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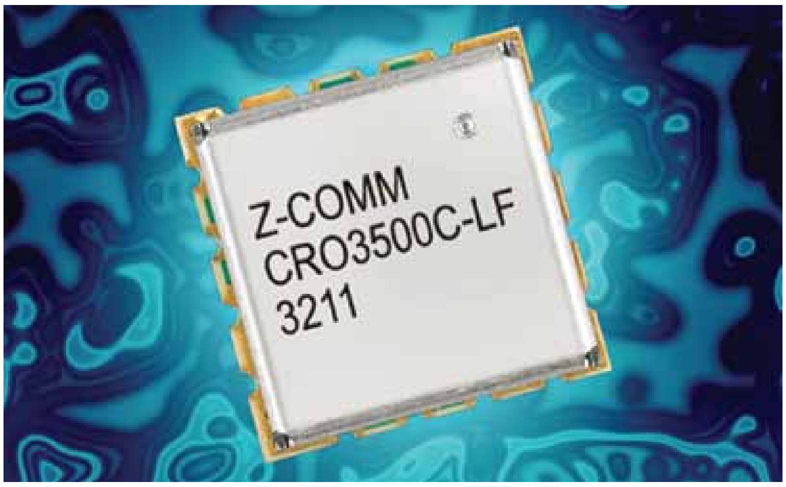

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Tackling Thermal Issues In Microwave PCBs

by John Coonrod, Rogers Corporation, Advanced Circuit Materials Division

Thermal characterization of printed-circuit boards (PCBs) has received a great deal of attention recently, and deservedly so. As electronic circuits continue to integrate more functions into smaller areas, PCBs are being tasked with handling more power with greater reliability. With higher power levels and increasing circuit densities, it is important to understand the short- and long-term thermal issues that can impact the performance and reliability of a PCB material.

Short-term PCB thermal issues are generally related to circuit fabrication and assembly processes. For example, PCB fabrication can involve numerous temperature swings, as the material undergoes the lamination and baking cycles required to create a PCB. Multiple lamination cycles are needed to construct the multilayer PCBs increasingly being used in both digital and high-frequency analog circuits. In a multilayer PCB the greatest stress, of course, will be on the first material to be laminated and then endure successive lamination cycles.

Perhaps the best way to detail various PCB material thermal concerns is by means of an example, a six-layer PCB with buried via holes (vias). The multilayer construction will employ a copper-clad laminate which will eventually become internal copper layers 3 and 4. Circuit images are formed on the copper laminates of layers 3 and 4 with plated-through-hole vias formed for interconnections (Figure 1A). The first lamination step involves adding layers of bonding material (prepreg material) above and below layers 3 and 4 to provide a surface for bonding the next two copper layers, layers 2 and 5.

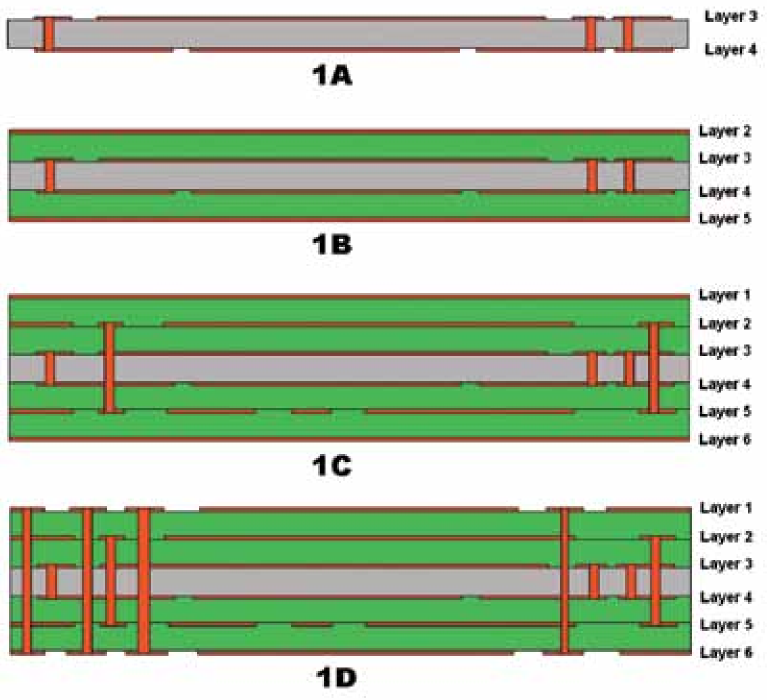

Figure 1: Cross-sectional view of a six-layer PCB with buried via holes. The layers consist of (a) copper-clad laminate with copper-plated vias and circuit layers imaged; (b) bonding layers added (the green layer indicates prepreg material) to adhere copper foil to the top and bottom of subpanel 3-4; (c) copper-plated vias added, circuit images created on copper layers 2 and 5, more prepreg added, and copper foil bonded to the top and bottom of subpanel 2-5; and (d) copper vias added and circuit images created on copper layers 1 and 6.

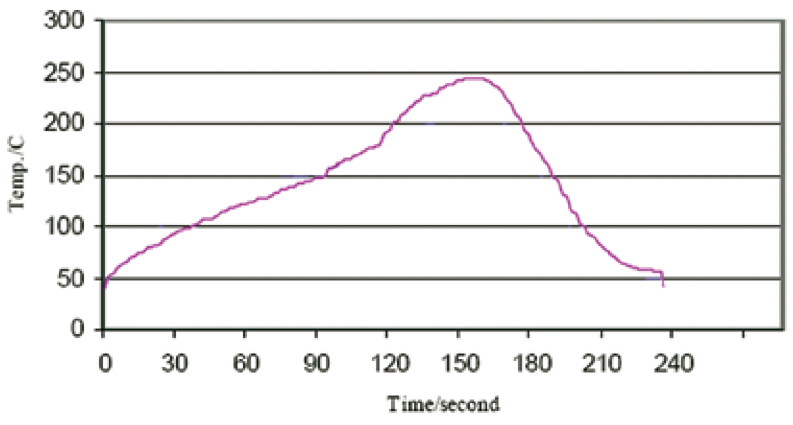

Figure 2: Typical lead-free-solder process profile

During this high-temperature lamination cycle, materials are held under high pressure for a required duration of time. A typical lamination cycle consists of 300 psi pressure, +350°F (177°C) temperature, and duration of one hour. There is considerable time allowed for the ramp up and cool down cycles; this will expose the material to elevated temperatures usually for two hours or more. The lamination cycle is necessary to bond the copper layers to the copper clad laminate which has copper layers 3 and 4 (Figure 1B). This panel is processed through the plated via process and the circuit images are generated on the copper layers 2 and 5. Circuit layers 3 and 4 are now buried and subjected to the elevated temperatures of this and any succeeding lamination cycles.

This process of adding prepreg and laminating to bond copper layers is repeated to form the outermost copper layers, layers 1 and 6 (Figure 1C). The plated via process and circuit imaging is then performed on layers 1 and 6 (Figure 1D). Following this, the multilayer assembly is processed to apply a solder mask, plating finish and/or solder and white nomenclature ink. Most of these processes are performed at elevated temperatures.

After the multilayer PCB has been constructed, it typically goes through further assembly steps to solder components to the circuit board. When lead-free soldering processes are involved, the PCB is exposed to extremely high temperatures. The process is often performed on both sides of the PCB, implying that the PCB must endure the lead-free soldering reflow process twice. A typical lead-free soldering reflow process involves peak temperatures to about 482°F (+250°C) (Figure 2), although the profile in terms of time and temperature can vary due to the heat sinking effects of a particular circuit design and construction.

In the multilayer PCB example, the copper-clad laminate with copper layers 3 and 4 has endured the longest "thermal history," having gone through its own processing steps and then surviving through the subsequent processing steps. In total, it went through two lamination cycles, multiple thermal processes, and two lead-free-solder procedures. Because of the number of thermal steps, it is this layer, or the bonding layer against it, that is the most susceptible to thermal reliability issues.

Multilayer PCBs can be fabricated with a number of different approaches, and each has its issues. Using the configuration of the six-layer example, if a higher-layer-count PCB is fabricated, it is possible that the thermal exposure to one of the copper laminates or an adjacent bonding layer might even be more severe. Some materials are more thermally robust than others, and some materials may not be ideally suited for enduring

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extended thermal processing or multiple thermal steps in a multilayer process.

In selecting PCB materials for multilayer designs in which the material might be expected to endure excessive short-term thermal steps, several material characteristics should be considered. These include the coefficient of thermal expansion (CTE), the glass transition temperature (T_g), and the decomposition temperature (T_d). The CTE describes how a material changes dimension with temperature. For a given material, it will be specified in all three axes, with the z axis being through the thickness of the material. Ideally, a PCB material's CTE should be closely matched to copper, which is about 17 ppm°C. It should also be isotropic, with the same CTE in all three axes. For most PCB materials, however, the CTE is typically much higher in the z-axis (the thickness) than in the x or y axes. The z-axis CTE is a concern because as the PCB expands during heating, it can elongate plated via holes and cause fracturing. If the z-axis CTE is closely matched to copper, expansion of the PCB material and copper will be more uniform and the plated via holes will be more robust during thermal cycling.

Thermal mechanical analysis (TMA) of a PCB material can help determine the CTE for that material. Most thermoset PCB materials exhibit two distinctly different CTE characteristics: one that is at temperatures less than T_g and one that is at temperatures greater than T_g. For a given material, the T_g is the temperature at which that material undergoes a molecular change, with the material thought of as making a transition from a rigid to a softer or even fluid composition. PCB material data sheets should always specify which CTE value is being presented, lest they be misleading.

Figure 3 shows an example of the TMA curve for a thermoset material with T_g of +180°C. Two lines are drawn tangent to two slopes on the curve. One line is for the CTE at temperatures below T_g, the other for temperatures higher than T_g, with the intersection of the two lines occurring at T_g. That material is a Theta® laminate from Rogers Corp. used for high-speed digital applications. It is halogen free and capable of withstanding multiple lamination cycles and lead-free-solder processing. With a CTE of 56 ppm/°C, the material is considered thermally robust for PCB fabrication processes and multilayer assemblies.

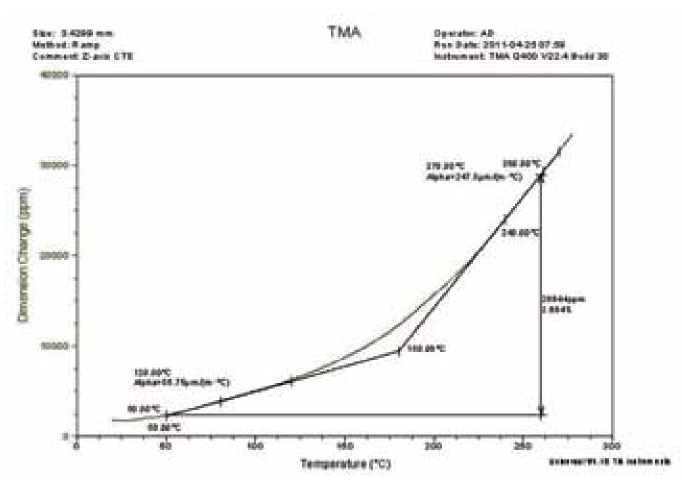

Figure 3: TMA curve for a thermoset PCB material

In general, materials with a CTE below 70 ppm/°C are considered suitable for applications requiring good thermal reliability.

The decomposition temperature, T_d, is sometimes a good indicator of which PCB material is suited to withstand multiple lead-free-solder processes. Some qualification requirements for such materials state that a candidate PCB material should be able to survive five or more lead-free-solder processing cycles. PCB materials which perform best under these extreme conditions typically have low CTE, high T_g, and very high T_d. The Theta PCB materials, for example, meet these requirements. A high-frequency laminate in particular that surpasses these guidelines is RO4350B™ laminate material from Rogers. It exhibits a CTE of 35 ppm/°C, T_g greater than +280°C and a T_d exceeding +390°C.

Testing Thermal Reliability

There are several tests that can be performed to evaluate a laminate or PCB for thermal reliability, including the T288 test widely used by the PCB industry. It subjects a laminate or PCB to a TMA test in which the temperature ramps from room temperature to 550°F (+288°C) in a controlled manner. Dimensional changes in the material are closely monitored, especially for rapid expansion, which can indicate PCB delamination and circuit failure. A laminate or PCB is considered reliable if it survives more than 15 minutes in the T288 test. As an example, RO4350B laminate material from Rogers Corp. consistently survives more than 60 minutes in the T288 test (Figure 4).

In addition to the short-term thermal issues mentioned, long-term issues can also impact PCB performance and reliability. For example, some PCB materials age differently than others. The requirements of different applications can vary widely, including the effects that PCB aging can have on those applications. Good engineer-

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ing practice requires evaluating PCB materials for both their short-term and long-term suitability for selected circuit-board processes and applications.

Among its various test methods and certifications for PCBs and PCB materials, Underwriters Laboratory (UL) has developed a long-term thermal rating related to PCB material: the relative thermal index (RTI). The rating represents the maximum temperature that a material can be subjected to indefinitely, without unacceptably compromising its critical material properties. A similar rating given to the PCB itself is the maximum operating temperature (MOT). It is the maximum temperature that a PCB can be subjected to without causing significant changes in its critical properties. A MOT rating applies to a particular PCB construction, using specific materials, processing, and fabrication site. A given material's MOT can never be greater than its RTI. More information and details regarding these test procedures and certifications can be found at http://www.ul.com.

The interconnect stress test (IST) is another well-defined method for evaluating the integrity of a PCB with long-term thermal exposure. This accelerated procedure evaluates a PCB's interconnect structure based on a specific construction, build, and materials. It monitors a specifically designed PCB for any variations in electrical continuity performance during well-controlled thermal

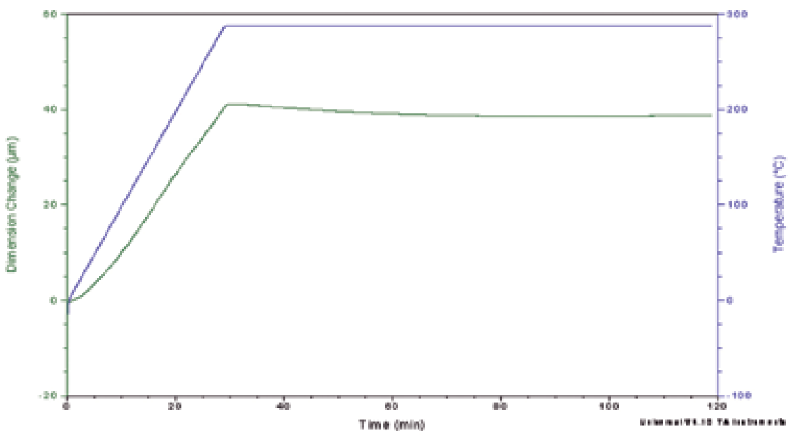

Figure 4: Results of RO4350B laminate subjected to a T288 test

cycling. Based on the earlier discussions of CTE and for evaluating plated vias in multilayer circuits, it can be seen that the IST method is a useful approach for evaluating long-term thermal effects on PCB integrity. More information on this test method can be found at IPC's website at http://www.ipc.org and in reference to test method IPC-TM-650 2.6.26.

Long-term thermal aging can sometimes exhibit the effects of electromigration in a PCB. A basic example is when a conductive filament can grow between two conductors, resulting in a change in electrical potential between the conductors. While these effects occur over a very long period of time, the electrical performance of the PCB will change as the filament grows. A critical long-term thermal issue with PCBs is called conductive anodic filament (CAF) and this typically occurs at a laminate's glass bundle and usually in the areas of plated vias. PCB fabricators typically offer more information on CAF phenomena on their websites; in addition, IPC (http://www.ipc.org) offers a test method for evaluating CAF in PCBs.

PCB materials vary widely in their performance and characteristics. Some of these materials have been in service in high-power microwave applications for decades with little change in their performance. In some other cases, the effects of long-term thermal exposure have caused changes in the performance of some applications.

Two types of PCB materials are typically used in the high-frequency industry: PTFE and hydrocarbon materials. The two types of materials are considerably different; PTFE materials are relatively inert while hydrocarbon materials are more reactive. As a result, the materials age differently. It is not unusual for any hydrocarbon system to oxidize over time, and this may or may not impact the electrical performance of a PCB. Hydrocarbon-based laminates used in high-frequency PCBs vary widely, with varying oxidation rates, and a given circuit design and board layout may be more or less sensitive to the effects of oxidation. In any case, it is important to understand and account for laminate aging effects.

Both short and long-term thermal effects should be considered when selecting a high-frequency PCB material, and weighing such material parameters as T_g, CTE, and T_d can help with the material selection process. Long-term effects can be more varied and problematic, although several test methods presented here can help in understanding these long-term thermal effects on different PCB materials.

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