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Digital Printing Systems for Printed Circuit Board Legends

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Abstract
The development of digital printing systems for printed circuit board legends (a.k.a. nomenclature, indent or letter screening) is a major technological leap. Legend marking on printed circuit boards (PCB) is presently being accomplished with screen-printing. This method of marking legends on PCB's provides a permanent, high contrast mark, however, this technology is costly in terms of material and labor. Screen-printing is a mature technology that is well understood in the industry and well supported by screen ink providers. A successful digital printing solution for this application will retain the benefits of permanent, high contrast marks and offer advantages of demand printing including efficient runs of small production batches.

An emerging technology in PCB legend marking is drop-on-demand (DOD) ink jet. DOD ink jet offers the flexibility of digital printing while also providing high contrast, high resolution marks with the required performance properties. The primary advantage of DOD ink jet printing enables PCB's to be printed directly from image files eliminating the need for screens and greatly reducing the setup time required between batches. As the PCB industry is challenged to reduce costs and improve turnaround times, drop-on-demand ink jet shows promise in reshaping the printing process.

Driving Factors
Legends on a printed circuit board (PCB) are a set of identification marks on the outer layer of a PCB, indicating component placement locations, manufacturing information and other data that might be used for servicing or tracking the PCB (Figure 1).

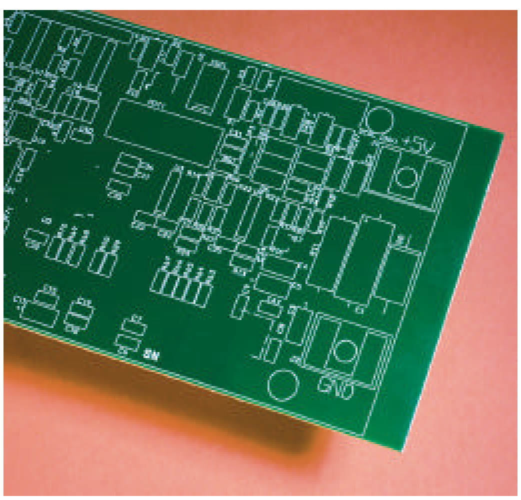

Figure 1 – PCB Legend

Today, fabricators of PCB's are utilizing mature technology such as screen printing for applying

Legends
As a result of that maturity, there is a variety of screen printing product offerings that meet the stringent marking requirements of this application. Competition has helped drive innovations within this technology and has helped drive the price of supplies down. The screen-printing process is well known and has been optimized to improve efficiencies through automated machinery. It performs best with large production batches and static information. Screen-printing technology has served the PCB market well, but the needs of this industry have changed and these changes demand a technological progression to digital printing.

There are a number of factors driving the need for digital printing technology including:

- Reducing setup time between jobs
- Improving turnaround time
- Reducing job costs
- Providing unique identifiers (serialization)
- Improving print quality

Setup time - While the supplies costs for screen-printing are low and production methods have been optimized, there are still significant limitations with screen-printing. Setup time required between production runs is one of these limitations. Approximately 80% of PCB fabricators produce PCB's in low volume, high product mix production runs. Because of the high mix of production, these fabricators change screens often. Reducing the changeover time between jobs could improve the efficiency of their production. As an example, a PCB fabricator with semi-automated screen printers whose typical production batch is 60 pieces, with an average setup time of 15 minutes per job will spend as much as one half of their available production time in setup. A prototype PCB fabricator with very low volume, high mix would be affected even more. While the larger PCB houses with high volume, low mix production are less affected by setup time (few screen changes per production shift), they represent a small portion of the global PCB fabricators. So while screen-printing may continue to be a cost effective solution for high volume production houses, the majority of PCB fabricators are saddled with a process that could benefit from digital printing.

Turnaround time - There are many steps required to create the screen that will produce the legend on the PCB. These steps limit the ability of fabricators to quickly run a job from start to finish. Positive slides (film) that represent the legend layout must be produced. These positive slides are produced from a digital file created by CAM software. The slide is then overlaid onto a screen coated with a photo-emulsion. The non-printing portion of the legend is then exposed and the uncured emulsion is washed away leaving a screen that can be used to mark panels. In some cases this screen must be allowed to dry for as long as 24 hours before use. This lengthy, necessary process can make quick turnaround difficult.

Reducing costs - As with any industry, the PCB industry is under constant pressure to reduce production costs. Screen-printing has several of costs inherent in the process. There is the capital cost associated with purchasing screen frames, and supplies costs associated with the photoplotter film, screen mesh, chemicals, and screen ink. Labor costs are incurred with all the steps in creating and maintaining screens. Perhaps the most significant cost is the lost opportunity associated with the time delay in screen creation and setup.

Unique identifiers - There is an increasing need to uniquely identify each individual panel as well as each individual board within a panel. Screen-printing does not lend itself to print variable information such as serial numbers, date codes, or other identifiers. Today, this requirement is met by secondary processes including adding labels to the panels and hand stamping the individual boards, adding time and cost to the production process. Serialization effectively reduces jobs to batches of one, a task for which digital printing is well suited.

Print quality - Despite a long history in the PCB industry, screen-printing still exhibits printing quality problems. These quality problems include filling of characters and non-printing of entire sections of screens. Changing incorrect data is difficult and may require a new screen. Also, rework of panels is a significant task if the error is detected after the ink has been cured.

The overall message from PCB fabricators is that it is time for a change. Screen-printing technology has been developed near its full potential and the technology now exists to bring PCB legend marking into the digital age. There are enough technology companies developing this expertise and enough end users recognizing its potential to drive this application forward. PCB fabricators need to improve turnaround time, increase production, reduce costs, add variable data to legends and improve print quality. Digital printing can offer solutions to these needs.

Digital Printing

Digital printing can be defined as the process of transferring a digital image through a printing method to a substrate. An example of digital printing is creating a text file on a PC (digital image), sending it to an office printer (printing method) to be printed on a piece of paper (substrate). Industries such as office printing, graphics arts, textile and product identification have pushed the growth of digital printing as the need to change information quickly has increased. While the substrates are somewhat dependent on the industry (standard office paper, silk screens, fabric, candy bar wrappers, packaging labels, etc.) the printing methods are much less dependent. Some of the more popular industrial methods include ink jet, laser and thermal transfer. The inherent advantages of digital marking over traditional non-digital methods include printing directly from a digital image, printing variable data, quick editing of data and the availability of multiple printing methods. Digital printing can offer the following advantages specific to the PCB industry:

- Increased production for low volume fabricators – by eliminating legend screens and their setup times.
- Quicker turnaround time – by producing legends directly from digital files rather than through the multi-step screen creation process.
- Reduced costs – by improving production and eliminating screens, digital marking reduces the number of steps required for PCB production.
- Serialization and date coding – variable data is an inherent property of digital printing.

Digital printing can offer solutions to many of the shortcomings of screen-printing. Selection of the proper digital printing method is important in order to take full advantage of the attributes of digital printing.

Ink Jet Technology

Drop On Demand (DOD) ink jet is a digital printing method. As such, it offers the positive attributes of digital printing while also meeting the speed and print quality needs of the PCB market. The fact that DOD ink jet is a non-contact method allows the traversal of the nonuniform surface of a PCB while still accurately placing the legend. The variety of commercially available print heads offers choices between higher speed and higher print quality. It has a proven track record in industrial marking applications and is continuing to become a more cost effective solution. Of the digital marking methods, DOD ink jet seems to be the most adaptable to the PCB fabrication market.

The two leading ink jet technologies are continuous ink jet (CIJ) and drop on demand (DOD) ink jet. CIJ has been in use in industrial applications for many years and the name is descriptive of the way the system functions. Droplets of ink are created in a continuous stream, usually from a single jetting orifice. Electrically charged droplets that are selected to hit the substrate are allowed to pass through high voltage deflection plates. Electrostatic force that is applied to the deflection plates directs the droplet properly on the substrate. Droplets that are not selected are not deflected and go to a gutter or catcher and then recirculated back into the system. As the requirements of the CIJ ink call for fast dry time, some of the solvent in each of these recirculated drops will have evaporated in flight. Once returned to the system, these droplets are resupplied with solvent or "make up" fluid. Advantages of CIJ systems include good adhesion to substrates, long throw distances of drops, and lower cost of machinery and supplies. The primary disadvantages of CIJ systems are that the inks are messy to handle and often contain hazardous solvents including MEK (methyl ethyl ketone). Inks that are more environmentally friendly are available, but the adhesion characteristics are not as good.

DOD ink jet has also been in use in industrial applications for many years. Ink droplets are ejected from a nozzle to the substrate only as needed. No ink recirculation system is needed. The droplets are expelled from a nozzle by an internal change in pressure. DOD printheads always have many nozzles, since each individual nozzle is relatively slow compared to CIJ. The history of the technology has been a drive towards even higher numbers of nozzles per head, from 9 to 12 in the early 1980's to 500 or more today. DOD ink jet offers accurate drop placement and more environmentally friendly inks that contain no solvents.

A leading type of DOD ink jet technology for industrial applications incorporates piezoelectric ceramic material. Such piezoelectric (PZT) implementations of DOD ink jet printhead technology are offered commercially from companies in the USA and the U.K. A typical DOD ink jet print head consists of a linear array of evenly spaced jetting orifices. Ink is fed into a chamber via a small supply orifice. When the jet is commanded to expel a drop, an electrical charge is applied to the PZT material that is adjacent to the chamber. The action of the PZT deflecting can be compared to the action of an old style oilcan. As the bottom of the oilcan is depressed, the area within the chamber of the oilcan is reduced and oil is ejected out of the tip. Piezoelectric DOD ink jet works much the same way. As the PZT deflects, the area within the chamber is reduced and a droplet of ink is ejected from the jetting orifice at speeds on the order of 8 m/s. As the PZT deflects in the other direction, ink is drawn back into the chamber and prepared for the next actuation. This can happen at a frequency of 12,000 times per second depending on the printhead used.

The Xaar XJ500 print head and the Spectra Nova JA256 print head are examples of DOD ink jet printheads that are in commercial use in the PCB industry. The first print head mentioned has 500 jetting orifices and allows jetting of UV curable (and other) inks at temperatures up to 40 °C. The inks used in this print head are liquid at room temperature. This ink is typically jetted in drop volumes from 25 pL to 80 pL. The liquid ink hits the PCB and begins to wet (spread). If left uncured, the ink would continue to spread past a size that would be optimum for print quality and reflection density (contrast) leaving a large, thin spot. The result would be an image with undesirable line definition and contrast. An immediate tack cure of the ink can control the drop spread leaving a smaller diameter, thicker spot that meets industry print quality and contrast requirements.

The second print head mentioned above, contains 256 jetting orifices, jetting drop volumes of about 80pL, and can jet ink at temperatures up to 90°C. The heating of inks in the print head is necessary to ensure that proper jetting viscosity is attained. In addition, jetting at higher temperatures helps the system overcome thermal fluctuations in the production environment. Another advantage for jetting hot ink is that the ink will typically be higher in viscosity at lower temperatures. Therefore, as the drop of hot ink hits the cooler PCB it becomes higher in viscosity, and thus the ability of the drop to spread across the substrate is limited. Furthermore, the restriction in spreading, due to this viscosity change when cooled, results in improved control of print resolution. While the ink still needs to be cured to meet adhesion requirements, this particular approach allows for the UV cure process to take place after inspection. This allows the removal of the image if inspection reveals defects, since the ink has not yet been cured.

Advantages of DOD ink jet technology include inks formulated without solvents, generating ink droplets on demand, eliminating the need for recirculation and make up fluid, cleaner operation and higher print resolution. Additionally, reworking panel legends becomes a simple process if the handling system provides optical alignment of panels. A legend can be overprinted following corrections to the digital image or maintenance of the printhead.

Relative to CIJ, disadvantages of DOD ink jet include significantly shorter throw distances for the drop, slower operating frequency, the need for ink cure, and less availability and selection of inks. The cost of curable DOD ink jet inks is high compared to screen inks. Printhead maintenance can be troublesome and the cost of printhead replacement can be high.

A number of technology companies have identified the advantages of DOD ink jet technology and have implemented this technology into commercially available PCB legend marking systems. DOD ink jet technology is in its infancy in the PCB legend marking application, and as with any new application, there is likely to be technical challenges to overcome before commercially acceptable performance is achieved. Fortunately, history indicates this period is predictable and should be expected.

Print Quality

Print quality may be defined in many ways depending on the printing application and the printing method. Print quality of DOD ink jet on PCBs can be measured by quantifiable metrics such as character size, drop spread, extraneous drops, drop placement error and whiteness. These metrics are intended to quantify an acceptable legend on a PCB. There are particular attributes inherent in DOD ink jet marking that affect these measurements:

- Spot size – is the final diameter of the spot of ink once it has been cured on the PCB. Typical spot sizes are 0.003" and larger. Assuming a particular DPI, the rule of thumb for optimal spot size is the 1.41 / DPI, or the square root of 2 / DPI. The dot pitch is the distance between the center of the dots and is defined as the inverse of the DPI. So, a 300 DPI system has a dot pitch of 1 / 300 = 0.0033". The optimal spot size is 1.41 / 300 = 0.0047". This is illustrated in Figure 2.

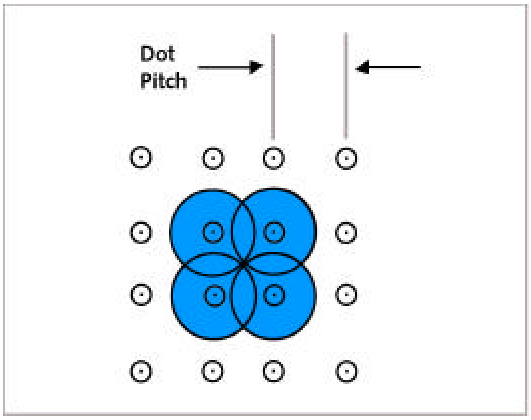

Figure 2 – Spot Size and Dot Pitch

Ideally this provides complete coverage of the substrate with slight overlap of adjacent spot areas. Spot size affects the number of discernable (resolvable) dots you can fit in a particular area, or the resolution of a print. The smaller the spot size the finer the resolution and the smaller characters you can achieve. This formula applies to the general case but there are instances where other spot sizes are desirable.

- Reflection density – refers to the contrast of the ink once it has been placed on the substrate. In the case of legend marking on a PCB, the reflection density refers to the whiteness of the cured ink on the PCB. UV curable screen inks can have a reflection density in the 0.22 range. Single pass DOD ink jet UV curable inks can be in the 0.30 range, slightly less opaque than the screen inks. Reflection density can be improved by several methods including multipass marking, increased pigment loading in the ink, greater number of dots per inch, and spot size control. Each of these methods has a cost associated with it.
- Dots per inch (DPI) – is the number of addressable dots that may be placed along a one-inch path. The DPI of a marking system is somewhat interdependent with the size of the spot and the print quality required.
- Drop shape – DOD ink jet drops are not spherical immediately after being jetted. Initially drops have a larger leading head with a smaller tail shown here in Figure 3.

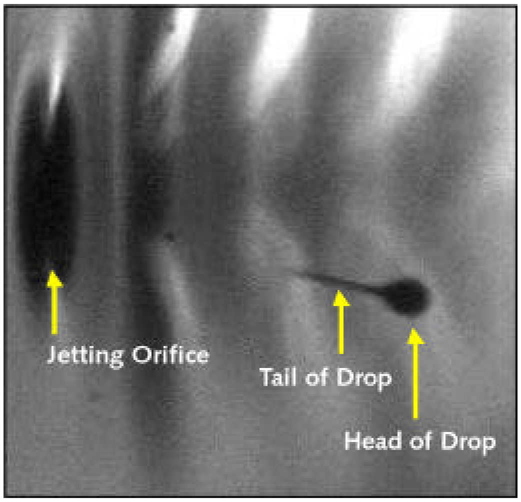

Figure 3 – Head and Tail

The head and the tail typically travel at different velocities. If the head and the tail separate a satellite drop is formed (Figure 4).

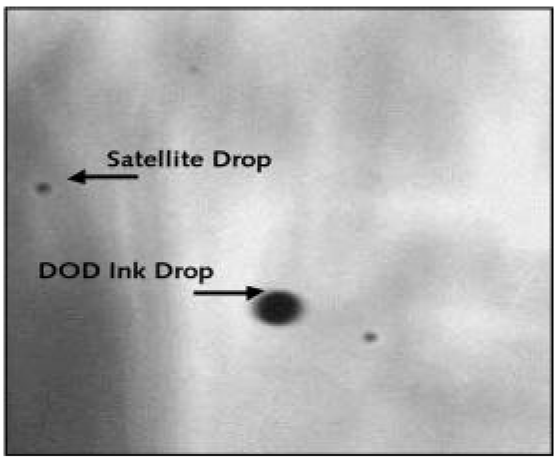

Figure 4 – Satellite Drop

These satellite spots on the substrate are the result of tails that have broken off that land on areas of the substrate not intended for ink. They appear as faint drops that produce a double image or ghosting as illustrated in Figure 5.

Figure 5 - Ghosting

The satellites can often be controlled by limiting the throw distance between the printhead and the PCB or by adjusting print speed.

- Drop volume – is the amount of ink within a single drop. Typically this is 25 – 80 picoliters (pL) for industrial DOD ink jet marking, though drop volumes well outside this range are both possible and available. The drop volume determines the amount of ink that is available to create a printed dot. The more ink there is in a drop the greater potential there is for either a larger diameter or thicker (more opaque) spot. The smaller the drop volume the easier it is to produce a small spot size and therefore allow a higher resolution image.
- Drop spread – refers to how much a drop of ink wets (spreads) once it hits the PCB. Some amount of wetting (spreading) is expected, but allowing the drop to spread without control can lead to poor line definition. It manifests itself as a blurry print. Figure 6 shows an example of a 300 DPI print where the spot size is well controlled. Figure 7 is also a 300 DPI print but the spot size is not well controlled and the same image appears blurred.

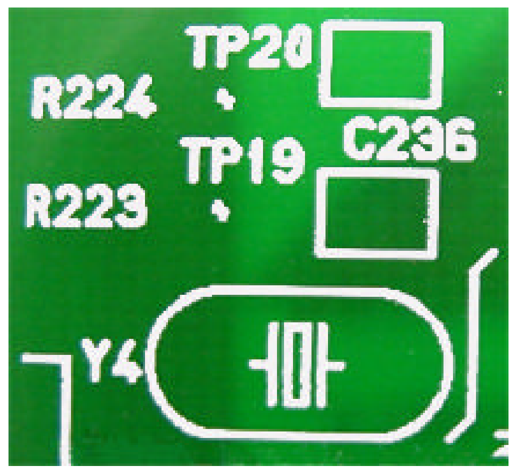

Figure 6 – Well Controlled Spots

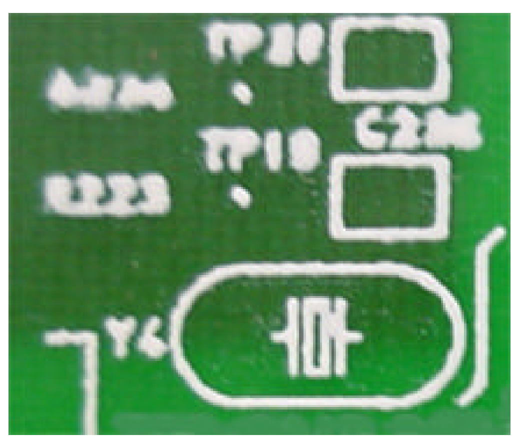

Figure 7 – Poorly Controlled Spots

Considering the ideal case in which the drop of ink is a perfect sphere and neither the printhead nor the PCB is moving, as the drop of ink hits the substrate it transforms from a spherical shape to a dome shape (Figure 8).

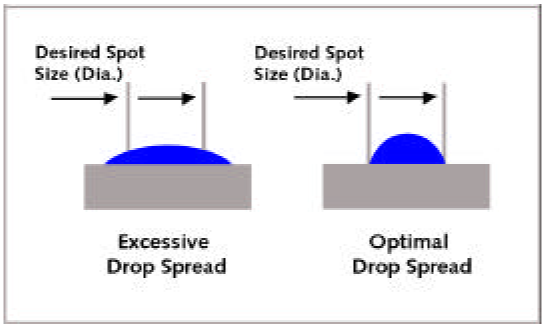

Figure 8 – Drop Spread

The ink drop begins to spread along the substrate. The diameter that this drop is allowed to reach plays a significant role in print quality. Excessive drop spread may cause characters to be filled in and line edges to be blurred. If the spot does not spread enough there will be space between the spots leaving part of the PCB uncovered.

Print quality is dependent on a number of attributes that must be tuned to work together to deliver the desired results. As an example, a 300 DPI mark can be described by an 80 pL drop being ejected from a print head orifice at a distance of 1 mm from the PCB. The drop, initially consisting of a head and a tail, travels toward the PCB at 8 m/s. In flight the tail is drawn into the head forming a spherical drop. Upon impact with the PCB the 80 pL drop begins to spread until the spreading is controlled by some method proprietary to the marking system. Ideally the result is a spot of approximately 0.005" in diameter and reflection density around 0.30 placed precisely where it was intended.

Properly forming a drop of ink and placing it exactly where it was intended to go is a complex task, though it is a task that has been mastered in other industries.

Challenges of DOD Ink jet Development

Perhaps the greatest challenge in industrial ink jet printing is ink formulation. DOD ink jet hardware has matured and has proven to be reliable when used with inks of known and specified physical properties. Substrates however, vary widely, not only from industry to industry but from product to product within the same industry. These varying substrates often require unique ink formulations necessitating a match between the ink, the substrate and the print head components. This is also the case in the PCB industry. The PCB fabrication industry has specific requirements for ink adhesion, chemical resistance, whiteness ,(reflection density) and print quality. Ink must adhere to a variety of solder mask materials as defined by industry standards, must remain white (non-yellowing) while being subjected to high temperature processes and caustic baths all the while being legible down to small point sizes. Developing these white inks is further complicated by the jetting requirements of typical DOD ink jet systems. Titanium dioxide (TiO_2) pigments are used to make ink white. The ink must have properties that allow the TiO_2 material to remain in suspension while also remaining at a viscosity appropriate for jetting through a DOD ink jet print head. This TiO_2 pigment is difficult to keep in suspension. Low viscosity base fluids that jet well typically do not keep the TiO_2 in suspension well. Conversely, higher viscosity base materials that keep TiO_2 in suspension do not jet well at room temperature. Mixing low viscosity inks and heating higher viscosity inks are typical methods of solving this problem.

Ink development is the most critical part of developing a DOD ink jet solution for this market and has been an early barrier to acceptance in other industrial applications.

DOD ink jet is a mature technology but is new to the PCB legend marking application. As a general statement, DOD ink jet is becoming more reliable and less expensive in other industries. As DOD ink jet technology companies learn more about the PCB industry, DOD ink jet reliability will grow in this market as well. Because this technology is just now emerging in the PCB industry there are few choices for supplies. As DOD ink jet gains acceptance more companies will enter the supplies market. The effect will be improved ink performance, a greater range of choices and lower ink prices. Ink development will be a challenge early on as will system design, but as more units are placed these issues will subside as in other industries where market demand has driven solutions.

Common User Problems

The most common problems experienced with DOD ink jet systems include jet outages, satellite spots, poor adhesion and ink management failures. The degree of acceptance for each of these problems is dependent on the tolerance of the end user. For example, while one end user may find a single jet outage is not acceptable, another may tolerate many more jet outages across an array.

- Jet outage – A jet may stop firing for several reasons and may be categorized as recoverable or non-recoverable. A nonrecoverable jet out, also described as a hard jet out, is often the result of internal contamination of the printhead and is not field serviceable. A recoverable jet outage is typically due to surface contamination of the print head array. This is the most common form of jet outage and is generally recovered with routine printhead maintenance. End users can expect to perform printhead maintenance as frequently as once per hour with an industrial DOD ink jet system depending on environmental factors and their tolerance for jet outages. Figure 9 is an example of a legend mark with a single jet out.

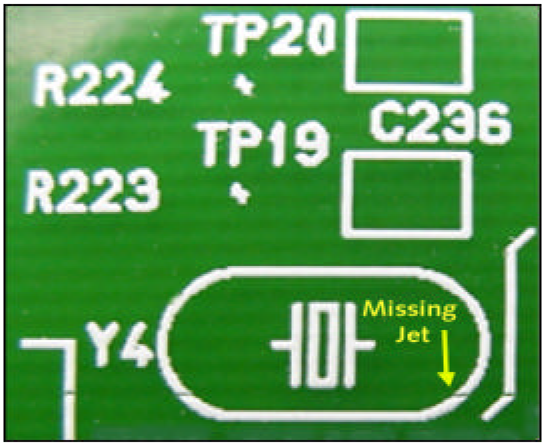

Figure 9 – Missing Jet

- Satellite spots – As previously described, satellite spots can cause significant problems in PCB applications if these spots do not land in their intended location. The may land on pads or other locations that cannot tolerate ink. Reducing the standoff distance between the printhead and the PCB and reducing the print speed are the most common solutions to this problem.
- Poor adhesion – Assuming the DOD ink jet ink and the PCB substrate have been previously matched for adhesion compatibility the most likely causes of intermittent adhesion difficulties are surface contamination of the PCB and inadequate curing. Cleaning the PCBs prior to marking or replacing UV bulbs may be required.
- Ink management – DOD ink jet systems must be supplied with ink via some type of ink management system. Moving fluid from an ink container through an ink management system to the printhead typically involves pumps, valves and reservoirs. As with any mechanical device they are subject to malfunction and failure. While relatively simple to diagnose and fix, problems with ink management systems are common.

While other issues may arise during the legend marking process, these are the most common. These problems have been recognized by technology companies operating in other industries and have been addressed to the point of minimizing but not eliminating them. The same will be true for the PCB fabrication industry.

Conclusion

The PCB industry is demanding improvements in legend marking technology including:

- Reducing setup time between jobs
- Improving turnaround time
- Reducing job costs
- Providing unique identifiers (serialization)
- Improving print quality

Digital printing is well suited to meet these needs. Drop-on-demand ink jet technology is a digital printing method that is widely used in industrial marking and is adaptable to the PCB industry. Technology companies are making investments in PCB legend marking machinery that incorporate DOD ink jet technology and as the PCB application of DOD ink jet matures the machinery will become more robust and supply materials will become more widely available. The PCB industry is ready for a digital solution and the technological leap to DOD ink jet marking will answer the legend marking needs of PCB fabricators.