Proof is in the PTH -- Assuring Via Reliability from Chip Carriers to Thick Printed Wiring Boards

Kevin T. Knadle
Virendra R. Jadhav
Endicott Interconnect Technologies, Inc
1701 North St, Endicott NY 13760
Kevin.Knadle@eitny.com VirendraR.Jadhav@eitny.com

Abstract

The reliability of Plated through holes (PTH's) is presented as "PTH life curves" which plot cycle to fail vs. temperature for the entire range of field, accelerated thermal cycling, and assembly reflow thermal exposures on a Printed Wire Board (PWB) or Laminate Chip Carrier (LCC). The curves represent years of testing with the Current Induced Thermal Cycle test (CITC) covering different resin systems, via constructions, and metal finishes. The curves reveal a number of critical factors in PTH reliability including the significant effect of Pb free reflows, resin system formulation, and copper plate chemistry on via life. The critical importance of the "assembly life" region of the life curves is presented along with E/SEM photos of a crack opening during a reflow cycle. A finite element model is developed for one of the PTH constructions in this paper to show the complementary use of Finite Element Analysis (FEA) with this approach, since a valid model allows extension of the life data to other design and stress variables. The FEA fatigue life calculations correlated well with the experimental life curves. Examples of cumulative damage life projections for a number of PWB and LCC cases are given using the life curves. Finally, the importance of aggressive monitoring of PTH quality with the CITC 220C test is discussed.

Background

Though today's microvias and high aspect plated through holes (PTH's) look nothing like the earliest through holes of 40 years ago, the PTH in its various forms remains the "weak link" and most critical element of printed wiring boards and laminate chip carriers.

There are many things that have not changed since the first PTH's-- the main reliability problem continues to be the extreme difference in Z-axis coefficient of thermal expansion (CTE) mismatch between the copper plating and the laminate materials of printed wiring boards (PWB's) and laminate chip carriers (LCC's). This mismatch is especially extreme at assembly temperatures above Tg where laminate Z-axis CTE approaches 200–400 ppm/C, compared to 15 ppm/C for copper. As arguably the greatest CTE mismatch in all of electronic packaging, the PTH failure mechanism as a result of temperature cycling has been studied exhaustively. Published approaches involve either modeling or a variety of empirical accelerated thermal cycle (ATC) tests, and usually focus on either the reflow cycle or more general temperature cycling to reflect usage conditions. [1-9]

In addition to the CTE mismatch, other "constants" regarding PTH life that have not changed with time might include: a) thicker copper is better with all else the same, b) higher aspect ratios holes are more difficult to produce and tend to have reduced life, and c) defects from drill, conditioning, or plating process are the root cause of most actual PTH problems in the field.

However there are other aspects of plated through holes that are completely different today. The probability and mode of failure on a non-solder filled high aspect ratio wiring via are completely different from their solder filled predecessors. Even within the same laminate, the stresses on through holes are completely different than those of buried or blind vias next to them. And today there is a large the variety of resin systems, which can each have a very different PTH test result depending on the temperature range tested, a difference which in some cases has little to do with which one is more reliable.

Moreover, the challenge of making and evaluating today's PTH's go even deeper than the visible differences. For example, the choice of copper plating chemistry can make a significant difference in resulting via life even for barrels that appear identical in terms of copper thickness. And the higher temperatures of today's Pb free assembly can reduce PTH life significantly more than conventional SnPb reflows. The result is that the complex mix of different via constructions, materials, and applications that embody today's diverse PTH family demand a more flexible evaluation approach than is provided by a simple fatigue equation or a single ATC test.

Approach

This paper presents PTH life curves generated with the Current Induced Thermal Cycling (CITC) test to address a number of the examples and pitfalls mentioned above, including the effect of resin system, construction, aspect ratio, Pb free assembly process, and surface finish. The paper outlines an approach to evaluating PTH reliability and quality that involves characterizing PTH life across a range of temperatures to reveal intricacies not seen by testing at a single delta-T, and certainly difficult to predict by modeling alone. The tools of this approach are:

1) A CITC test coupon with a simple daisy chain of 100 vias per coupon that can be replicated in large quantities on a test vehicle panel or collected from the unused edge of product panels.
2) Cycle to fail data using the CITC test from 23C to T(high), where T(high) includes a range of temperatures from 125C to 260C. CITC 23 to 220C is the preferred test for single temperature evaluations. [1]
3) Accelerated thermal cycle tests at other temperature ranges with air to air ATC, and/or Wet thermal shock, as needed to extend life projections to other temperature ranges.

4) FEA modeling. Once a model is built and verified with experiment life data, it can be used for fast comparison of construction, material, and process variables, as well as for life projections across a wide range of stress conditions.
5) Miner's rule for cumulative linear damage calculations to estimate PTH life for any combination of stresses and data generated with the above methods. [10]

Test Definitions

The main PTH test at Endicott Interconnect Technologies Inc., for the past 14 years is the CITC test, our version of Current Induced Thermal Cycling. [1-3] The tester uses proportional control algorithms to continuously adjust the current for each coupon in each cycle in order to achieve a precise and repeatable temperature cycle with a prescribed linear ramp and dwell time. The typical ramp rate, as used for all the data in this paper, is 3 degrees/second. The high temperature dwell time is between 30 to 40 seconds, which has been shown by modeling and measurements to be sufficient to achieve thermal equilibrium. [2] Fans are then turned on to start the cooling phase. A CITC cycle is illustrated in Figure 1.

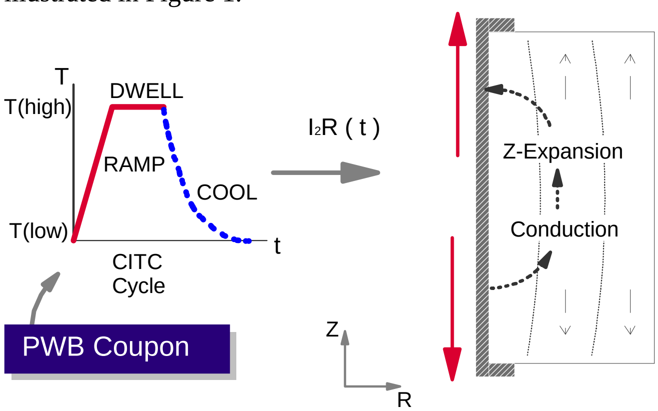

Figure 1- CITC test and cycle definition

For this paper, all coupons are run to failure from ambient to single prescribed temperature T(high). Failure is usually defined as a 10% resistance increase above that resistance expected for the present cycle (not from time-0); this criteria has been the best at detecting a catastrophic crack such as would cause an open in the field, as opposed to the inevitable resistance increase each cycle from plastic deformation (stretching) of high aspect ratio barrels. For Z-axis failure modes, this failure definition has been excellent at determining the exact cycle of first fail (open) due to a complete 100% barrel crack.

PTH Life Curves

A valuable experimental tool for evaluating and understanding PTH behavior under cyclic temperature stress, and a critical starting point for any new resin system, construction, or surface finish, is the PTH life curve. An example of such curves for 4 different commercially available resin systems generated using the CITC test is given in Figure 2. Each point on the curve is the mean life from 4-12 coupons tested from room temperature (23C) to T(high), where T(high is usually between 125C and 260C. Each data point is a pure measure of life at that temperature— there is intentionally no prior preconditioning cycles.

The coupons used for the curves of Figure 2 are similar in design and construction: 0.010" drilled vias on approximately 0.120" thick test vehicle board, 100 vias per coupon on a 0.050" grid. Despite the high number of cycles necessary to produce failure at the lower temperatures, each curve can usually be completed in 1 week of test time given the speed of the CITC test, which runs at between 300 to 500 cycles per day depending on temperature and coupon type.

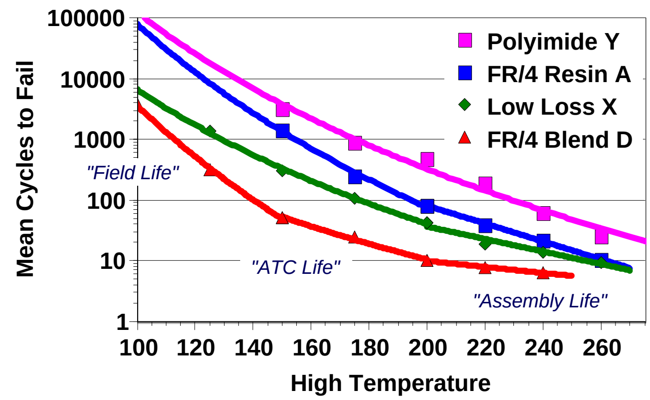

Figure 2-- "PTH life curves" for 4 resin systems with CITC 23C to T(high). Coupons 0.120" thick, 0.010" vias.

The first observation from Figure 2 is that each laminate system has its own "personality", and the curves reveal significant characteristics of the base resins, in particular. Other than polyimide, which has a Tg above that of the temperature range tested, the approximate Tg of the materials is evident as the point of distinct change in slope of its curve. In fact, the 2 inflection points observed for vendor resin system D in the CITC data are also real-- two distinct Tg points were consistently observed during Tg testing (DSC) of that material. The material is known to be a blended resin system, which is likely the reason for the two Tg points in this case.

The single change in slope around Tg for most PWB materials, as exemplified by the middle 2 curves of Figure 2, has mechanical, as well as material, implications. It likely represents the elastic to plastic strain transition common to metal fatigue, as represented by the full Coffin-Manson equation with both elastic and plastic terms, where here strain is assumed proportional to ΔT. [10] Note that the Coffin-Manson (C-M) equation is commonly plotted on Log-log axes, but most of the curves in this paper are plotted vs. Linear temperature for clarity and presentation.

In addition to differences in shape and slope, clearly the materials differ in cycle to fail magnitude. The differences are best discussed in terms of the life regions indicated in Figure 2, which represent the three main thermal exposures on most PWB and LCC barrels. "Assembly life" is the response of barrels exposed to the temperatures of SnPb and Pb free reflow and rework cycles as part of board assembly. "ATC life" can be compared to the expected lifetimes under many typical thermal cycle tests such as 0 to 100 or -40 to

125C. Finally, the "Field life" region to the left of the plot and beyond represents the type of delta-T exposure and expected PTH life due to operational cycles only.

Aside from the fact that it is difficult and expensive to process, Polyimide has excellent life in all three regions, including assembly life—this fact is of course well documented and known, and is the reason why it remains popular in military markets. Note that the advantage of polyimide is greatest near SnPb assembly life and ATC life; its life appears to drop off considerably near Pb free temperatures and it is not much different from a good FR/4 near the Field life region.

The curve for Resin X introduces another point about Figure 2. Resin X is an excellent vendor available prepreg for low loss applications. It has good assembly life and field life, and is one of the few low loss materials to survive Pb free reflows in our evaluations without delamination. However, it has relatively low cycles to fail in the "ATC life" region, and lasts only one or two hundred cycles tested at 23 to 150C. The reason for the reduced life below Tg compared to other resins is likely a function of the material properties such as CTE and/or modulus.

But here is a problem with the 23 - 150C test recommended by the IPC specification [3], when used alone and not as part of the total life curve. Those that evaluate a PWB with Resin X with 23-150C might reject it compared to other products or materials even though it may be more reliable in actual use due to its excellent ability to survive field cycles, as well as both SnPb and Pb free reflows.

Assembly Reflow-- The most critical PTH exposure

However, the most important observation from Figure 2 is also what has been widely experienced in the industry since the advent of unfilled wiring vias for surface mount technology (SMT)-- assembly reflow stresses are by far the most demanding thermal excursion on a PTH, and the highest risk in terms of survival per cycle[1]. Clearly, the assembly life portions of the life curves are the low point of the curves, and represent only a finite number of cycles. That is, if PTH's from standard resin systems only survive 10, 20, or even 30 reflow cycles before failure, on average, then each reflow cycle consumes a significant portion of PTH life. To a mechanical engineer that means there is very little safety factor to a nominal PTH structure exposed to reflows, and to a process/quality engineer that means that controlling and monitoring PTH defects (which quickly bring the curve to zero life) becomes critical.

Figure 3 shows how assembly reflow cycles can be counted in the same way as other temperature cycle requirements for a particular laminate board or chip carrier product. For example, a PWB application may have a requirement for 8000 on/off cycles from 20 to 75C. But that same board also has a requirement for some number of reflow cycles before it reaches the customer's office—most boards see at least 1 or 2 reflow cycles for initial assembly. In addition, there may be another 4-6 reflow heat cycles for rework of Ball Grid Array or other SMT components, since each rework includes a remove + replace heat cycle on the board and assembly lines like to have the option to rework 2 or 3 times per site. While a total of 8 reflow cycles sounds like a much smaller number than 8000 on/off cycles, the reality of Figure 2 is that the reflow cycles are by far the most critical temperature cycle for a PWB. The reflow cycle requirement for Laminate chip carrier vias is similarly counted, though there are likely more reflows involved in the manufacturing of the LCC than in the 2nd level attach.

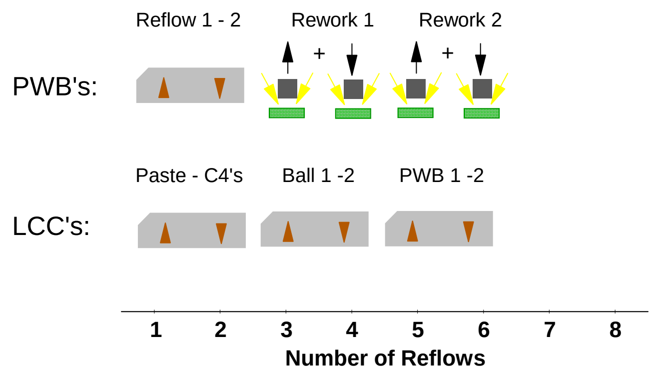

Figure 3— The reflow temperature cycle requirement for PWB and LCC vias

In Figure 2, the problem with assembly life is best illustrated by resin D. This material showed the lowest PTH life in all life regions of any that we have tested especially at reflow temperatures. The mean life at CITC 23-220C test was less than 10 cycles. This result was verified by running CITC coupons through an assembly reflow oven profiled to approximately 220 C, removing the coupons while still warm through a unique access panel in this oven, and probing the coupons electrically. The oven reflowed coupons failed around 9 cycles and were 100% failed by the 12th cycle, matching the CITC results. This resin system was also linked to specific cases of barrel cracking problems in products by others in the industry. PTH crack problems are easily predicted by considering the assembly life in Figure 2 compared to the reflow requirements of Figure 3. That is, if 1 – 6 reflows are necessary for assembly, and nominal vias last 8 cycles on average, some distribution of product with cracked vias is expected. On the other hand, if a PWB with resin D did not require any assembly but was shipped directly to a typical office system environment with T(high) = 50C, for example, it would "last forever". Extrapolating the field life region of the curve with a power law (C-M) fit to T=50C predicts the vias would last millions of cycles from 23 to 50C.

Viewing PTH expansion during "reflow" with E/SEM

Finally, nothing compares to actually visualizing the effect of reflow cycles on a PTH to see the relative importance of evaluating assembly life of PTH's. An environmental SEM at the Binghamton University IEEC was used to photograph and even video tape the opening and closing of a PTH crack during a reflow cycle. The crack sample was from a failed coupon that had been cycled to first fail with the CITC test, and then dry-sectioned to expose the newly formed crack. The sample was then placed in the E/SEM chamber (no coating is required for E/SEM). The crack area and resulting expansion was photographed during a slow cycle from room temperature up to 230C, and then back to room temperature.

Figure 4 compiles some photos of key temperature points during the E/SEM temperature cycle, showing significant Z-axis expansion especially above Tg (175C). The amount of expansion at the crack is exaggerated somewhat over that which an unfailed barrel sees during cycling due to the presence of the crack and the modified boundary conditions on a barrel sectioned to the mid-point. However, the relative change in expansion at the crack across the entire temperature range, especially between 175 and 230C, is indicative of the excessive expansion of PWB materials at reflow temperatures.

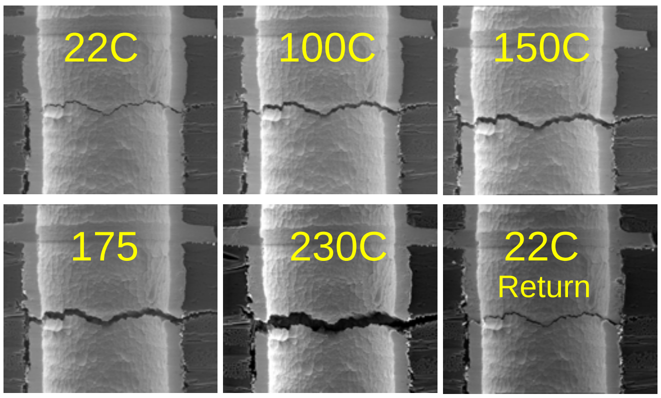

Figure 4-- Environmental SEM images of a PTH crack at select temperatures of a reflow cycle and return.

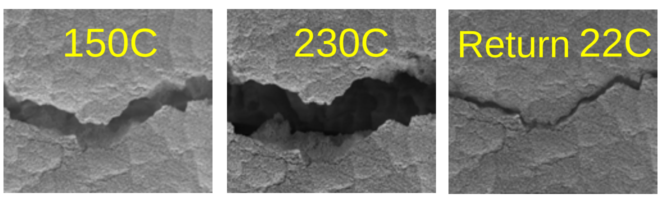

Figure 5-- Close-up of crack areas from E/SEM cycle.

PTH cracks as latent defects

The SEM photos of Figure 4 reveal a critical aspect of PTH cracks from high temperature cycling-- however large the crack opening at reflow temperatures, the crack tends to close tightly on return to room temperature and is in fact an electrical connector through most of the first temperature cycles after formation. The implication is that PTH cracks formed during assembly processing are often undetectable to in-circuit tests and can escape to the field. Experiments conducted with pre-cracked coupons subjected to ATC cycling and event detection monitoring show that the cracks eventually become intermittent open with subsequent cycling.

Close-up photos from three of the temperature points in Figure 4 are shown in Figure 6. Note the three dimensional depth to the cracks, such that even at 150C there are areas of copper within the crack that are prone to make contact. And the crack is clearly an electrical contact at 22C room temperature. In fact, the crack is actually under compression as a result of the conditions in which it was formed at high temperatures: that is, the plastic deformation of the copper (barrel is permanently "longer") plus the viscoplastic flow of the resin from the barrel (laminate near barrel is "shorter").

The latent problem of cracks produced during an assembly cycle is further illustrated electrically in Figure 6. A group of coupons with weak copper barrels produced by multiple passes through a copper etch process were found to fail during the first cycle of CITC test. 10 virgin coupons from the same group plus a control coupon (not over-etched) were wired for 4-wire continuous resistance measurements and subjected to a reflow cycle using a lab oven.

The resistance of all coupons during the cycle is plotted on the left axis of Figure 6, while the temperature of the coupons from an attached thermocouple is plotted on the right axis. Note that the good coupon shows a small increase in resistance due only to the temperature change. In contrast, the weak coupons crack and become electrically open with a sudden sharp increase in resistance during the 1st heat-up cycle, in the temperature range of approximately 125 to 175C. During the cooling cycle, these cracks close up with a similar sharp change in resistance and within approximately the same temperature range. The final ambient resistance of each cracked coupon was within 5% of the starting pre-cracked resistance of the same coupon.

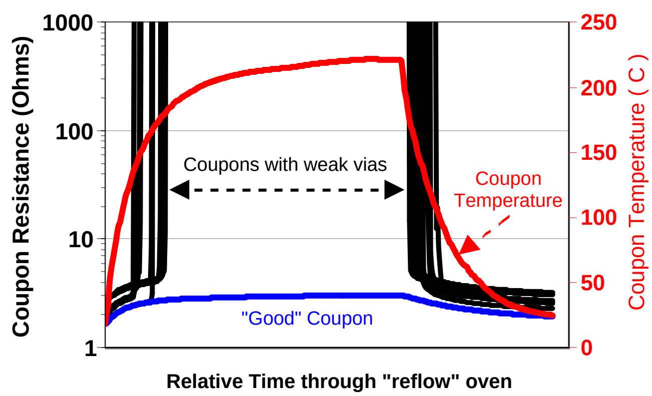

Figure 6-- Resistance and temperature measurements on weak copper barrels through an oven reflow cycle

Pb free reflows—"Kicking it up a notch"

Figure 7 highlights the assembly life portion of the life curves for Resin A and X to illustrate the effect of higher reflow temperatures such as are generally required for assembly with Pb free solders. While ATC cycling after a specified number of reflows can also show the effect of Pb free temperatures [9], life curves graphically reveal the root of the problem as a function of construction, material, and surface finish. In the case of the two examples in Figure 7, each 260 C Pb free reflow cycle can consume from 50 to 75% more reflow life than a SnPb reflow at 220C! That is, the effect on PTH reliability from Pb free reflows is the same as with SnPb reflows, only "up a notch" in magnitude. More PTH life consumed by reflow means less life available for ATC and field life, and that even more rigorous process control and quality monitoring may be required by PWB manufacturers to maintain PTH reliability.

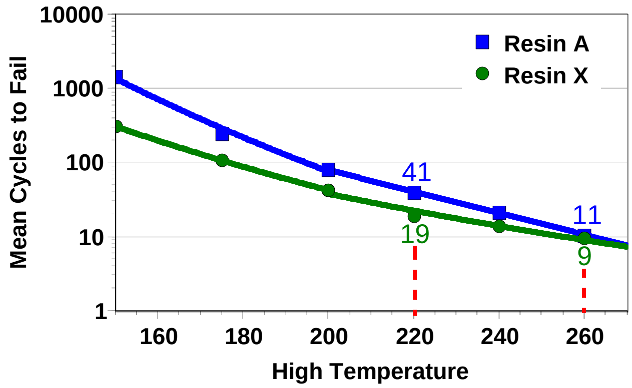

Figure 7-- Pb free versus SnPb Assembly life

Surface finish and Nickel plate

In addition to comparing resin systems as in Figure 2, CITC "Life curves" can be used to understand and quantify the effect of any significant PTH design and process variables. For example, Figure 8 shows the effect of electroless nickel plate over copper using coupons from a 10mil drill on 130mil thick board. When the processed correctly, nickel plate can significantly extent PTH life in all regions of the life curve, and is especially useful for test vehicle cards that require unlimited ATC life. Cross sections of nickel plated vias pulled from test at some number of cycles between the 2 curves in Figure 8 reveal that the nickel plate remains uncracked despite cracks in the underlying copper plate. [1] Note that the curves tend to converge at Pb free assembly temperatures.

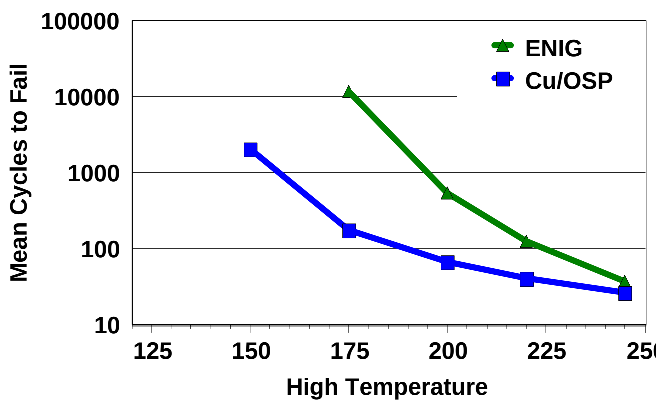

Figure 8-- PTH life curves for bare copper vs. electroless nickel plate

Copper plate chemistry and thickness

The curves of Figure 9 show that there are differences even between different types of copper plating. These curves are generated from coupons with 0.014" drilled vias on a 0.070" thick card, plated with three different types of electrolytic acid copper plate to a common thickness around 0.8 mils. Note that there is up to an 8x different in cycles to fail between the plating types, though the difference in plate chemistry would be difficult or impossible to distinguish with a cross section alone. The various plating chemistries each have their purpose and advantage—chemistry 1 is not "always better" than chemistry 3. However, it is critical that the PWB manufacturer can quantify and understand the difference.

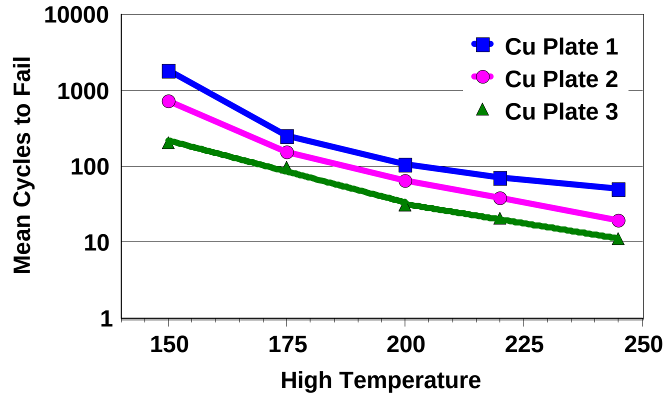

Figure 9-- PTH life versus 3 different acid plate chemistries / processes.

The fact that PTH life can be a strong function of both copper plating chemistry (above) and base resin system (Figure 2) leads to another important result— plating thickness, often viewed as the most critical variable in PTH reliability and a "non negotiable" in specification requirements, is only one of many factors that can be varied as needed to meet a specific reliability requirement.

For example, PTH life curves from identical test vehicles (TVs) built in-house and at another vendor are compared in Figure 10. The vendor resin system and plating chemistry are not known, but the nominal copper plate thickness was measured at around 1.2mils. The in-house test vehicles were constructed with Endicott Interconnect Technology's own Driclad® resin system and copper plate chemistry #3.

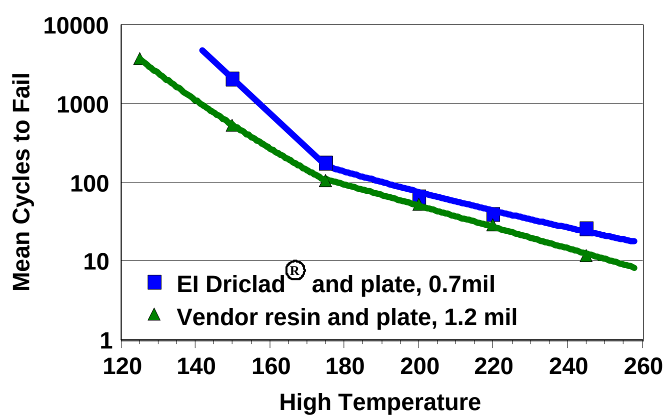

Figure 10—Life curve comparison of EI Driclad vs. vendor test vehicles showing important of resin + plating chemistry over copper thickness alone.

The nominal copper plating thickness on the in-house Driclad boards was measured at around 0.7 mils. Nevertheless, as shown in Figure 10, the PTH life curve for the in-house TV's exceeded that of the vendor TV's with almost twice the copper thickness. In fact, Driclad consistently has the best PTH life curve than any other standard resin system we have tested. This result, that the right resin system in combination with the right plating chemistry can make up for ½ mil of copper thickness, may be critical to enable very high aspect ratio vias and other future technology where thick copper is no longer an option.

Laminate Thickness and construction—LCC's vs. PWB's

Finally, Figure 11 compares PTH life curves at two extremes of construction. The top curve is from a 35mil thick laminate chip carrier with 6mil finished (8 drilled) vias. The two bottom curves are from a 190 mil thick board with 8 and 12 mil PTH's (10 and 14 drilled). Both are constructed with Driclad resin and similar acid plate chemistries (pulse plate in the case of the thick board). Note that the two different via sizes on the same thick board had almost identical life, in this case; plating thicknesses were confirmed to be the same for the 2 via sizes.

The thinner laminate chip carrier has higher overall PTH life than the thick board, but otherwise the appearance of the curves is very similar, showing how the life curve approach and related discussion in this paper is independent of via construction, and applies to the thinnest LCC and the thickest boards.

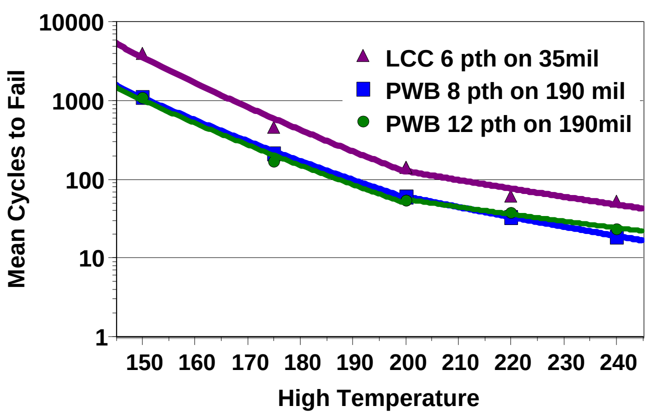

Figure 11-- Life curves a thin LCC and a thick, high aspect ratio PWB.

Extending life curves with Finite Element Analysis

The value of PTH life data as presented in this paper is increased even further with the complementary use of Finite Element Analysis (FEA). A model, once developed and verified for Product A, can be used to explore the effect of other construction, material, and even process variables to either improve Product A, or to help develop the next product.

As an example of how well FEA can complement this approach, the life curve of the 190mil thick board curves in Figure 11 was also predicted using Finite Element Analysis. Figure 12 shows the Finite Element model used for these predictions. Sixty four thousand first order linear elements (C3D8) of Abaqus were used to discretize 1/8th symmetry of the plated through hole and layers of prepreg. The three dimensional model provides greater flexibility in terms of allowing uneven PTH wall thickness, eccentricity of hole, and other variables which may be of interest. Although the analysis could be done more efficiently using axisymmetric elements, it was decided to use 1/8th symmetry model with 3D elements so as to be able to perform additional sensitivity studies in future, while keeping a common model as the control case, which is the case presented in this paper.

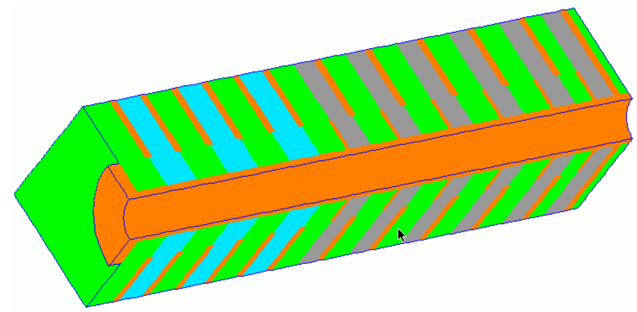

Figure 12 : One Eighth Symmetry Model (Three Different Cloth Styles)

As was shown experimentally in a previous section of this paper, the material properties of the electrodeposited copper in the plated through hole vary significantly with the chemistry and process parameters. The properties used for this analysis were taken from historical database of properties. Laminate materials were modeled as linear elastic with temperature dependence, and copper was modeled as elastic-plastic with temperature dependence. Material Properties used in the analysis are listed in Table 1. Yield stress of copper ranges from 10Ksi at 20C and 4 Ksi at 400C. Properties of the three different cloth styles used were measured using TMA for CTE and DMA for modulus as a function of temperature.

Table 1 : Properties Used in FE Model

Material	E(Mpsi)	CTE(ppm/C)
Cu	17	17
106 Cloth	1.09 at 20C 0.9 at 155C 0.13 at 190C 0.13 at 265C	X/Y: 17-19 Z : 42 at 20C 75 at 190C 380 at 260C
1080 Cloth	1.23 at 20C 1.05 at 155C 0.14 at 190C 0.14 at 265C	X/Y: 17-19 Z : 50 at 20C 75 at 190C 370 at 260C
2313 Cloth	2.2 at 20C 1.9 at 170C 0.8 at 190C 0.7 at 265C	X/Y: 10-13 Z : 33 at 20C 120 at 195C 300 at 260C

The following Coffin-Manson type equation was used to predict the fatigue of Cu.

$$N_1 = N_0 \left(\frac{\varepsilon_o}{\varepsilon_1} \right)^n ,$$

where ε_o = the value of critical strain at N = N_o
ε_1 = the value of critical strain at N = N_1
n = the fatigue exponent.

For the study presented here, the equivalent plastic strain in the copper wall was used as the critical strain measure to predict the fatigue life of PTH's. The fatigue exponent was assumed to be 2-- values of n for copper have been reported to be in the range of 1.67 to 2.22 in literature. [5,11]

Figure 13 shows the variations of the equivalent plastic strains in the wall of the plated through hole as well as all copper planes. It can be seen that the maximum value of strain occurs at the center of the plated through hole wall. This location matches with the observed failure location in CITC testing.

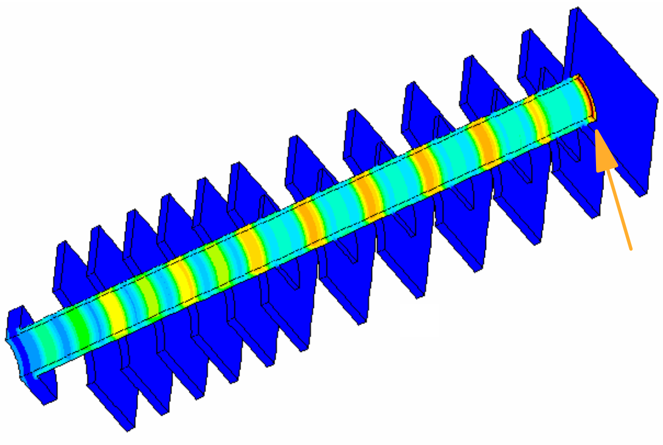

Figure 13-- Equivalent plastic strain results on 1/8th symmetry model

Figure 14 shows the comparison of experimental data with Finite Element predictions. Fairly good correlation is observed. It can be seen that the rate of increase in PTH life is higher in experimental data as T(high) of the thermal cycle is reduced. The FE model does not characterize this trend as well. Further studies could be used to understand the correct measure of strain as well as to adjust the copper fatigue equations in order to match the FE predictions with the experimental data over a wider range of temperatures.

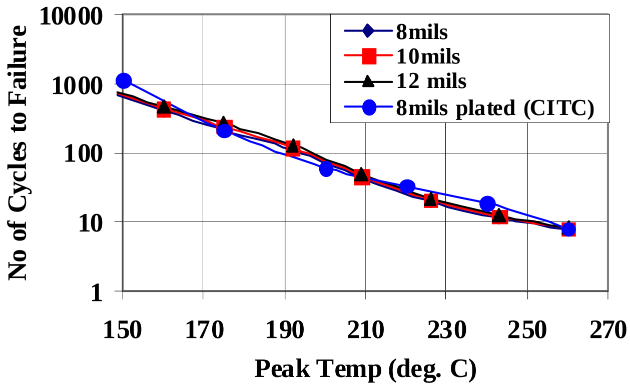

Figure 14-- FEA fatigue life predictions vs. CITC life data

Figure 14 shows that the difference in fatigue life of the plated through hole does not change significantly when the diameter of the plated through hole changes from 8mils to 12mils, at least on a 190mil thick board. Indeed, this also closely matches the result of CITC testing as shown in Figure 11.

Extending Life Curves with ATC Testing

Where the application or customer requires life data at temperatures outside the 23 to T(high) space, the test coupon is easily adapted to testing in other forms of Accelerated thermal cycle testing at other stress ranges. For example, an LCC may have to pass 1000 cycles of -40 to 125C cycling for in a JEDEC specification, or a military PWB may need to pass some requirement at -55 to 150C. Once both the life curve and ATC data is collected on equivalent coupons from the same group, life projections at any stress, or combination of stresses, becomes possible.

The two preferred methods for collecting such alternate stress data is air to air chamber cycling with event detection, or wet thermal shock testing with interval resistance readouts. The later requires use of a sensitive 4-wire resistance measurement and criteria (such as 5% resistance change from Time-0) due to the contact nature of PTH cracks. Figure 15 shows an example of cycle to fail data at -55 to 150C using ATC + event detection on a polyimide coupon similar to that used for the life curve of Figure 2. The resulting mean life of 763 cycles will be used for a life projection example in the following section.

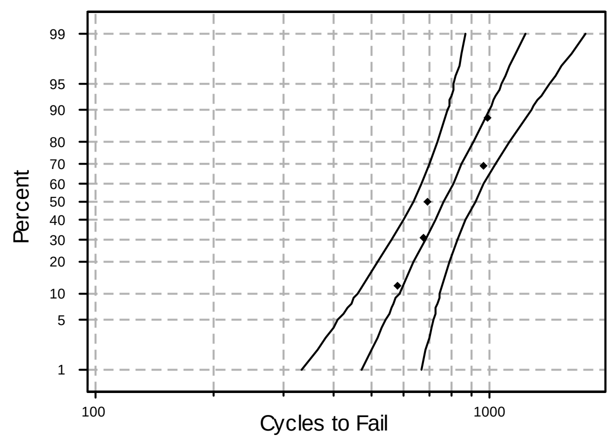

Figure 15-- Lognormal probability fit of cycle to fail at -55 to 150C on polyimide coupon

PTH Life projections

Finally, one of the most important uses of the PTH life curves, especially in combination with FEA and other ATC testing, is that they can be used to directly estimate PTH life for any product or stress test application. The procedure is outlined as follows:

1) Generate life curves with CITC across the desired field and assembly life spaces.
2) Fit the each of the curves separately with a Coffin-Manson (log-log) or exponential equation (more conservative), as appropriate, to obtain mean life estimates at desired temperature points.
3) Use ATC testing on the same coupons to generate mean life estimates at stress points, if desired.

4) Use of a cumulative linear damage calculation such as Miner's rule to estimate PTH life with any combination of the above stresses. [10]

This procedure is illustrated with 5 examples using results from this paper, as outlined in Table 2. Table 3 compiles the results of the cumulative damage calculations for each of these cases, including the curve fit estimates from the Figures in this paper that are used for the calculation. In this case, a Coffin-Manson log-log relation was used to extrapolate or interpolate "mean life" estimates at both reflow and use conditions as inputs in Table 3. These examples are illustrations on a mean life, "per coupon" basis only—there is no attempt to statistically adjust projections for PTH sample size (coupon vs. product) or to apply confidence bounds.

Table 2-- Example cases for PTH Life projections

Case	Laminate	Example to Estimate:
A	Resin X (Figs 2,7)	Product Field life at 23-50C with assembly = 3x SnPb reflows, 23-220C.
B	Resin X (Figs 2,7)	Product Field life at 23-50C with assembly = 3x Pb free reflows 23-260C.
C	LCC (Fig 11)	Product field life at 23-100C (Tj=125C) with 6x reflows 23- 220C.
D	Resin A (Fig 2)	ATC life at 0-100C as TV carrier for a LCC qualification with 3x reflow 220C.
E	Polyimide Y (Figs 2,15)	Life at -55 to 150C for military requirement with 3x reflow 220C.

Table 3— Net life calculations based on Reflow and Use conditions.

	Reflow (Stress 1)				Use conditions (Stress 2)		
Case	Cycle T1	Mean Life at T1	# Reflows	% Life consumed by reflows	Cycle T2	Mean Life at T2	Net Life at T2 after T1
A	23 - 220C	19	3	16%	23 - 50C	1,087,218	915,552
B	23 - 260C	9	3	33%	23 - 50C	1,087,218	724,812
C	23 - 220C	75	6	8%	23 - 100C	481,420	442,906
D	23 - 220C	41	3	7%	0 - 100C	9856	9,135
E	23 - 220C	145	3	2%	55 - 150	763	747

Case A and B represent a standard PWB laminate, in this case Resin X from Figure 2 and 7, with an office system on/off cycle requirement of 23 to 50C (measured at the board PTH's). Case A assumes 3x reflows to standard SnPb temperatures of 220C, while case B considers 3x reflow at a 260C Pb free temperature. Note first how the results in Table 3 once again reiterate the ongoing theme of this paper— the life of Resin X vias once they are reliably shipped to the field is on the order of millions of cycles; the problem is making vias that survive the assembly reflow stresses, which consume a significant portion of the total via life, and will readily cause PTH cracks in the presence of defects. Note further that in this case Pb free reflow consumes twice as much via life as does the SnPb reflow.

Case C shows how the same calculation can be used for Laminate Chip Carrier applications. Due to the temperature hierarchy of most applications, vias in the LCC will run hotter in an office system application because they are much closer to the chip, where Tj's around 125C are common. Therefore, even though the life curves of LCC may start higher than for PWB's, more life is required for their applications; at the same time, reflow is still a significant portion of the via life and will readily cause defective vias to crack.

Case D predicts the ATC 0-100 life of vias used for a test vehicle to collect solder interconnect fatigue life data for a BGA module. The authors have observed several cases where attempts to collect such solder joint have resulted in a waste of expensive hardware and testing due to cracks in test card that mask any solder joint failure data. This live curve approach has been successfully used to verify TV cards will survive the target number of cycles before populating the cards with valuable modules. For case D, the mean life at 23 to 125C from Figure 2 was used as an estimate of 0 to 100C (same delta-T =100C). The calculation predicts the cards to last over 9000 cycles.

Lastly, case E shows that the same approach can be adapted to other temperature ranges, such as in the military market. The polyimide coupon ATC data from Figure 15 is used in conjunction with the life curves from Figure 2 to adjust for the effect of initial reflows, which in the case of polyimide is a reliability low effect, at least for SnPb reflow temperatures. The same approach however can be used to explore the effect of additional reflows, Pb free temperatures, and indeed any other combinations of stresses.

The optimum PTH quality test

Finally, PTH life curves are vital for life projections and for understanding new materials, constructions, and surface finishes, but they are neither useful nor necessary as an efficient "stress test" of PTH quality and reliability for day to day uses. At Endicott Interconnect Technologies, once the base PTH curve is understood for a particular PTH construction, the standard test for comparing, qualifying, and monitoring PTH reliability and quality is the CITC test run to failure at 23 to 220C. [1] If the assembly life region of the PTH life curve is the most critical for most applications, then it is also well suited as the best test for monitoring PTH quality.

The CITC 220C has been used as our main PTH stress test for over a decade because 220C represents typical assembly reflow temperatures, and therefore the results have the most real and useful physical meaning for ensuring PTH reliability. That is, since reflow cycles are the greatest risk for barrel cracks and consume the greatest proportion of PTH life, why not use a test that measures this risk directly.

Another significant advantage of this test is that it is very fast — coupons usually may be cycled to fail in a matter of hours. The speed of this test allows Endicott Interconnect Technologies to be "relentless" with PTH quality at both ends of the product life cycle. The CITC 220C test can be used as a verification and qualification tool for every new process change before introduction. Figure 16 is an example of CITC 220C results comparing two different drill bits. The curves were generated in less than one day of testing, and allowed the engineers to make an informed and timely decision about a drill process.

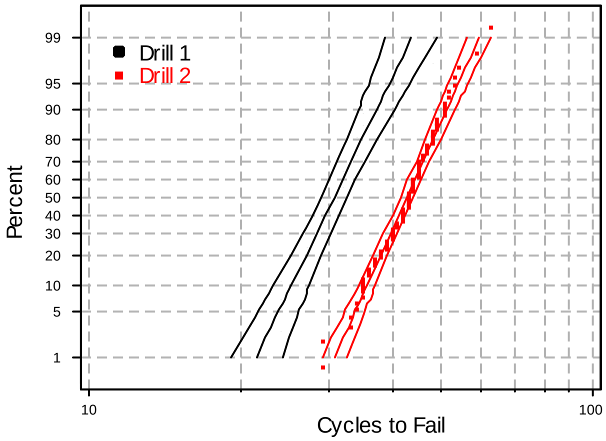

Figure 16-- CITC 23 to 220C cycle to fail data for two different drill bit designs.

In addition to its use for fast process and design evaluations prior to product introduction, the ability to produce relevant cycle to fail data quickly makes CITC 220C a very useful tool for PTH quality monitoring during manufacturing. The test not only readily exposes defects or other process problems, but the resulting cycle to fail data can analyzed and plotted in the same way as "control charts", to actually track and monitor trends in PTH quality and life over time. Aggressive use of the CITC 220C test in this way within Endicott Interconnect Technologies as both a qualification and a monitor tool, in combination with rigorous process control, has resulted in near perfect PTH performance. Our return rate for PTH related problems of any kind in the last several years has been less than 10 parts per billion per via drilled.

Conclusions

Since plated through holes remain a critical element to the reliability of PWB's and LCC's, and may only become more important in future technology, any claims of good reliability for a board or module demand that the "proof is in the PTH". This paper has demonstrated how the reliability of any via construction, base material, process change, or surface finish can be characterized, quantified, and monitored effectively by generating the "PTH life curve" for that product. The regions of the life curve reveal aspects of a PWB of LCC product that can not be understood with a testing at a single temperature. Finite element models can be developed and verified in conjunction with the life curves, and then be used to explore beyond the current design and stress space. The life curves may also be used, especially in combination with the Finite element model and other ATC testing, to project via life at any combination of stresses. Finally, the critical importance of the assembly life region of the curves for most laminate materials also makes CITC 220C the best test for process verifications and aggressive quality monitoring. This aggressive approach to PTH evaluation, qualification, and monitoring is one reason for the exceptional PTH performance of PWB's and LCC's produced by Endicott Interconnect Technologies.

Acknowledgments

The authors acknowledge the contributions of many colleagues from Endicott Interconnect Technologies including Christine Boyko, Ron Clothier, Beth Dougherty, Bob Edwards, Bob Harendza, Bob Hartmann, Bob Japp, John Konrad, Ron Lewis, Matt Nealy, Bill Rudik, Bob Testa, Doug Thorne, and Rick Wade.

The environmental SEM images of Figures 3 and 4 were created in conjunction with the Binghamton University Integrated Electronics Engineering Center (IEEC), www.ieec.binghamton.edu/ieec.

Trademarks

Driclad® is a registered trademark of Endicott Interconnect Technologies, Inc.

References

1. Knadle, K.T, Ferrill, M.G., "Failure of Thick Board Plated Through Vias with Multiple Assembly Cycles—The Hidden BGA Reliability Threat", SMTA Journal of Surface Mount Technology, Vol 10, Issue 4, October 1997, www.stma.org.
2. Ramakrishna, K., Sammakia, B., "Analysis of Strains in Plated Through Holes During Current Induced Thermal Cycling of a Printed Wiring Board", 7th Symposium on Mechanis of Surface Mount Assemblies, 1995.
3. IPC-TM-650 2.6.26 DC Current Induced Thermal Cycling Test.
4. Iannuzelli, R. "Predicting Plated-Through-Hole Reliability in High Temperature Manufacturing Process" ASME Conference Proceedings, November 1994.
5. IPC-TR-579, "Round Robin Reliability Evaluation of Small Diameter Plated Through Holes in Printed Wiring Boards".
6. Ramakrishna, K., Subbarayna, G., Sammakia, B., "Effect of Non-uniformities and Defects on PTH Strain During Assembly and Acclerated Thermal Cycling," Advances in Electronic Packaging, ASME 1992.
7. Gross, T., "Deformation of Plated Holes: The First Soldering Thermal Cycle, EEP-Vol-4-1, Advances in Electronic Packaging, ASME 1993.
8. Ahmed, M., Teng, S., Hu, M., Brillhart, M., "Assessing the Reliability of Plated Vias", PC FAB, November 2002.
9. Estes, T.A. "The effect of Lead-free Reflow Profiles on Through Via Reliability", IPC D-36 Subcommittee report from IPC PCQR2 database, February 2005.
10. Collins, J.A., Failure of Materials in Mechanical Design, John Wiley & Sons (New York, 1981). Pp. 384-385 and 240-243.
11. Knadle, K.T. "Analysis of Transient Thermal Strains in a Plated Through Hole using Current Induced Heating and Transient Moire Interferometry" Master's Thesis, Binghamton University, 1995.