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Thermal Reliability of Printed Wiring Boards: What's Coming From the OEM?

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Abstract
Several of the major OEMs are introducing a variety of thermal reliability requirements for printed wiring boards as a result of increasing demands during assembly. These increasing demands manifest themselves as multiple soldering operations and/or higher soldering temperatures using lead free alloys. This paper is based on a correlation study between reliability testing and thermal shock testing using a common set of multilayer coupons produced in the same pwb fabrication shop in real time. Reliability testing involves the Interconnect Stress (IST) test and thermal shock data includes both TMA (T_{260}) and Multiple Shock Testing (6X solder float). There is also discussion concerning the importance of reviewing the TMA scan when interpreting thermal performance of a multilayer coupon in addition to considering the compatibility of the fabrication process with the material being tested.

Introduction

There has been an evolution in qualification techniques of finished multilayer packages in the electronics industry over the years. The first widely recognized functional qualification of a multilayer package was the military test protocol which involved a single ten-second 550 °F solder float of a ten-layer test coupon. The one float allowed for no defects; lifted pads, hole wall pullaway, post separation or plating cracks at the barrel or knee to any degree were grounds for rejection. Given just the one float, such stringent requirements were realistic and achievable.

Functional testing of finished multilayer packages via thermal cycling in air or liquid media was later adopted by certain electronic market segments, such as automotive. In this type of testing, a daisy chain coupon is subjected to exposures to maximum and minimum temperature extremes in a conditioning chamber and the resistance of the daisy chain circuit is monitored at fixed intervals. Test methods such as this simulate worst-case environmental conditions the board will see in the field and identify the long-term functional integrity of the board under these conditions. While such testing is effective at identifying board integrity using a "fit for use" test procedure, testing takes a relatively long period of time and does not lend itself to being utilized as part of a quality monitoring system at the fabrication level.

The Interconnect Stress Test (IST) was then developed to abbreviate traditional thermal cycle testing so that it could be used at the fabrication level. This testing involves the application of current to an appropriately designed multilayer coupon in order to quickly reach the desired temperature extremes right at the circuit as opposed to subjecting the entire package to those extremes in a chamber. Unlike traditional thermal cycling where minimum temperatures are typically well below 0 °C (typically minus 40 °C in automotive testing), IST testing focuses more on the maximum temperature and as the name implies, applies stress to the internal post / wall interconnect as well as the plated barrel. More and more OEMs are starting to specify IST performance criteria or are at least inquiring what comparative IST performance various materials possess.

Most recently, there has been wide interest in a return to thermal "shock" performance as opposed to thermal "stress" field reliability such as thermal cycling and IST. The purpose is to simulate more demanding assembly process conditions which are being driven either by multiple soldering operations or the higher soldering temperatures of lead free alloys. Any of the lead-free alloys currently being evaluated in the industry require higher processing temperatures for successful assembly in comparison to traditional 63/37 eutectic solder. This has given rise to an interest in utilizing Thermal Mechanical Analysis (TMA) in addition to multiple solder float testing.

In the case of TMA, a sample is ramped up to a predetermined temperature; typically either 260 or 288 °C. Time to failure from isotherm is then reported. Failure is typically a separation within the sample (usually a delamination of some type) which is indicated by an irreversible change in the thickness of the sample. These tests are designated as T_{260} or T_{288}, depending on isothermal temperature and units are reported in minutes to fail. The most popular multiple solder float test is six successive 10 second solder floats at 288 °C with a one-minute hold between floats. Depending on the test criteria, cross sections can be observed between intermediate floats or only after six floats. Unlike the acceptance criteria of the single military solder float, however, some degree of hole wall pullaway or pad lifting have been allowed after a certain number of floats.

Background

In response to requests from OEMs to provide IST data directly comparing the performance of various material grades from one manufacturer, ten-layer IST coupons were processed through the same multilayer process in real time. Five different material grades were processed and glass constructions were held constant using .008" base laminates clad with 1 oz. copper and two plies of high resin content 2113 prepreg throughout the package. Finished coupons averaged 85 mils in overall thickness. It was determined that this was a good opportunity to compare thermal shock to thermal stress performance of a common set of multilayer samples. T_{260} was chosen over T_{288} in order to maximize the resolution of the material comparison. It has been our experience that T_{288} performance of finished multilayer boards would not give a good comparative scale of data due to the failure mechanism of multilayer packages that will be discussed later in this paper.

Two panels of each grade were produced and coupons were selected near the center of each panel for testing. Coupons were in arrays of 12 per panel and each array has four coupons with two sets of alternating coupons having .0135" and .040" plated holes. Coupons with the smaller hole size were selected for IST testing and an entire array of four coupons with both holes sizes was used for 6X solder float and T_{260} testing.

IST preconditioning consisted of five successive cycles of ambient to 230 °C with a two minute forced air cool down. Actual testing consisted of a two-minute ramp from ambient to 150 °C with a two minute cool down. Failure criteria was set at 10% increase from the original resistance which is a calculated value based on the maximum temperature of 150 °C.

Multiple (6X) solder float and T_{260} testing was performed on four coupons of each grade, two coupons of each hole size. Multiple solder floats were performed on unconditioned coupons as well as coupons conditioned for two hours at 135 °C prior to testing. Coupons were held for 60 seconds at room temperature between each float. It was originally intended to perform two T_{260} tests per coupon, one sample with internal copper and the other without. It has been our experience that samples free of internal copper last longer on a TMA than samples having internal copper. Due to the coupon design and panel layout, it was not possible to extract a copper free sample that was large enough to perform TMA testing. Therefore only one T_{260} test per coupon was performed on a sample with internal copper. A temperature ramp of 100 °C per minute was used throughout all testing.

Test Results

Figure 1 summarizes IST results through 2000 cycles. Given the magnitude of the resistance increase and location of the failure on the coupons, all failures were determined to be barrel cracks rather than post interconnect fatigue.

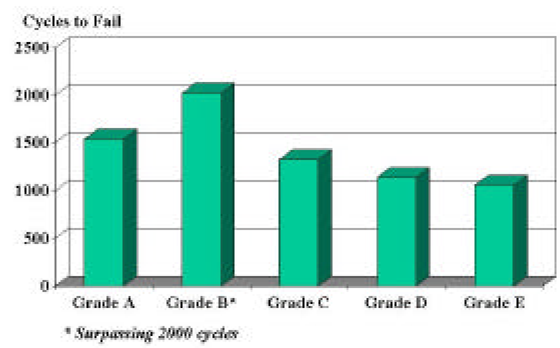

Figure 1 – IST Performance Ambient to 150 °C (Cycles to Fail for Barrel Cracking)

A close review of the actual TMA scans revealed some interesting observations. Figures 2 and 3 summarize two separate numbers by coupon and hole size. The T_{260} figure indicates the amount of time the sample lasted upon true isotherm at 260 °C. An adjusted number is also included which reflects the amount of time the sample lasted upon first reaching 260 °C. In just about every case where a T_{260} of zero minutes was originally reported, a careful review of the thermal ramp revealed that upon exceeding 260 °C just over two minutes into the scan, the liquid nitrogen cooling system of the TMA only took the sample down to about 259.5 °C. Isotherm back up to 260 °C was gradually reached over the course of an additional two to four minutes. The adjusted figure designated as T_{259} in the graphs takes this into account. Failures were also defined strictly as irreversible events where the thickness shift of the sample at that point in the scan was never restored.

The purpose of indicating T_{259} for each grade is to show that there was some level of thermal performance for some of the coupons that would otherwise have been missed without closely examining the scan. The nature of the failure varied significantly by grade. Grades A and C generally displayed very abrupt and irreversible failures while grade D often experienced subtle and reversible events. In every sample that irreversibly failed, the location of the TMA failure was identified as a prepreg to copper interface within the multilayer coupon.

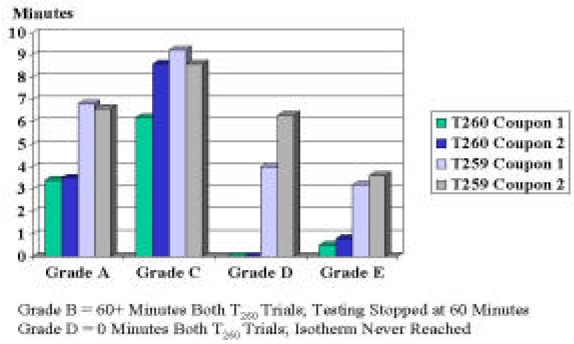

Figure 2 - TMA Performance By Grade .0135" Holes

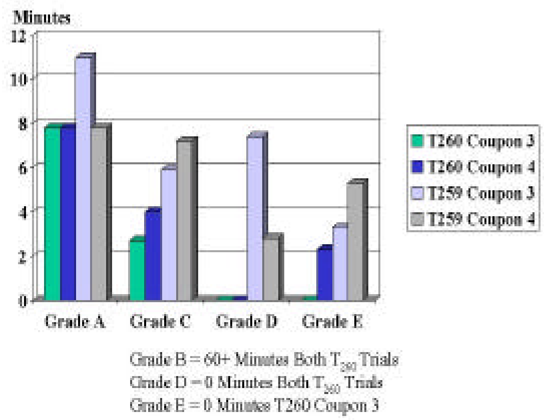

Figure 3 - TMA Performance By Grade .040" Holes

All floated coupons were cross sectioned and examined at 100 X to 200 X magnification for pad lifting, hole wall pullaway, post separation and barrel cracking. No barrel cracking or post separation was observed in any of the samples after six floats. The extent of pad lifting and hole wall pullaway were rated on a scale from 0 to 10 for each coupon with 10 representing severe. Since the results by hole size and conditioning were very repeatable, Figures 4 through 7 represent the plotted average ratings for each set of two coupons tested.

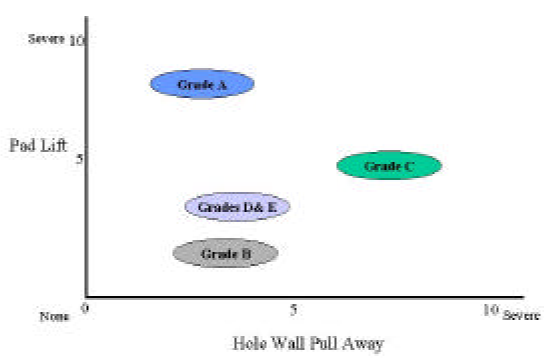

Figure 4 – 6X Solder Float Performance By Grade .040" Holes (Condition A)

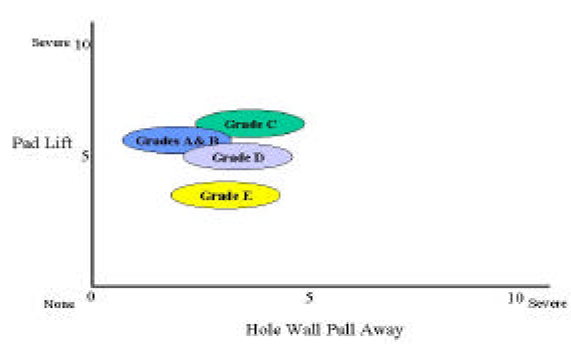

Figure 5 – 6X Solder Float Performance By Grade .040" Holes (E-2/135)

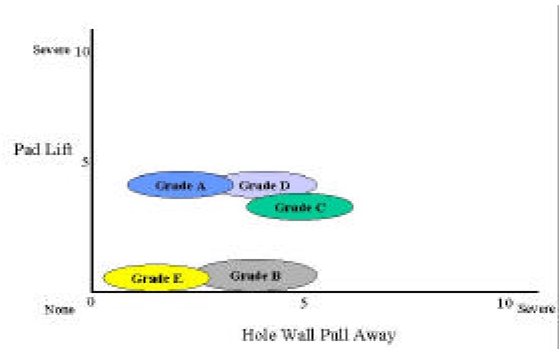

Figure 6 – 6X Solder Float Performance By Grade .0135" Holes (Condition A)

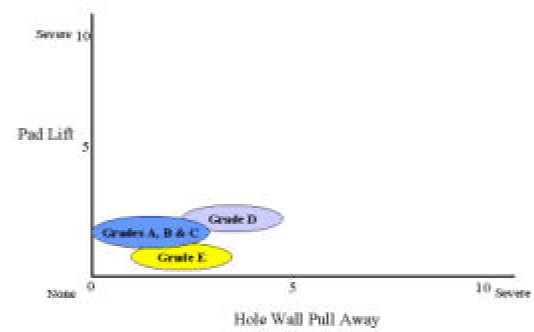

Figure 7 – 6X Solder Float Performance By Grade .0135" Holes (E-2/135)

Figures 8 through 12 show the overall scale of severity of the two conditions indicated. In the case of pad lifting, the most severe condition was observed to be about a 20 degree lift from the board surface as shown in Figure 8. Moderate pad lift was considered to be only 5 to 10 degrees as shown in Figure 9. Hole wall pullaway was more difficult to rate because there could either be a localized and obvious separation between the barrel and dielectric as shown in Figure 11. This condition has often been called resin recession, although there has been a longstanding debate in the industry as to whether this is simply localized hole wall pullaway or a completely different phenomenon. Figure 10 shows a much more widespread separation between the barrel and dielectric even though the gap between the two may not always be as wide as in Figure 11. The main criterion for rating hole wall pullaway in this study was the percentage of the barrel that was separated from the dielectric.

Figure 8 – Pad Lift = 8

Figure 9 – Pad Lift = 4

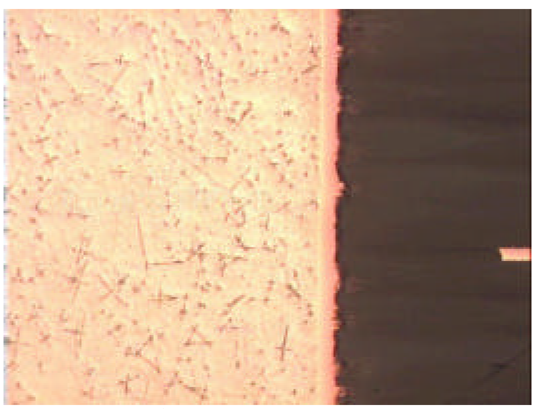

Figure 10 – HWP =10

Figure 11 – HWP = 5

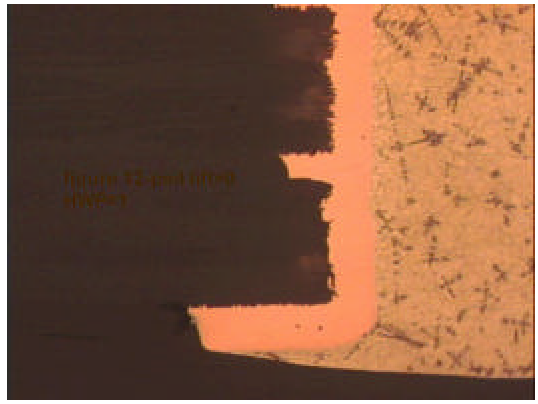

Figure 12 – Pad Lift = 0, HWP= 1

Analysis of Data

Comparing the IST results to the TMA results shows that while there may be a general correlation between the two tests in this particular study, it is not an absolute correlation. While grade B clearly prevails in both tests, results of grade A seem to confound an absolute correlation. In every T_{260} scan which involved an irreversible failure, the observed failure was a delamination of a prepreg to copper interface. As mentioned above, those grades with an apparently lower performance (grades D & E) often displayed subtle and reversible events. Such events are generally interpreted to be either a release of moisture or stress relaxation while irreversible failures signify some degree of internal delamination.

There appears to be even less of a correlation to multiple solder float testing. Factors such as conditioning and hole diameter have a greater effect on coupon performance than the grade. Preconditioning has a beneficial effect on all grades with the exception of grade B for larger holes, which may simply be due to noise or the sample size involved. Although it is not captured in Figures 4 through 7, all grades had some slight separation of resin to the etched end of the pad/interconnect out away from the barrel on at least one of the unconditioned coupons. This condition generally went away after preconditioning. As in past evaluations with this coupon design involving multiple solder floats, the smaller holes generally outperform the larger holes, especially when coupons are preconditioned.

Discussion

Given the IST test procedure used in this study, all five grades exceeded 1000 cycles which is generally considered to be excellent performance. Most IST test protocol we have encountered would have stopped testing at 500 cycles. All grades in this study had resin systems with glass transition temperatures of 170 °C or greater.

While it can be concluded that there was a fairly wide range in performance by grade for IST as well as TMA testing, the trend by grade in this study has not necessarily been repeatable as a function of other fabrication processes. Around the same time that these coupons were being fabricated, testing was being performed on multilayer boards made with material grade B from a different fabrication process. These boards yielded an average T_{260} of only 9.3 minutes and 6X solder floats of these boards would have been rated in the center to upper right corner of the plots in Figures 4 through 7. At the time this paper was written, testing of thick, high layer count qualification boards made with material grade D in yet another fabrication process were yielding far superior T_{260} and 6X solder float results to those results presented here. It is reasonable to conclude that material grade B happens to be particularly compatible with the bond enhancement process of the fabricator that produced the coupons for this study.

For the most part, the 6X solder float acceptance criteria we have heard from various OEMs has been that there can be no barrel cracks after six floats. The other defects summarized above are typically observed and noted after either three or four 10 second floats at 288 °C. As the data above shows, there is certainly no such thing as a cross section that is completely free of all defects after six floats even though some preconditioned sections may come fairly close. It is interesting to note that some OEMs have been more concerned about testing of component sized holes than smaller via holes which is supported by the 6X solder float data in this study.

Conclusions

Based on the data presented here, in addition to data previously generated from multilayer samples produced in different multilayer processes, the following conclusions can be drawn:

1. There is no absolute correlation between IST, TMA (T_{260}) and Multiple Solder Shock Testing (6X solder float) even when evaluating a set of coupons from a common multilayer fabrication process.
2. Data sets such as the one presented here should be regarded mainly as thermal shock or long-term reliability performance of a finished package from a particular multilayer fabrication process.
3. The comparative trend by grade presented here has not been repeatable between different multilayer fabrication processes. Both coupon design and multilayer fabrication process are key variables, which need to be considered when evaluating a material's performance.

In regard to TMA and multiple solder float testing, it has been observed that a wide range of results by grade as a function of the fabrication process exists. Based on the failure modes observed, the compatibility of the multilayer bond enhancement with a given material should demand specific attention. Copper clad laminates have generally outperformed multilayer packages in both T_{260} and T_{288} testing. The failure mode in laminates has been observed to be external copper to laminate in the majority of instances, rather than either resin-to-glass or interlaminar failure. There is an increasing number of OEMs who are interested in utilizing TMA testing and some of these OEMs are in the process of designing TMA coupons both with and without internal copper.

Finally, when interpreting a TMA data point from a multilayer sample, it is essential that the actual scan be examined before drawing conclusions about the thermal reliability of that sample. Such interpretation is necessary because TMA instruments vary in ability to promptly reach a true isotherm. This is due to variations in heating and cooling capability. Even though interpretation of such data may deviate from the exact test method called out in IPC-TM-650 method 2.4.24.1, as it pertains to attaining a true isotherm. It is important to capture the relative performance of the sample when comparing materials to each other.

Follow up IST trials are planned with significantly thicker coupons having higher aspect ratios.

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