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Process for Plugging Low to High Aspect Ratio Through-Holes with Polymer Thick Film Conductive Ink in Production Volumes

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Abstract
With an increasing number of designers specifying conductive material for plugging through-holes, a more robust process to produce 100% fill is needed for the whole range of aspect ratios. With via sizes ranging from 8 to 20 mils in diameter and board thicknesses approaching and sometimes exceeding 200 mils, a method to plug reliably and consistently with ease is necessary for the future of the conductive filling process.

It is very common in the industry to use a vacuum table to assist in "pulling" the material into the through hole. Typically this requires several passes with a squeegee to attempt to fill the through hole completely. Because this vacuum assist is enabled throughout the process, air ingression is inevitable. Further aggravating this issue is the fact that many production houses still squeegee this material by hand, offering no control over other important process parameters such as squeegee angle, speed and pressure. The end result is an inconsistent process, with incomplete fill of the though-hole and large air pockets.

This paper will identify the process variables that affect the through hole fill quality and offer solutions to control them. It will also investigate an alternative production method that eliminates the need for "vacuum pull" to draw the material (and air) into the through hole. Rather it utilizes a "direct imaging" method that applies positive pressure within an enclosed print head to press the material into the through hole while maintaining control over all process parameters. With this process, it is now possible to fill through holes more quickly and efficiently, providing a more reliable process that enables a high-volume application of conductive through-hole.

Introduction
As electronic products continue to push for smaller, faster and cheaper components, printed circuit board technology is constantly evolving to meet these needs. The focus of much of the PCB industry's technology development are through-hole and via structures, as these typically limit the size and high-frequency performance of circuit boards. Additionally, the via formation process is the largest cost driver in PCB production. Microvia-based board fabricators can choose from a number of different technologies for formation and filling of vias, including the traditional laser drilled microvia but also extending to a variety of solid silver or copper paste plugged processes such as ALIVH and B2it or electrodeposited copper via structures such as the Neo-Manhattan and AGSP processes.

Formation of the ubiquitous and larger-diameter through-hole, on the other hand, provides a more limited set of options, commonly satisfied by using mechanical drilling followed by sidewall plating and plugging with non-conductive materials. An alternative approach increasing rapidly in usage is the plugging of through holes with conductive thick-film pastes. This approach offers a number of advantages to board designers including improved high-frequency performance, miniaturization, and improved thermal properties. One of the most common uses of this approach is in via-in-pad structures for BGAs, as it enables more efficient space utilization. The solid plugged through-hole gives a convenient surface for metallization and prevents penetration of solder through the board during the assembly process.

The history of solid through-hole plugging with thick film paste dates back many years. DuPont first released its CB100 product in 1997 and described a variety of potential uses in 1997 and 1998 IPC Expo papers.[1,2] However, usage at that time was constrained as the fabricator infrastructure for processing conductive paste was limited and designers were unaware of the benefits this approach offered. This situation has changed quite a bit in recent years, as the use of conductive through-hole filling has exploded and most fabricators are capable of processing such boards.

As the industry has matured and higher-volume applications are utilizing conductive through holes, it is necessary for the process of through-hole plugging to become more automated and standardized. The time required for filling needs to be reduced, while improving the overall quality of the process. These requirements necessitate the new equipment and process technology development for through hole filling presented in this paper.

The Application

The majority of OEMs require 100% fill, planarity on both sides of the via and minimal air voids. The lack of continuity in via plugging processes used industry wide results in improper and unreliable vias. Silver conductive via plug inks are typically high in viscosity and solids. With this consistency, the manual processing of plugging with conductive via fill materials is laborious and lacks repeatability (see Figure 1). The method of filling via holes varies greatly in the industry today, from the simplistic hand-fill application to a fully Automatic Stencil Printer. The quality of results achieved with the method of “doctor blading” material into the vias/through holes using vacuum assist is dependent upon the technique of each technician. Squeegee pressure, angle and speed are a few of many operational variables that affect the fill quality. Other variables include the amount of paste applied in front of the squeegee, strength of vacuum and the wide range of aspect ratios. In order to minimize the effects of said variables, an automated process is desired and well over due. Where the cost of equipment is obviously a consideration, the via fills performance criteria, and therefore its quality of fill specifications, will dictate the best method for each application.

If all vias on the board require conductive ink fill, then the material can be placed directly onto the board surface. However, it is more typical for a board to require selective via filling. To accomplish this a template is used that matches the configuration of the vias to be filled. This template acts as a mask that, once aligned over the board, exposes only the vias requiring fill. This can be a sheet of machined Mylar® or a metal stencil, typically 3-7 mil thick. Due to the relatively high viscosity and large particles of the Conductive Ink paste, a mesh screen is not applicable for this application.

The via filling process should always be performed from one side of the board. Filling from both sides is not recommended as it will cause a large air void to develop as the two printed materials meet in the middle of the via barrel or the second side is capped with minimal ink penetration (see Figure 2).

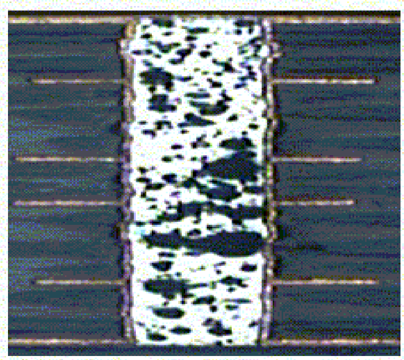

Figure 1 – Typical Hand Filled Results

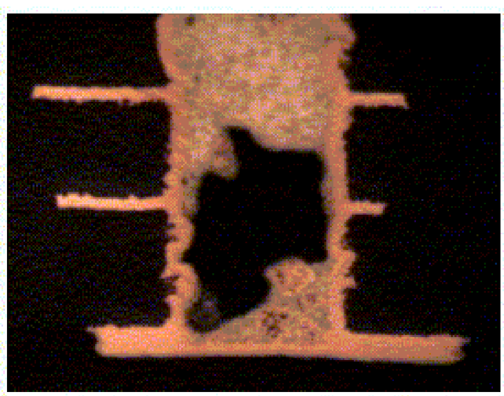

Figure 2 - Results after Filling from both Sides of the Board

A simple "Hand-Fill" application is the least expensive, slowest and least controllable method (see Figure 3). The board is placed on a flat surface and paste material is pressed into the via using a hand-held Squeegee. The number of print strokes required is dependent on the board thickness to via diameter ratio. The higher the aspect ratio the more strokes required. A 90mil thick board with 15 mil via (6-1 ratio) can require as high as ten to fifteen print strokes to achieve a complete fill. However, repeated print strokes will encourage air voids with each stroke, so minimizing the print strokes is always the goal.

To assist the paste material into the via holes a *"Vacuum Table Assist"* method has been used. The board is placed on a tabletop with a matrix of through holes connected to a vacuum source, which is turned on during the filling process. Filter paper is placed between the board and vacuum table to contain the overprinted material. With this negative force applied, the material will more easily flow into the via, reducing the number of print strokes required. However, even with this vacuum assist method, to achieve a complete via fill for high aspect ratio applications, several print strokes may still be required. As a general rule, if the panel can't be filled completely in one pass with vacuum assist, it should be filled using multiple passes without vacuum assist.

Figure 3 – Hand Fill Application, with the Board Tapped to a Vacuum Table using a Clear Mylar® Template

The critical process parameters for this application are squeegee angle, print speed, pressure applied, maintaining the proper roll volume as well as material handling (see Figure 4). Printing too fast will trap air within the paste material. Squeegee angle and pressure variations change the amount of material pressed into the via changing the number of strokes required to completely fill the via. Because this is a totally manual process, it is not possible to offer settings for these parameters, which is why the "*good*" technician who "*knows how to do it*" is usually tasked with this job.

Also, care must be taken while handling the paste material. If the paste material manufacturer suggests mixing the material before use, this must be done gently to avoid introducing air bubbles within the paste. The process of spooning material onto a template and then transferring it back into a holding jam between prints is another opportunity for air to be trapped. Obviously, trapped air within the paste material may find it's way into the filled via.

Another consideration is the UPH (Units Per Hour) requirements. The time it takes to manually set up and process each board by hand typically takes five to ten minutes per board. This time is spent securing the board onto the table, blocking off unused vacuum ports, aligning the template to the via holes and securing it in position, loading the paste material onto the template, in addition to the actual process of printing. Once printed, the paste material is transferred to a holding jar so the area can be cleaned up for the next board. Realistically, this method of fill is limited to 10 to 12 boards per hour. To achieve higher production volumes, an automated equipment solution is required. Stencil printers available on the market today offer cycle times for this application in the range of 60 boards per hour.

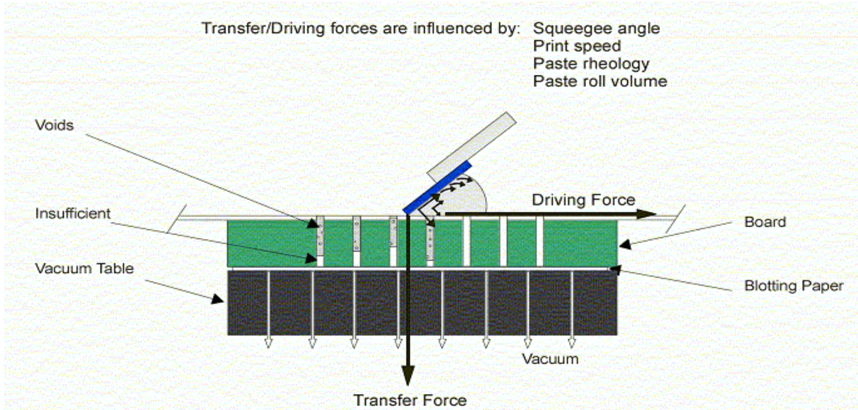

Figure 4 – Via Fill Process Using Squeegees

Taking Control of Your Process

To improve the quality of the fill, a complete fill with minimum micro and no large air voids, the process must be under control (see Figure 5). To achieve process control, all variables that affect the desired end result must be known, measurable, and repeatable. Automatic stencil printers provide this level of control by offering computer-controlled axes for critical process parameters, allowing them to be monitored and optimized. Fully automatic stencil printers also provide computer controlled stencil alignment. This eliminates stencil-to-board alignment issues while allowing a smaller stencil aperture to be used, minimizing the material left on the board after printing.

The ability of computer-controlled equipment to save product recipes is another significant process control feature. This enables the process engineer to not only establish the optimum process but also to save the product file, enabling production to repeat the same proven process, and therefore the same good results, time and time again.

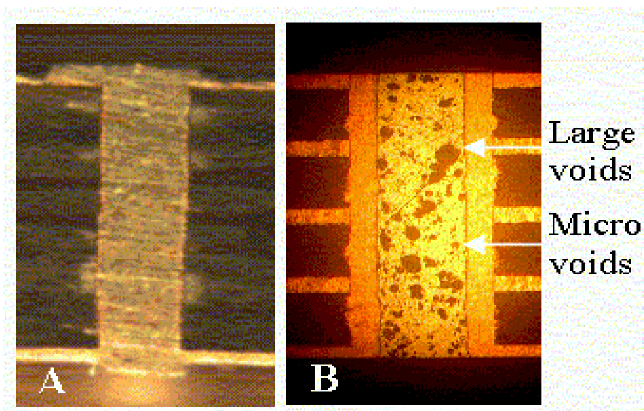

Figure 5 - (A) No Voids Present Using an Enclosed Head (B) Voids Present Using Multiple Squeegee Pass Method

Paste Material Management

As mentioned earlier, maintaining control of the paste material is critical to achieve a quality void free fill. Aggressive handling of the paste material, either during the mixing stage, while transferring it to the work area, or during the print process can trap air within the paste material increasing the percentage of air voids in the via.

An enclosed "Direct Imaging" print head offers several benefits to this application (reference 3). Because it operates by applying a positive downward force to transfer the paste material into the via holes, vacuum assist is not necessary. In most cases, only one or two print strokes is required to achieve a complete via fill. For very high aspect ratios, additional strokes may be required, but this is significantly less than the ten or more print strokes required by the hand fill method.

Another advantage of the Direct Imaging method is that multiple strokes will not encourage air voids. This is because vacuum has been removed from the process, in addition to the superior parameter controls available on automated equipment.

An enclosed print head system utilizes a novel technique for the printing of conductive inks and other viscous materials. The three key elements to the system that differentiate it from the conventional squeegee system are:

1. A totally enclosed print head, which ensures that the paste material is not exposed to the environment and is maintained in an optimum condition.
2. A direct downward transfer pressure mechanism eliminating the need for squeegees.
3. Independent programmable paste pressure.

Figure 6 shows the "ProFlow, Direct imaging" print head concept. The paste material is placed inside a transfer head, which is directly attached to the machine's print carriage in place of the squeegee (see Figure 7).

For the print cycle, pressure is applied to the outer transfer head to ensure that a good seal is made between the paste retention system and the stencil. Pressure is then applied to the central piston and the paste is forced directly downwards into the conditioning chamber, through the stencil apertures, filling the vias. As the unit moves across the stencil, the trailing wiper lifts up the paste material from the stencil surface and creates a rolling movement within the chamber. As the paste material is consumed, the volume within the conditioning chamber is kept constant by the pressure applied to the upper chamber. At the end of the print stroke, the print head does not lift up, maintaining a seal between the head and the stencil as well as reducing the printing cycle time.

There is no need to remove the paste material from the "Transfer Head" for storage. The Transfer Head itself is easily removed from the printer and can be stored in a refrigerator, paste enclosed (see Figure 8). Due to the added mass around the material, you should allow additional time for the material to reach room temperature before the next production run.

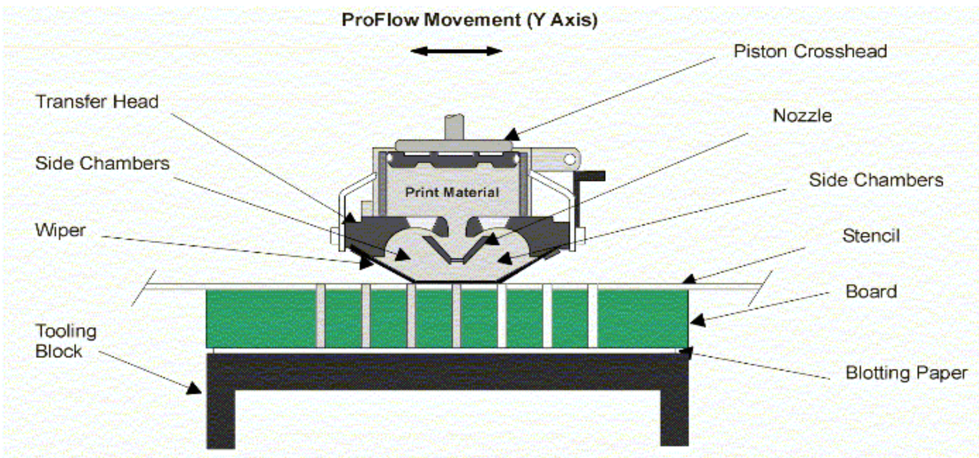

Figure 6 – Via Fill Process Using the Enclosed Print Haed

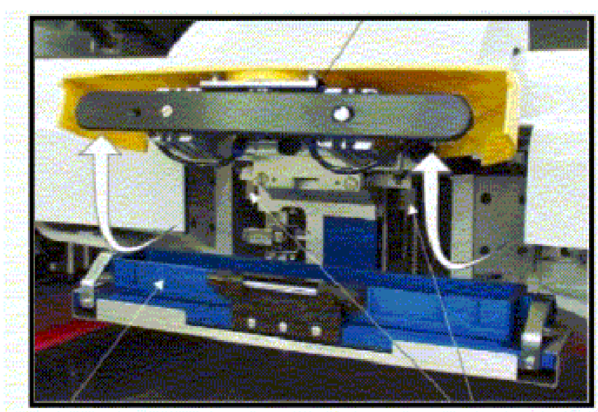

Figure 7- Transfer Head Mounted to a DEK Printer

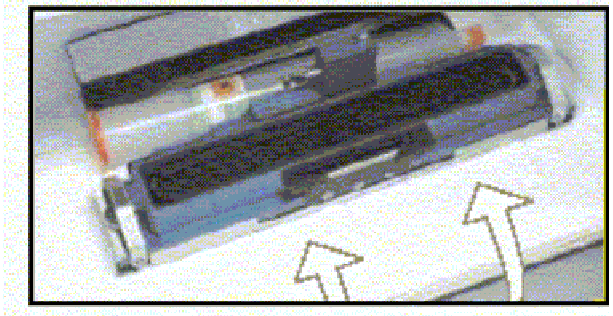

Figure 8 - Transfer Head Stored with Paste Enclosed when not in Use

Stencil Design

The stencil design criterion is relatively simple for this application. Stencils are usually stainless steel foils 3-7 mil thick, mounted in a frame sized for the printer being used. The thinner 3mil foil will leave less material (nail head) to be removed after the dry/cure process. However, the thicker 5-7mil foil is sturdier and will usually have a longer life on the production floor. The apertures are either chemically etched or laser cut, and most stencil manufacturers provide next day delivery. Because of the superior alignment capability of the fully automatic stencil printer, the aperture size can match the via diameter of the board. However, if board stretch is an issue, which would cause a stencil misalignment at the far ends of the board, this tolerance should be added to the aperture size. Realistically, via diameter plus 5mil will be fine for most applications.

Print Trials

Print trials were run to evaluate the quality of via fill using an automatic stencil printer and enclosed print head. Figure 9 shows X-rays of a hand printed board compared to a board filled with the Proflow enclosed print head.

A DEK automatic stencil printer fitted with the print head, was used with DuPont CB100 polymer thick-film conductive ink for all trials. Immediately after printing, the percent of fill and air voids were inspected using a "Phoenix" X-ray machine. The boards were then cured and sections taken for further inspection.

As expected, the variables for achieving a complete fill are print speed, paste pressure and the number of print strokes (see Table 1). The "paste pressure" parameter sets the internal pressure within the enclosed head and forces the paste material into the vias. The "Print Speed" parameter determines the duration of time the aperture is exposed to the paste. The slower the print speed, the longer the via hole is exposed to the print head paste area.

Table 1 - Critical Parameters

Parameter	Range available
Paste pressure	0 to 4 bar
Print speed	0.1 to 70mm/sec
# of print strokes	1 to 30 per cycle

The desired fill was easily achieved by adjusting these control parameters. When attempting a partial fill, the deviation range via-to-via was a maximum of 15%, allowing a stable 85% to 100% fill process (see Figure 10). Figure 10-B shows the over fill achieved by increasing the paste pressure.

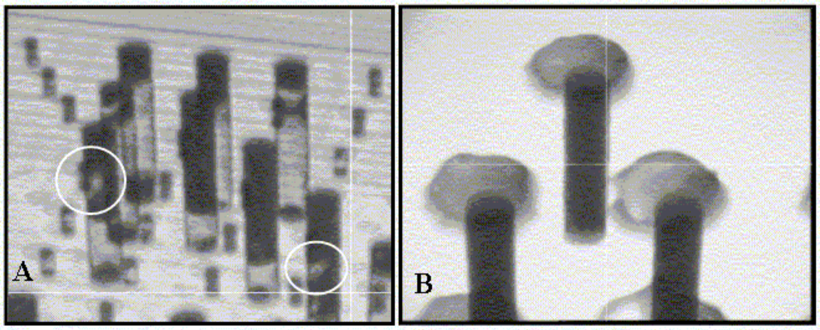

Figure 9 – (A) Hand Filled Method (B) Proflow Enclosed Print Head Method

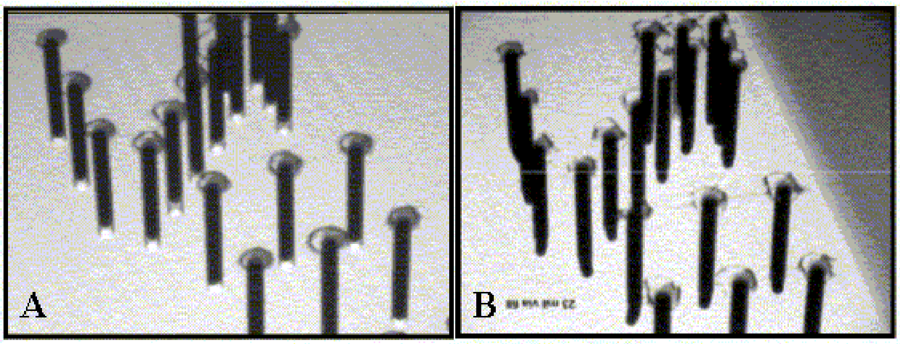

Figure 10 - X-ray Results of (A) a Partial Fill, and (B) the Over-fill Achieved Using the Enclosed Print Head

Limiting the over fill is suggested to assist the planarization process. Long protruding material, sometimes called noodles, beyond the board surface increases the possibility of chipping during the planarization process. One method of limiting this overprint is to use a carrier, which will dam the exit side. For this test FR4 material of the same size as the board was used as a carrier with blotter paper placed between the two boards to collect the over print.

Print trials on a copper plated test board, 18”x 12”x 0.062” with via hole diameters of 0.011” after plating (5.6 to 1 aspect ratio) proved to be a robust process with 100% via fill using the following parameters, (see Figure 11).
Paste pressure = 3.6 bar
Print speed = 25 mm/sec
Print strokes = 2

A single stoke process was also achieved by slowing the print speed to 10 mm/sec. It was noted during these print trials that the print side, the side of the board in contact with the stencil during print, maintained a cleaner deposit of material at print speeds of 20 mm and up. Slowing the print speed will increase the fill time allowing a higher aspect ration to be filled in a single pass, but will cause the print side to smear a little more.

A 10 to 1 aspect ratio board, 18”x 12”x 0.180” with via hole diameters of 0. 018” after plating also achieved a 100% via fill by adding additional paste pressure.
Paste pressure = 4 bar
Print speed = 25 mm/sec
Print strokes = 2

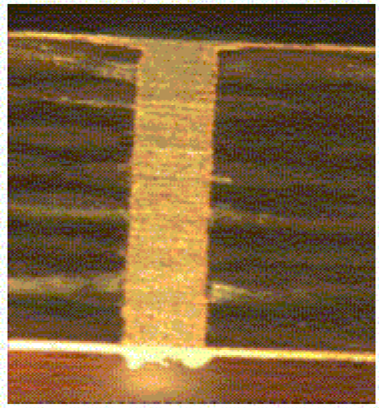

Figure 11 – Via fill Quality Using the Enclosed Print Head

Conclusion

A robust production level via fill process is possible by utilizing stencil printers already used in the electronic manufacturing industry today. The enclosed print head enables the polymer thickfilm conductive ink material to be "printed" into the via holes, rather than using a squeegee to pack it. This method eliminated large air voids, and decreased the occurrence of micro air voids to a minimum. Via hole to board thickness aspect ratios of up to 10 to 1 have been accomplished in these trials. With additional paste pressure and print stokes, higher aspect ratios are also possible.

In addition to these process benefits, automatic stencil printers bring a level of process control and paste material management not available to those attempting the manual hand-fill method, with realistic production throughput levels in the range of 45 - 60 boards per hour.

References

1. J. J. Felten and S. A. Padlewski, "Electronically Conductive Via Plug Material for PWB Applications," IPC Printed Circuit Expo 1997, March 1997, San Jose, CA.
2. P. Charest, J. Henderson, R. Wessel, "Polymer Thick Film Via Plug for PCB's and Packaging Applications," IPC Printed Circuit Expo 1998, April 26-30, 1998, Long Beach, CA.
3. Mark Whitmore, "Direct Imaging - A New Technique for Dynamic Print Control", Proceedings – NEPCON West 1998, Anaheim, CA, 1998, pp. 134-145.

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