A Second Look At Injection Via Fill Process Capability, And Material Property Issues

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Abstract:
In the United States, focus turns toward enabling technology for quick-turn printed circuit board and laminate package manufacturing. The current corporate mandate is to develop advanced, enabling technology, and to integrate it rapidly. Reduced via diameter, and higher layer count at lower cost for laminate packages and printed circuit boards continue to be pursued, as they are key elements for higher density products. Filling vias with increased aspect ratios (depth/hole diameter) had become a poser, and inefficient squeegee print methods were replaced to a great extent by injection methods. Novel via fill injection and or vacuum applications, along with peripheral devices for post-fill processing enable the manufacturer to fill higher aspect ratio vias having diameter to depth ratios greater than 10:1, with reduced cycle time.

Hold the phone! Are all the necessary elements in place? As with any new technology, we discover missing pieces as we go, and new demands are placed on any given process that must be dealt with in turn. As via protection becomes more defined, hole-fill tolerances are made more stringent and correspondingly, more difficult to measure. How do we now inspect the product as efficiently as we process it? Other questions emerge. How are higher Tg laminate materials affecting both board and process? How well do the laminate and via fill materials compare regarding Z expansion? What are materials suppliers doing to address the disparity of x and y thermal expansion in ppm vs. z expansion in the percentile range.

Studies regarding various paste materials, their behavior, and integration into advanced production applications from the printed circuit board, to hybrid microelectronics materials and others, have afforded an opportunity to observe and assess current capabilities, as well as to gain insight into issues that have cropped up in terms of via protection. This paper will (in common-sense terms), attempt to look at pertinent issues regarding via fill paste and laminate material properties, general process enhancements, perhaps some novel approaches to inspection of post-via fill panels and repair methods, with a smattering of selective via process concepts, and paste rheology contribution to that process as well.

Introduction
This technical paper has been written with the intent by the author to follow up on previous offering presented at the IPC Annual Conference in 2001[1], and to make good on a promise to provide more in-depth discussion of the injection process. This will consist of three categories; function of design, process guidelines, and materials issues. Hopefully carried out in practical, pragmatic, and commonsensical terms. It makes sense to recount some of the more important points of the previous paper as they bare significant weight to current processing issues. This will be done minimally out of respect for publisher and the reader.

The global push for higher density circuit boards, and the inclusion of plated, filled via interconnect as an enabler remains with us. Via-fill technology developers have responded well, considering the number of new players offering high aspect ratio via fill capability. Let's review some recent history. Via fill processing has evolved considerably from the slow, and limited squeegee print methods of past years. As aspect ratios increased, fill efficiency decreased to the point of becoming a bottleneck for production purposes. A variety of technologies were quickly (relatively speaking), developed in order to enable circuit board manufacturers the ability to fill and protect plated thru-hole vias of greater depth and smaller diameter (aspect ratio). Equipment design has evolved from simple pressurized print-head adaptation, to a variety of more complex systems. Typical via-fill approaches range from positive fluid pressure injection, to vacuum drawing from paste reservoirs/ chambers, to a combination of pressure-head with vacuum assist. (*The vacuum chamber process is apart from injection, thus will not be addressed in this paper*). Complexity varies from hand-held devices, to semi-automated, and fully automated design. Each system has its' merits as well as design specific limitations. Decisions regarding the choice of application are normally based on reliability, process cycle time, cost of operation, which includes labor, downtime, material consumption and waste. The desired result from each application is a process that will uniformly fill 100% of the vias across a variety of substrate configurations without inducing air voids. Additional requirements are: minimal overfill and excess surface material that would effect surface planarizing steps. As an inventor of one such system of devices, the patented 'FulFill' system, which was introduced by Honeywell Advanced Circuits in 2001, subsequently sold to TTM Technologies Inc, I will stick to basic injection via-fill device concepts, process guidelines, and related general material issues that have come to light, covering each, as previously stated as distinct yet co-dependent categories. Most of the issues addressed are shared, no matter what device is used for the via fill process. With this in mind, we will concentrate, in general terms, regarding the previously mentioned system, with occasional references to alternate designs, and explanations as to why one was chosen over the other.

A Review of past considerations

Desired Via fill material properties [1]

- Volatiles less than 1.5% by iso-thermal TGA
- If particle-filled, particle size of< 20 microns
- Low VOC for dense cured material & happy environmentalists
- Appropriate paste rheology that allows proper flow into vias.
- Void-free paste material from the vendor, shipped in containers that prevent the folding of air into the paste during shipment.
- Good leveling properties & cohesive strength to withstand planarization, yet offer ease of excess cured paste removal
- Good via wall adhesion, especially for conductive materials.
- Ability to withstand post fill plating processes and solder-float stress testing of 6x @ 550deg.F

Substrate issues regarding a fill process

- Foreign material in vias , or surface contaminants such as photo-resistthat can be carried into vias by the injection device.
- Dog-boned plating that limits paste flow.
- Copper nodules that restrict paste flow, and additionally entrap effluents from prior wet processing.
- Residual copper slivers in the vias resulting from planarization steps.
- Under-plated, or porous via wall plating which allows resin interaction.
- Undue coining, or excessive isolated stacked copper in multiple layers that produce non-uniform surfaces inhibit essential surface gasketing.
- De-lamed or lifted copper on the substrate surface, or fractured copper near pinning slots.This will contaminate paste, block vias, and causes injection-head wear-part, or gasket surface damage.
- Broken drill bits in the vias.

After reading the long, (and still partial) list of paste material requirements, and potential via-fill failure modes, one might be skeptical regarding mass via- fill processing. One might even question the capability to fill 100% of the vias in a single board. We were, and did, and set about the implementation of 6-Sigma process engineering tools such as Process Maps, 'Cause and Effect charts, FMEA, and phased steps of process evaluation. Completed 'Components Of Variation' and 'Full-Factorial' Designs of Experiment statistically removed our doubt regarding both equipment design, and high volume process capability. For the few whom have yet to become familiar with the plethora of 6 Sigma acronyms, rest assured that the overall process is a very good thing indeed. LEAN and 6Sigma practice significantly reduces cost while assuring maximized quality and profitability. The patented injection device, peripheral equipment, and via-fill process have been in high volume production now for more than a year.[1] So, enough background, let's get into the actual basics of a via fill paste injection system and related material items.

Design & Functional Aspects of a Via Fill Injection System

Ns - In simple terms, the via fill injection system can be broken down into five interlinked components:

1. The injection head body, which contains the paste material, and may be designed as a single unit, or as a more complex device having an internal paste cartridge and pressure bladder, or an auger.
2. A Wear- part, or gasket system that provides a semi-seal over the substrate which allows pressurized paste transfer into the vias The head-body and the wear-part, or surface contact sealing mechanisms should be considered together, as overall paste injection function is a combination of the two. Gasket systems vary in approach and design.
3. A fluid supply and pressurizing system that must capable of delivering consistent pressure under varied volume/ mass conditions.
4. A machine, or conveyance supporting the injection apparatus in a planar x and y position relative to the substrate in process.
5. A stationary, or shuttled platform support for the work-piece to be via-filled. This would also have a fixture that provides separation of the bottom of the vias from the surface of the support to allow clearance, thus preventing wicking of the paste from the via area. We'll discuss this in the Process Section.

Basic Head Design and Function

Numerous types of injection system have shown to be of excellent design and construction, each having merits along with some process specific limitations. Here's a short list of some process/ head design related limitations common to most devices:

- Injection-head units, combined with their respective wear-part, or contact gasket, are typically designed for a specific substrate dimension, and specified active fill area on the substrate. Some units have interchangeable gaskets to allow for arrange of board widths.
- Uniform fluid pressure inside the heads is ultimately determined by the semi-sealed contact between the substrate and the head's wear-part/ gasket system, thus requiring a minimum of substrate non-planarity. Additionally, collective via density on the board affects material pressure and flow. But to a lesser extent.
- Injection devices are the most efficient when used in direct contact to the substrate. Incorporating a stencil in the process (for selective hole-filling, etc), provides opportunity for pressure loss between the stencil and substrate surface., which would lead to under-filled vias. We'll look at some options regarding this later on in the paper.
- The via fill injection process nearly always requires an excess paste scavenging step. This is
- not a showstopper, as devices are in-place that quickly, and efficiently remove excess material prior to cure-cycle with no deleterious effect on the filled via.

The 'FulFill" tm System was designed for very high volume production runs. It incorporates internal paste feed and flow chamber design as well as secondary pressure leveling aids which combine to provide uniform pressure throughout the head, and a proprietary thermal control for paste viscosity reduction.. Attached to the head-body is a machined gasket material having low friction co-efficient to allow the minimum of drag on a printed circuit board, while providing uniform contact across the breadth of the active area of the board to be filled. Thus we term the design to be passive, as there are no internal moving parts. It should be noted that the wear-part does not truly contact the board during the process. The paste itself forms a thin film as it is forced onto the board, and into the vias. The paste feed system incorporates both a smaller scale cylinder reservoir for short-runs, and a stand-alone unit that allows multiple, eight-hour shift operation without having to re-load material. The pressure system holds constant air volume/ pressure that is isolated from the paste supply, and incorporates additional volume/ flow- control. Some would argue that paste will not compress, but even micro-bubbles that remain in a vacuum processed paste have enough volume to provide compression under pressure, which allows residual paste flow. The injection head, swivel-mount device, and attachment system was designed for retrofit on various ' four post', and 'clam-shell' design screen printers. The main criteria for these printing machines would be that the cross-bar support and traverse normally used for squeegee attachment be robust enough to prevent any forward or backward tilt, or bending under pressure. One item that sets this system apart from others, is that it incorporates a patented ramp and landing system that allows the head to dock in both the front and back position while the printing machine shuttles boards in and out. Thus the work-piece thru-put is rapid, averaging total cycle- times of under 60 seconds. Of course the cycle-time will vary in terms of board thickness, via aspect ratios, and paste material used. After the fill cycle, the board is removed, and immediately placed on a device that will scavenge any excess material from the board surface. The "FulFill System" device used for scavenging allows tape-free operation thus shorter processing time. The remaining film will be uniform, and thin enough to enable minimal sanding or surface planarization.

Ahh! The need for speed! I distinctly remember both the marketing folks and management asking for higher speed. "Raise the fluid pressure", "increase the head contact pressure!". "How fast can we make this thing go!" Sound familiar to any of you process engineers or product developers out there? Here are a few fundamental factors apart from the machine that govern the via-fill process speed.

<u>Un-cured Paste Material Characteristics</u>

- Rheolgy -This goes beyond viscosity alone. Some paste materials list equal viscosity numbers when tested by roto-viscometers. Each material provider may have different equipment for measurement, and often provides a single data point relative to spindle speed. One should compare the over-all range of viscosity and thixotropic slope of each material.
- Surface tension - This has <u>significant impact on process speed</u>. Numerous co-polymer epoxies have very long-chain resins that create resistance to flow, and often have a tendency to smudge, and drag air into the system, rather than shear off during the print cycle. They also require slower scavenge-blade speeds for removal of excess material, and are more difficult to clean from the equipment. Fortunately there are some material suppliers out there whom have listened regarding requests for reduced surface tension among other properties, and have materials that ease the process without effect on the cured materials.
- Visco-thermal properties - Ambient and board temperatures have significant effect on surface acceptability (wetting). Additionally, there is a vast difference between paste products regarding viscosity change from 23°C, to 26°C. Some pastes have exhibited viscosity drops from 50Kcps to 40Kcps (in centipoises) in that temperature range. S*ubtle hints to refrain from placing via fill equipment near air vent. It would wreak havoc on the process, let aloneprocess control charts*.

Board surface and thru-hole aspect Ratios

- Via wall pre-conditioning - Etching of the via's plated copper surface, while promoting adhesion, also creates resistance to paste flow through the via. Moderate surface etch might be wise.
- Via diameter and depth determine the amount of 'residence-time' over a via for complete fill, as the injection head traverses the length of a board.
- Via diameters on a given board should vary nomore than 0.003 mils in order to prevent excess paste material on the bottom of the board. To clarify the impact of diameter variation, one should look at the difference in terms of aspect ratio. Consider a 0.100" thick board with 0.008", and0.012" via diameters. The aspect ratio would be 12.5:1, and 8.33:1 respectively. At a 50% decrease in ratio, combined with flow dynamics, one can see where most of the paste would go…, towards the path of least resistance.

This is where a selective process would come in handy.

By weighing in these variables and their potential contribution to the via fill process as a whole, one can see that process speed is not based on machine alone. Much can be done to improve a process as environment is controlled, and new materials are developed. Let's get on to the important issue of customer/ manufacturer communication for injection via-fill processing.

Via-Fill Process Guidelines

Injection heads are typically designed to meet specific printed circuit board dimensions, incorporating a specified active fill area wherein the paste will fill 100% of the vias. Normally the head will travel in the long direction. For example, if a board's dimensions are 18.0" by 24.0", an 18" head would be used. Other head sizes are available for various board dimensions. Note that the wear-part will be of shorter length, in order to provide clearance for tooling pins, and borders where sample coupons, IST coupons etc, would be located. It is most important that the customer understand the significance of this. Any sheared holes, large tooling slots. Or pinning holes will be flooded with excess paste, and reduce fluid pressure uniformity in the head. They may also damage the wear-part. Applying tape over slots may occasionally be used on the perimeters, but becomes a messy and slower process. That said, here are some basic process guidelines that should be established between the manufacturer and the customers' design engineering groups:

- The via-fill service should provide clearly defined process guidelines, including detailed drawings that map the active fill area per given board size. This would include tooling-slot locations, and clearance required for the head's wear-part from tooling slots, pinning holes, and ramps that allow the head to clear from the board. (See fig.1)
- If the service provider is to manufacture tooling for board stand-offs, or a bed'o'nails, for clearance between the board and support platform, the customer should provide location datum for drill-files that include vias, and pinning holes. (see Fig.2)
- The customer should also state any copper thickness after planarization requirements, as some copper is always removed during the removal of cured, excess via fill material.
- The customer should state the type of via fill material, and via planarity requirements as well.

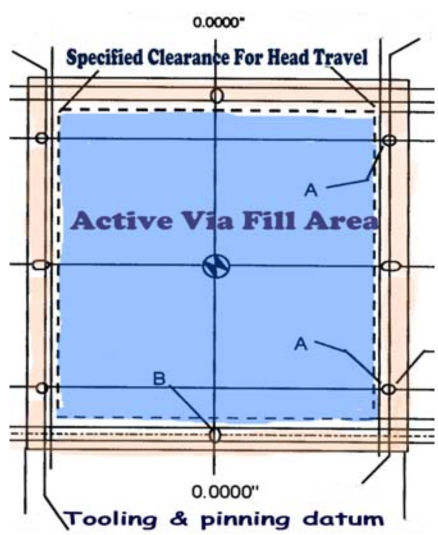

Figure 1 – Typical Schematic For Drill File, Tooling Location, and Maximum Area for Filling Vias

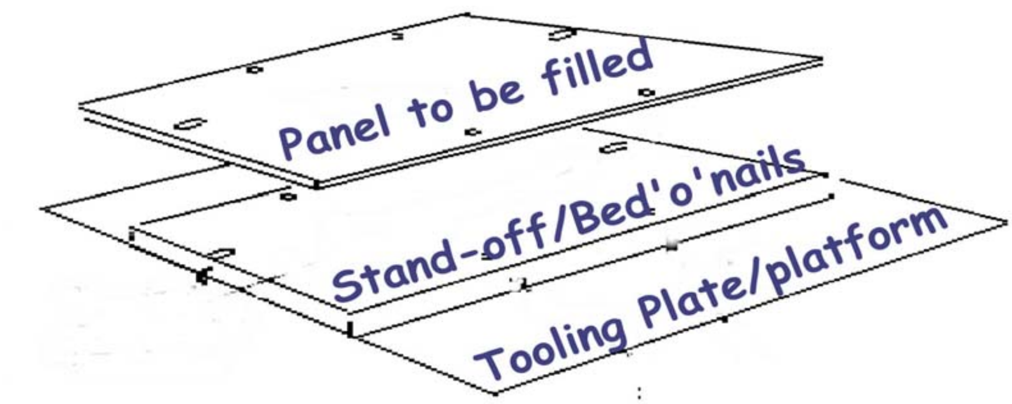

Figure 2 - Depiction of Panel and Support Mechanisms for Via Filling

Regarding the active via fill area of a board, experience has proven that every board designer wants to push the limits and put some wayward vias as close to the edge as possible. When the poor production folks try to dream up ways to stretch a non-flexible head to compensate for that, you can bet there are copious comments regarding parental marital status. As previously stated, life is much smoother when accurate guidelines are in place, and adhered to. Now that we've covered (albeit briefly), some process guidelines, it's time to look at some potential process capabilities, and mull over some issues that pester and cause heartburn.

Material Properties, Expanding Expectations, and More

It has been a matter of record that printed circuit boards exceeding 0.200", containing vias with aspect ratios of 17:1 and more, have been successfully filled using injection and/or vacuum methodology, (At slower process rates, of course).Board designers are now asking for a selective via-fill process, and thermal stability tests call for survival at 6x solder-float at 255^{o}C.There are some limitations to be overcome. It would appear that the ability to fill very deep vias may have out-paced other areas of board manufacture, and bumps are in the road head. In order to avoid a lengthy paper, and potential self-imposed political assassination I'll slightly crack open Pandora's box with some stimuli for thought.

Board and Material Issues

The combination of increased board thickness and increased laminate material Tg values have exacerbated the frequency of post thermal shock cracks appear in gin the proximity of filled vias. Not all board customers deem them as failure criteria. Yet! The combination of 3 to 4% Z-axis expansion of current resin systems, reduced flexibility as a result of higher Tg requirements, and the plated copper interface, would all play a great role in building stress. Subsequent high Tg resin layers over the via pads would also be effected by the previous layers of high Z-axis expansion. History indicates that the old Dutch Masters paintings lasted because they understood the need to use more flexible paint media over rigid base-paints. (just a little food for thought).

Some printed circuit board material suppliers are making strides in producing lower Z expansion materials, GE for example[2], but it may be time to bring in the molecular and stress modelers, and polymer scientists to bring about a new generation of chemistry that would approach ppm level z expansion.

Of Selective Via Filling

There are numerous war stories that came about during the first months of filling vias for external customers. Some panels had tooling holes, and or device mount holes throughout the surface. Others had entire sections, or large coupons removed, or had boards populated with combined via diameters ranging from 8, to 50 mils. Often the expectant observers of this new direct contact process would break out such panels, and stand by to watch the show. Do the words controlled panic, and diplomacy come to mind? Thus, the afore-mentioned customer process guidelines came into being, along with confirmation that a selective via filling process would be in demand in short order.

Numerous papers could be produced on this subject, so will have to be condensed. Selective via filling requires that a stencil, or other masking device be incorporated. Nothing new, regarding the history of solder-paste, bump-interconnect processing. In terms of via filling however, it brings back the need for optical registration, repeated process steps, and a closer look at paste material properties, along with air-entrapment potential. Alternatively, some companies are providing two-step drill, and two-step fill sequences. I would not term this as a true selective fill process. Each method could be termed cumbersome, or at least more difficult. The balance of additional process cost, and reliability must be considered for each. Let's do some basic add-on process items.

Selective Stencil or Masking

- Two or more sets of photo-tools and superior gasketing stencils
- Optical alignment requirement introduced
- Potentially two sets of stand-offs
- Potentially a second planarization step, may not effect copper thickness call-outs, as resin removal is easier with small dots vs. solid film
- Tracking of panel stretch/ registration prior to second fill, A potential requirement for scaling the artwork for a second stencil
- Cure steps prior to second fill. May serve as dimension stabilization
- A second cure step, followed by the second planarization step
- In the case of vias slated for no fill, avoidance of via fill materials that exhibit resin-bleed, or phase separation. One should additionally look for a material that has thixo-tropic properties that prevent flow, and tend to shear during the Stencil process, and have co-catalysts that exhibit on-set early in the cure process to prevent low viscosity material flow.[3]

Multiple Drill, Fill step Process

- Multiples of artwork, drill files
- A second drill step, substrate clean , hardboard mask and image steps, hole plate, strip, clean, inspect (sectioning). In other words, another trip through drill & wet rooms.
- Additional dress-down sanding on one side of the board to allow smooth surface for second fill, as scavenging would become a nightmare on a surface having raised copper bumps.
- Potential effect from wet chemistry on cured via-fill paste material
- Potential re-scale for artwork, drill file etc. as the first planarization step for direct contact fill may stretch the boards.
- Registration issues lessened for the fill process but increased due to multiple drill steps
- A second planarization step of solid via-fill residual film will most likely require call-out for initial copper thickness

I leave it to the reader to weigh the added cost of selective or multiple drill processes. One might lean toward the selective process if only for the sake of choosing the process with the least steps involved. There are a few comments and suggestions regarding the selective fill process. Use advanced-fill materials that have the thixotropic, low thermal sensitivity regarding viscosity, and little if any phase separation, or resin bleed-out[3,4]. This is especially true for close proximity to via arrays. Stencil materials may vary. Plate-up, or "grown nickel" stencils provide the best paste shear- separation for the least amount of wicking. Polymer coated stencils may allow improved gasketing over the vias. For proper gasketing, a stencil requires minimal 2-3 mil surface around a via, so one must take into account registration accuracy. If tight tolerance within an array exists, consider an alternative of using very accurate dispense apparatus, especially if the via population is low. Perhaps a non-setting material could be dispensed to prevent fill in isolated vias. We'll leave the multiple drill suggestions to the circuit board production and process engineers, as they would, by experience, have plenty to suggest. With that in mind, a brief re-cap of the whole article is in order.

We've had a review of a past article regarding via filling in general,[1] looked at the basic functional concepts of a via-fill injection system, presented the need for a defined process guideline for both customer and service provider included some hopefully meaningful details, and possibly riled a few people regarding perspective selective via fill processing. It is obvious that much work is ahead regarding next generation materials, and advanced selective via fill process development. Let's get to it!

Caveat: This paper does not represent Honeywell, or TTM Advanced Circuits, as it is written with permission as a former employee of Honeywell Advanced Circuits.

References

1. J. Pedigo, M.Kittelson, "A Review Of filling High Density, High Aspect Ratio Vias, In A High Volume Printed Circuit Board Industry", IPC Journal, Nov. 2001,Circuitree, March, 2002
2. A. Chris Garlington, "Laminate Z Axis Expansion And PTH Reliability" GE Electro publications, rev.3- 11/23/01
3. J. Pedigo, N. Iwamoto, C. Zhou, "Advancing Via Fill Materials For Next Generation Interconnection Technology", HDI Magazine, April, 2000
4. "Method of Decreasing Bleed from Organic Based Formulations and Anti-Bleed Compositions" Patent No. 5,859,110, issue date January 12, 1999

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