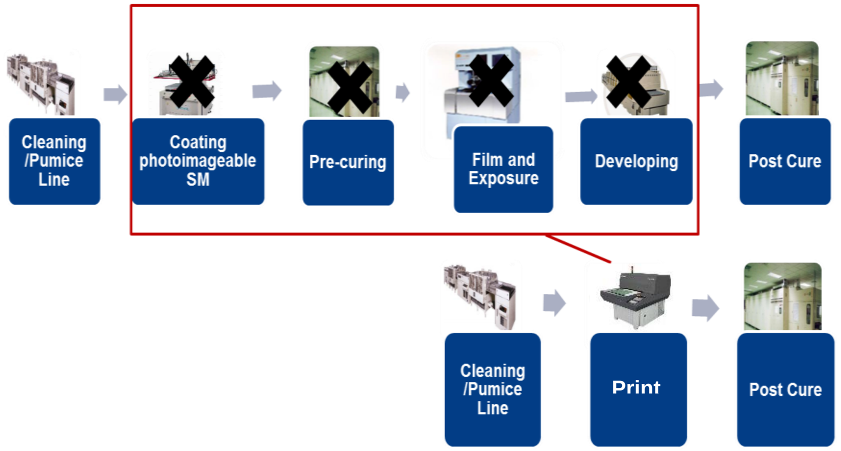

Figure 2 – Comparison of Process Differences Between Photolithography and Direct Jetting

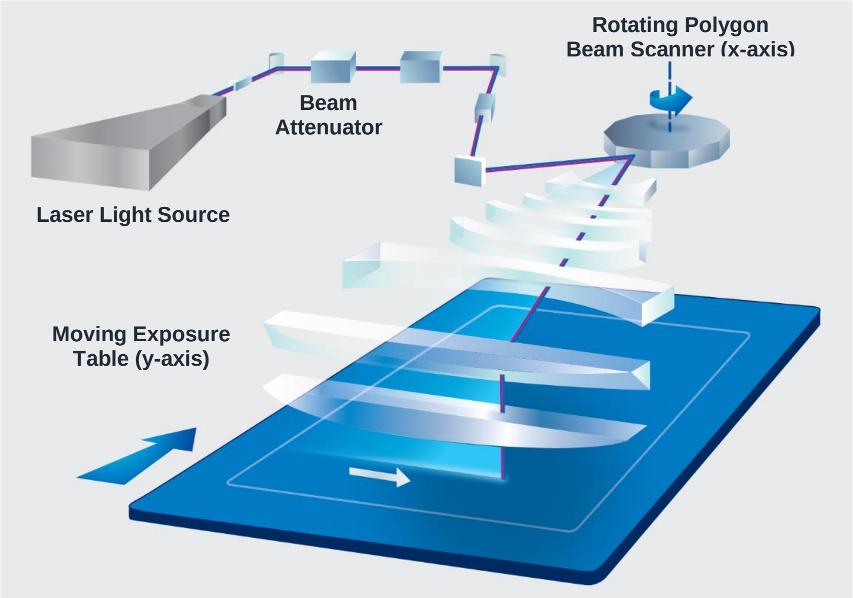

Figure 3 - Schematic of a Laser Based DI System

Direct Imaging Technology

Today, PCB manufacturers can choose from a wide variety of direct imaging (DI) equipment. Most offerings will incorporate three main subsystems: (1) a camera system for target acquisition to determine the position of the panel surface to register the SM image to the underlying circuitry; (2) an exposure mechanism that delivers UV light to the panel surface in a controlled manner; and (3) a movement apparatus that synchronizes between the panel position at any point in time and the delivered exposing light. The various systems can be characterized by the operation principle of their exposure mechanism, which may be separated into two main categories: (1) a laser beam scanning mechanism; and (2) a digital micromirror device (DMD) based mechanism.

With laser scanning systems (Figure 3), a UV laser light source generates a beam that passes through a series of conditioning optical elements. One of these elements functions as a controlled attenuator or deflector that can either allow the beam to reach the panel surface, in turn exposing the SM, or can block the beam from reaching the SM. An additional optical or mechanical element is used to scan the beam across the exposed surface on one axis, while the panel or the exposure mechanism is manipulated in the perpendicular axis. [5]

A DMD is an optical micro-electrical-mechanical system (MEMS) that contains an array of highly reflective aluminum micromirrors that can be individually rotated to reflect light projected on the DMD in one of two directions. DMD chips used in DI equipment typically contain a few million mirrors per chip, with a micromirror pitch on the order of 10 microns. DI systems will utilize a light source (e.g., light emitting diodes, UV lamps) to project light onto the DMD surface. (Figure 4)

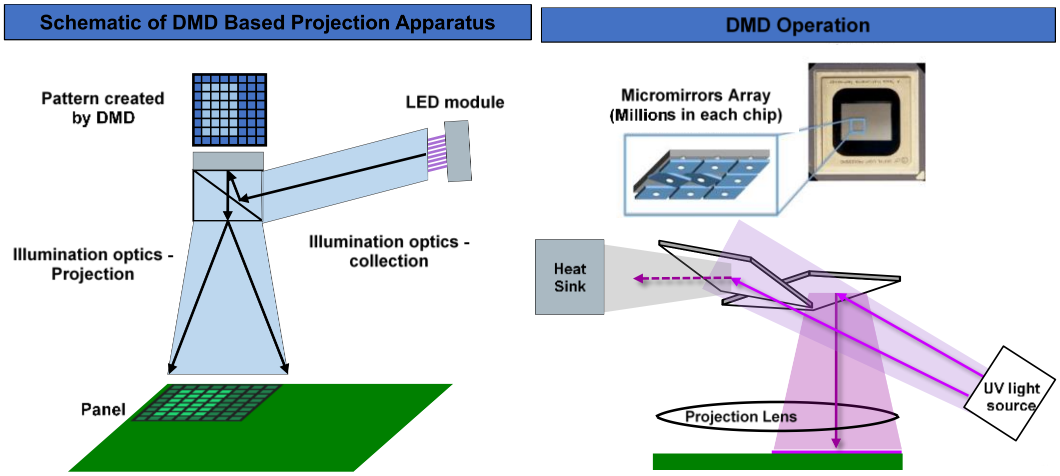

Figure 4 - Principal of DMD Based DI systems

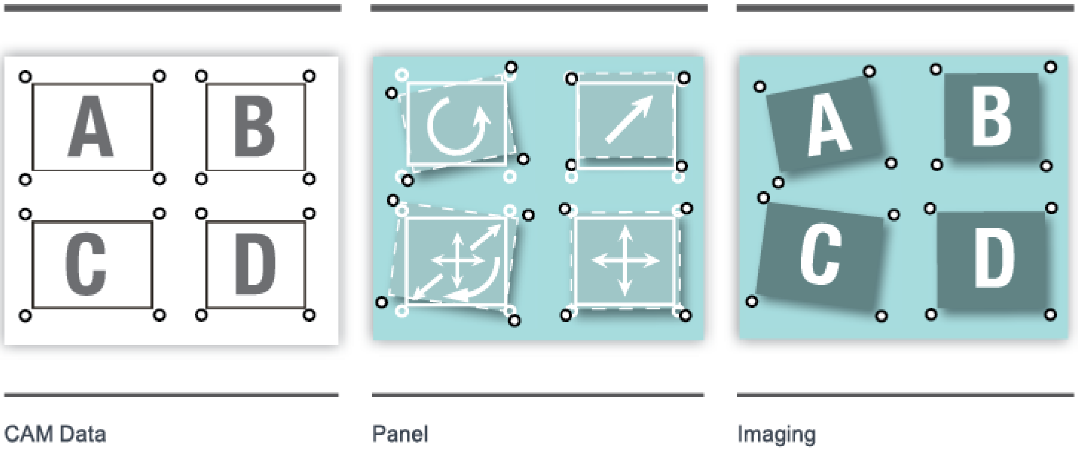

Figure 5 - Principal of SM Image Data Registration and Manipulation to Fit Underlying Circuitry

The DMD is positioned over the panel surface and individual micromirrors are directed to transfer the projected light either to the panel surface or away from the panel surface (usually to a heatsink). The controlled tuning of the micromirrors in the on or off position defines the exposure pattern that will be projected onto the SM. As with the laser scanning systems, the DMD based systems also include mechanical manipulation that allows movement of the table, the projecting apparatus or both to scan the entire panel. Each DMD projecting apparatus exposes only 5 to 15 cm^2 of SM area at any point in time, so most industrial exposure systems will incorporate several apparatuses to cover a wider exposure area simultaneously. [6]

As a comparison, the two exposure forms, laser scanning and DMD based, can both be used to effectively expose SM for high quality PCBs. The main advantage of laser scanning is that it provides higher resolution due to the coherent nature of the laser beam, which may not be critical for typical SM pattern designs. The DMD based method, on the other hand, allows for fast exposure rates since a larger surface area is exposed at one time as compared to a singular scanning beam. Given the relatively high exposure energies required for common SM material (i.e. on the order of hundreds or even thousands of millijoules per square centimeter), this higher exposure rate may be more pragmatic for general SM applications.

The target acquisition system, present in virtually all DI systems used for PCB production, incorporates charge-coupled device (CCD) cameras to locate and acquire images of the targets within the circuitry beneath the SM layer. Once the targets are found, the coordinates are calculated, and the SM image data is transformed. The transformation includes transposing, rotating and scaling the image data to best fit the underlying circuitry. (Figure 5)

Testing Solder Mask Exposure on DI Systems

An important aspect of process testing is to have a clear understanding of what needs to be achieved and what type of data is needed. The testing method should be repeatable, allow for variations in process parameters, and result in meaningful information applicable to production. Within such a framework of requirements, it is best to divide the test process into three segments: (1) preparation, (2) implementation and (3) analysis. We will discuss these three stages as they relate to DI exposure of SM.

In the preparation stage, the expected performance criteria should be defined. Relevant performance criteria for SM imaging include: the minimum solder dam retention; the minimum opening that is resolved; the maximum allowable undercut; the minimum required Stouffer step; the acceptable image growth; and all other quality parameters that the process engineer deems important for the production process. The scope of the exposure and process variables must also be defined. Such variables may include the SM ink type; copper and coating thicknesses; exposure energies; exposure spectrum variations; number of developing cycles; curing conditions; type of final finish; and more. Next, a test vehicle should be designed to allow efficient collection of the required quality data at the varying exposure parameters. Lastly, during the preparation stage, the test must be planned in as much detail as possible, including the scheduling of all the required resources such as production equipment availability, SM inks, materials and test panels.

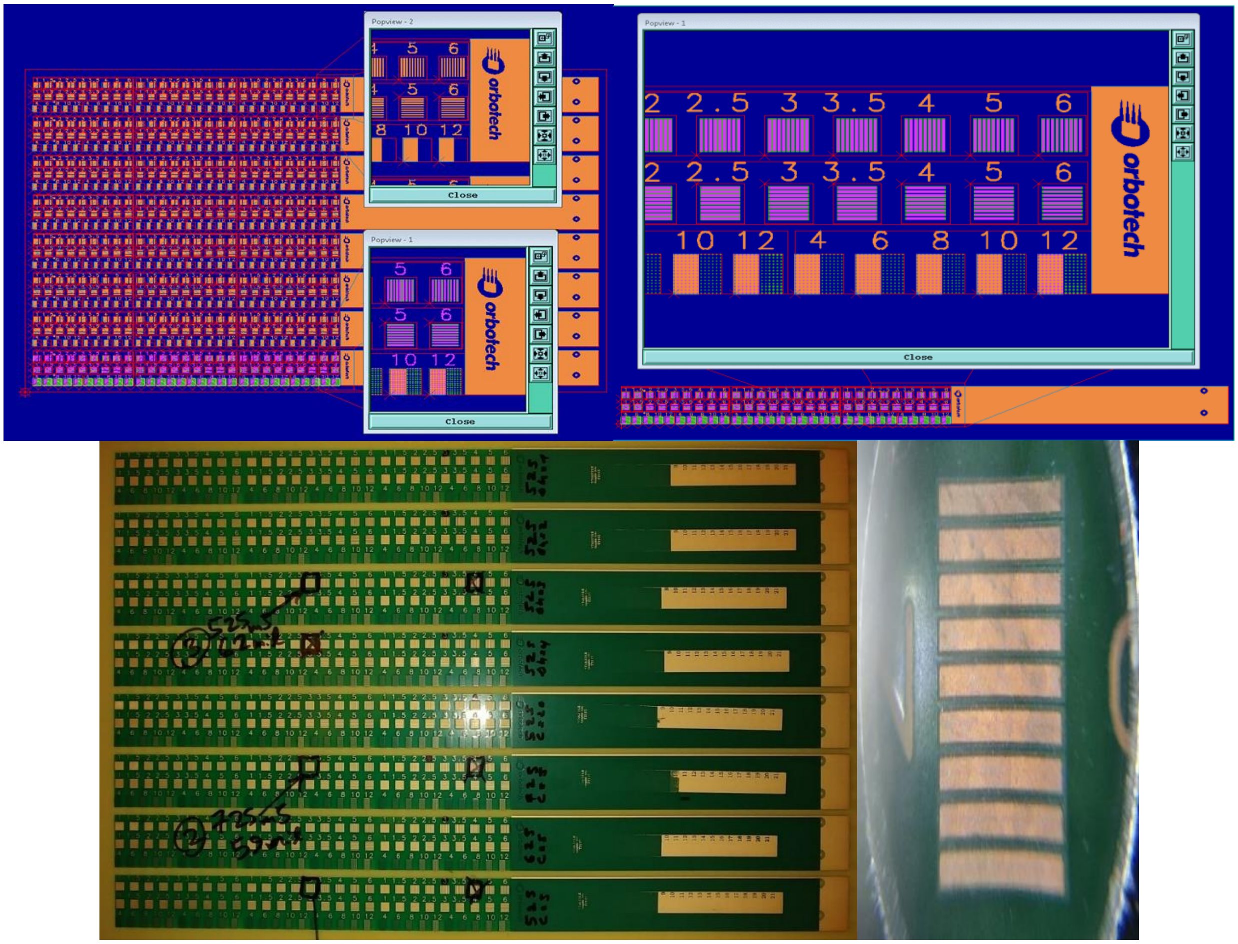

Figure 6 - Computer image of a test vehicle design for testing DI of SM; image of an actual prepared panel; and microscope image of a single solder dam test area.

Above (Figure 6) is a test vehicle design that satisfies most of the relevant data and scope of process variables for investigating DI of SM inks. The author has used this design repeatedly to obtain valuable quality process data in true production environments. The panel design includes individual strips, each with its own registration targets. This allows each strip to be exposed individually. A single strip is divided into two sections: one is a flat copper area for placing an optical transparency guide (e.g., Stouffer 21 step wedge), and the other contains a copper pattern to facilitate the imaging of solder dams and SM openings at varying dimensions. The designed dimensions of the solder dams in this pattern are 1, 1.5, 2, 2.5, 3, 3.5, 4, 5 and 6 mils. The dimension of the openings, as designed, are 4, 6, 8,10 and 12 mils, located on both bare laminate and bare copper areas.

The specific design displayed here has eight separate strips, with a total panel dimension of 12″ x 18″. The copper image is exposed and fabricated, either through a print and etch or pattern plating process. Print and etch allows more uniform copper thickness and fewer processing steps, while the pattern plating sequence may be more representative of actual production. Based on the author’s experience, producing the test pattern on a 1 to 2 mm core with 2 oz of copper (approximately 70 um copper thickness) using a print and etch process will suffice for most PCB applications to obtain results representative of actual outer layer conditions.

Once the copper pattern is prepared, the implementation stage of the test process may be initiated. The test panels should be processed through the surface preparation line, coated with SM ink and dried. If any variables are to be tested at these stages of the process, separate panels must be used, for example, to determine the optimal exposure conditions of different SM ink colors or the effect of different coating methods on the end quality performance. With the test panels coated and dried, the exposure test plan should be followed. If the general range of the exposure energy is not known, it is recommended to test a wide range of energies from 100mJ/cm^2 to 800mJ/cm^2 in increments of 100mJ/cm^2. That is, each strip of the proposed test pattern above would be exposed at a different energy: the first strip at 100mJ/cm^2, the second at 200mJ/cm^2 and so on, until the eighth and last strip is exposed at 800 mJ/cm^2. Each strip must be registered using its individual registration targets for accurate image placement of the fine SM features. It is also highly recommended to place a 21 step Stouffer scale in the intended space for each exposed strip.

Following an initial exposure trial and development of the panel, the following results should be recorded for each exposure energy: the achieved Stouffer step, the minimum dam adhesion and the minimum resolved opening. Comparing these initial results to the requirements set out in the preparation stage should make it possible to narrow down the necessary exposure energy to within ±100mJ/cm^2. At this point, it is advisable to perform an additional exposure test within a tighter energy range around the energy level that presented the best result in the initial exposure trial. Increments of around 5% from the energy level in the initial exposure trial are suggested. For example, if the selected energy from the initial trial is 500mJ/cm^2, then an additional exposure trial should be run at an energy increment of 25mJ/cm^2, which would be 425, 450, 475, 500, 525, 550 and 575mJ/cm^2.

Today, many DI systems offer the option of varying the exposure spectrum by increasing or decreasing the relative power of light sources with specific wavelength peaks. Regarding variations to the exposure spectrum, it is best to start off the exposure testing with the nominal spectrum recommended by the equipment manufacturer, as this will typically provide the highest intensity light output yielding the fastest exposure speed. Once a generally satisfactory exposure energy is determined per the above testing, it may certainly be worthwhile to test variations in the exposure spectrum to understand effects on the performance of the SM. For many SM materials, increasing the relative power of the longer UV wavelengths (385 to 420nm) will have a positive effect on solder dam retention and sidewall quality, since these wavelengths tend to penetrate deeper into the solder mask and polymerize the ink at its base. A relative increase of power to the shorter UV wavelength (355-385nm) will tend to promote surface polymerization of the SM leading to increased gloss and improved surface resistance.

Following the exposure of the test panels at all the required conditions, the panels should be developed, cured and processed through final finish coating (e.g., ENIG, HAL, etc.). After completing the post exposure processing, a tape adhesion test (IPC-TM-650 test method # 2.4.1) should be performed to determine the minimum dam retention for each test condition. Cross sections of solder dams should be prepared and measured (for undercut and image growth) from those strips on the test panel that met the established criteria; that is, those strips that were exposed at conditions found to be relevant per the defined quality requirements. It is advisable to collect and organize in a spreadsheet (e.g., Microsoft Excel) all the generated data (Stouffer step value, minimum solder dam retention, minimum resolved openings and cross section measurements), correlated to the tested processing and exposure parameters. Organizing the data this way will improve the final step of the testing process, the analysis.

Once all the test data is gathered and input into the spreadsheet, it is possible to determine the optimal exposure conditions per the required performance criteria laid out in the preparation stage. The aim is to find the exposure and process conditions that would result in or exceed the quality requirements. For example, if the performance requirements are to hold 3 mil solder dams with no more than a 0.2 mil undercut per sidewall while maintaining at least a first clear Stouffer step of 10 (of 21), the lowest exposure energy should be selected that results in the required performance. A trend analysis can also be performed by plotting the collected data. Such plots (Figure 7) allow better visualization and understanding of the behavior of the SM as exposure parameters are varied. In the sample plot below, the first clear Stouffer step was plotted as a function of the exposure energy.

Such a graph aids the decision about which exposure energy may be acceptable for moderate processing conditions (e.g., low copper profile, moderate final finish process) that require a relatively lower Stouffer step, and which exposure energy should be used for more challenging process conditions (e.g., thick copper, aggressive final finish) that require a higher step.

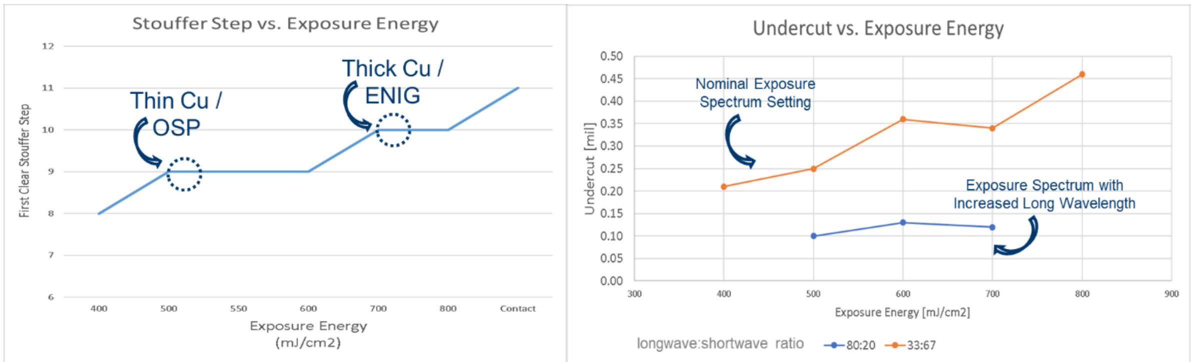

Figure 7 - Plots Derived from Test Data that Display the Relationships Between the Exposure Energy, Stouffer Step, Undercut and Variations in the Exposure Spectrum.

Another useful plot presented displays the relation between the undercut and the variation in the exposure spectrum. In this case, when the SM was exposed using a high percentage of longer wavelengths, the undercut was reduced by more than 50%, as measured from cross sections. This information may be critical in determining the optimal exposing conditions for SM designs with tight tolerances.

The conclusions derived from this test method should be verified using the manufacturer's own test vehicle or panels that are representative of production. Subsequently, limited and controlled production should be run with the determined exposure conditions, preferably with careful inspection of each article up to the completion of the production cycle, prior to proceeding with employing the exposure conditions under full standard operation.

Direct Jetting (DJ) Technology

As previously mentioned, the use of ink jetting technology has been prevalent in PCB manufacturing for two decades, primarily for printing nomenclature on the board's surface. Developments in jetting print heads as well as in jettable materials have introduced the possibility of implementing DJ in other printing steps of the PCB process. In this paper, the focus will be the utilization of DJ for solder mask printing.

Like DI systems, DJ equipment incorporates three main subsystems: (1) a printing system based on inkjet printing heads and a mechanism to supply ink to the printing heads; (2) a camera system for target acquisition to determine the position of the panel surface to register the SM image to the underlying circuitry; and (3) a movement apparatus that synchronizes the panel position at any point in time and the printed ink. The actual printing of the SM ink is achieved with a drop on demand piezoelectric mechanism. This method incorporates a piezoelectric material inside a small ink filled chamber with a nozzle opening. (Figure 8) When an electrical voltage is applied to the piezoelectric material, it generates a pressure pulse inside the ink chamber causing an ink droplet to eject from the nozzle. [7] A typical DJ print head will consist of thousands of nozzles that can be individually controlled by computer software. The targets acquired by the camera system are used by the movement synchronization apparatus to direct the ejected ink droplet to a specific point on the panel surface according to the required SM pattern.

Most commonly used SM inks for DJ applications are UV curable, which allows the drops to be "pinned" on the PCB surface to achieve high image resolution. The spectrum of UV light used to irradiate the ink matches its photochemistry in order to increase its viscosity, thereby allowing more control over the drop size and flow. For this reason, a UV light source is usually mechanically coupled to the inkjet head to facilitate this ink "pinning," as well as preliminary curing. (Figure 8)

The target acquisition and registration system for DJ systems operate similarly to those found on DI and can perform the required data transformation to scale and accurately fit the SM image to the copper pattern.

Testing Solder Mask Printing on DJ System

It is also recommended to employ a three-stage approach when testing the printing performance of DJ equipment; that is, preparation, implementation and analysis. In the preparation stage, one should consider and define the performance characteristics required of the DJ solder mask. Characteristics commonly required include: minimum coverage over conductors; edge roughness around openings; minimum feature size; adhesion on laminate and on copper; and resistance to final finish processes. The testing procedure details should also be defined, specifically the test vehicles design; types of base materials; copper thicknesses; the surface preparation; and the post printing processes (i.e., curing and final finishes). Once these aspects are determined, the next step is to gather and allocate resources to perform the testing, such as production equipment availability, materials and test panels.

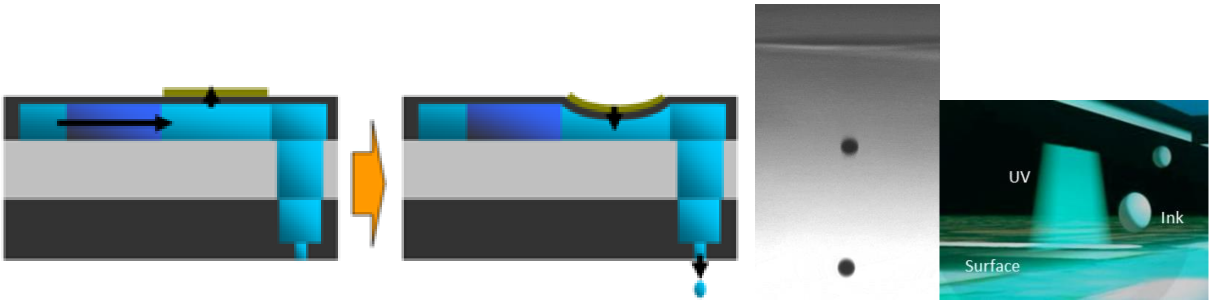

Figure 8 - Operation Principal of Ink Jetting Using a Piezoelectric Mechanism; Image of Ink Droplets Ejected from a Nozzle; and Schematic of Utilization of UV Light to Pin Ink to Surface.

Many times, the parameters which control the DJ printing inside the system are not accessible to the user but are programmed by the equipment manufacturer and then selected by the user as individual recipes or printing profiles. This is done to avoid erroneous parameter setting combinations that may damage the delicate print heads. The user can select from a range of printing profiles that will induce variations in the printing outcome. Though not always directly accessible to the equipment operator, common printing parameters affecting the printing performance include:

1. The waveform or periodic electrical signal sent to the piezoelectric elements in the print heads, which impacts the amount of ink jetted and the frequency of the drop ejection.
2. The overlap between the ink drops, which affects the SM thickness and the image resolution.
3. The number of passes that the heads repeatedly print ink over a specific area, which increases the height of the deposited SM layer.
4. UV irradiation timing, intensity and spectrum, which have a big influence on the flow of the ink on the surface as well as its tackiness.
5. Manipulations to the pixelization of the image data, which affect surface coverage and feature shaping.

A select number of printing recipes, or variations in the underlying parameters, should be chosen for testing.

A test vehicle design for DJ is shown in Figure 9. This panel design is comprised of a repeating array of features that may be used to extract valuable data to determine the ideal process conditions. Each of these arrays includes: (1) an SM grid pattern printed on a areas of copper and laminate to test for adhesion; (2) vertical and horizontal lines and openings at varying widths printed on copper and laminate to determine feature quality; (3) full SM printing on grouped and isolated conductor to assess ink coverage and encapsulation; and (4) characteristic surface mount technology (SMT) component designs with varying solder dam widths to determine the adhesion and quality of the printed dams. Each array is repeated eight times in the design shown and can be individually registered, so different printing profiles may be employed for each array, or arrays with identical printed profiles may be cleaved off for differential post printing processing and examination (e.g., different final finishes or destructive testing).

Preparation of the copper test pattern is recommended so the surface copper will match typical production panels. The surface characteristics of different copper types may have significant influence on the interaction with the DJ SM and thus, the printing quality. Once the copper pattern is prepared, the implementation stage of the test process may be initiated. If any variations are to be tested in the process steps or parameters prior to DJ, separate panels must be used (e.g., copper thickness, laminate type, surface preparation). It is worth noting that the condition of the panel surface can have a significant effect on the DJ printing quality. For example, fingerprint residues, mechanical damage and copper oxidation will often cause a localized printing defect. It is imperative to have a uniformly clean and well-prepared surface prior to DJ.

The printing recipes selected in the preparation stage should be registered and printed separately on individual test arrays. The panel may be visually examined after printing and before curing to note any quality issues, such as smearing of the ink or lack of coverage on tracks. However, care must be taken not to damage the uncured SM. After printing, the test panels should be cured and post processed.

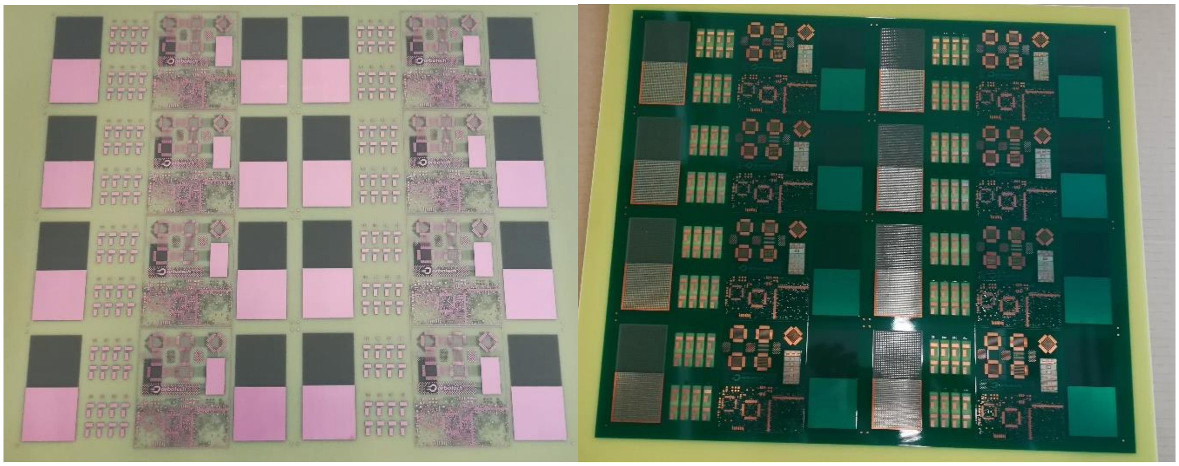

Figure 9 - Image of Test Vehicle Design for Testing Direct Jetting of SM Before and After Printing.

The individual test arrays may be detached from the whole panel to test variation in the post processing conditions (e.g., different curing cycles or final finishes). Once the processing is complete, inspection and testing of the panels should be carried out according to the testing plan laid out in the preparation stage. Cross sections should be taken to determine if the profile of the solder dams is acceptable and if there is sufficient encapsulation of the conductor lines. Adhesion testing should be conducted to ascertain the minimum features that hold on the surface (copper and laminate) at the variable conditions. Test panels must also be run through assembly simulations to verify the robustness of the printed SM and its functional compatibility.

All the process parameters and test results should be gathered and organized, preferably in a spreadsheet. Once this is complete, the analysis phase may begin. The main goal of this step is to find those DJ printing parameters or recipes that satisfy the quality requirements for each process setup. Thicker copper may require a recipe that deposits more ink on the surface. Different base materials may require variations in UV irradiation to control ink flow and resolution. Changes in image data compensation may assist in clearing small openings in ball grid array (BGA) pattern designs. The conclusions derived from the analysis of the test results should be verified using the manufacturer's own test vehicle or panels that are representative of production. Furthermore, limited and controlled production should be run with the determined DJ printing conditions, preferably with careful inspection of each article up to the completion of the production cycle, and prior to implementing DJ of SM under full standard operation.

Conclusion

In this paper, we reviewed the two distinct technologies used for processing SM on printed circuit boards: (1) direct imaging of the SM pattern used to expose photoimageable ink, and (2) direct jetting (additive inkjet printing) of the SM pattern using jettable ink. The operational concepts of these technologies were described along with the underlying parameters that dictate the produced result. It guides an engineer potentially introducing these technologies into a production process on how to carry out efficient and beneficial testing to derive data that can be used to implement such technologies reliably.

For both DI and DJ, a three-step approach was outlined, covering preparation, implementation and analysis. The preparation step is used to plan out the variable parameters, both for process conditions and materials, as well as the testing to be performed. Recommended test vehicle designs were introduced for each method to allow for multiple test variations to be implemented using relatively few panels. These test designs aimed to reduce the time and production resources required, while providing valuable data critical to determining the optimal parameters that should be implemented in actual production. The implementation step is carried out per the devised test plan, considering the resources required and the testing criteria. The implementation step is completed by the collection and organization of the processing variables and the correlating test results. In the third and final analysis stage, the collected data is referenced to the quality requirements as laid out in the preparation step. Those conditions that yielded the results that best satisfy the required performance criteria should be chosen for further investigation and process setup.

Readers may contact the author with requests for the test pattern data described in this paper or other technical inquires.

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