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An Assessment of the Impact of Lead-Free Assembly Processes on Base Material and PCB Reliability

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Abstract
Environmental regulations are forcing the elimination of lead (Pb) from electronic equipment. Solders containing lead have been the standard in printed circuit assembly processes. Lead-free solders currently being used and developed for printed circuit assembly require higher processing temperatures that can degrade the base materials commonly used in printed circuits, resulting in decreased long-term reliability. Following a brief discussion of the regulations and lead-free materials and processes, this paper will discuss several base material properties and present test data that highlights the importance of specific properties that should be considered when selecting materials for lead-free applications.

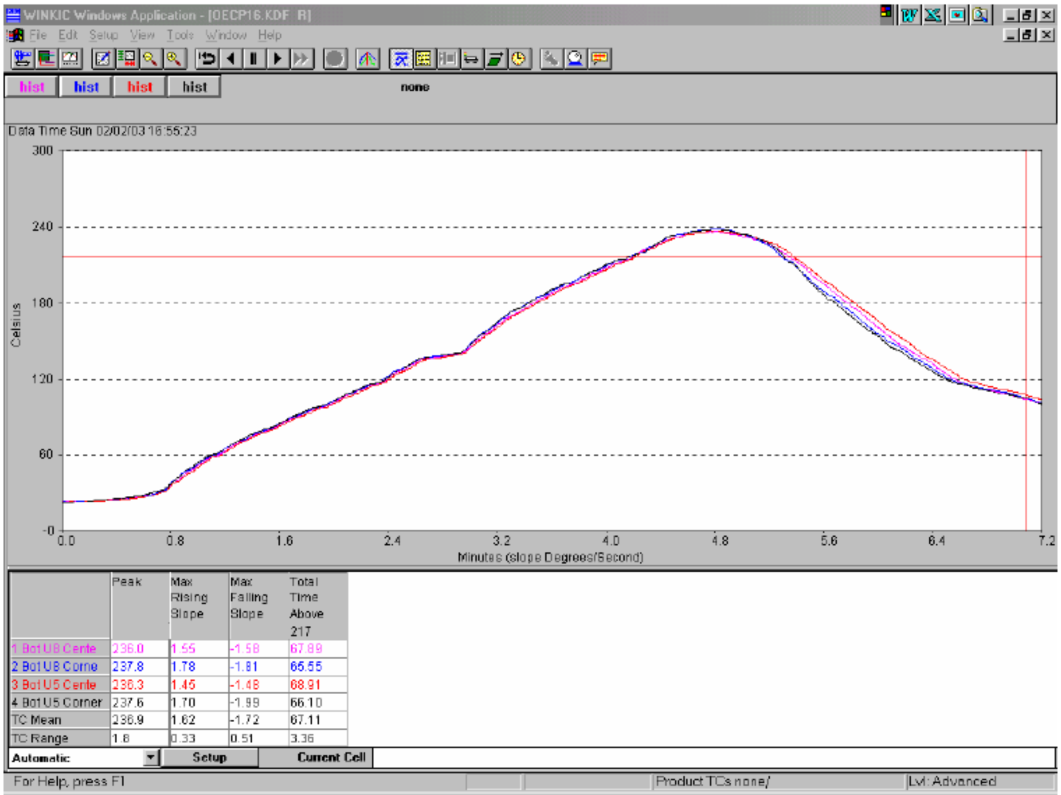
Introduction

The use of environmentally friendly materials in electronics manufacturing is not a new topic. Debates over specific initiatives have gone on for many years, and the topic of lead elimination is no exception. While it is usually the case that the motivation driving environmental initiatives is admirable, some have argued that there are marketing strategies that influence the scientific debate, and others have argued that unintended consequences from some initiatives are worse for the environment than the status quo. Of course, economic tradeoffs are always present. In any event, it is clear that the elimination of lead from electronic equipment has begun. Initiatives in Japan and the Waste from Electrical and Electronic Equipment (WEEE) and Reduction of Hazardous Substances (RoHS) legislation in Europe are the obvious examples.

For example, RoHS covers specific elements such as Pb, Cd, Hg, and Cr^{VI} as well as specific halogenated compounds such as polybrominated biphenyl (PBB) and polybrominated diphenyl ether (PBDE). Products that do not meet these requirements will not be allowed to sell into the EU, and while exemptions currently exist for specific applications, a review of the RoHS criteria is due in 2004 and the rules could change. So very soon, a wide range of products will face restrictions on the use of lead. This has an obvious impact on electronics assembly, which has relied on lead containing solders, but also has implications for printed circuit manufacturing and more to the point, the base materials used. The reason for this lies in the alternatives to lead containing solders and the changes they necessitate in the assembly process.

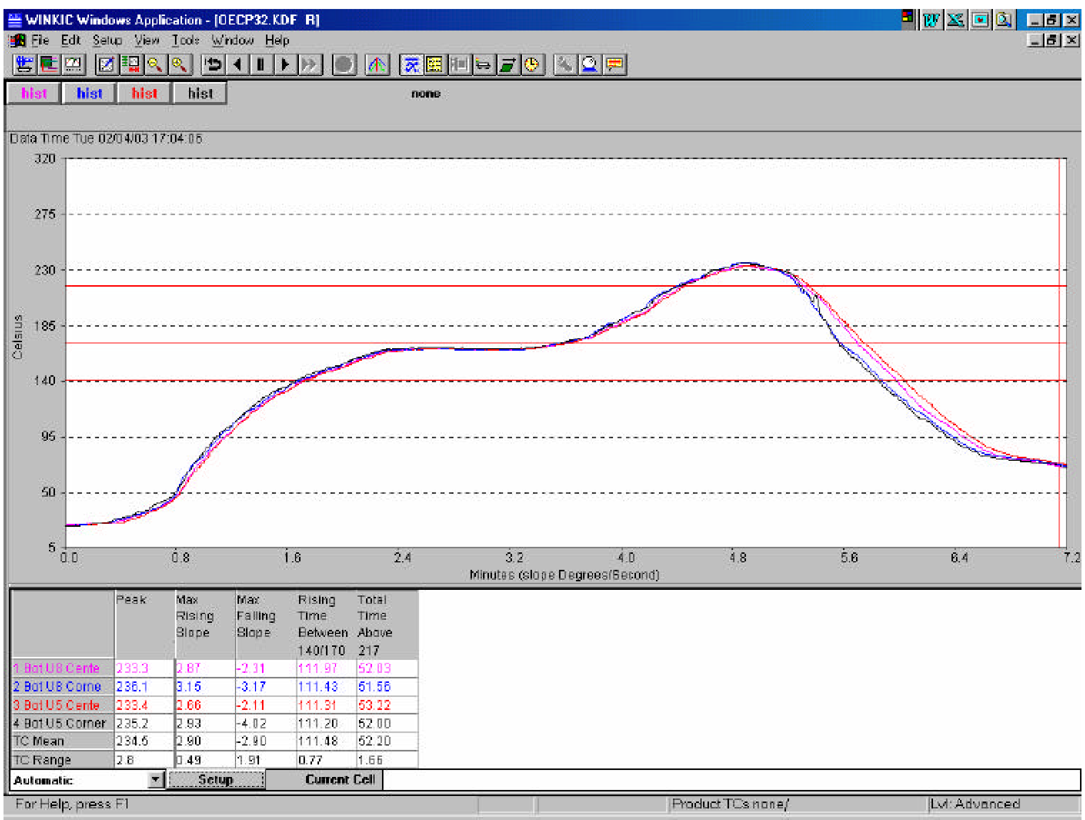
Many alternatives to Sn/Pb have been developed, but it appears that Sn/Ag/Cu (SAC) alloys will be the most widespread. The advantages of SAC include the availability of the raw materials, the relative simplicity of the alloys, and the relatively low cost. The major disadvantage to SAC is the higher melting point of these alloys compared to Sn/Pb. The melting point of SAC is about 217^{o}C, or approximately 34^{o}C higher than Sn/Pb, which has a melting point of 183^{o}C.

For proper wetting and solder joint formation with Sn/Pb solder, it is common to see peak reflow temperatures of 230-235^{o}C, or about 43-48^{o}C above the melting point. Assuming a similar temperature above melting is required for SAC, this implies that peak temperatures for lead-free assembly will be approximately 260^{o}C. While the peak temperatures are not maintained for extended periods of time, multiple reflow cycles and rework cycles are not uncommon, so components and printed circuits must be able to withstand repeated exposure to the peak temperatures. Figures 1-3 illustrate common thermal profiles associated with Sn/Pb assembly. SAC assembly profiles may be similar in design, but with the higher peak temperatures.



	Peak	Max Rising Slope	Max Falling Slope	Total Time Above 217
1 Bot U8 Cente	236.0	1.55	-1.58	67.89
2 Bot U8 Corne	237.8	1.78	-1.81	65.55
3 Bot U5 Cente	236.3	1.45	-1.48	68.91
4 Bot U5 Corner	237.6	1.70	-1.99	66.10
TC Mean	236.9	1.62	-1.72	67.11
TC Range	1.8	0.33	0.51	3.36

Figure 1 – Example of a Linear Assembly Profile



	Peak	Max Rising Slope	Max Falling Slope	Rising Time Between 140/170	Total Time Above 217
1 Bot U8 Cente	233.3	2.87	-2.31	111.97	52.03
2 Bot U8 Corne	236.1	3.15	-3.17	111.43	51.56
3 Bot U5 Cente	233.4	2.66	-2.11	111.31	53.22
4 Bot U5 Corner	235.2	2.93	-4.02	111.20	52.00
TC Mean	234.6	2.90	-2.90	111.48	52.20
TC Range	2.8	0.49	1.91	0.77	1.66

Figure 2 – Example of a High Hold Assembly Profile

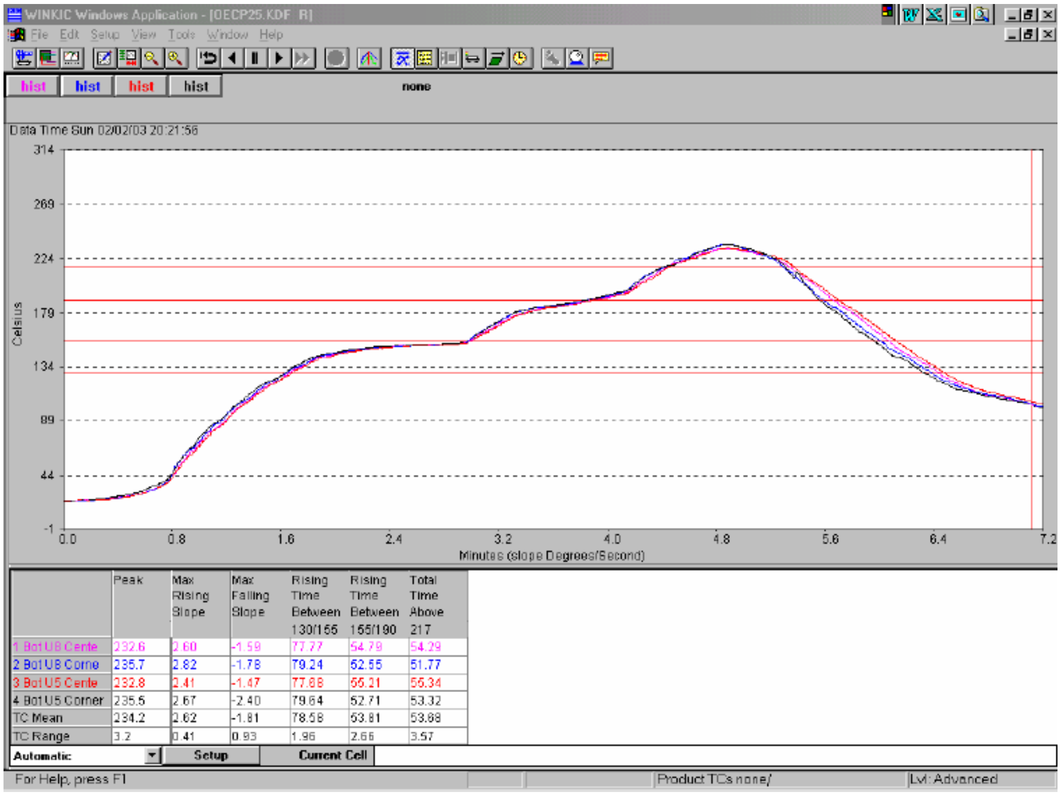


Figure 3 – Example of a Double Soak Assembly Profile

PCB Base Material Property Considerations

FR-4 epoxy based materials remain the most commonly used substrate for printed circuit boards. These materials have offered a good combination of electrical, physical and thermal performance for a wide range of applications. The most commonly referenced base material property used to classify these materials is the glass transition temperature, Tg.[1] The T_g of a resin system is the temperature at which the material transforms from a relatively rigid or "glassy" state, to a more deformable or softened state. T_g is important to understand since the properties of base materials are different above the T_g versus below the T_g.

All materials undergo changes in physical dimensions in response to changes in temperature. The rate at which base materials expand is much lower below the T_g than above. Thermomechanical analysis (TMA) is a procedure used to measure dimensional changes versus temperature. Extrapolating the linear portions of the curve (see Figure 4) to the point at which they intersect provides a measure of the T_g. The slopes of the linear portions of the curve above and below the T_g represent the respective rates of thermal expansion, or as they are typically called, the coefficients of thermal expansion (CTE's). CTE values are important since they influence the reliability of the finished circuit. Other things being equal, less thermal expansion will result in greater circuit reliability as less stress is applied to plated holes. While the T_g is typically described as being a very precise temperature, this is somewhat misleading, since the physical properties of the material can begin to change as the T_g is approached. This explains the curved line in Figure 4.

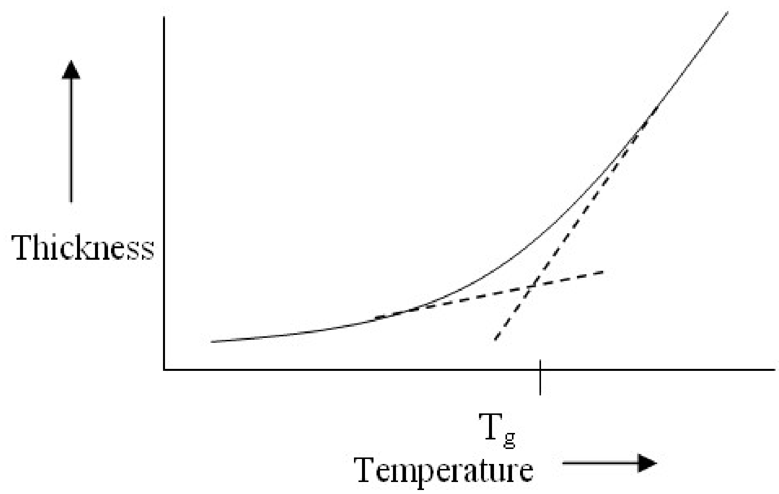


Figure 4 – Measuring T_g by Thermomechanical Analysis (TMA)

Besides TMA, two other thermal analysis techniques are also commonly used for measuring T_g. These are Differential Scanning Calorimetry (DSC) and Dynamic Mechanical Analysis (DMA). DSC measures heat flow versus temperature rather than the dimensional changes measured by TMA. The heat absorbed or given off will also change as the temperature increases through the T_g of the resin system. T_g measured by DSC is often somewhat higher than measurements by TMA. DMA measures the modulus of the material versus changes in temperature.

Implicit in many discussions of T_g is the assumption that higher values of T_g are always better. This is not always the case. While it is certainly true that higher values of T_g will delay the onset of high rates of thermal expansion for a given resin system, total expansion can differ from material to material. A material with a lower T_g *could* exhibit less total expansion than a material with a higher T_g, due to differing resin CTE values or, for example, by incorporating fillers into the resin system that lower the CTE of the composite material. This is illustrated in Figure 5. Material C exhibits a higher T_g than material A, but material C exhibits more total thermal expansion because its CTE value above T_g is much higher. On the other hand, with the same CTE values above and below the T_g, the higher-T_g material B exhibits less total thermal expansion than material A. Finally, although the T_g values are the same, material B exhibits less total expansion than material C due to a lower CTE value above T_g.

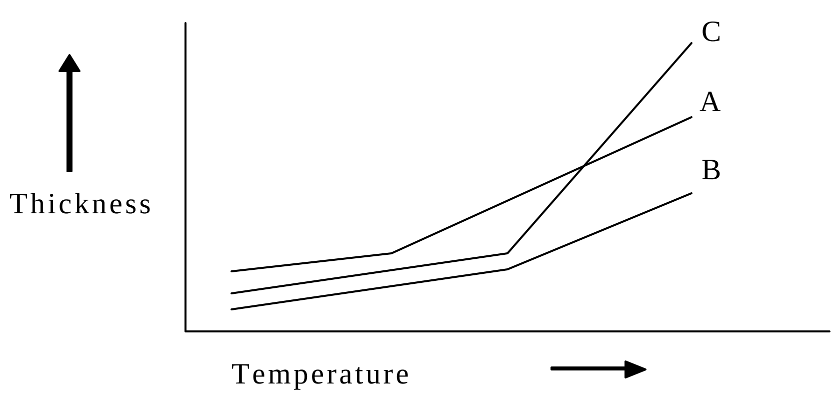


Figure 5 – Impact of T_g and CTE Values on Total Expansion

Time to delamination is another common measurement used to assess base material performance. The time to delamination is a measure of the time it takes for the resin and copper, or resin and reinforcement, to separate or delaminate. This test utilizes TMA equipment to bring a sample to a specified temperature and then measures the time it takes for failure to occur. Temperatures of 260°C (T260) and 288°C (T288) are commonly used for this testing. Many high-T_g FR-4 materials will exhibit *lower* times to delamination than low-T_g FR-4 materials. With Pb-free assembly temperatures reaching 260°C, the T260 test has become a much more relevant measure of performance.

A base material property that has gained very little attention up until now is the decomposition temperature (T_d). The decomposition temperature is a measure of actual chemical and physical degradation of the resin system. This test uses thermogravimetric analysis (TGA), which measures the mass of a sample versus temperature. The decomposition temperature is reported as the temperature at which 5% of the mass of the sample is lost to decomposition. Figure 6 provides an example of two FR-4 materials with the same glass transition temperature, but different decomposition temperatures. Experience is showing that the decomposition temperature is a critical property, and appears to be at least as important, if not more important than the glass transition temperature when planning for Pb-free assembly conversion. For example, data presented below will show a 140^{o}C T_g material with a 350^{o}C T_d that exhibits superior thermal performance when compared to a 175^{o}C T_g material with a 310^{o}C T_d. This notion that a 140^{o}C T_g material can provide superior thermal performance to a 175^{o}C T_g material runs counter to the conventional wisdom in our industry. Yet there is now more data than ever to support the fact that the T_g of a material is just one property that must be considered when choosing a resin system. Balancing this property with others is important in achieving good circuit manufacturability and reliability.

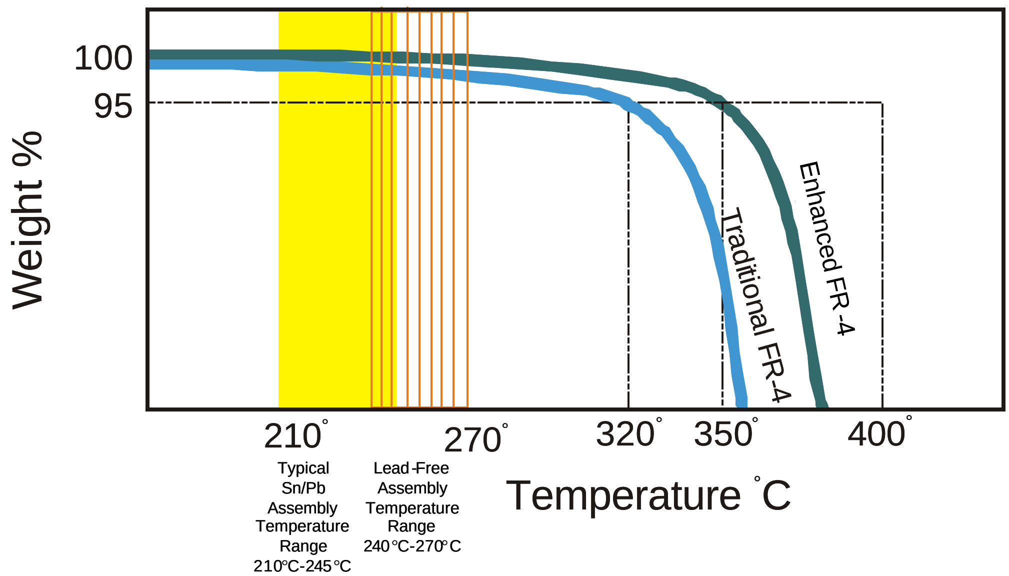


Figure 6 – Decomposition Curves for Two Different FR-4 Materials with T_g Values of 175^{o}C

A Comparison of Four Different Base Materials

In order to support this claim, consider the four materials described in Table 1 and graphed in Figure 7. The materials characterized as "low decomposition temperature" materials are very common, industry standard types of laminate materials. The materials characterized as "high decomposition temperature" materials are specially formulated resin systems designed to offer superior thermal performance. These materials have now been available for years, and are gaining widespread acceptance as demands for increased thermal reliability and compatibility with Pb-free assembly become critical.

Table 1 – Materials with High and Low Values of T_g and T_d

Material	Notation	Glass Transition Temperature, oC	Decomposition Temperature, oC
Low **G**lass Transition Temp., **L**ow **D**ecomposition Temp.	LGLD	140	320
Low **G**lass Transition Temp., **H**igh **D**ecomposition Temp.	LGHD	140	350
High **G**lass Transition Temp., **L**ow **D**ecomposition Temp.	HGLD	175	310
High **G**lass Transition Temp., **H**igh **D**ecomposition Temp.	HGHD	175	350

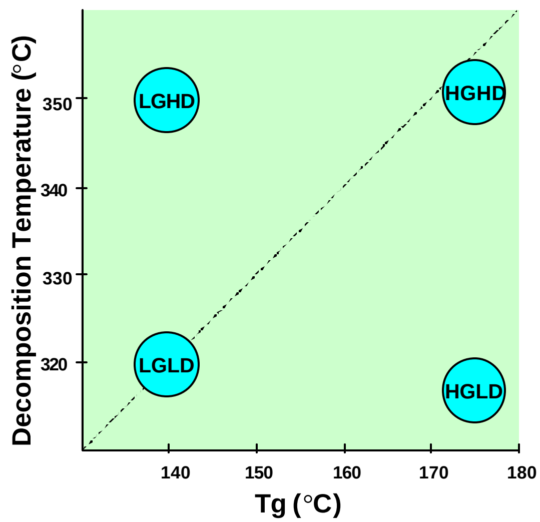


Figure 7 – Material T_g vs. T_d

Time to Delamination Comparison

In time to delamination tests, it is not uncommon to see low-T_g FR-4 materials outperform high-T_g FR-4 materials. In Figure 8 you can see that this holds true for the "standard" materials (LGLD and HGLD) whereas the materials with higher decomposition temperatures outperform the materials with lower decomposition temperatures. Furthermore, the low-Tg material with the high decomposition temperature outperforms the high-Tg material with the low decomposition temperature. The importance of this should not be underestimated. Last, in the case of the materials with high decomposition temperatures, the high-T_g material does exhibit longer times to delamination than the lower-T_g version.

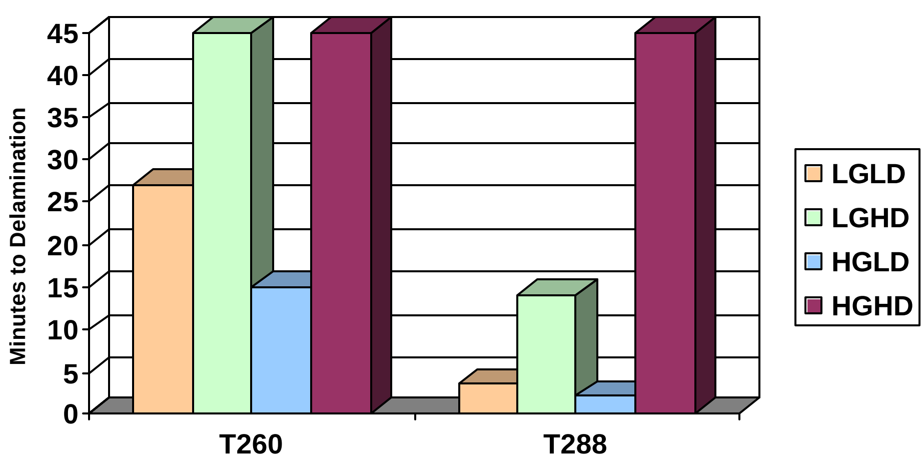


Figure 8 – Time to Delamination Comparisons for 4-7628 Laminate Construction

Multiple TGA Cycle Analysis

A recent technical paper[2] used traditional thermal analysis techniques to assess the performance entitlement offered by various base materials. The performance entitlement is simply defined as the full capability offered by a given base material. The performance entitlement may be fully realized in the finished PCB, but never exceeded. On the other hand, the performance entitlement may not be fully realized in the finished PCB for a variety reasons that often relate to processing variations in the PCB fabrication process. The paper used various thermal analysis techniques, including thermogravimetric analysis (TGA), to assess changes in base material properties when samples of various laminate materials were cycled multiple times to 235°C in order to simulate standard assembly temperatures, and 260°C in order to simulate Pb-free assembly temperatures. The four materials described above were included in this study, and the TGA data for these materials is shown in Figures 9 and 10. The weight loss percentages are graphed cumulatively from the original sample weight.

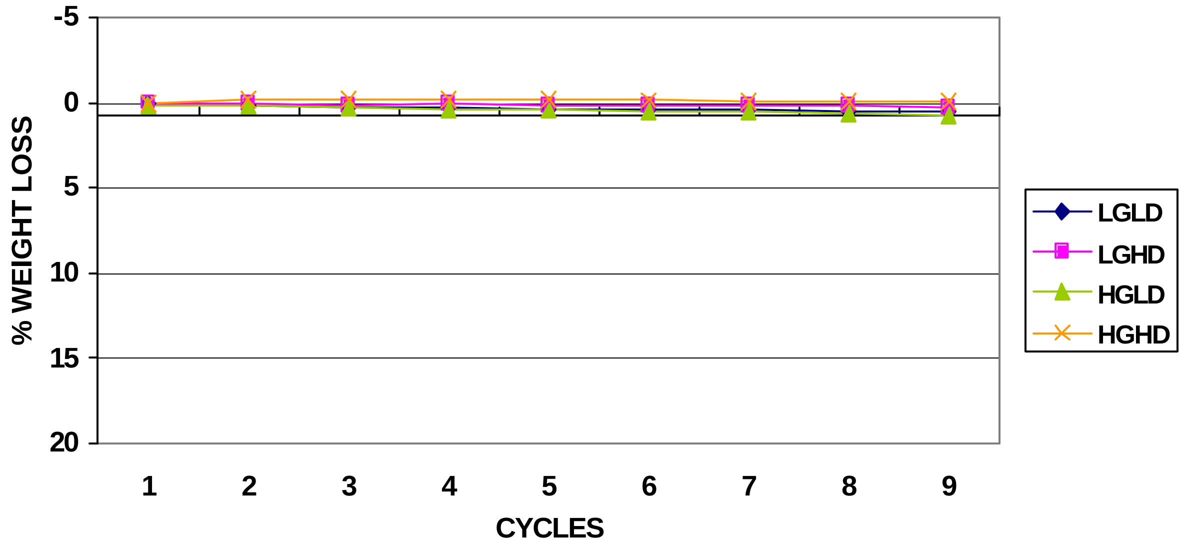


Figure 9 – Multiple TGA Cycles to a Peak Isotherm Temperature of 235°C

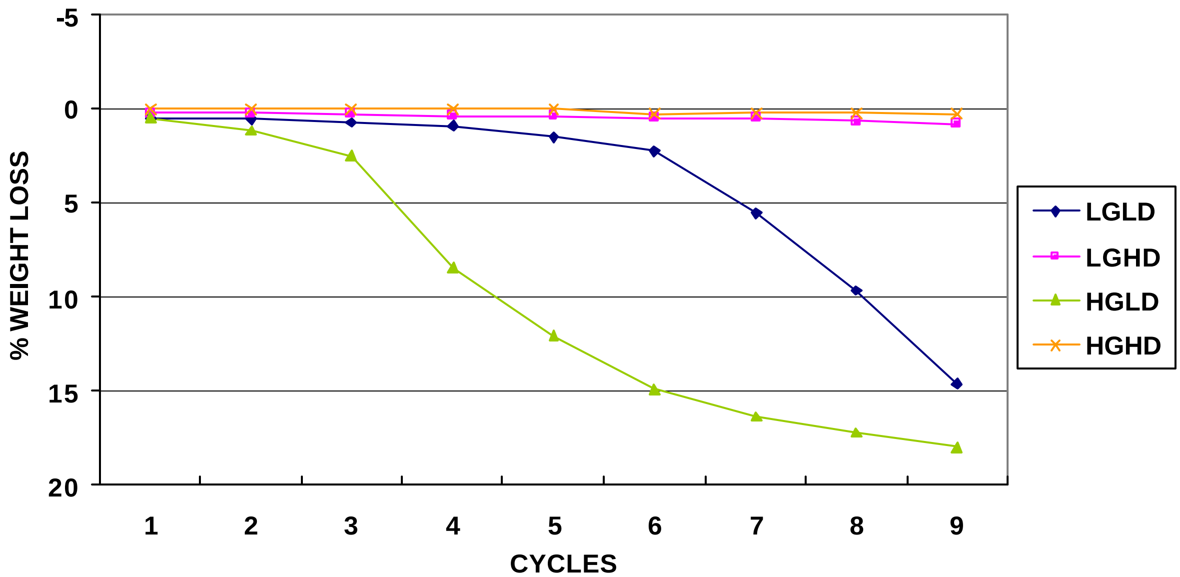


Figure 10 – Multiple TGA Cycles to a Peak Isotherm Temperature of 260°C

As evidenced in Figure 9, all four materials perform well when cycled to 235°C. Virtually no degradation is observed for any of the materials, regardless of T_g or T_d value. However, Figure 10 tells a different story. The obvious conclusion is that the materials with the higher decomposition temperatures still perform well, with little evidence of any degradation, whereas the "standard" materials with the lower decomposition temperatures begin to degrade significantly when exposed to multiple cycles to 260°C. The other interesting observation is that when the materials with the low decomposition temperatures are compared, it is the higher-T_g material that degrades sooner and more rapidly than the low-T_g material. Note that the decomposition temperature for HGLD is 310°C while the decomposition temperature for LGLD is 320°C. While these temperatures are obviously higher than the 260°C temperature being discussed for Pb-free assembly, if you look at Figure 6, you can see that with a decomposition temperature of 320°C, the traditional FR-4 material exhibits 2-3 percent weight loss at 260°C. Losing 2-3 percent at 260°C combined with multiple assembly and/or rework cycles will result in either defects during assembly or significantly reduced field reliability.

Multiple Assembly Cycle Evaluation on Multilayer PCBs

The data presented so far is based on measurements of the base materials themselves. Obviously, performance of the finished PCB is the next question. One method to assess the impact of Pb-free assembly temperatures on multilayer PCBs is simply to run samples of PCBs through multiple assembly profiles and assess survivability after the multiple exposures to different peak temperatures. However, in order to increase the sensitivity of the test and to gain meaningful comparison data with fewer samples, we chose a board design that was specifically designed to fail earlier than a normal PCB design. While the test vehicle was only 10-layers and 0.093" thick, the design of the internal copper planes and circuits was chosen to maximize the stress created by the thermal profiles and induce defects sooner than would be observed in actual board designs. So while this test does not answer the practical question of how many thermal cycles an actual board could withstand before failure, it does provide a good performance comparison between material types. Once again, the four materials with various combinations of T_g and T_d were compared. Peak temperatures of 220°C, 240°C and 260°C were used and survival through six cycles was assessed. In addition, baseline data was collected on the multilayer PCB test vehicles and is included in Table 2.

Figure 11 graphs the survival rate after six assembly reflow cycles for PCBs made from each material type at the three different peak temperatures.

Table 2 – Baseline PCB Data for Multiple Assembly Evaluation

Property	LGLD	HGLD	LGHD	HGHD
T_g by DSC, °C	140	172	142	175
T_d, Decomposition Temperature, °C	320	310	350	350
Total % Z-Axis Expansion 50-250°C	4.40	3.40	4.30	3.15
T260 (minutes)	4.5	2	12.5	15

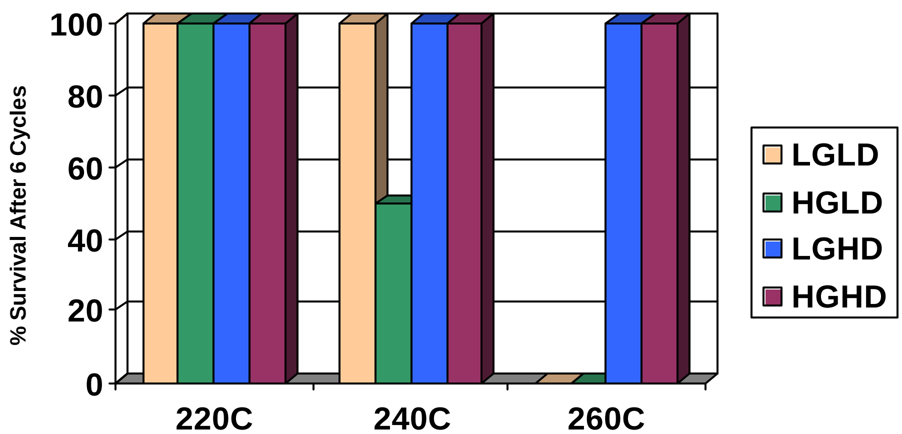


Figure 11 – Survival after 6 Assembly Cycles

As with the TGA tests on the base materials, this test on multilayer PCBs shows that both the low-T_g and high-T_g materials with high decomposition temperatures outperform the materials with low decomposition temperatures, including the high-T_g version. In addition, the high-T_g/low-T_d material begins to fail before the low-T_g /low-T_d material as the temperature increases. Remember that the decomposition temperature for the high- T_g /low- T_d material is about 10°C lower than the low-T_g /low-T_d material. Last, at a peak temperature of 260°C, only the materials with high decomposition temperatures perform well, with 100% survival after 6 cycles, whereas the materials with low decomposition temperatures, regardless of T_g, all fail after 6 cycles.

Interconnect Stress Test (IST) Data

Another method used to assess reliability of multilayer PCBs is the interconnect stress test (IST) procedure.[3] The IST method uses a daisy chain plated through hole (PTH) design. The PTH's are thermally cycled to 150°C by applying an electric current to the network of plated holes and then allowing them to cool back to room temperature. Measuring how many cycles the test coupons can withstand before failure provides an indication of long-term reliability. Failure is typically defined as a 10% change in resistance of the PTH net. It is common to evaluate the performance of PCB test coupons as manufactured, or "as is" and then also evaluate performance after preconditioning of the IST test coupons performed to simulate multiple exposures though PCB assembly profiles. At the time this paper is being written, we do not have data on the low-Tg materials discussed above. However, the figures below present data on both of the high-Tg materials in the as is condition as well as with preconditiong to both 230°C (Figure 12) and 255°C (Figure 13). Evaluations of both 3 preconditioning cycles (3X) and 6 preconditioning cycles (6X) were performed. The PCB used for this evaluation was an 14-layer, 0.120" thick board with 0.012" diameter holes.

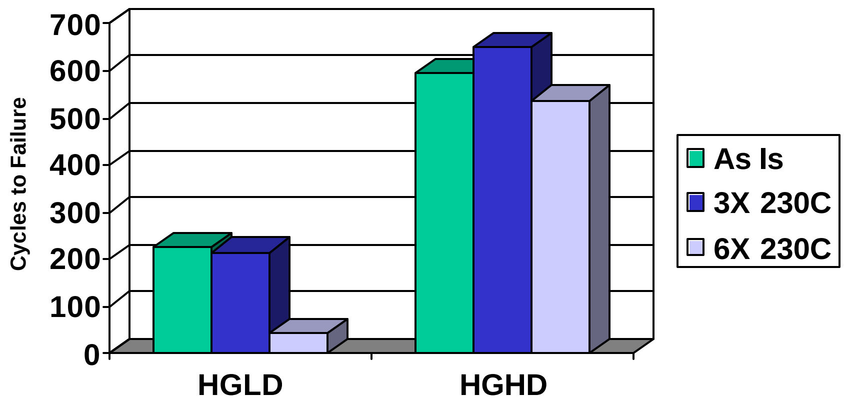


Figure 12 – IST Results with Preconditioning to 230°C

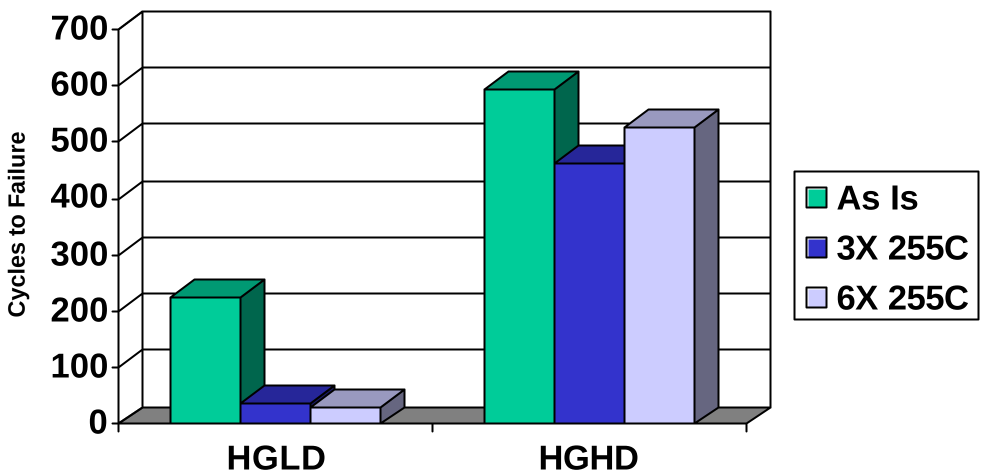


Figure 13 – IST Results with Preconditioning to 255°C

Once again, the difference between the materials with high vs. low decomposition temperatures is striking. The high-T_g material with the high decomposition temperature exhibits significantly more cycles to failure than the high-T_g material with the lower decomposition temperature, regardless of preconditioning level and including the as is condition. In addition, the high-T_g/high-T_d material exhibits an exceptional level of reliability even after 6X preconditioning to 255°C.

Summary and Conclusions

Current and future PCB designs, and complexities of component assembly require ever-increasing levels of reliability from the PCBs and base materials used to manufacture them. On top of this, the conversion to Pb-free assembly adds an additional, very severe requirement for improved thermal performance since the peak temperatures in Pb-free assembly processes significantly exceed the temperatures commonly used with Pb-containing solders. Two aspects of reliability must be considered when conversion to Pb-free assembly is undertaken. First, we must consider what PCB and base material properties are required to survive Pb-free assembly cycles without blisters, delamination or other defects. Second, we must consider what we have done to the long-term reliability of the PCB assuming it does survive Pb-free assembly. Just because a board survives Pb-free assembly without obvious defects doesn't mean that we now have a reliable board. More evaluations of long-term reliability after exposure to Pb-free assembly will be required.

This paper has taken a first step towards identifying the base material properties required to provide reliable PCBs through Pb-free assembly processes. While much more work is needed, a few conclusions can be drawn from the data presented here:

1. 1.Conversion to Pb-free solders and assembly processes poses a significant challenge to PCB and base material reliability due to the increased temperatures experienced during assembly and rework.
2. The glass transition temperature, T_g, is only one base material property and while it is necessary to consider T_g values, it is insufficient for complete specification of reliable materials for Pb-free assembly.
3. Low-T_g materials that are compatible with Pb-free assembly temperatures exist, and may be preferable in some applications to some high-T_g materials. The conventional view that high-T_g materials are always more reliable than low-T_g materials is wrong.
4. T260 evaluations have increased relevance when considering Pb-free assembly conversions.
5. The decomposition temperature is a critical base material property to consider when specifying materials for Pb-free assembly compatibility.

Further Work

As noted above, this paper provides a first step towards a more complete understanding of the proper specification of Pb-free compatible materials. Additional work will be focused on:

1. A more complete multivariate statistical analysis including various levels of T_g, T_d, and CTE values. For example, given a high decomposition temperature, how much can be gained by reducing CTE values.
2. Identifying the specific applications where a low-T_g/high-T_d material is sufficient versus those applications where both a high-T_g and a high-T_d are required.
3. Further develop the use of thermal analysis techniques on base materials for prediction of long term PCB reliability.
4. Last but not least, answer the obvious question, what is the minimum decomposition temperature required for Pb-free assembly compatibility? The materials discussed in this paper compared materials with decomposition temperatures of 310-320^{o}C with materials with decomposition temperatures of 350^{o}C. Early work on materials with decomposition temperatures of 335-340^{o}C (including some halogen free materials) is yielding very good results.

Acknowledgements

The various test results contained in this paper were obtained by several different people, each answering a specific question related to base material and PCB reliability. Their intelligent test design and hard work enabled this general assessment of the impact of Pb-free assembly temperatures on base material and PCB reliability as well as an understanding of what base material properties must be considered. The people responsible for this include Erik Bergum[2], Bill Varnell, Ron Hornsby, Marcia Cournoyer and others in the Polyclad Analytical Services Department. It is my ongoing privilege to work with these people at Polyclad Laminates/Cookson Electronics.

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