Via Hole Filling Technology for High Density, High Aspect Ratio Printed Wiring Boards Using a High Tg, low CTE Plugging Paste

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Abstract

The continued fast pace towards miniaturization is leading circuit board designers to push the envelope on integration density. This trend is driving fabricators to closely look at methods and processes that will enable the move towards sequential lamination and blind and buried via technology. Circuit board fabricators particularly in North America are adopting techniques such as via filling capability with non-conductive, high Tg, low CTE plugging pastes. This paper describes the implementation of the via filling process in a highly effective and reliable fashion for high density, high aspect ratio printed wiring boards. Close attention is paid to use of these via filling materials under high temperature assembly conditions. In addition, via plugging material requirements, equipment considerations and process limitations will be presented. Further, the pros and cons of different filling techniques are discussed. Finally, desmear and metallization techniques to insure adhesion of the plating to the filled via are presented in the context of "Best Practices."

Introduction

Filling of plated through holes is not new to the pwb fabrication industry. For many years, end users required some or all via holes to be partially plugged with solder mask. This task was required in order to prevent solder from wicking through the holes (to the component side) during the assembly process and to create a vacuum for electrical test. Minimizing flux residues in the holes is another valid reason to undertake this operation.

The concern of plugging through holes with a standard LPI resides in the fact that these inks are typically 60-80% solids content. During the drying/curing process, the solvent evaporates and the hole plug shrinks, often leaving a small gap between the through hole barrel and the plug. This of course, can lead to a lack of adhesion of the plug to the hole wall. There is a second risk: residual solvents from the LPI. During the curing process, operating conditions may lead to a "skinning over" of the plug. This scenario causes solvent to remain entrapped within the hole. The consequence is the solvent will expand during the heat of the soldering operations, leading to cracking of the fill. As through hole aspect ratios increase, it may become impossible to evacuate all of the solvent. Process curing temperatures and ramp up time to cure must be carefully monitored, regardless of the technology level of the pwb. This issue will be presented in detail elsewhere in this paper.

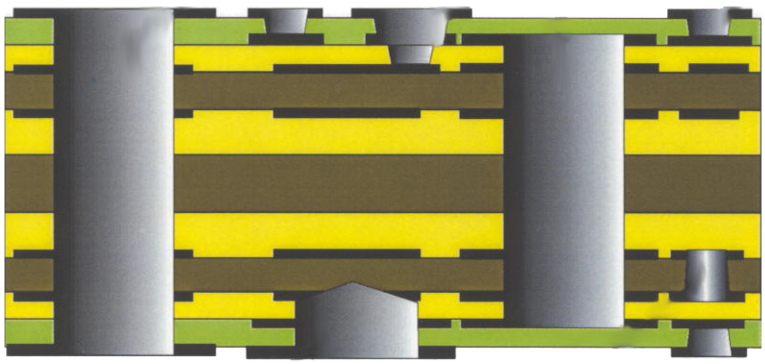
While many fabricators continue to be somewhat successful with conventional plugging with LPI's, the growing density and miniaturization of complex electronic interconnection substrates requires new process technology. The LPI's have limitations that can only be addressed with the so-called plugging pastes. These plugging pastes are nearly 100% solids content and were primarily developed for blind and buried vias and sequential build technology. However, other formulations have been developed for filling through holes in order to replace the LPI inks, based on the same principle of 100% solids content.

Definitions

It is helpful to understand the term, "Via hole plugging" versus "via hole filling." This is an important distinction, but nonetheless must be put in the proper perspective. Via hole filling is used for the non-planar filling of plated through holes. Via hole plugging is synonymous with the planarization of blind and buried vias, as well as through holes. Via hole plugging is applicable to HDI and microvia designs. Brushing (or planarization) is required to remove the excess material and create the flat surface. This technique will be discussed in the section on " The Process of Via Hole Plugging."

Via hole plugging is in demand due to the explosive growth in HDI designs employing area array for IC packaging, via in pad, and landless designs. Achieving planarity of the via for dielectric formation is another key market driver. Uniform dielectric spacing between layers of circuitry and the ability to metallize the dielectric as well as achieve plating adhesion is critical.

Examples of vias are shown in Figure 1. (IPC Technology Roadmap-National Technology Roadmap for Electronic Interconnections 2000-2001 (4).



In Figure 1, the construction describes an HDI substrate with both plated through holes, filled buried vias and microvias. The plated through holes pass through the entire board and do not require a planar and complete filling. A standard via hole fill would suffice. In this example, the substrate has a core that has been fabricated using conventional methods. The core has a dielectric layer on each side. Microvias have been formed connecting layers 2 to layer 3, and layer n to layer n-1. The top layer is then metallized, and a second dielectric layer applied to each side. Microvias are again formed to connect layer 1 to layer 2. A PTH is formed connecting all of the layers. It should be noted that this example includes a buried via connecting layer 3 to layer 4. The buried via is a candidate for hole-plugging. With respect to the blind vias, generally sufficient resin is available through the use of resin coated foils to fill the vias. This is only recommended for small diameter blind vias that are low aspect ratio. Larger diameter blind vias or small diameter blind vias of high aspect ratios will not have sufficient resin available to fill the vias. Air inclusions during the lamination process may reduce long-term reliability. The concern with air inclusions is that in effect, air is an insulator. Thus, air reduces both electrical and thermal conductance. While it is acceptable to endure very small voids in the via simply due to processing and material properties, it is desirable to minimize air voids through material property selection, via plugging techniques and equipment designs (1).

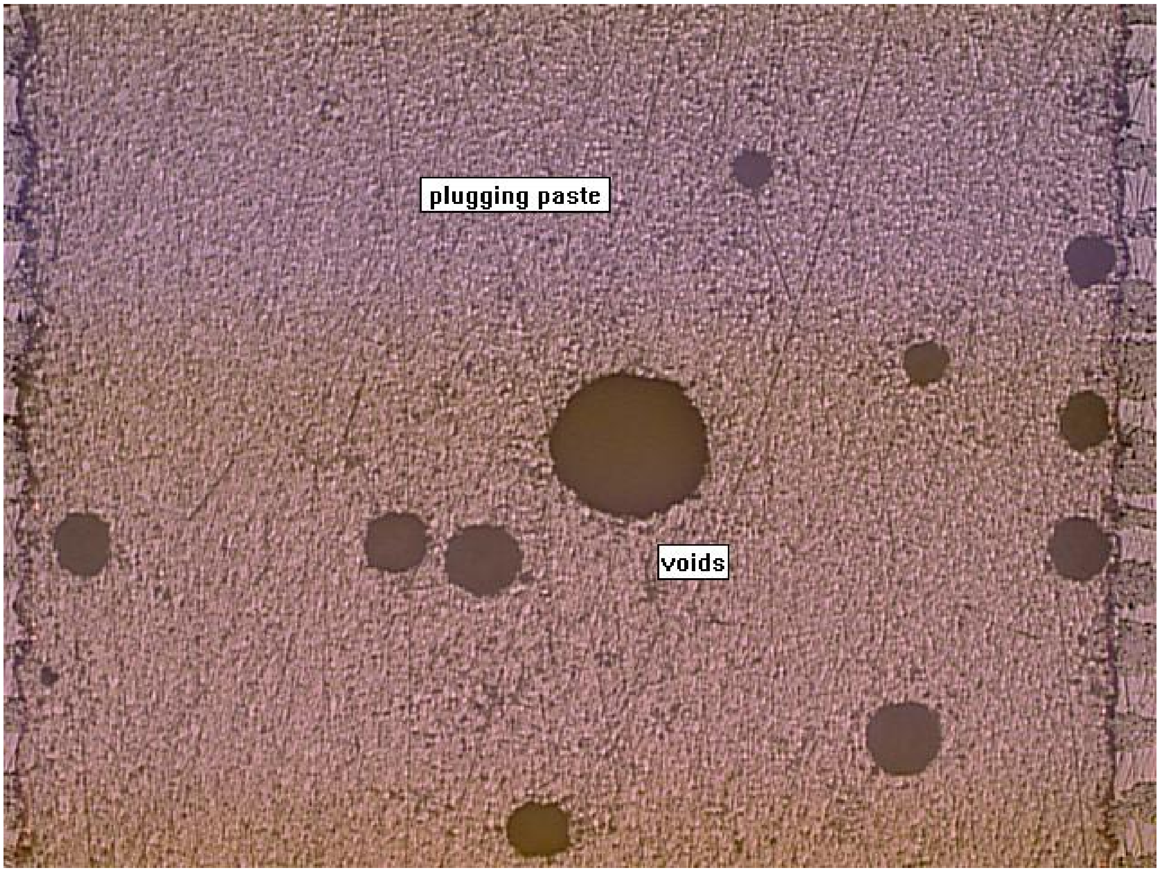


Figure 2-Example of air pockets (voids) in a plugged via.

Thus, the best alternative to the dependence on resin to fill vias is to use specially formulated conductive and non-conductive via filling or via plugging pastes. The purpose of this paper is to focus on non-conductive via filling materials.

Plugging Paste-material and properties

The formulated plugging paste materials as described in this paper are used primarily to fill multilayer buried vias. However, the process has been adapted for via in pad as well as for through holes. More specifically, overmetalization of the paste must be carried out without issue.

There are specific requirements for the plugging paste material. These are:

- Good adhesion between copper and paste even under temperature influences
- Good adhesion of copper, dielectrics or photo resist
- Solvent free, one pack system
- No air inclusions in the paste
- Tg > 140 °C
- CTE < 40 ppm (below Tg)
- No shrinkage during curing
- Easily planarized

Additionally, the plugging paste material must maintain a reasonable shelf life at room temperatures. Some commercially available formulations have a one-month shelf, greatly reducing the processing window (2).

A 100% solids content of the paste material with the thermally cross-linkable epoxy resin and specially designed ceramic fillers ensures a low coefficient of thermal expansion. Interestingly, the coefficient of thermal expansion must remain in the 40-60 ppm range in order to insure that no cracking occur in the filled via. In addition, it is critical that z-axis expansion be minimized in order to prevent the plated cap from lifting (Figure 3).

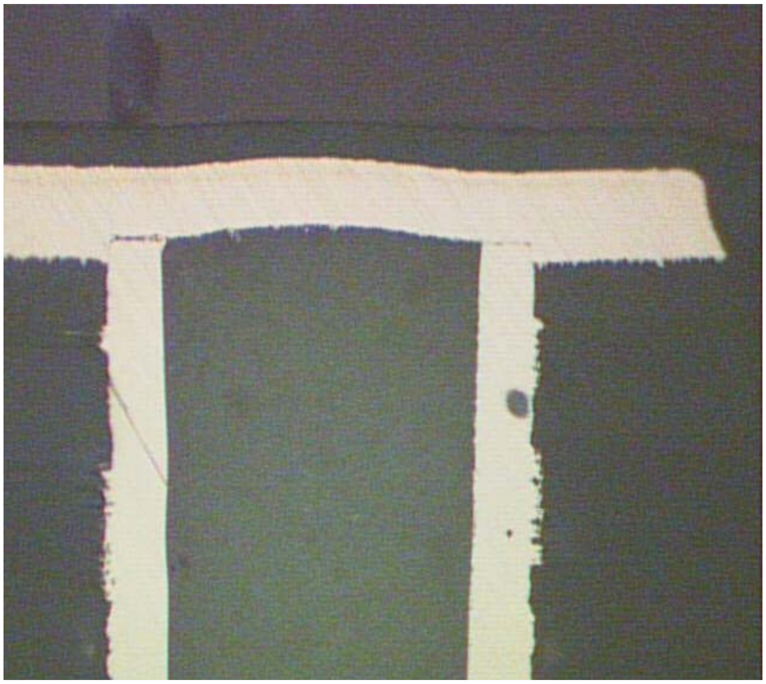


Figure 3-Excessive CTE leading to plated copper lifting from filled via.

Z-axis expansion not withstanding, the second critical thermal characteristic is the glass transition temperature of the cured paste material. Typically a Tg of 140 C is ideal. However, the Tg can be increased by prolonging the final curing time and increasing curing temperature from 140 C to approximately 175-180 C. It is desired to have the highest possible Tg without impacting the flow and metallization properties (1). With increased densification leading to higher I/Os, smaller components, higher assembly temperatures and smaller vias, the CTE gains increased importance. It is considered that the hole wall quality, especially the thickness and leveling of the plated via copper plays an important role with respect to via fill quality and integrity. The elasticity of the plated via copper must be sufficient in order to absorb thermal expansion within the barrel caused by thermal cycling type stresses as well as thermal shock stress from soldering. Thus the CTE values of the paste must be minimized in order to relieve stress that will cause the plug to over expand, allowing the overmetalized copper deposit to lift (2). It is critical that to attain long term stability within the filled via under load conditions, load amplitudes must be minimized as much as possible. This means that the CTE must be as low as possible over the temperature ranges (2).

It should be noted that temperature control of the via fill material curing process influences the Tg. As a consequence, uncontrolled reactions that include excessively fast or aggressive curing times will lead to a cross-linked network with many voids and potentially cracking within the plugged via. This type of situation leads to low Tg and higher CTEs, which are both undesirable (2, 5).

Additional material considerations include paste rheology, leveling properties, ability to withstand thermal stress. The particle size and distribution of the filled materials also play a significant role in the material's characteristics. Rheology is an important property as it governs material flow during the via filling process. Optimum rheological properties enhance the uniform filling of small and large diameter vias (3, 5).

Via filling: Methods of Application (3)
There are several methods used to fill or plug vias. Those are described below as well as the advantages and disadvantages.

Roller coating
Plugging vias with the roller coating technique requires investment in capital equipment. Forcing the paste through the vias by means of a roller effects the plugging operation. Paste is held in a trough and the action of the roller picks up the paste on the underside of the roller. The pwb is pressed against the coating roller from above, and the paste that is located between the pwb and the roller is pressed through the vias. The board then passes through squeegees designed to remove excess paste.

The advantages and disadvantages of the roller coating process are detailed below.

Advantages:

- Rapid filling of vias
- No screen stencils required
- Ease of planarization due to relative cleanliness of surface
- Fewer process parameters to control versus screen process

Disadvantages:

- Vias not required to be plugged must be masked off
- Higher risk of dip formation in the plug
- Trough volume of 8-10 kg's required(paste must have good shelf life)

The issue of dip formation has to do with the flow characteristics of roller coating formulations. These particular pastes formulated for roller coating posses certain flow characteristics. These flow characteristics are related to capillary effects, meaning the smaller the hole diameter, the greater the dip. Newer formulations have been developed that have had their curing characteristics modified to eliminate this potential for sagging.

Screen printing
This process employs a stencil with the via pattern drilled to match the pattern of vias on the pwb. Screen printing requires that the vias be completely filled with one stroke of the squeegee. Otherwise, air will be entrapped within the plugging paste.
One particular requirement for the screening process is that ink should protrude equally from both sides of the via. This requirement is met by placing a backup board (a stencil drilled with then same hole pattern underneath the pwb. This allows the paste to fill the via while minimizing air inclusions. A small nail head is formed on the underside, ensuring a complete fill.

Of course, unlike the roller coating process where few operating parameters were considered critical, screen plugging of inks is a different matter. Screen mesh, screen tension, squeegee profile (rounded or right angled), off contact and squeegee hardness affect the quality of the fill. A manufacturer must make adjustments in these process parameters depending on via aspect ratio. Often, several test panels must be processed in order to dial in the process.

Advantages of screen printing include:

- Vias not requiring fill are kept free of plugging ink
- Well known and easy to control process
- Wide availability of screen printing equipment

Disadvantages are:

- Screen stencil required for each layout
- Some difficulty printing designs with significantly varying hole diameters

Vacuum Plugging Application

The latest equipment iteration to gain the largest share of the via plugging market is based on automated vacuum plugging equipment. This machine is designed to fill holes in printed circuit boards with conductive or non-conductive paste. The hole filling can be applied in via and in blind holes. The filling from blind holes is possible in a double side mode in one step. The machine is equipped with a glass cover for visual quality control on both panel sides.

Functionality: Once the printed circuit board in vertical position has been hanged upon pins, the door is closed and the vacuum process started. The vacuum has built up after about 30 seconds. The filling process begins with the paste being pressed out of a cartridge into the bores while the squeegee is moved over the printed circuit board. Both the kiss pressure of the filling heads to the printed circuit board and filling pressure are adjustable. The vertical motion is realized by an adjustable servomotor.
If there are still some hole voids, the operator can replug the same printed circuit board. That’s the great advantage when “plugging under vacuum”.
The paste is kept in refillable cartridges. Subject to the printed circuit format, different squeegee sizes are available.

The latest vacuum filling equipment is equipped with various options that allow the operator to vary certain parameters. Typically, the following parameters can be adjusted by the operator to effect an optimal process.

Curing of the plugging paste

Once the paste has been applied to the vias, the via hole plugging material must be cured. There are both thermal curing and UV curing versions of plugging pastes commercially available.

Thermal curing requires a temperature of approximately 150^{o} C for 30-45 minutes depending on the particular product used. The thermal curing version is single stage. However, with this version, one must be careful not to over brush the pwb as plugging paste from the via, causing the dip. The use of brushes with a ceramic surface gives very good results. The formation of the nail head (mentioned above) is beneficial in providing sufficient material in the plug so as not to create the “dip.”

It is critical that the plugging paste be thoroughly cured. If the material is undercured, there is a significant risk of inadequate plating adhesion and the possibility of excessive Z-axis expansion. This risk is magnified when very high aspect ratio vias are filled. Typically, for aspect ratios greater than 8:1, a dual stage cure cycle can be used. Regardless, the fabricator must insure a complete cure of the material. Thus, it is essential that the cure temperature be maintained for the recommended time. Excessive cure temperatures have been known to over-oxidize the plugging paste. When the filled vias are processed through an alkaline permanganate desmear system prior to metallization, an excessive amount of the cured paste maybe removed. The problem manifests itself as a dish down as shown in Figure 4.

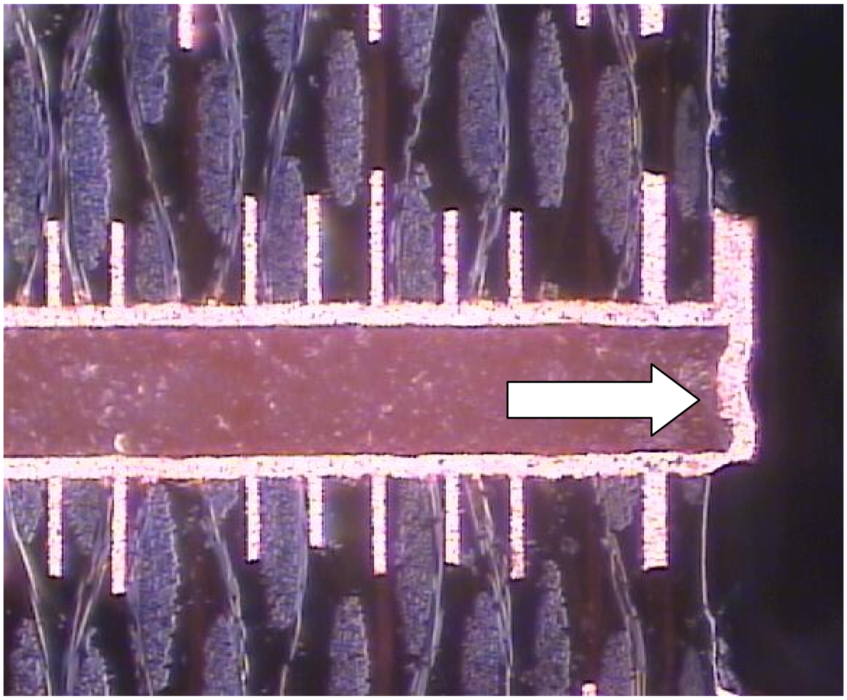


Figure 4. Arrow points to dishdown area within the filled and plated via.

In a soon to be released document from IPC, standards writers have commented on the dimple or depression as shown in Figure 4. While no set depression limit has been established, it is suggested that a depression of not to extend below the lower portion of the copper surface foil. Deep depressions will cause issues with subsequent metallization processes as well as interfere with component mounting if used for sequential build (6).

An example of an unacceptable dimple (at least until the standard is fully established) is shown in figure 5. A possible cause for the dimple is shown in Figure 6. As the photo clearly shows, the discoloration near the top portion of the plugged via indicates excessive curing temperatures and or time. The discoloration indicates oxidation of the plugged material making the material more susceptible to attack from alkaline permanganate. Of course, there are other causes of dishdowns or dimples. Some of the more common causes are volume shrinkage of the paste due to moisture, improper processing parameters for the filling operation, and a very fast cross-linking of the material due to an incompatibility between the catalyst and the resin materials (5, 6)

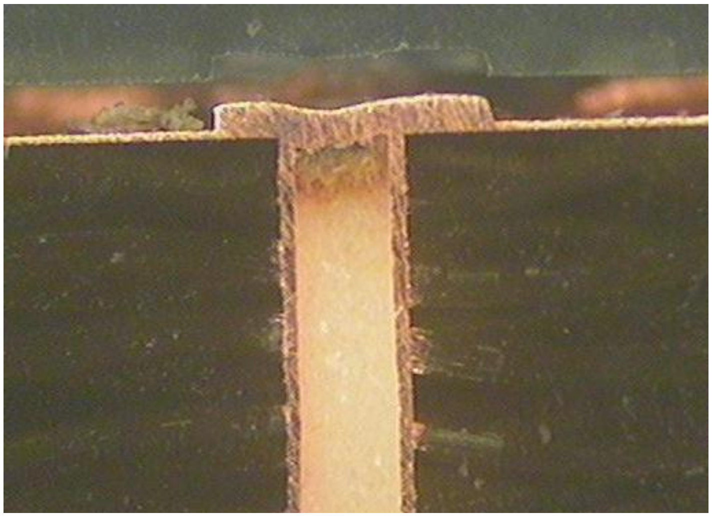


Figure 5-Dishdown issue. Excessive and most likely caused by over curing. See the discoloration near the top of the filled via.

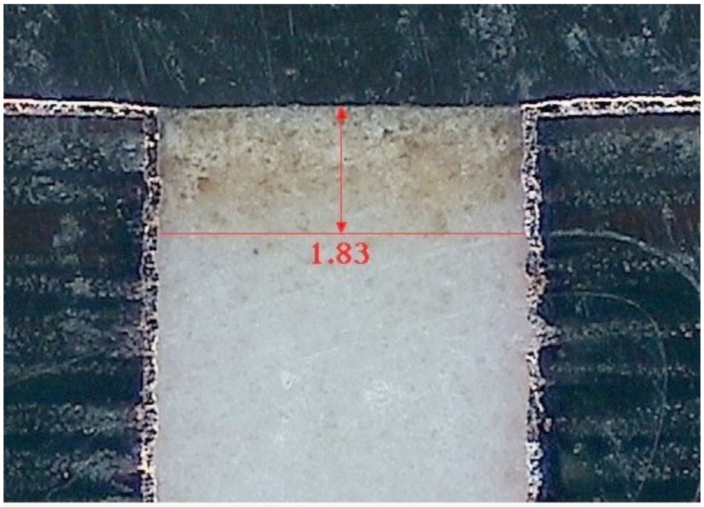


Figure 6-Discoloration of the cured paste due to excessive curing temperature and time.

Planarization(brushing)

After the curing step, some of the cure plugging material will protrude from the via. This material must be removed through a planarization process. For planarization to be deemed successful, complete removal of the protruding ink while not removing any of the material from the via is required. The brushing process must not damage the knee of any unplugged holes, and copper should only be removed evenly and minimally along with the excess plugged material. Brushing equipment should be equipped with a very precise and fast pressure control system, as well as an automatic system for measuring panel thickness.

The brushing or polishing step must provide a level surface and as smooth as possible. Uneven surface must be avoided. Soft brushes must not be used over concerns of causing the excess removal of the plugging paste. The UV hole plugging processes must then receive a final cure to increase the hardness and advance the final properties of the plugging paste. The thermal cure only process is ready for brushing after the thermal excursion.

Once this is complete, the buried via layer is ready to be processed for metalization with conventional technologies. These processes are well documented and will not be repeated here. However, a short dissertation on the use of alkaline permanganate is necessary.

Alkaline Permanganate Process

A critical success factor in sequential build fabrication and via in pad is to insure adhesion of the plated metal to the surface of the plugged via. Treating the surface of the plugged via (the cured paste) with a desmear process will impart a roughened topography to the surface. However, as stated elsewhere in this paper, the treatment must not be so aggressive as to remove more cured paste than required. The key is to maintain a planar surface (2).

In figure 7, one can see the “as is” topography of a cured plugging paste material followed by (figure 8) a micrograph of the same material treated with an alkaline permanganate solution.

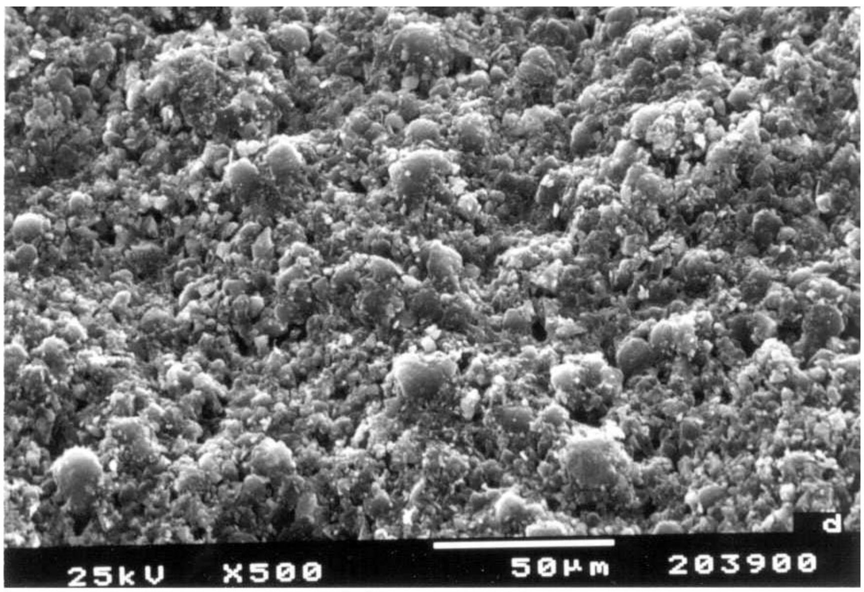


Figure 7-Commercially available non-conductive via fill material after curing and planarization

In figure 7, one should note the “particle” like appearance to the plugged material. The appearance is due to the filler mixed in with the thermally curable epoxy material. The filler serves to restrain movement in the Z-axis and aids in the material fill properties.

Figure 8 shows the condition of the cured material after the recommended desmear cycle. It is advisable to work closely with both the paste supplier and wet process chemistry providers to determine the optimum desmear cycle. Again, the critical success factors include sufficient roughening of the plug material (in order to insure sufficient plating adhesion) and minimal material removal.

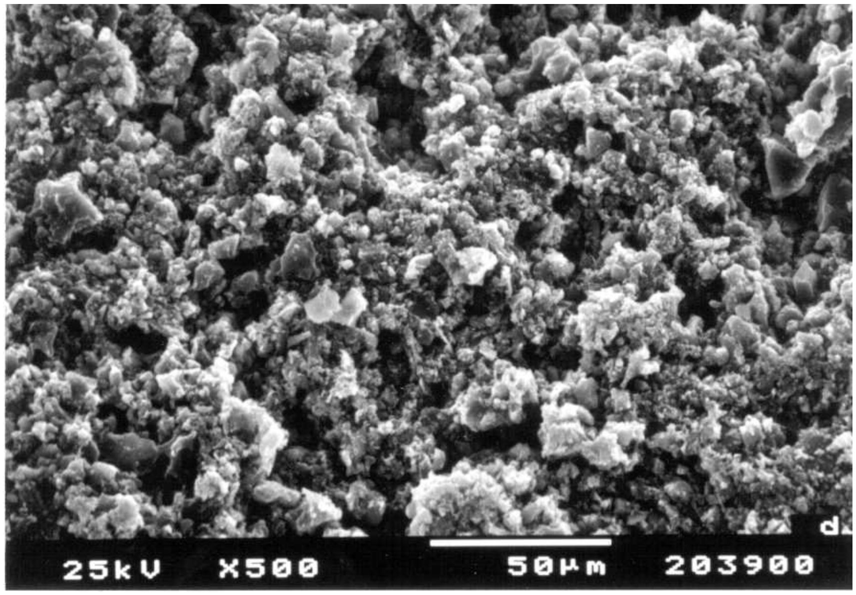


Figure 8-after desmear. Note good roughening of the material.

The topography after desmear is vastly enhanced with respect to surface roughness. The altered topography serves as an anchoring site for the electroless copper catalyst and subsequent electroless copper deposit.

Generic Process Steps
There are two acceptable techniques employed by industry when using the via filling process. The process flow is shown in Chart 1:

One process uses a technique known as "wrap around." In this technique, the drilled vias are desmeared, and metalized. Then, the electroplated copper is panel plated or flashed with an additional .3 mils of copper. Then the image is formed and the vias and pads button plated to the required one mil of plated thickness. The goal of the flash copper plate is to deposit copper up over the knee of the soon to be filled via. Next, the photoresist is stripped and the via filled with paste, then cured. At this point, the planarization or brushing step takes place. The excess protruding paste is removed as well as some surface copper.

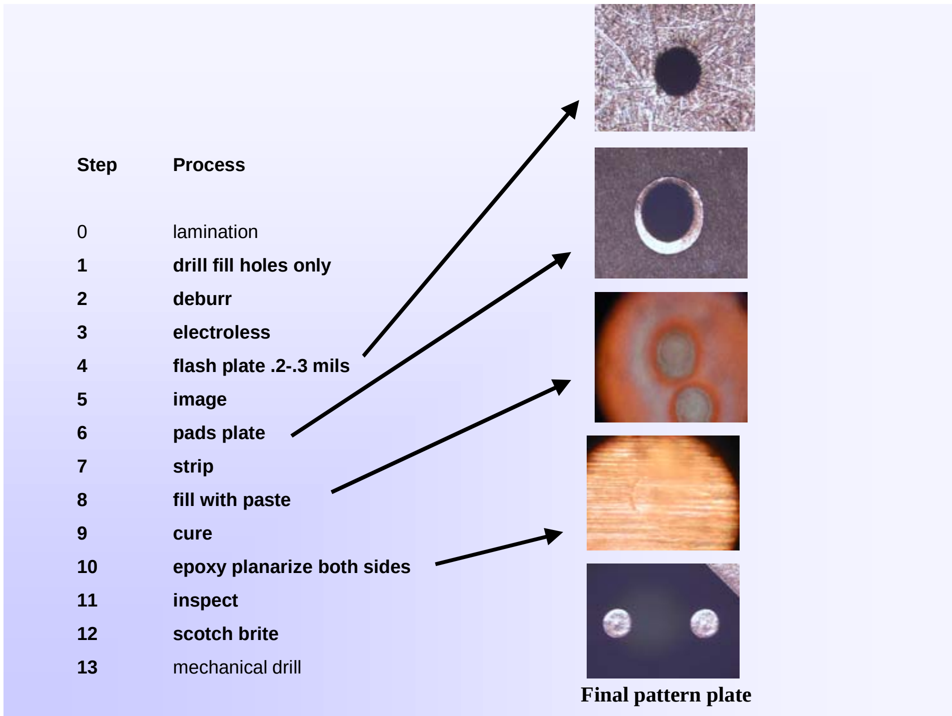


Chart 1

However, the additional plating on the surface provides the wrap around necessary to enhance the adhesion of the plated copper when the boards are subjected to load.

A variation of the wrap around technique is to simply metalize the vias and then image for pads plating. There is no flash electroplated copper present as in the wrap around technique. An example of this variation is shown in figure 9. Note that there is no wrap around that is evident with a flash or panel plate technique.

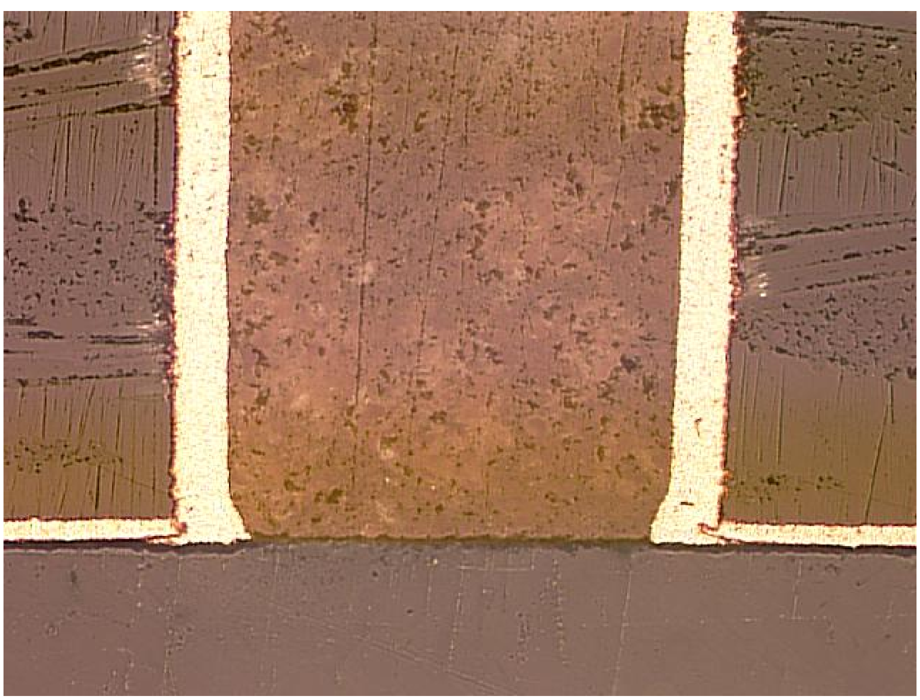


Figure 9-The planarization has removed the majority of the copper on the surface of the panel.

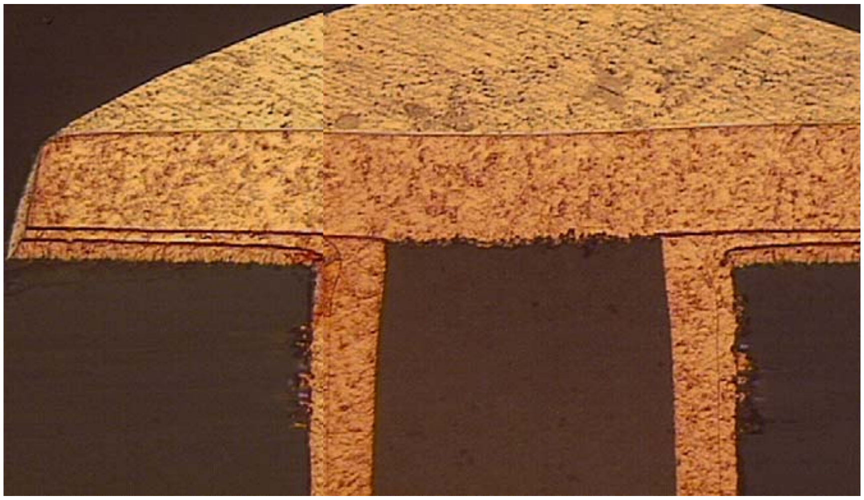


Figure 10-Section of a via processed with via plugging material. Note the plated flash copper up over the knee of the foil providing “wrap around.”

Summary and conclusions

PWB manufacturing firms looking to establish a niche and end-users looking for interconnect solutions with ever increasing circuit density would be wise to acquire via filling capability. This is easier said then done. Via filling is a blend of art and science. Certainly, process providers have developed and will continue to develop improved material properties and paste filling systems. In addition, one must consider the art of process development on the factory floor. Since printed wiring board designs are always changing, fabricators must be skilled in the art of experimental design. This is necessary in order to optimize the various via filling process parameters at one’s disposal.

For the end user, via filling utilizing a ceramic-epoxy material that has a low CTE and the highest possible Tg is a key enabler for HDI technology including via-in-pad, sequential build and stacked via designs. The higher Tg and lower CTE properties provide additional measure of reliability for high end pwbs.

With vastly improved paste filling systems and paste material properties, capabilities have expanded to include the complete filling of higher aspect ratio through holes as in the range of 15-20 to 1 and to fill blind vias as small as 3 mils in diameter.

References

1. Karsten Andra, “Hole Plugging Technology for Multilayeers and HDI Packages,” EPC PCB Convention, 1999.
2. Internal communication with Lackwerke Peters
3. Sven Kramer and Manfred Suppa, “Via Hole Filling and Plugging-Trends, Possibilities and Limitations for Conventional and SBU-type Fillers,” IPC Printed Circuit Expo 2001.
4. The National Technology Roadmap for Electronic Interconnections 2001-2002, IPC.
5. Jess Pedigo and Mike Kittelson, “A Review of Filling High Density, High Aspect Ratio Vias in a High Volume Printed Circuit Board Facility,” IPC TMRC, October 2001.
6. IPC-4761 (Draft): Design Guide for the Protection of Printed Board Via Structures-August, 2005.