As originally published in the 2010 IPC Printed Circuit Expo, APEX & Designer Summit Proceedings.

Characterizing the Lead-Free Impact on PCB Pad Craters

Brian Roggeman and Wayne Jones
Advanced Process Lab
Universal Instruments Corp.
Binghamton, NY 13902

Abstract

Pad cratering in Printed Circuit Boards (PCBs) is typically associated with lead-free products. This paper addresses laminate materials and the failures associated with the higher Pb-Free reflow temperatures and the acceptability requirements for use in Pb-Free products. The use of testing methodology, including pad pull testing and IPC peel testing to rank materials and processes is investigated, with a general relationship between pad size and strength being offered. Two cases studies illustrate the value in pad pull testing.

Introduction

The transition to Lead-Free soldering, and more generally the RoHS initiative have resulted in quality and reliability concerns of electronics. One such concern typically related to Lead-Free is damage to the printed circuit board, including thermally induced issues as well as pad cratering. Thermal failures typically present as delamination, barrel cracking and resin recession during reflow, while pad cratering is often associated with mechanical loading. With dozens of advertised Pb-Free compatible and RoHS compliant materials being offered from a variety of suppliers, it is getting more critical to have methods for selecting optimal materials rather than relying on the manufacturer's data sheets. No longer can we rely on simply specifying "Tg > 170 °C" when selecting materials for our Pb-Free products.

The following presents various testing results that look to evaluate PCB materials for Pb-Free products. Reflow survivability testing looks for damage related to multiple Pb-Free thermal excursions. While this test is admittedly a "torture" test, it does produce useful results that the material engineer can then use in selecting the proper laminate. Peel testing provides a measure of the adhesion between the outer copper foil and the underlying laminate while pad pull testing directly measures the pad strength and produces similar failure modes as seen when assemblies fail by cratering. The value of pad strength testing is illustrated in two case studies.

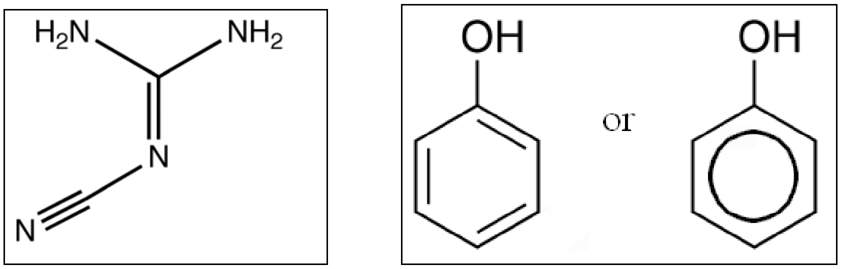
Moving to RoHS and Pb-Free Compatible PCB Laminates

The Restriction of Hazardous Substances (RoHS) directive was adopted by the European Union in 2003 and took effect in 2006. This directive restricts the use of six substances from the manufacture of electrical and electronic equipment. These substances are:

1. Lead (Pb)
2. Mercury (Hg)
3. Cadmium (Cd)
4. Hexavalent Chromium (CR^{6+})
5. Polybrominated Biphenyls (PBB)
6. Polybrominated Diphenyl Ether (PBDE)

Cadmium is restricted to 0.01% by weight while the other five substances are restricted to 0.1% by weight of the homogeneous material.

The restriction of Pb had a drastic effect on several factors of electronics assembly. Common Pb-Free solders melt at temperatures about 30 °C higher than eutectic SnPb solders, so the assembly temperatures are likewise increased. To meet these thermal demands, new PCB laminate materials were developed which could withstand multiple Pb-Free thermal processing steps. Typical SnPb compatible materials use dicyandiamide (DICY) curing agents, while Pb-Free compatible materials have generally transitioned to hydroxyl (Phenolic) based curing agents (Figure 1).



(a) (b)

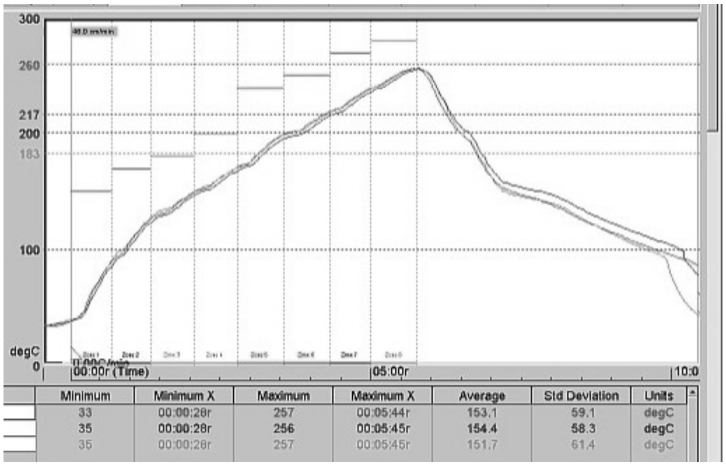
Figure 1 (a) molecule for dicyandiamide curing agent; (b) molecule for hydroxyl or phenolic curing agent [1,2].

Typical engineering and design requirements of laminates (prepregs and copper clad) may be classified into the following specifiable and measurable categories:

- Mechanical strength - to support components.
- Heat dissipation.
- Manufacturability for drills and/or punch through.
- Ability to withstand processing heats and chemicals.
- Low thermal expansion.
- Low dielectric constant.
- Ability of dielectric material to receive plating.
- Resistance to absorption of excessive moisture.

While DICY materials satisfied most requirements for typical SnPb assemblies, they do not withstand the higher Pb-Free processing temperatures. Phenolics on the other hand have superior heat resistance, but are more brittle than DICY materials, which leads to increased propensity for cracking of the laminate [3]. In certain cases, the use of a DICY material in a Pb-Free assembly may be an option. The concern is that the laminate integrity, whether DICY or Phenolic, may be impacted by the higher Pb-Free reflow temperatures, especially in the case of multiple thermal excursions.

PCB Failures as a result of excessive thermal stressing can be assessed through IPC 6012 A/B class 3 criteria. Visual and micro-sectional observations are made to determine the presence of resin recession, delamination, pad lift, blistering, etc. To evaluate the Pb-Free compatibility of commercially available laminate materials, a survivability testing procedure was developed which subjects test vehicles to nine reflow cycles with a 260 °C peak temperature (Figure 2). The peak of 260 °C was selected based on the assumption that a product would have a mixture of large and small components, and while the target reflow temperature might be 240-245 °C it is very likely that somewhere on the board would experience temperatures as high as 260 °C. The number of cycles was selected on the basis of a double sided reflow, wave solder and 2 rework operations. Each rework operation involves component removal, site redress and component reattach for total of three thermal excursions per rework. Therefore, the total number of possible thermal excursions for a product would equal nine.



	Minimum	Minimum X	Maximum	Maximum X	Average	Std Deviation	Units
	33	00:00:28r	257	00:05:44r	153.1	59.1	degC
	35	00:00:28r	256	00:05:45r	154.4	58.3	degC
	35	00:00:28r	257	00:05:45r	151.7	61.4	degC

Figure 2. Reflow Profile with 260 °C Peak Temperature.

Initial Pb-Free reflow survivability testing was performed on 38 unique boards from multiple sources. These boards represent a wide variety of products, board thickness, layer count, and materials. Table 1 summarizes the test vehicle attributes. Some materials are duplicated, but only on different products and/or stack-ups. Included in the table are failure times, measured as number of reflow cycles before IPC 6012 criteria failures were observed. Typical failures include inner-layer delamination; interconnect defect and barrel cracking, as shown in Figure 3.

Table 1. Attributes for Bare PCBs subjected to Pb-Free Reflow Survivability Testing

Laminate System	Final Finish	Product Thickness	Layer Count	Reflow Failure	Laminate System	Final Finish	Product Thickness	Layer Count	Reflow Failure
BT Resin	N/A	0.049	10	>9x	Multifunctional FR4	ENIG	0.100	6	>9x
DICY FR4	ENIG	0.011	2	>9x	Phenolic FR4	Bare Cu	0.093	18	5x
DICY FR4	ENIG	0.011	2	>9x	Phenolic FR4	Bare Cu	0.093	18	>9x
DICY FR4	ENIG	0.016	2	>9x	Phenolic FR4	Bare Cu	0.093	18	>9x
DICY FR4	HASL	0.022	6	3x	Phenolic FR4	Bare Cu	0.093	18	>9x
DICY FR4	N/A	0.049	10	>9x	Phenolic FR4	HASL/Sel Au	0.115	24	>9x
DICY FR4	ENIG	0.056	12	>9x	Phenolic FR4	Bare Cu	0.180	32	3x
DICY FR4	HASL	0.058	4	>9x	Phenolic FR4	Bare Cu	0.180	32	7x
DICY FR4	HASL	0.062	4	3x	Phenolic FR4	Bare Cu	0.180	32	>9x
DICY FR4	HASL	0.062	6	4x	Phenolic FR4	Bare Cu	0.180	32	>9x
DICY FR4	HASL	0.062	8	4x	Polyimide	ENIG	0.009	4	>9x
DICY FR4	OSP/Au Tabs	0.062	4	5x	Polyimide	ENIG	0.009	4	>9x
DICY FR4	ENIG	0.062	12	3x	Polyimide	Cu OSP	0.012	4	>9x
DICY FR4	OSP	0.062	12	5x	Polyimide	Cu OSP	0.012	4	>9x
DICY FR4	Imm. Ag	0.063	4	5x	Polyimide	Cu OSP	0.012	4	>9x
DICY FR4	ENIG	0.067	8	2x	Polyimide	Cu OSP	0.012	4	>9x
DICY FR4	OSP/Au Tab	0.093	8	>9x	PPO/CE	N/A	0.049	10	>9x
DICY FR4	HASL/Sel Au	0.093	20	5x	PPO/CE	ENIG	0.115	24	>9x
DICY FR4	HASL	0.093	16	8x	Halogen Free	ENIG	0.067	2	5x

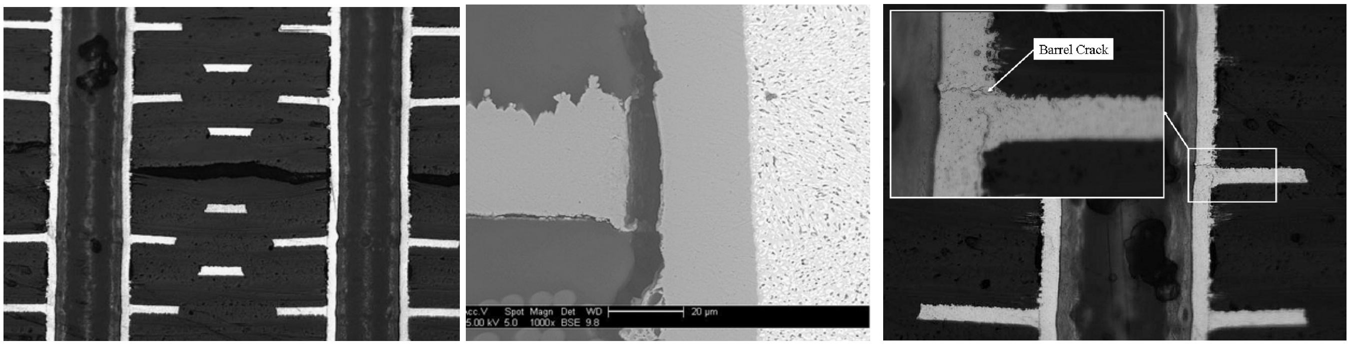


Figure 3. Examples of failures seen in Pb-Free reflow survivability testing, per IPC 6012. Left: Inner layer delamination; Middle: Interconnect defect/inner-plane separation; Right: barrel crack of a through-hole.

The failure times of each of these 38 unique test vehicles are plotted in Figure 4. As expected, most early failures occur on DICY FR4 systems, which are not intended for the high Pb-Free reflow temperatures. The Phenolic failures occurring at cycles of 3X and 5X represent the same material on two different products. This particular Phenolic proved to be insufficient for higher Pb-Free processing temperatures, and recommendations were made regarding the acceptability of this material. There were several DICY materials that did survive past 9X reflow cycles, however these were typically found in thinner boards less than 0.062" thick. Most of the phenolic materials, and all of the PPO/CE, and polyimide survived past 9X reflow cycles, indicating superior thermal resistance.

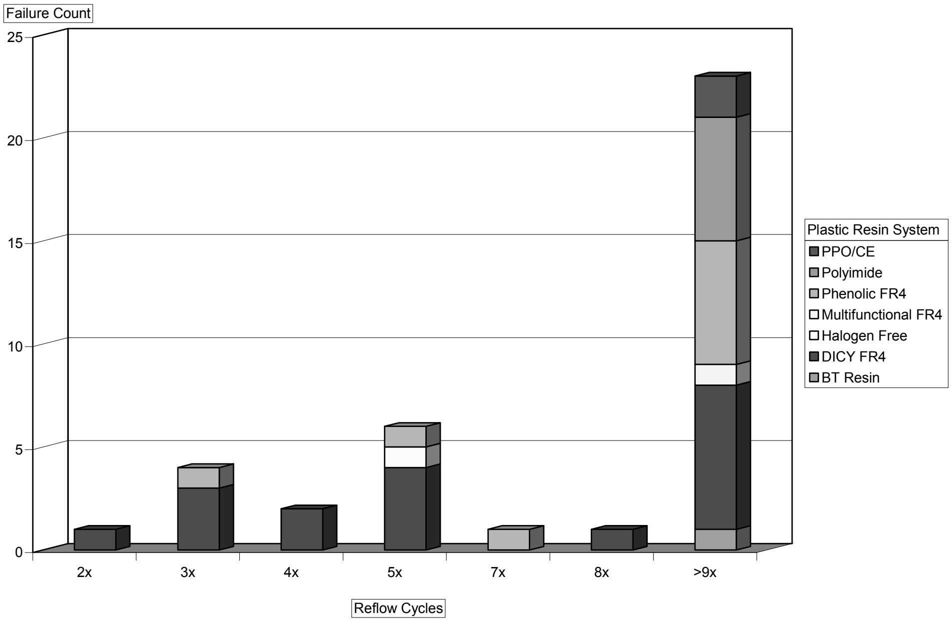


Figure 4. Number of failures by material type per Pb-Free reflow cycle

While global board survivability in Pb-Free processing is a primary concern in selecting a suitable material for a particular product, pad cratering is another failure mode that will reveal itself only after the board has been populated. For that reason, it is critical to have a valid technique for assessing the cratering performance of laminate materials. Simply choosing a material based on supplier data sheets, or a material that survives 9X Pb-Free reflow cycles is not adequate in optimizing product reliability.

Testing for Pad Cratering

Testing PCBs for pad cratering has been gaining much attention in the past couple of years due to the increasing occurrence of this failure mode and the urgent need to evaluate laminate materials and suppliers for Pb-Free processing. While much work has gone into defining a specific test method for pad cratering [4-7], there is still a desire to use traditional mechanical testing of copper clad laminates like peel testing, per IPC TM-650, Method 2.4.8 [9]. This test specifically measures the adhesion between the copper and the laminate. Specific structures are designed for peel testing (Figure 5) where the force per unit width is recorded during the pull, and a minimum spec of 0.7 N/mm (4 lbs/in) is typical.

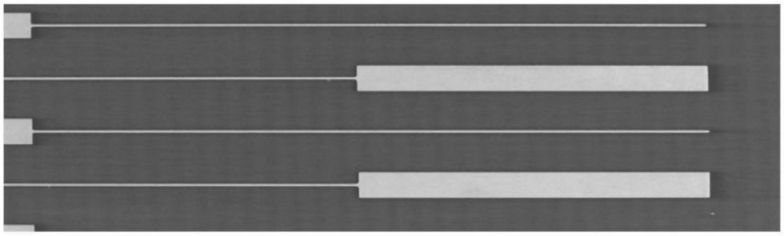


Figure 5. Copper peel test structure on laminate.

Peel testing, however, does not replicate the failure mode seen during pad cratering. Pull testing on BGA pads better simulates the overstress type failures that result in pad cratering on assemblies. Both Cold-Ball-Pull (CBP) and Hot-Pin-Pull (HPP) (Figure 6) directly measure the strength of the laminate under the pad by pulling BGA pads from the PCB [4-7]. A Dage series 4000 bondtester was used to produce the CBP data which is presented in this paper. The method is described in the section below.

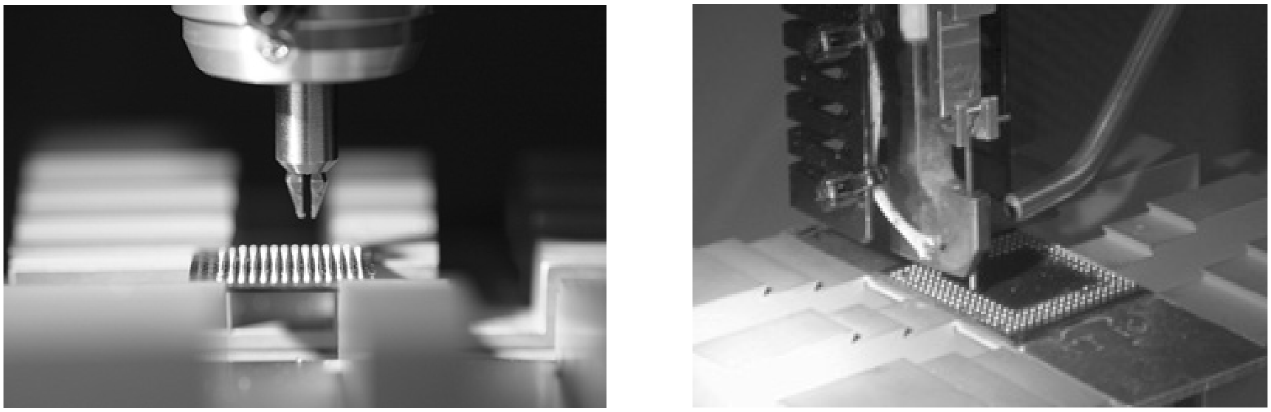


Figure 6. Left: Cold Bump Pull uses special jaws to grip and pull solder balls. Right: Hot Bump/Pin Pull solders a copper pin to the pad for pulling.

The CBP test method requires that samples have appropriately sized solder balls attached to the pads of interest. The process involves printing or otherwise depositing a small amount of tacky flux on the pad, and then dropping a solder ball onto that flux deposit. The sample is then reflowed to bond the solder ball to the pad. During the test, specially designed jaws clamp onto the solder ball and pull the pad from the PCB in the vertical direction with the maximum force being recorded. Test speeds are typically between 0.5 – 5mm/s.

The difference between peel testing and pull testing can first be seen in the failure mode. Peel testing removes the copper foil from the resin surface, while pull testing fractures the through the resin and may expose the underlying glass reinforcement layer. The two failure modes are distinctly different, as shown in Figure 7. Peel testing measures the adhesion between the copper foil and the resin, while pull testing directly measures the strength of the resin.

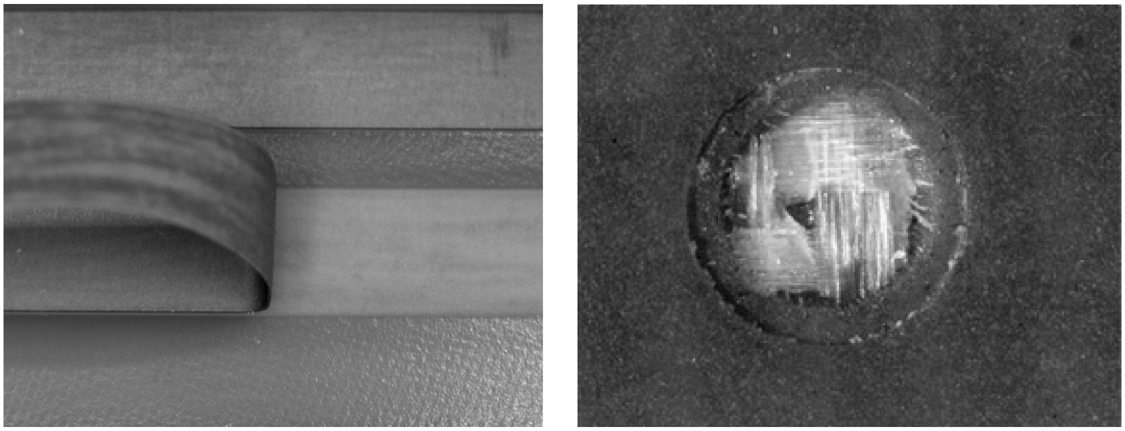


Figure 7. Left: Peel test removes foil from laminate; Right: pull test removes pad by fracturing through the laminate.

Testing was performed to determine the correlation between peel and pull testing. Test vehicles were designed with both peel test locations and BGA locations for Cold Ball Pull testing. Initial testing was performed on two different DICY FR4 systems, both of which were subjected to multiple reflows at 260 °C peak. The strength data (N/mm for peel, grams-force for pull) is shown in Figure 8, with all data normalized to the 1X results. These initial results offered some correlation between the two test methods. However, when the same testing was run on a 2nd set of test vehicles, all using Pb-Free compatible materials, the results show no correlation between peel and pull test (Figure 9). These results show that while peel testing is a valuable metric for the adhesion of copper to laminate, it does not offer insight into the pad integrity, especially when cratering is a concern on the product.

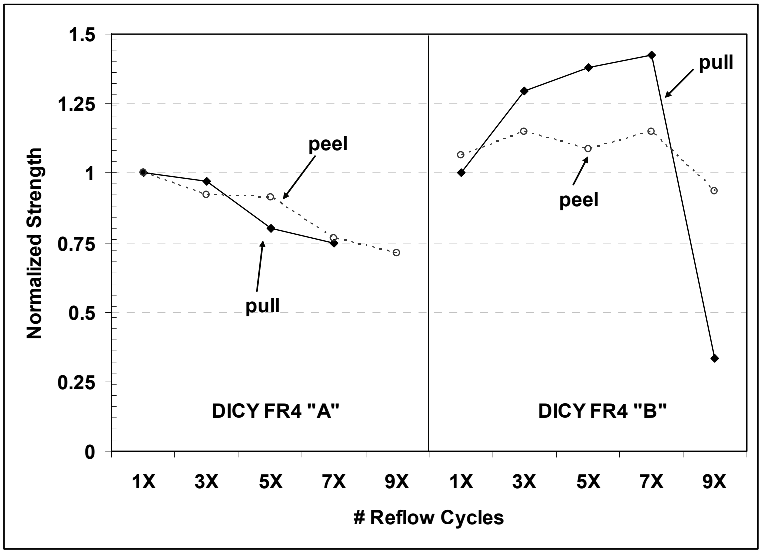


Figure 8. Normalized peel and pull strengths over multiple reflow cycles for two DICY materials. There appears to be some correlation between methods.

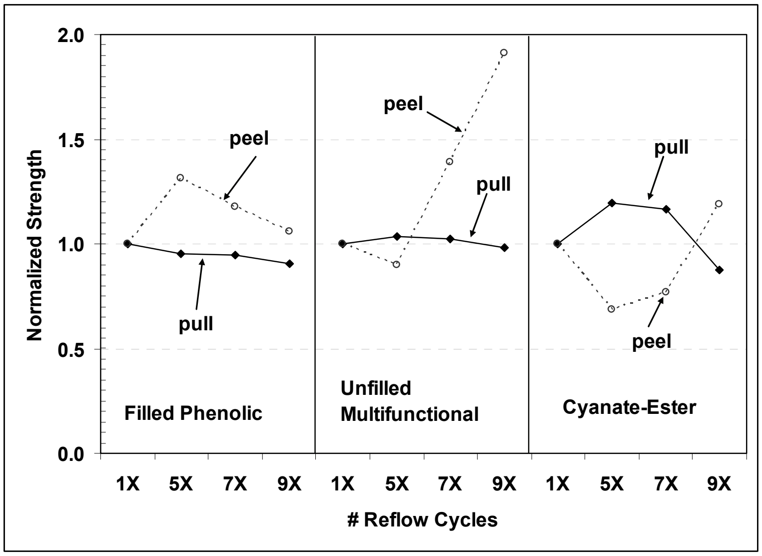


Figure 9. Normalized peel and pull strengths over multiple reflow cycles for three Pb-Free compatible materials. There is no correlation between test methods.

The use of pad strength testing by either CBP or HPP is useful only if the strength data correlates to failures seen on actual assemblies. For this to occur, the loading modes should be consistent. For example, if cratering is occurring during ICT or handling during the manufacture of the device, it is likely that a strength test will correlate to the failures because they occur during a single overstressing condition. However, if cratering is occurring on product in the field, the loading may be a repeated force resulting from multiple drops, bend or vibration cycles. In that case, pad fatigue testing is more relevant because it induces similar crack propagation that is seen on the product [4].

Another case of cratering is seen during rework, where the pads fail under high temperature/high stress conditions during the process [8]. Pb-Free rework requires higher temperatures than SnPb, so both the degradation of the material as well as the just the weakening at temperature can become critical factors. Pad strength testing allows the temperature dependence of the laminate to be investigated with the use of special heating stages. Current investigations show that not all laminate materials have the same temperature dependence (Figure 10). The typical drop in strength for these laminates is between 5% – 10% from room temperature to 65 °C. Further decrease in strength is expected at higher temperatures approaching reflow/rework conditions. However, other laminate materials have shown to exhibit little to no temperature dependence in strength [5], so universal trends can not be concluded, and every material should be examined.

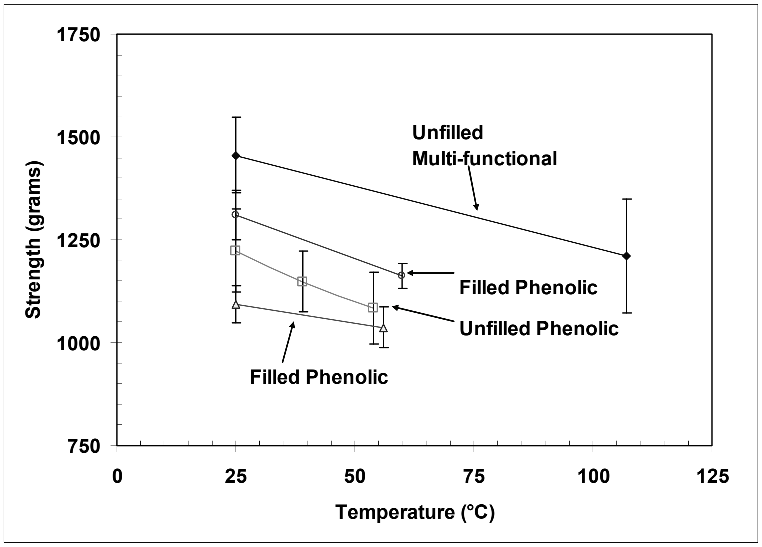


Figure 10. Temperature dependence on pad strength for selected laminates. Error bars represent one standard deviation, which is generally 5-10% relative to the mean.

Another case that has yet to be investigated is the constant load situation. Here, the load may be related to component warpage or fixturing of the board that induces a long duration stress on the pad. In that case strength testing may not be relevant because the crack does not have the same propagation mechanism. Efforts are currently underway to investigate constant loading on pads, which will induce relatively slower crack propagation than a single overstress or strength test.

Regardless of the loading condition, pad strength is the quickest and easiest test to use to compare laminates for Pb-free processing or use for optimizing pad design. Since no specifications for pad strength yet exist, we must gather as much data as possible for better understanding of our products. Using the CBP method for strength testing, several different non-solder-mask defined pad sizes were tested on a Filled Phenolic laminate (Figure 11). The relationship shows a clear quadratic trend with the pad diameter, which is defined by the equation: $F = 1.56(d^2) + 33.92(d)$, where $\boldsymbol{F}$ is the measured pad strength in grams-force, and $\boldsymbol{d}$ is the nominal pad diameter in mils. While the data shown in Figure 11 is not comprehensive by any means, it does provide at least a starting point for expected values of Pb-Free laminates (filled phenolic in this case).

The obvious tendency would be to normalize the pad strength to the pad area, or calculate a failure stress, which should be constant for all pad sizes. However the line fit between pad diameter and strength includes a non-trivial linear term so caution is advised when using area normalizations. One reason that simple area normalization is not accurate is because the actual crack area is greater than the pad area due to the depth of the crater. As pad size increases, the error will decrease due to the aspect ratio of [crack area: pad] area relationship.

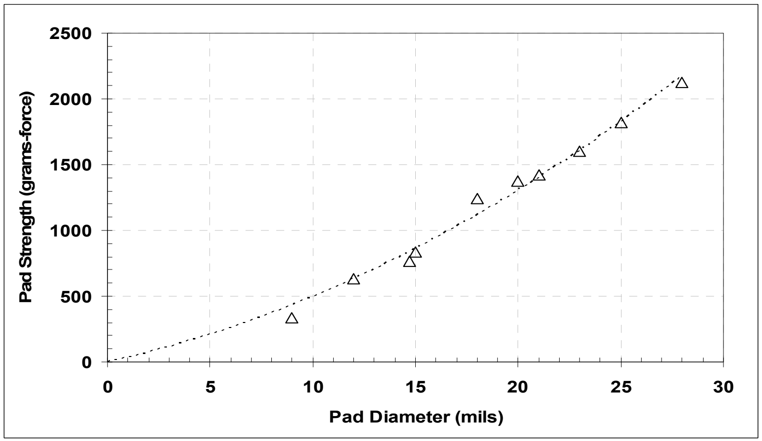


Figure 11. Relationship between pad diameter and strength for a filled phenolic resin.

Case Studies

The issue with RoHS and the Pb-free transition is felt within many industries, and pad cratering is near the top of the list of concerns. The following two case studies highlight cratering concerns on two very different products.

Transition to Pb-Free Assembly

In this Case Study, a product that was originally built as SnPb was transitioned to Pb-Free. This included of course a change in solder material and assembly process, but the laminate material was also re-spec'd to be compatible with the Pb-Free processes. After the transition many early failures were observed. Cross-sectional analysis showed that multiple failure modes existed, with Pad Cratering being prominent (Figure 12).

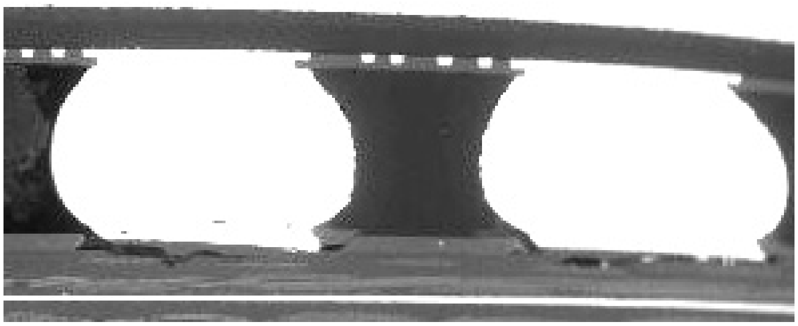


Figure 12. Multiple joints exhibited pad cratering. The distortion in the image is due to parallax view and is not a real feature of this sample.

The new material selected for the Pb-Free assembly was a filled phenolic, while the original SnPb assembly used a typical DICY material. Pad strength testing was conducted to compare the pad integrity of the original and the revised system. The testing first pre-conditioned the samples by 3X reflow cycles using the appropriate reflow parameters, i.e. a SnPb profile for the DICY system and a Pb-Free profile for the Phenolic system. The DICY system was also subjected to 3X reflow at the Pb-Free profile to determine if it would be acceptable for Pb-Free assembly. The strength data in Figure 13 shows that the Phenolic system is approximately 500 grams-force, or about 25% weaker than the DICY system. Also, the DICY system shows no degradation between the SnPb reflow temperature and the Pb-Free. The solution for this particular case was to revert back to the DICY material for the Pb-Free product. The increase in pad strength and the lack of degradation allowed for the use of a DICY material on this product, but that is not always the case.

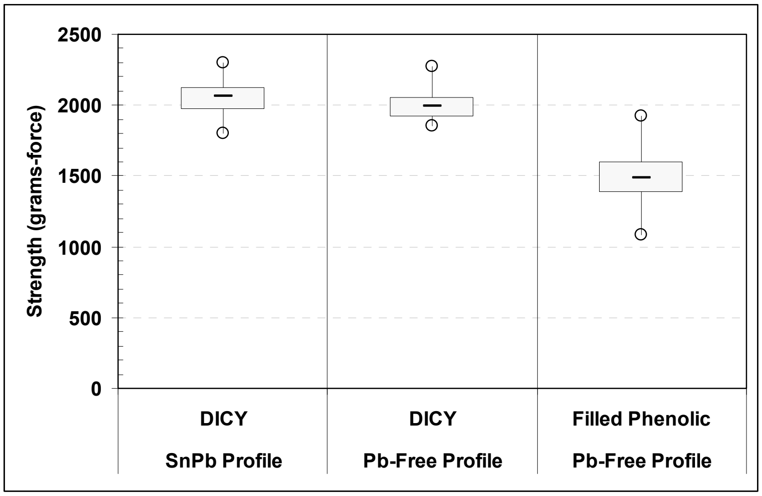


Figure 13. Measured pad strength for a DICY and Filled Phenolic laminate under selected reflow conditions.

Selection of material

This second study examined the potential for using a particular laminate material in a Pb-Free application when it had been previously used in legacy SnPb products from the same manufacturer. The test vehicles for SnPb and Pb-Free analysis were not the same, although they used identical laminate material and very similar stackup/construction details. The PCB design details simply called out for a metal-clad laminate with a minimum T_g of 170 °C, which could represent a wide range of laminate materials. Because of the different TVs, a range of pad sizes was selected for each to develop the relationship between pad size and pad strength for a more general comparison between the two processes. For the SnPb process, a SnPb reflow profile was used to pre-condition the boards, while a Pb-Free reflow process was used to pre-condition the Pb-Free boards.

Cold Ball Pull testing evaluated the strength of the various pad sizes after 2X reflow in this case. The comparison shown in Figure 14 illustrates that the Pb-Free process tends to result in weaker pads overall than the SnPb process. In fact the difference is consistently near 25% between the two processes. The trend lines represent a quadratic function, similar to Figure 11. When compared to the data in Figure 11, the SnPb process results in stronger pads, while the Pb-Free process exhibits a very similar trend line. The recommendation for this product was to use caution when applying this laminate to a Pb-Free process, as the pad strength tends to be weak. This methodology shows the value in creating a database of material pad strengths for use as a first order comparison.

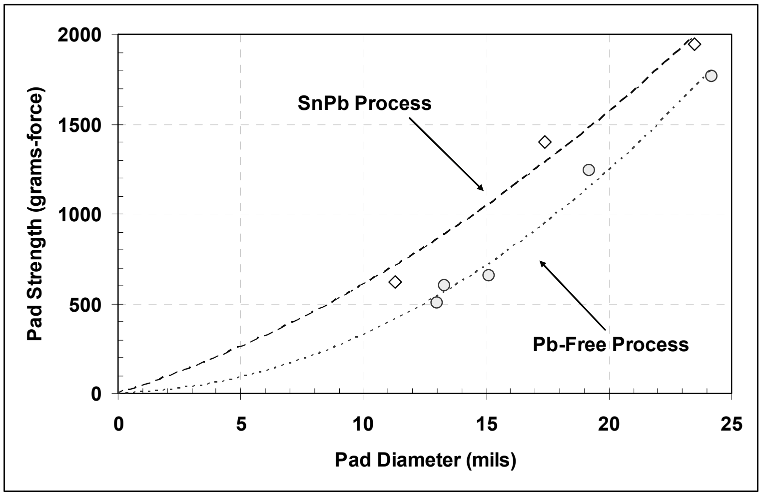


Figure 14. Relationship between pad size and pad strength for different reflow process on the same laminate.

Conclusions

With the transition to Pb-Free soldering, PCB laminates have evolved to meet the stricter requirements for thermal survivability. In doing so, pad cratering has presented itself near the top of the list of concerns of Pb-Free laminates and processes. Pad cratering testing, through the use of either Cold Ball Pull or Hot Pin Pull are leading methods to offer a first order comparison of materials and processes. These methods directly measure the pad integrity where traditional peel tests only measure the adhesion between the copper and the underlying laminate. Pad strength testing and peel testing not only result in completely different failure modes, but the results of the two tests do no correlate. The use of peel testing to evaluate pad integrity is not advised.

Pad strength testing has been successfully implemented to optimize product designs. Two case studies have been presented here, which offered significant value to the manufacturer. While no strength specification exists for pad strength, the use of a "baseline" relationship between pad size and pad strength offers value in the interpretation of new data. It should be cautioned however that strength testing only provides strength information, and may not offer value to those cases which result in crack propagation, such as cyclic loading and constant stress.

Acknowledgements

This work was part of a major research effort supported by the AREA Consortium. The authors would also like to gratefully acknowledge Dage Precision Industries for providing the tools to perform much of the testing presented here.

References

1. "2-Cyanoguanidine", http://en.wikipedia.org/wiki/Dicyandiamide, last accessed December 3, 2009.
2. "Phenols", http://en.wikipedia.org/wiki/Phenols, last accessed December 3, 2009.
3. M. Mukadam, G. Long, P. Butler, and V. Vasudevan, "Impact Of Cracking Beneath Solder Pads In Printed Circuit Boards On Reliability Of Ball Grid Array Packages", Proc. Of SMTA International, 2005.
4. B. Roggeman et al., "Assessment of PCB Pad Cratering Resistance by Joint Level Loading", Proc. Of 58th ECTC, 2008.

5. M. Ahmad, D. Senk, J. Burlingame, “Methodology to Characterize Pad Cratering Under BGA Pads in Printed Circuit Boards”, Proc. SMTA Pan Pacific Symposium, January 2008.
6. M. Ahmad, J. Burlingame, C. Guirguis, “Comprehensive Methodology to Characterize and Mitigate BGA Pad Cratering In Printed Circuit Boards”, SMTA Journal, Vol22, Issue 1, 2009, pp. 21-28.
7. M. Ahmad, J. Burlingame, C. Guirguis, “Validated Test Method to Characterize and Quantify Pad Cratering Under BGA Pads on Printed Circuit Boards”, Proc. Of APEX, March 2009.
8. L. Harvilchuck, B. Roggeman, R. Aspandiar, J. Wade, G. Godbole, “Impact of PCB Pad Site Dress Methods on Pad Array Damage”, Proc. Of SMTA Pan Pacific, February 2009.
9. IPC TM650 Method 2.4.8C “Peel Strength of Metallic Clad Laminate”, December 1994