PRINTED CIRCUIT
DESIGN & MANUFACTURE

Demonstrating the Lead-Free Capability of PCBs

By Paul Reid

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It takes performance testing - as well as conformance testing - to ensure that your board can survive the increased temperatures of lead-free assembly.

The industry is rapidly approaching the deadline for implementing the requirements of the European Union's Restrictions of Hazardous Substances (RoHS), which will go into effect on July 1, 2006. The legislation will ban six substances from import into the EU, including lead and lead-bearing solder.

RoHS compliance requires that an unpopulated PCB substrate cannot exceed specified maximum levels of the offending elements, especially lead. While many companies have achieved lead-free compliance, the PCB challenge has become the ability to survive lead-free assembly and rework. The additional strain induced by material expansion, that is in turn induced by the increased temperatures needed for lead-free assembly, might cause interconnect structures to fail and/or the dielectric materials to delaminate. This article will address the PCB's ability to survive the rigors of lead-free assembly and rework; embracing lead-free capability testing.

One needs to understand that the establishment of a lead-free capability in a PCB should be based not solely on conformance testing, but it should also require performance testing.

As companies scramble to prove that they "got the lead out" of their product, fewer firms are putting in the effort to assure that the product will survive lead-free assembly and rework. More often we are hearing that fabricators are trying to limit their liability to assembly and field failures with various statements of limited warrantee instead of proving that their product is robust enough for the lead-free environment.

Most assembly and rework protocols are currently specifying tin-lead assembly at a typical temperature of 230°C, while lead-free assembly is generally performed between 245°C to 260°C. The impact of the extra 15 to 30°C can be significant. A PCB performance test is necessary to determine if unpopulated boards are robust enough to survive the increased thermal excursions of lead-free assembly and rework.

When quantifying the performance of a product following exposure to lead-free assembly, a number of factors must be considered. Most circuit boards are unique in their application; no two designs are identical. They are unique in design, specific processes used in fabrication by various companies and unique by virtue of the materials used in fabrication. Because of their inherent uniqueness, PCB testing embracing compliance to a standard has proven not to be practical. Individual requirements for boards are as varied as the boards themselves.

The better approach is to test and compare results to a known performance baseline for the specific constructions. A test of the general robustness of a product and how that robustness degrades with the increasing temperatures, dwell times and number of cycles associated with lead-free assembly, gives the most insight in performance testing.

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DOW	11137.65
NDAQ	2326.11
CLS	11.16
ELCQF.PK	21.47
SANM	3.96
FLEX	10.78
CDN	0.00
PLXS	38.62
SLR	4.00

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Testing a board's capability to withstand the temperatures associated with lead-free assembly is to establish its reliability. This is done to develop an understanding of how assembly and rework degrade reliability. It is an exercise in comparing results of similar products to historical data and making qualitative decisions based on those findings.

The electronics industry considers that reliability testing is commonly achieved by thermal cycling, although this testing should really be classified as conformance testing. Most specifications require that test vehicles be cycled between 100 to 1,000 cycles, followed by microsection analysis to confirm that interconnect degradation has not occurred. It is not common that the product is taken to failure to understand the reliability. Thermal cycle testing can be done by many methods, but all use thermal excursions between specific temperatures while monitoring changes in resistance of designed circuits. Some methods require custom coupons; others could be performed on actual product. Whichever method is used, thermal cycles is the common variable, which is analyzed to obtain comparative results.

Considerations of Lead-free Capability Testing

1. A thermal cycling test method must be defined and the test vehicle chosen. The test methods that are usually employed are thermal cycling methods of various types (air-to-air, liquid-to-liquid), or interconnect stress testing (IST). Traditional thermal cycling techniques subject products to thermal cycles by heating and cooling their external environment. IST testing uses specifically engineered coupon that are heated internally. Both methods have been correlated by IPC and have advantages and disadvantages that are beyond the scope of this article.

2. The test vehicle should ideally be made with the same process and attributes as the actual product. Particularly important are overall thickness, hole size, grid size and material type. For accurate reliability testing copper plating, materials and all fabrication processes must be within acceptable operating parameters, or the test can be compromised. A hierarchy of influence on PCB reliability has emerged over the last few years. Testing coupons that have been subjected to tin-lead assembly and rework have demonstrated that the hierarchies of reliability influences are copper plating quality, followed by material capability and then design and construction influences. With lead-free assembly temperatures, copper quality and material capability are competing for the first order of influence, followed by board design and construction. Fourth-level parameters and variables including hole preparation, drilled hole quality, registration and other parameters. It is important to understand any one of these influences may become the dominant factor, when it goes beyond acceptable limits. Rough holes, from drill gouging or aggressive desmear, have the effect of making the PTH rigid, resisting X-axis and Y-axis expansion, much like corrugated metal. A rigid hole causes stress to be redistributed away from the barrel and toward the internal interconnects, and up to surface pads, accelerating damage. An appropriate test of reliability requires that all influences are optimized or the results may be confounded.

3. Lead-free testing has demonstrated two contrasting effects where material delamination can influence the cycles-to-failure. In some cases the stresses become focused into the PTH barrel, which leads to premature failures; in this article it is referred to as "stress focusing." The other condition creates a "stress relieving" type of delamination that redistributes the stress away from the interconnect structures, artificially extending cycles-to-failure. Testing of the base materials must be completed in parallel with reliability testing to confirm overall product performance.

4. The test vehicle should have resistance measurements completed on all test circuits as received, after assembly simulation (preconditioning) and during testing. The goal is to determine the effect of preconditioning on the reliability of the product. The electronics industry specifies that a failure is a 10% increase in resistance of any circuit being measured. Preconditioning alone has the potential to increase resistance by 5% in an unreliable product. Measuring resistances before and after preconditioning allows an understanding of how the products degrade.

5. The sample size should be large enough to be statistically valid, usually 18 test vehicles per variable. There are two parts to the sample size: the number of PTH per sample and the number of samples tested. The more interconnections, the better. Typically 200 to 300 interconnection structures per circuit, 2 to 4 circuits per test vehicle is a reasonable number. Typically 36 test vehicles are used to qualify a vendor, material or process variable. Thirty-six coupons with 2 circuits, each with 300 holes per circuits, allows for testing of 21,600 PTHs.

6. The test vehicles need to be subjected to a simulation of assembly for an effective evaluation. This step is called preconditioning; it can be performed by subjecting the test vehicle to thermal excursions similar to assembly and rework in an assembly oven, or, in the case of IST, profiled on the tester itself. Preconditioning by means of thermal ovens tend to be a variable from company to company. This variability is inherent in this process because no two boards require the same oven profile, no two assembly companies will run product exactly the same way, and a dwell time at certain temperatures is required to assure solderability between the PCB and electronic devices. The most commonly used number of preconditioning cycles to access reliability is between three and six - three cycles for assembly and three cycles for rework simulation.

7. A typical lead-free study would test 12 samples "as received," 12 samples preconditioned to tin-lead assembly and rework temperatures (6 X 230°C) and 12 samples preconditioned to lead-free assembly and rework temperatures (6 X 260°C). Following the appropriate preconditioning the samples are subjected to reliability testing.

8. Experience has taught that testing needs to be near the glass transition temperature (Tg). Tg is defined as the temperature at which the rate of coefficient of thermal expansion (CTE) in a dielectric changes. Typically with a FR-4 system, the CTE before Tg will be in the range of 20 to 50 ppm/C. After Tg the CTE can increase to between 100 to 300 ppm/C. During assembly the board will exceed Tg but in the end use environment temperatures rarely exceed Tg. By testing near Tg the maximum strain induced by Z-axis expansion is achieved without changing to the higher expansion rate. Testing significantly above Tg may induce different failure modes that would not be found in field failures. High temperature testing is valid but the failure modes shift. Testing significantly below Tg (125°C or less) requires extensive time before failures are found, which is necessary for meaningful results. Experience has demonstrated that a test temperature of 150°C is adequate for most PTH, buried and blind via structures. Microvias are not effectively stressed in a reasonable amount of time at less than 190°C. Flex circuits and thin polyimide based boards are tested at 210°C.

9. To obtain meaningful data testing should be aggressive enough to achieve a minimum 50% failure rate before the end of test. The test may be adjusted by increasing the cycles, or by increasing the test temperature. Testing at 150°C for most applications gives reasonable results in less than 500 cycles (2 days). Recently we found microvias require testing at 190°C for known compromised microvias to fail in less than 500 cycles. Polyimide-based products, particularly flex circuits, are tested at 210°C for 1,000 cycles.

10. Samples are cycled to the end of test (usually 500 cycles) or until there is a 10% increase in resistance in any test circuit. Thermal cycling ovens are limited in that there are usually many samples in an oven and thermal cycling does not stop when an individual sample fails. With IST testing, each sample is tested separately and testing stops exactly when a sample reaches 10% increase in resistance. Stopping the test immediately allows the advantage of better acuity in failure analysis. Stopped at a 10% increase in resistance, the failing structure has not progressed to catastrophic failure before thermal cycling stops.

11. Failed coupons are subjected to failure location using infrared thermal cameras. By applying a low current to a circuit that has 10% increase in resistance, we find the one via that is contributing the most to the increase in resistance. The single most damaged interconnect will be easily identified using thermal imaging techniques.

12. Microsections are done for the first failed sample in each test group and one of the samples that reached the highest cycles-to-failure. If there is no failed circuit in a test, then the circuit that has been most degraded needs to be examined using microsectioning techniques. Failure analysis is performed on selected samples to determine the demonstrated and latent causes of failure and to check for the presence of "stress relieving" delamination. The failure modes for lead-free testing are barrel and corner cracks that exhibit metal fatigue. Metal fatigue cracks generally start in areas adjacent to glass bundles and usually propagate on an angle of about 30 degrees; the cracks meander around copper crystals, which commonly close at ambient conditions (**Figure 1**). The elevated temperatures associated with lead-free assembly have demonstrated a propensity for increasing the risk of corner or knee cracking (**Figure 2**). The extended exposure to temperatures above Tg will increase the rotational strain between the PTH barrel and surface features, creating a bending moment at the apex. Microsections should be examined for traditional IPC-6012

criteria, with increased vigilance for the presence of "stress-relieving" delamination (**Figure 3). If any obvious fabrication discrepancies are found, lead-free capabi**lity cannot be established. If plating is thin or nodular, or the base material delaminates, the test is of the discrepant condition, not a statement of lead-free capability.

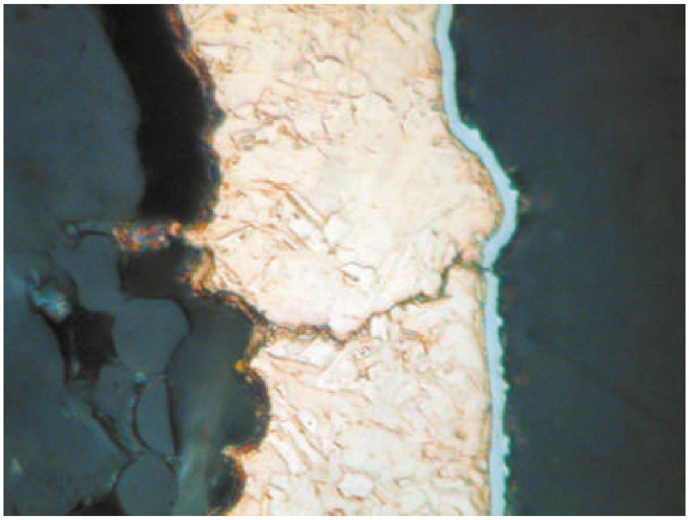

FIGURE 1. Barrel crack due to metal fatigue.

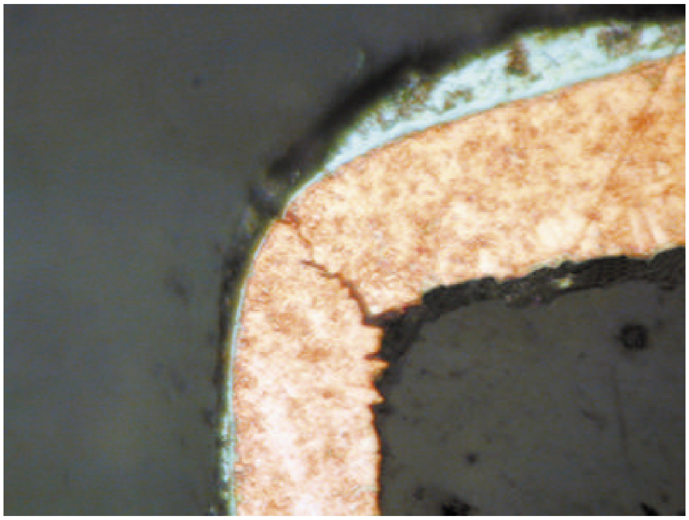

FIGURE 2. Corner crack due to metal fatigue.

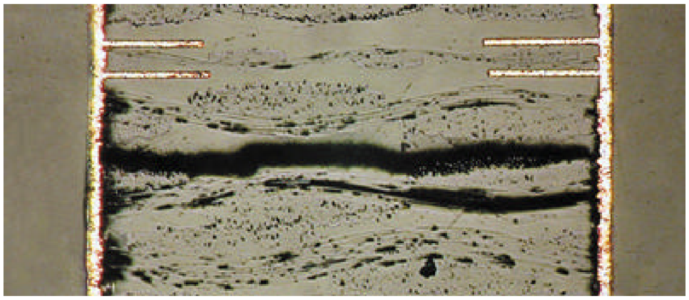

FIGURE 3. Stress-relieving delamination.

13. The reliability test data is then analyzed to compare cycles-to-failure with failure analysis results. A decision must be made to either include or remove data associated with coupons that demonstrated stress-relieving delamination. Standard and Weibull statistical analysis is then preformed. A typical approach would be the "as received" samples' mean cycles-to-failure establishes the specific boards' "entitlement." The

"entitlement" reflects the least stressed condition and is the control against which all other results are compared. The means cycles-to-failure of the tin/lead samples represent the typical degradation of the product. The third group of samples preconditioned to 260°C represents the effects of lead-free.

14. Concurrent thermal analysis of the samples must be performed. There are many tools available for materials analysis; one of the more flexible tools is thermal mechanical analysis (TMA). TMA allows measurement of CTE, Tg and time-to-delamination measurements T260 or T288. It is important to take the sample from the actual PCB, not only samples of rigid c-stage laminate. The goal is to understand how the material is performing by measuring a sample that has the same construction and has seen all the process steps of the boards. What is needed is to determine the CTE of the board's construction and the Tg after fabrication. Material analysis is a powerful tool for understanding a material's relative robustness applied against a backdrop of thermal cycles-to-failure. For example, there are materials that have a high Tg but do very poorly when exposed to the rigors of thermal cycling from hot-air solder leveling (HASL), sequential laminations or lead-free assembly and rework. Occasionally coupons or boards with low thermal cycles have no observable fabrication problems (thin copper, poor electroless adhesion). When the product produces low cycles, failure material analysis could reveal a possible cause. Taken together, thermal analysis of material coupled with thermal cycles-to-failure produces a synergistic combination for understanding lead-free capability.

15. All data is reviewed and observations made. The mean cycles-to-failure are recorded and used as the "baseline" against which all other tests are measured. We have found that lead-free assembly and rework may reduce the product's entitlement by 50%. If the sample were to achieve 300 cycles-to-failure in the "as received" state, then 150 cycles after lead-free preconditioning would be expected. If a test vehicle's entitlement is reduced greater than 50%, the product is sensitive to lead-free assembly and rework.

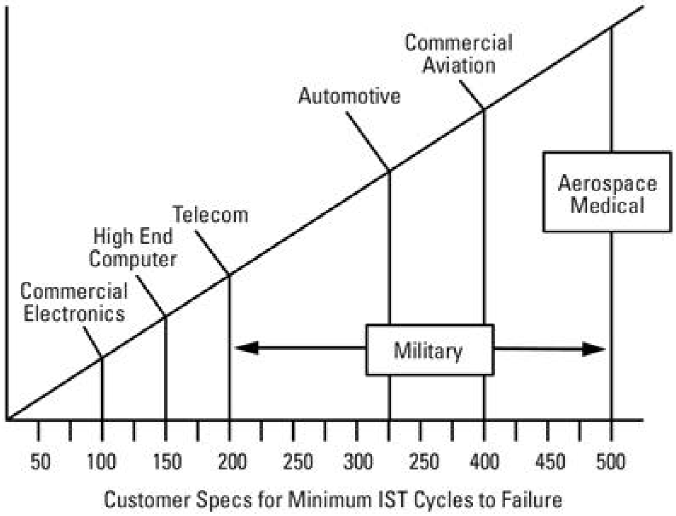

FIGURE 4. Minimum IST cycles-to-failure by industry.

16. Since no thermal cycles-to-failure standard has been established, nor is it likely to be established due to the complexity and variability of printed wiring boards, individual companies must establish their own performance requirements. Requirements are established taking into account specific company needs and the demonstrated minimum cycles-to-failure on their products. These requirements are set based on a wide variety of considerations including the company's product, end-use environment, assembly yields, field failure history, warrantees and customer needs. An overview chart of the typical minimum IST cycles-to-failure by industry is helpful in establishing requirements. Figure 4 should be reviewed knowing that recent correlation studies have demonstrated that one IST cycle is equivalent to approximately 3 thermal oven cycles. The chart shows various minimum cycles-to-failure generally established by different industries. This chart reflects the lowest acceptable IST cycles achieved by a product tested in the "as received" condition. **PCD&M**

Paul Reid is a program coordinator at PCB Interconnect Solutions, a supplier of IST test equipment and test services. He has a master's degree in science from Rivier College and 30 years of experience in PCB fabrication. Reid can be reached at paul.reid@pwbcorp.com.

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