QUALITY AND RELIABILITY INVESTIGATION OF PRINTED CIRCUIT BOARD MICRO-VIAS BY X-RAY INSPECTION

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ABSTRACT
A continuous drive to shrink device packages and printed circuit board (PCB) design, so that higher, and better, functionality can be provided to the user in an ever smaller footprint, demands the increasing use of micro-vias on-board. Micro-via diameters of 200 microns, 100 microns and below are now common. With such small features, the quality of their through-hole plating during manufacture and the implications of the lead-free surface mount process and thermal cycling during product life can severely affect production quality, yield and field failure rate with resulting costs to reputation and business.

The use of high resolution, high magnification x-ray inspection, as part of product quality control, allows a non-destructive test for investigation of micro-via quality and their on-going reliability. This paper will report on the results of x-ray examination of micro-vias, before and after production processing, taken from the last four years of lead-free assembly experience. Examples have been taken following processing by convection reflow, vapour-phase reflow, wave-soldering and rework operations as well as after subjecting certain boards to an accelerated thermal cycling regime. Analysis of the defects produced during these procedures will be discussed together with suggested guidelines on how to improve inspection quality.

Key words: Micro-vias, x-ray inspection, plating variation, reliability

INTRODUCTION
Those who assemble printed circuit boards are often stuck in the middle between the contractual constraints and design rules of the customer, who will always assume that the product does not work because of alleged poor manufacturing quality, and the assembler's expectation of top quality material always being provided by external suppliers that sadly may not always be the case! Nowhere is this dichotomy more exposed than in the increasing use of micro-vias, whose critical diameters continue to shrink, so that ever more functionality can be packed into smaller footprints (as in cell phones, for example). Should there be issues in the bare board for example, such as with the quality of the micro-vias – whether that be in the drilling quality itself or the plating thickness and coverage within the micro-via – then however good the final board assembly, the product will not work, to the distress of the final customer and the concomitant potential effect on perceived manufacturing quality and eventual future business, let alone the cost of repair and rework, which may initially be targeted on the wrong problem. For example, having (or being forced) to replace a BGA that, in actuality, may be fine, when the actual problem is in the board micro-via. Therefore, being able to check for such potential defects as part of the incoming supply quality procedures as well as inspecting the situation post assembly and after accelerated life testing, if required, becomes very important. Such testing should be non-destructive, quick and, ideally, be able to be accomplished by less expensive personnel.

Recent developments in 2-dimensional (2D) x-ray inspection [1 – 3], in particular the improvements in resolution magnification and greyscale sensitivity, especially when inspecting the sample at oblique angle views, now offers an ideal and non-destructive test to help differentiate potential assembly process issues from material supply issues. In particular, the inclusion of digital x-ray imaging detectors with their enhance greyscale range as standard within x-ray systems enables far better visual separation of similarly dense features [3]. This is particularly important for the inspection of micro-vias where the plating is very thin anyway and any plating variation will be small in overall density, especially when being viewed through the board, requiring the best separation of the similar densities to ensure effective identification and analysis (see image 1).

Together, these x-ray developments allow a relatively inexperienced operator to quickly assess and quantify the analysis within the production environment. With lesser x-ray inspection equipment, that lacks good magnification, resolution and contrast sensitivity, the clarity of the analysis may be more difficult to achieve.

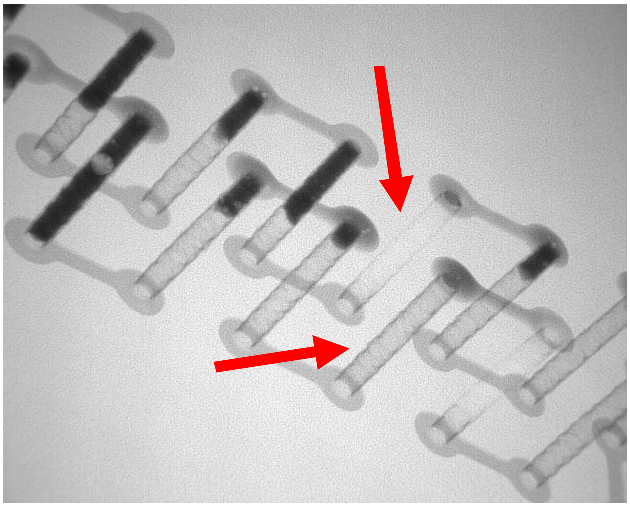


Image 1: Oblique angle view x-ray image of plating variation within 200μm diameter micro-vias. The thinner the plating then the less dense the image will be at that point. Compare the two highlighted micro-vias, for example.

For further analytical investigation, it is also possible to use 3-dimensional (3D) x-ray inspection or Computerised Tomography (CT). In this technique, the sample is rotated perpendicularly with respect to the x-ray tube to detector axis within the inspection system (see diagram 1). As the sample is rotated, a series of 2D x-ray images (or projections) are taken at every rotational step. These images, and in particular the density-variation data contained within them, are then manipulated by computer to reconstruct a 3D density model of the sample. This 3D model can then be viewed and manipulated. In addition, 2D x-ray slices through any plane in the model can be produced.

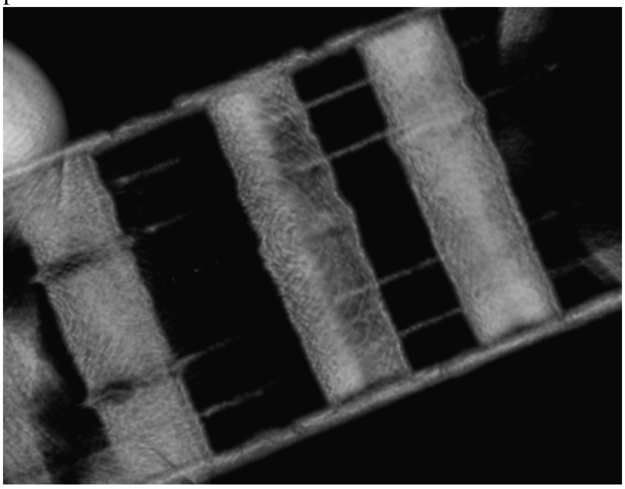


Image 2: 3D CT model image of micro-vias

Using CT to inspect micro-vias, therefore, allows a non-destructive investigation through any plane down the micro-via as well as cuts through the whole length of the micro-via. In this way, any plating variation can be highlighted and its relative position tracked that may provide additional information to help cure the defect (see images 2 and 3).

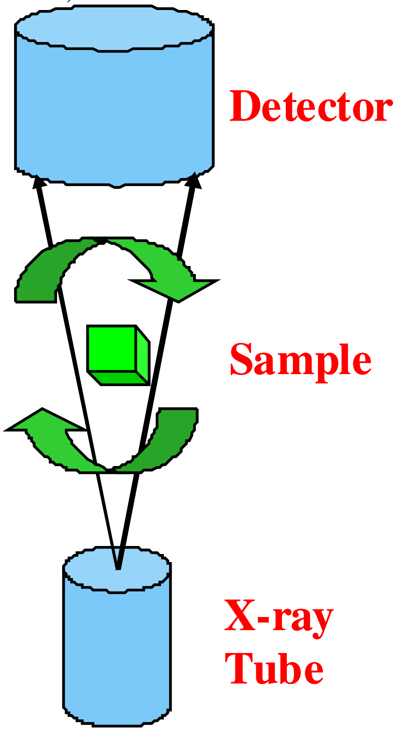


Diagram 1: Rotation of the sample perpendicular to the tube/detector axis is required for CT functionality. Images (projections) are taken at every step in the rotation.

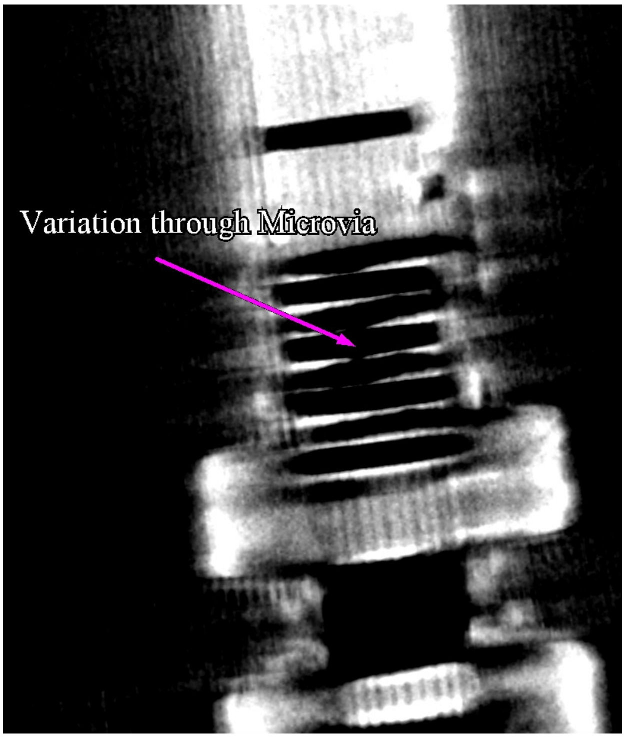


Image 3: 2D x-ray image taken through a plane in the CT model showing the plating variation down the micro-vias.

EXPERIMENTAL DETAILS

During the four years of running the Lead-Free Experience ('Experience') [4] lead-free processing trials were conducted on 1.6mm thick boards containing a via hole test pattern which featured 60 off 0.2mm (0.008") diameter holes, as shown in image 4. Image 5 is an x-ray image of the same micro-vias at an oblique angle of 45° that shows an even level of through-hole plating. Previously boards in another project on 1.6 and 2.8mm were found to be reliable and not affected by lead-free assembly provided the plating was satisfactory prior to assembly.

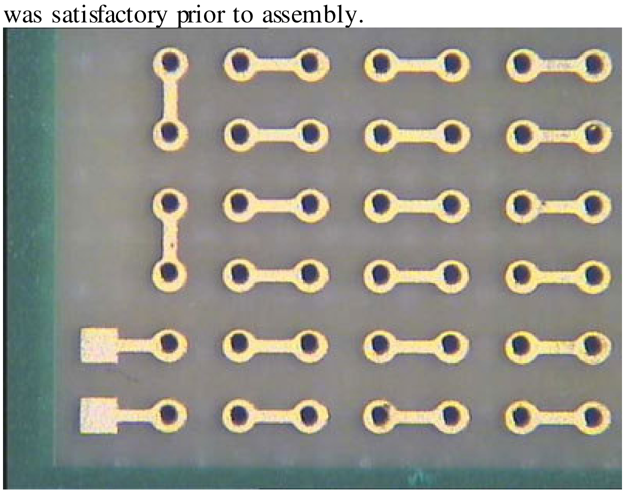


Image 4: Optical image of 200µm diameter micro-vias used in the test vehicle.

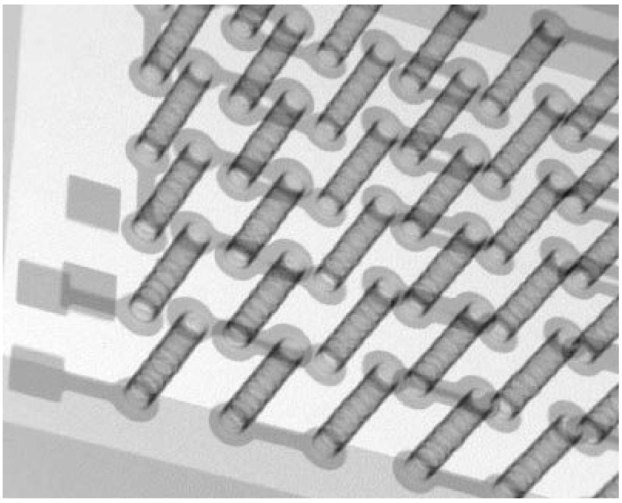


Image 5: Oblique view x-ray image of 200µm diameter micro-vias used in the test vehicle showing an even plating distribution.

In the Experience 3 experiments, boards were electrically tested for continuity prior to the assembly process. Boards were also inspected by x-ray before and after processing. X-ray has been used in previous Lead-Free Experience workshops as it is a fast and easy way of examining the quality of drilling and plating. All the boards used were blank during processing and did not feature components. Each of the boards assembled for demonstration were also tested for continuity, these were only processed through one or two soldering operations.

Three batches of test boards were subjected to the following different assembly processes:

Convection Reflow at 240°C – Nine boards were passed through a lead-free reflow profile. Six of these were then reflowed for a second time under the same profile. Finally, three boards were reflowed for a third time. One extra board remains un-reflowed as a reference.

Wave Soldering at 260°C – Six out of nine boards were put through a lead-free convection reflow process before all nine boards were passed through a lead-free wave soldering process. One extra board remains un-reflowed as a reference.

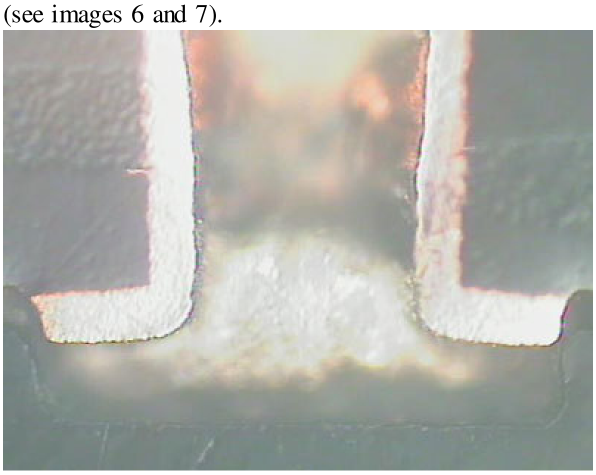
Vapour Phase Reflow at 230°C – Nine boards were passed through a batch reflow. Six of these were then reflowed for a second time. Finally, three boards were reflowed for a third time. One extra board remains un-reflowed as a reference. The vapour phase fluid used had a boiling temperature of 230°C. A dwell time of 60 seconds was used.

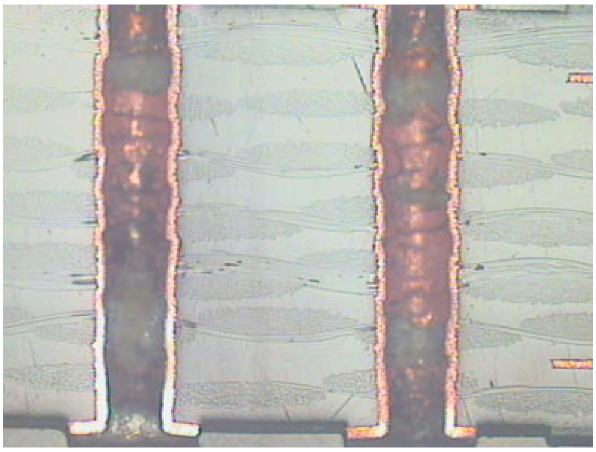
Rework Simulation – Nine boards went through a lead-free rework process once. Six of these boards were put through the rework process twice. Finally, three of the boards that were reworked twice were put through convection reflow. The boards were allowed to cool to ambient prior to re-testing. One extra board from the batch remains as a reference.

Two types of laminate construction were used:

- ISOLA 410 Materials - 1.08 mm cores 35/35 um + 2 x 7628 pre-pregs
- ISOLA 104 (Standard FR4) Materials - 1.00 mm cores + 2 x 7628HR pre-pregs

There was no evidence of failure on any of the test boards or any of the demonstration boards tested during this assessment. Selected micro-sections and x-ray examination failed to detect any issues with any of the samples tested (see images 6 and 7).





Images 6 and 7: Micro-sections of selected 0.2mm (0.008”) holes after testing of OSP board

For the Experience 4 experiments, a special test coupon was added to the test board that featured the 0.2mm diameter micro-via through-holes. These micro-vias were tested electrically, and by x-ray, for possible failure following the processing described above. In addition, and after an electrical test to confirm that the vias were still in satisfactory condition, these sample boards were then thermally cycled between -55°C and +125°C for initially 1000 cycles, and subsequently for a further 1000 cycles. The cycle duration was 48 minutes and the details are shown in image 8. The temperature cycling was kindly conducted by Milos Dusek at the UK National Physical laboratory (NPL) where free space was available in one of their test chambers. Each of the experimental boards was tested for electrical continuity at 500 cycles and again after 1000 and 2000 cycles.

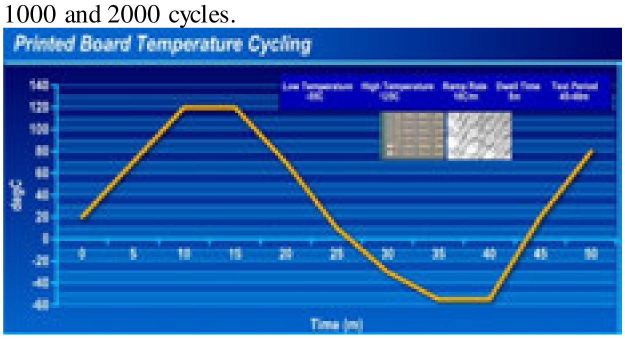
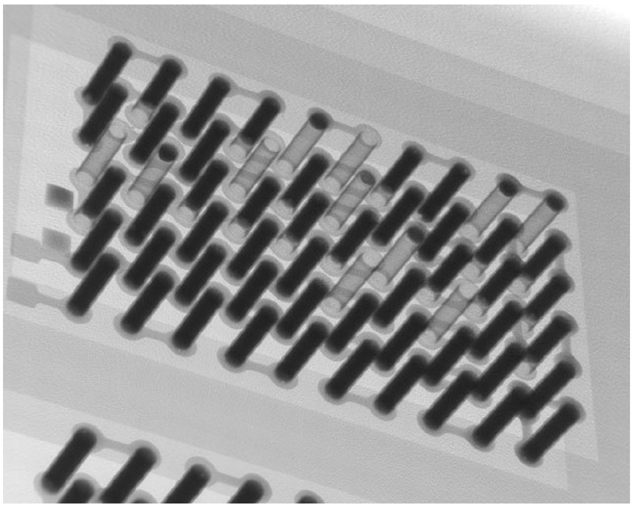
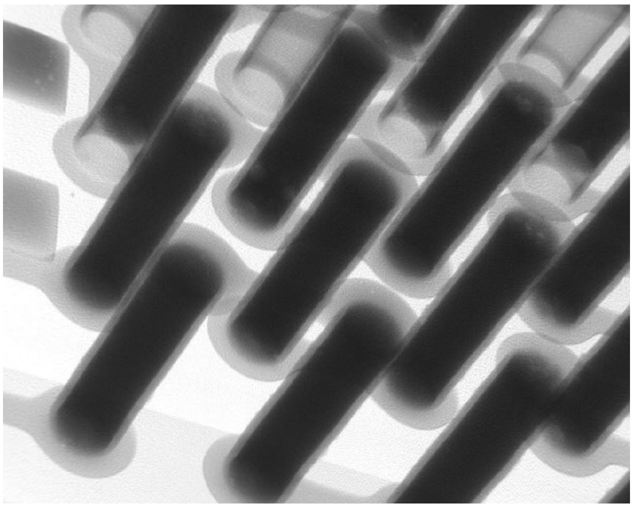


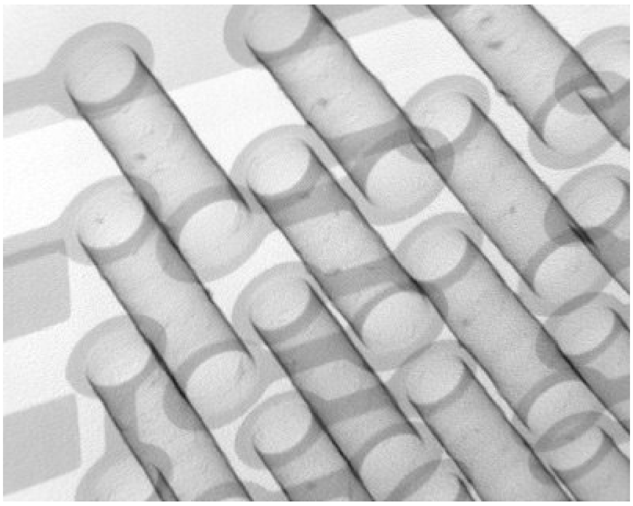
Image 8: Thermal cycling regime used on the test boards at the UK National Physical Laboratory

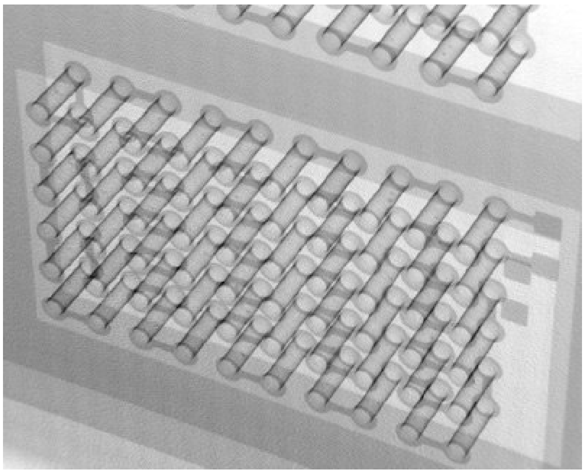
X-ray examination of the micro-via quality was conducted prior to assembly, after the soldering procedures and after 1000 and 2000 thermal cycles. Images 9 and 10 are the x-ray images of a wave soldered test board taken prior to thermal cycling. Images 11 and 12 are equivalent x-ray images from a convection reflowed board taken prior to thermal cycling. As there were no coupon failures in the micro-vias, even after 2000 thermal cycles, the x-ray images following the thermal cycling look the same as in images 9 – 12 and so are not repeated here.





Images 9 and 10: X-ray images of a wave soldered test board prior to thermal cycling





Images 11 and 12: X-ray images of a convection-reflow soldered test board prior to thermal cycling

A digital x-ray inspection system was used for this analysis. The x-ray system had a 'sealed transmissive' type of x-ray tube with sub-micron resolution that provided 16-bit greyscale sensitivity with a real-time x-ray image size of 2.0 Mpixels on-screen. The x-ray images were acquired at 30 frames per second. The system was able to provide oblique angles of up to 70° at any point 360° around any position on the test board without compromising the available magnification. This is achieved through tilting the x-ray detector instead of tilting the board.

ANALYSIS

Even after undergoing multiple reflow procedures followed by 2000 thermal cycles, none of the test coupons provided any electrical failures, when measured, and the x-ray images appeared consistent with their un-stressed counterparts. Therefore the quality of the micro-vias appears to be extremely robust. Looking at micro-sections of the coupons following the thermal cycling does show some modest modification in the micro-vias. However, these changes were insufficient to cause any reduction in via performance electrically. Reference images as to what was seen in the micro-section are shown in images 13 – 20.

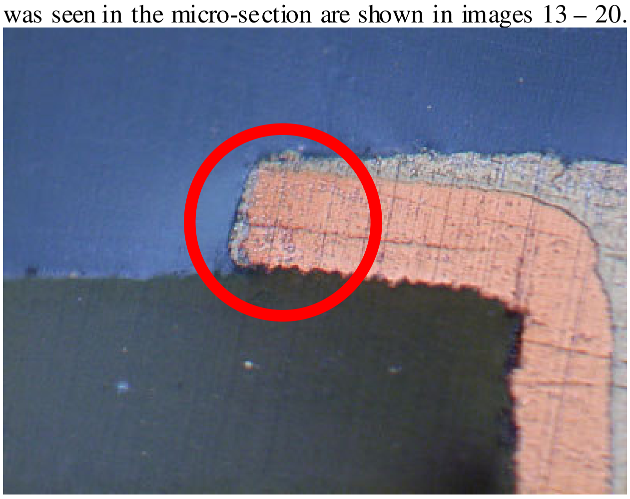


Image 13: Evidence of pad lifting caused by repeated expansion in the z-axis

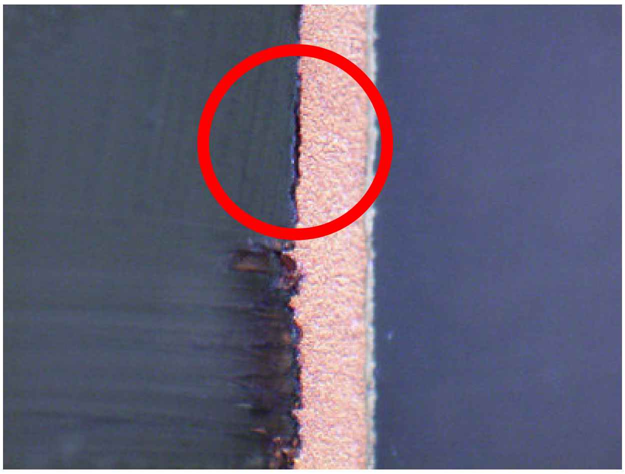
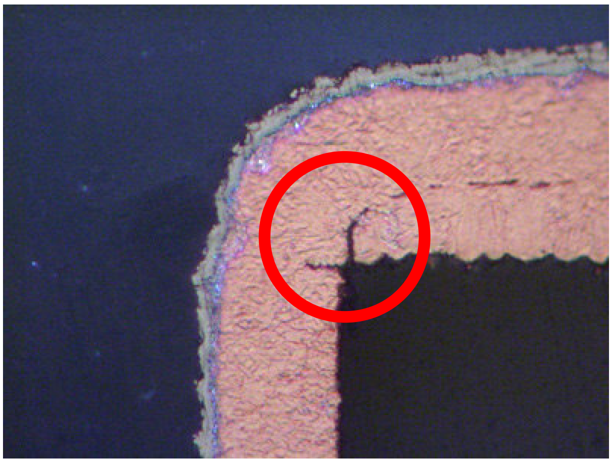
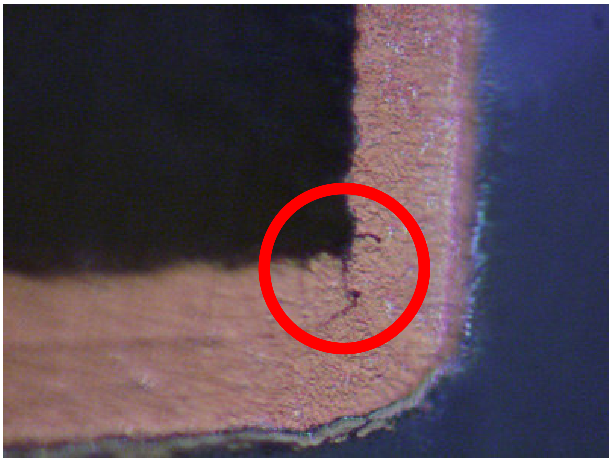
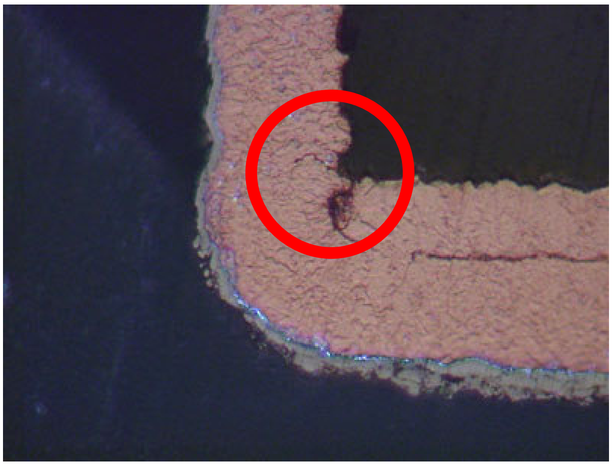


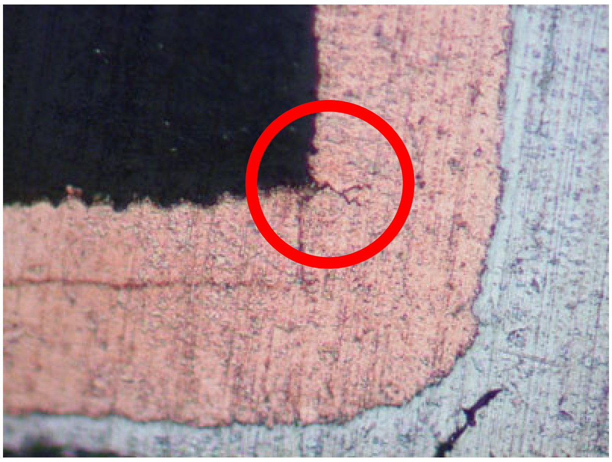
Image 14: Minor evidence of the copper plating pulling away from the hole wall. This is not uncommon on new high Tg laminates even without processing.

Images 15 – 18 below show minor copper cracking in the through-hole plating. In each of the examples, the copper is cracking in-line with the copper foil – as shown by the red circle. Normally in thermal shock testing, the cracking would be seen at the knee of the hole.

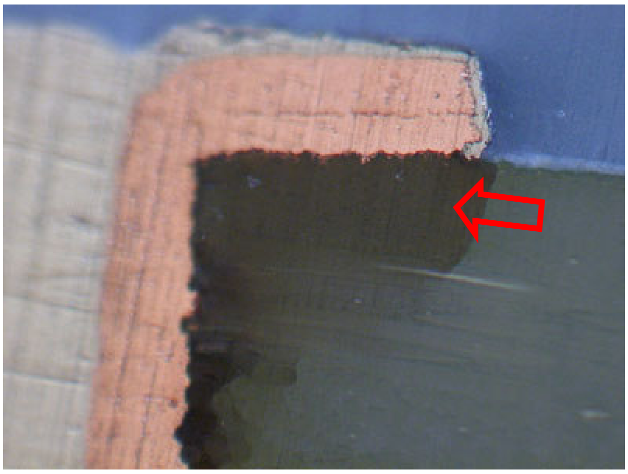


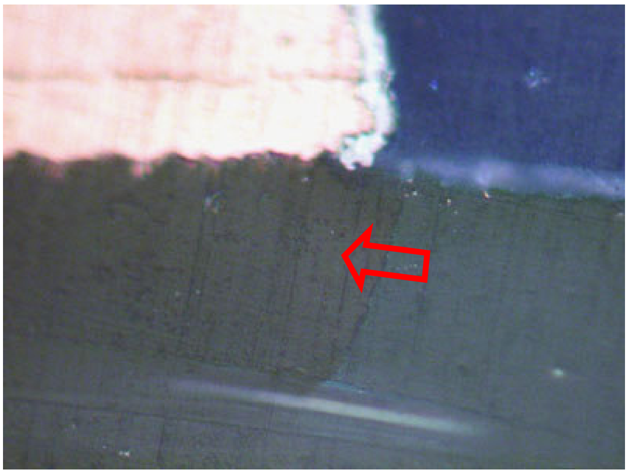






Images 19 and 20 below show two examples of laminate cracking that were observed during examination of the samples – as shown by the arrow location. This is often seen with high Tg laminate materials during mechanical testing after just one reflow operation due to the hardness of the resin.





CT ANALYSIS

Despite the best efforts of repeated thermal cycling to induce failures down the 'Experience' micro-vias, they continue to perform their task admirably and are of sufficient quality and reliability for their task. As such, it has not been possible to present in this paper, the hoped for, clear examples of micro-via degradation from the 'Experience' samples.

However, in a 'Studio Project' from the United Kingdom National Physical Laboratory (NPL) [5] some other boards containing micro-vias were also subjected to extensive thermal cycling (2000 cycles). Some of these, much greater aspect ratio, micro-vias did show electrical degradation, as well as optically visible delamination. With the kind permission of Milos Dusek at the NPL, some of these boards with known failures were investigated by the same 2D x-ray system as above and also by 3D CT x-ray inspection.

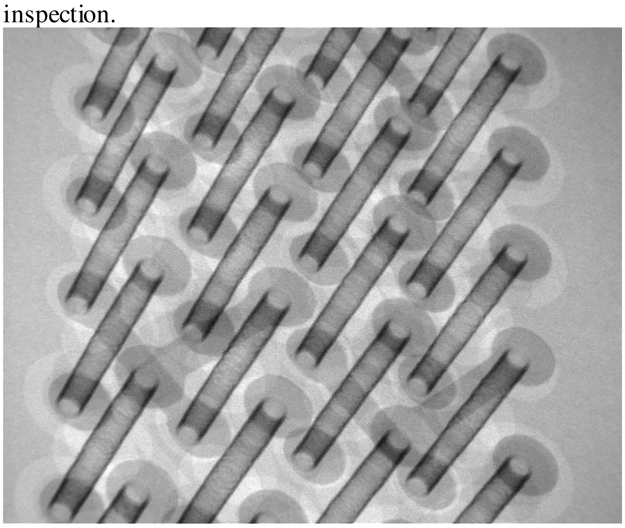


Image 21: 2D X-ray image at oblique angle view of NPL Studio Project micro-vias in a failed and visibly delaminated board

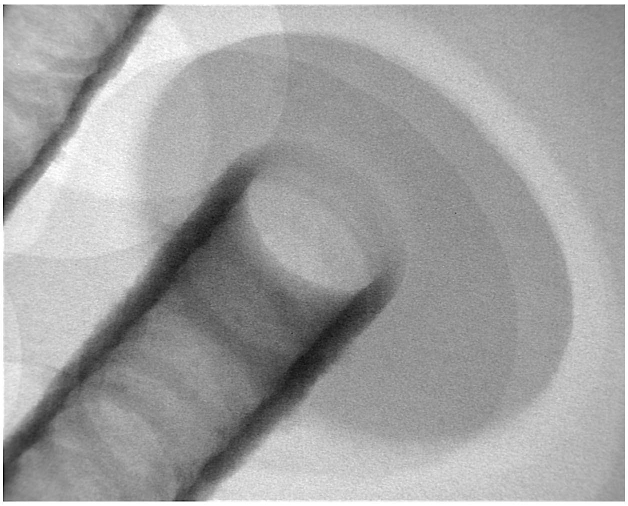


Image 22: High magnification 2D x-ray image at oblique view of part of a micro-via within a failed but visibly un-delaminated NPL board

The results of the 2D x-ray inspections can be seen in images 21 and 22. Although, a breakdown in the electrical efficacy was measured, the 2D x-ray images did not show any apparent variation in the micro-via plating or at the connection between the micro-via and the pad. Similar results were seen in the visibly delaminated as well as the non-delaminated boards and are therefore not shown explicitly here.

X-ray inspection requires that there be some density difference within the sample. The fact that these features are so small, and that any density variation will be very subtle especially when having to view them through the thickness of the board, makes it very difficult for even the most sensitive x-ray systems to show results. However, by producing a CT model of these micro-vias, it was hoped that any density variation might be made more visible. This is because taking many 2D images all around the sample may give views that provide better contrast (density) variation within different parts of the micro-via which, when re-constructed into the CT model, could provide more, and better information. The CT analysis used a Feldkamp cone beam reconstruction algorithm with a minimum of 360 projections of the sample being taken. The final CT models have a reconstruction size of 512^3 voxels.

Early results of the CT data are seen in images 23 and 24. Image 23 shows a narrow planar cross-section 2D view through some of the micro-vias on a visibly delaminated board. The locations highlighted by the arrows on this image show a slightly different density variation around certain micro-vias at this depth within the board. The board depth location of the view in image 23 is shown in image 24.

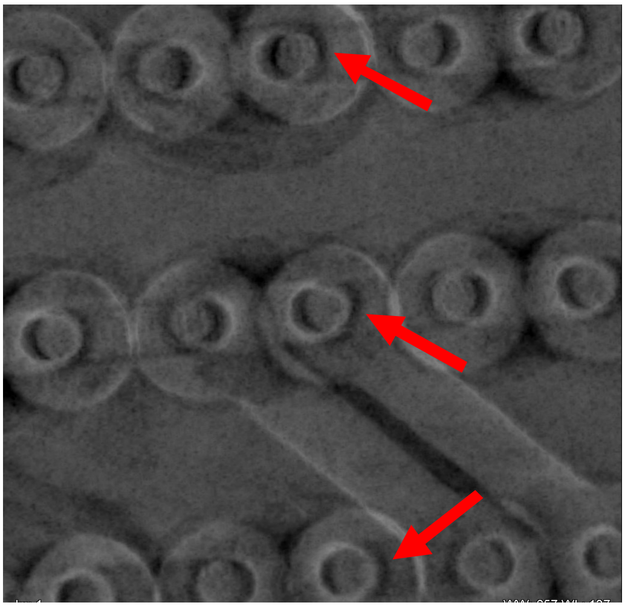


Image 23: 2D view from the CT reconstruction of a thin cross-sectional slice through some micro vias from a visibly delaminated NPL board. The arrows indicate regions where some density difference is seen around the micro-vias.

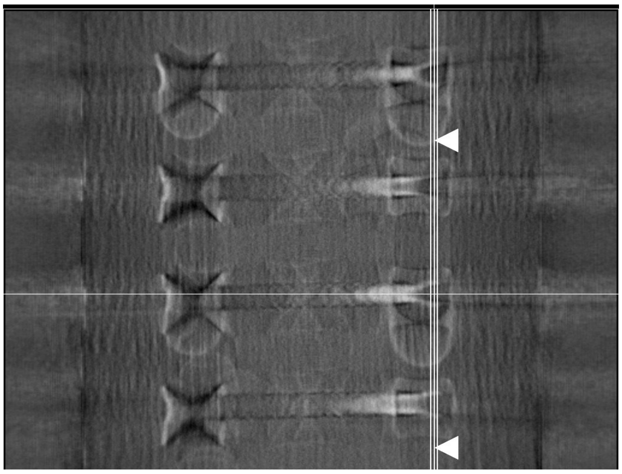


Image 24: 2D view from the CT reconstruction indicating the location relative to the micro-via depth of the cross-sectional slice shown in image 24 (between the white vertical lines).

The density variation seen in image 23 is very subtle and deliberately attributing it to degradation or damage within the micro-via is open to interpretation. Therefore, more work is required to confirm, or otherwise, this analysis. However, should it be confirmed then it suggests that a CT capability with an x-ray system may offer, in certain circumstances, additional analytical information over 2D x-ray images.

CONCLUSIONS

The sample boards created for the 'lead-free Experience' event gave the opportunity to investigate the quality and reliability of micro-vias post processing and post thermal cycling. The results show that quality and reliability were maintained even after 2000 thermal cycles and that no variation in their quality could be seen by 2D x-ray inspection. In results from boards from a different experiment, where micro-vias had failed after thermal cycling, 2D x-ray inspection did not show any apparent deterioration of the micro-vias. However, some early CT evidence on these latter boards appears to suggest some evidence of micro-via degradation through subtle density variations within the defect micro-vias, but additional work is required to further confirm this conclusion.

ACKNOWLEDGEMENTS

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