Effects of Printed Circuit Board Materials on Lead-free Interconnect Durability

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Abstract

This study investigates the effects of printed circuit board (PCB) material on interconnect durability of lead free assemblies. The assemblies involve soldering various packages (array and peripheral) on to FR4, high glass transition temperature (T_g) FR4 and Polyimide (PI) printed circuit boards using Sn3Ag0.5Cu solder alloy. The glass transition temperature of these materials ranges from 130ºC to 230ºC. Thermomechanical properties, such as elastic modulus and thermal expansion coefficients, of the board materials vary considerably. These properties have a direct impact on the interconnect durability. In this paper, thermomechanical properties are experimentally determined and used for solder joint durability simulation. Two kinds of environmental loadings are simulated: temperature cycling and random vibration loading. The results show that PI board provides a better solder joint durability than FR4 and high T_g FR4 under temperature cycling conditions. PI assembly has better durability than FR4 assembly under random vibration. The paper also presents the effect of temperature on the vibration response of the FR4 printed circuit board assemblies. The understanding of these changes can contribute to the study on interconnect durability under combined temperature cycling and vibration loading conditions.

Keywords

Printed circuit board, solder joints, lead-free, FR4, Polyimide, temperature cycling, random vibration, sinusoidal vibration, glass transition temperature, elastic modulus, coefficient of thermal expansion

1. Introduction

The electronics industry is migrating to lead-free electronics, both to comply with government legislations and to increase market share through product differentiation. The transition to lead-free electronics requires surmounting a host of technical, socio-political and economical issues. Key concerns in lead-free product development, including those related to lead-free compliance, lead-free part and supplier selection, lead-free manufacturing, lead-free reliability and lead-free training and education are being addressed to provide guidelines to help equipment manufacturers efficiently implement a transition to lead-free electronics [1, 2].

Considering that lead-based electronics have been in use for over 40 years, the adoption of lead-free technology represents a dramatic change. The reliability of lead-free soldered electronics is a key topic many researchers are focusing on. The reliability of lead-free solder joints is expected to be different from PbSn solder joints due to the differences in solder microstructure and its response to different loading conditions. It is also affected by many geometric and other materials factors, including dimensions of the solder joint, shape and thickness of the intermetallic compounds, PCB pad finish metallurgy, leadframe finish, and manufacturing defects [3].

The interconnect durability of components which are mounted on PCB will be also influenced by PCB thermomechanical properties, such as glass transition temperature (T_g), coefficient of thermal expansion (CTE), and elastic modulus (E). In this paper, three different PCB assemblies with various packages (array and peripheral) are investigated under temperature cycling and random vibration loadings. Sn3Ag0.5Cu (SAC) solder is used as the lead-free solder material.

The effect of temperature on vibration response of the FR4 printed circuit board assemblies is also discussed in this paper. The understanding of the effects can contribute to further study on interconnect durability under combined temperature cycling and vibration loading conditions.

2. PCB material properties characterization

Three kinds of PCB materials are used in this study: FR4, high T_g FR4 and PI. For our studies, two critical material properties, CTE and Elastic modulus, are experimentally determined and used in simulation.

2.1 Test vehicles

Figure 1 and Figure 2 show the surface mount technology (SMT) assembly for temperature cycling and vibration simulation, respectively. The PCB material is FR4 in Figure 1 and 2. Other two PCB (high Tg and PI) assembly are not shown to avoid redundancy since the layout are the same. Four type of components are mounted on PCB: 1 mm ball pitch, 256 I/O plastic ball grid array package (PBGA), 0.5 mm lead pitch, 100 lead low profile quad flatpack (LQFP), leadless ceramic chip carrier (LCCC), and resistors (2512 and 1210).

2.2 Material characterization

In-plane CTE and Elastic modulus of PCB materials are experimentally determined using PERKIN ELMER Thermomechanical Analyzer (TMA) and DMA-RSAS, respectively, based on IPC standards. Table 1 shows the material properties of three different PCBs.

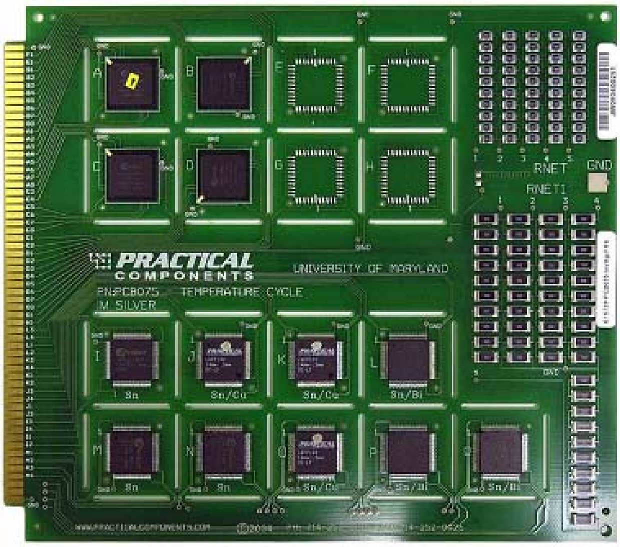

Figure 1: SMT temperature cycling test vehicle (FR4 PCB board)

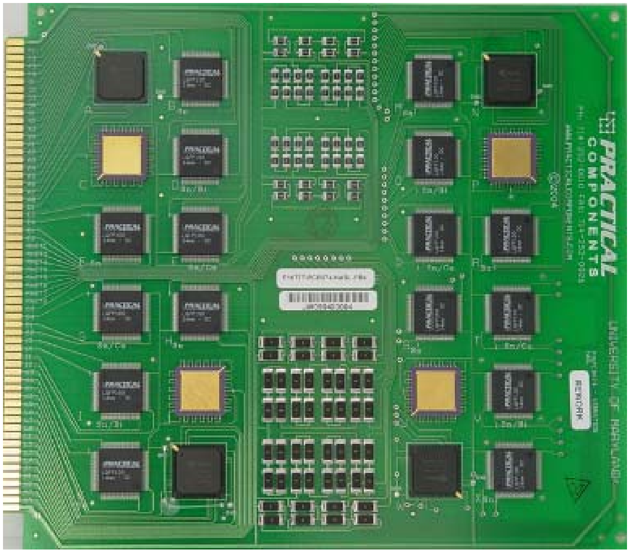

Figure 2: SMT vibration test vehicle (FR4 PCB board)

TABLE 1: MEASURED PRINTED CIRCUIT BOARD MATERIAL PROPERTIES

Board	FR4	High T_g FR4	PI
T_g (°C)	130	180	230
In-plane CTE ppm/°C	14.8	14.0	12.4
Elastic modulus at room temperature (below Tg, MPa)	17278	23982	23568
Elastic modulus (above Tg, MPa)	3699 (@ 150ºC)	5776 (@ 200ºC)	12227 (@ 280ºC)

3. Interconnects Durability Simulation

Interconnects durability was assessed using an existing software calcePWA.. The thermal fatigue model built in calcePWA was based on a Coffin-Manson type damage law [4]. The stress state was formulated in terms of the maximum shear strain using the CALCE first-order models [5-7]. Over the years, CALCE has developed and refined the constitutive properties of SnPb and SnAgCu solder alloys and these properties are included in the calcePWA database [8-11]. Vibration model [12] is also integrated in calcePWA and used to simulate random vibration loading conditions.

3.1 Temperature cycling simulation

Temperature range in the simulation is from -40 °C to 125 °C with dwell time of 15 minutes at extreme temperatures and ramp time of 15 minutes between extreme temperatures. Total duration per temperature cycle is 1 hour.

The durability of solder joints on three different assemblies are simulated and summarized in Table 2. The prediction shows the solder joint reliability of PI boards is better than FR4 and high T_g FR4 boards. The possible reason is the lower CTE mismatch between components and PI board than FR4. The CTE difference between PI and FR4 is about 19%. The failure sequence shows the solder joints of LCCC is the most susceptible and solder joints of LQFP is the most robust under temperature cycling. This is consistent with other researchers' work [13-16]. The reason is that LCCC solder joints are non compliant and are subjected to large thermal mismatch stress (component-PCB).

TABLE 2: SNAGCU SOLDER JOINT DURABILITY SIMULATION UNDER TEMPERATURE CYCLING

	FR4	High T_g FR4	PI
Package	Time to fail (cycles / days)	Time to fail (cycles / days)	Time to fail (cycles / days)
LCCC	77 / 3	112 / 5	252 / 12
Resistor 2512	760 / 32	1103 / 46	2732 / 114
PBGA	4523 / 188	5524 / 230	19490 / 2.2 years
Resistor 1210	6208 / 259	9007 / 1.03 years	22302 / 2.5 years
LQFP	13517 / 563	39237 / 4.48 years	> 30 years

3.2 Random vibration simulation

Power spectrum density (PSD) level for random vibration simulation is chosen at 0.04 G^2/Hz. The frequency ranges from 0 Hz to 600 Hz. Vibration loading duration is set as 24 hours per day at room temperature. Boundary condition is set as wedge clamp along left and right edges in Figure 2. At this point calce PWA vibration model uses the same constitutive properties for Sn-Pb and lead-free solder. This data will be updated with appropriate properties for these solders.

Through simulation, the first mode frequency for FR4 assembly vehicle is calculated as 185.9 Hz and 189.2 Hz for PI assembly respectively. Table 3 summarized the first failure for each type component on FR4 test vehicle and PI test vehicle under vibration loading.

TABLE 3: RANDOM VIBRATION SIMULATION UNDER 0.04 G^2/HZ LOADING AT ROOM TEMPERATURE

	FR4	PI
Package	Time to failure (days)	Time to failure (days)
PBGA	169	172
LCCC	2.40 years	2.55 years
LQFP	2.79 years	2.85 years
Resistor 2512	3.89 years	3.79 years
Resistor 1210	4.38 years	4.26 year

The simulations show solder joint durability on PI assembly is generally better than those on FR4 assembly, except resistors. This trend may possibly be due to the differences in vibration response (e.g. higher modal frequencies) in the case of polyimide PCB, resulting from the higher elastic modulus (and higher stiffness) of PI PCB at room temperature. Tests are being conducted to understand this behavior.

4. Effect of temperature on the vibration response of the PCB assembly

All the simulation performed for vibration in previous section was at room temperature. Since material properties can change when temperature changes, the response of PCB assembly to vibration will also be affected. Experiments were carried out to investigate the effect of temperature. In all these tests, sinusoidal vibration was used.

Figure 3 and Figure 4 show the vibration response test set up. There are 6 acceleration meters (location 1 to 6) attached on PCB assembly back side and 3 acceleration meters (location 7 to 9) attached on the clamp fixture. Vibration frequency ranges from 50 Hz to 1000 Hz. The temperature of the climatic chamber was set at 21 °C, 80 °C, and 125 °C. Vibration response at location 5 (the center of board) under different temperatures are drawn on Figure 5. The results show that vibration response of the PCB assembly is strongly influenced by the ambient temperature. Figure 6 shows the clamp fixture (location 7) vibration response. It can be seen over 600 Hz, the clamping fixture responds to the vibration dramatically, which means the vibration frequency should be limited under 600 Hz for real test to avoid effect of clamping fixture.

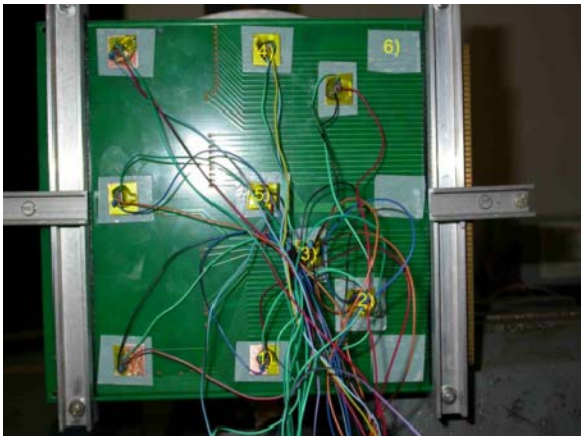

Figure 3: PCB assembly vibration response set up (back view)

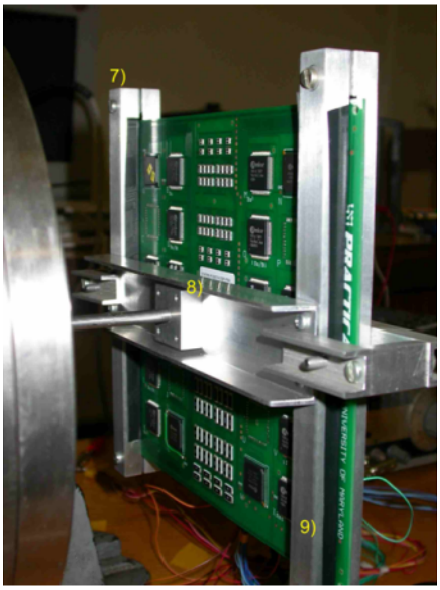

Figure 4: PCB assembly vibration response set up (front side view)

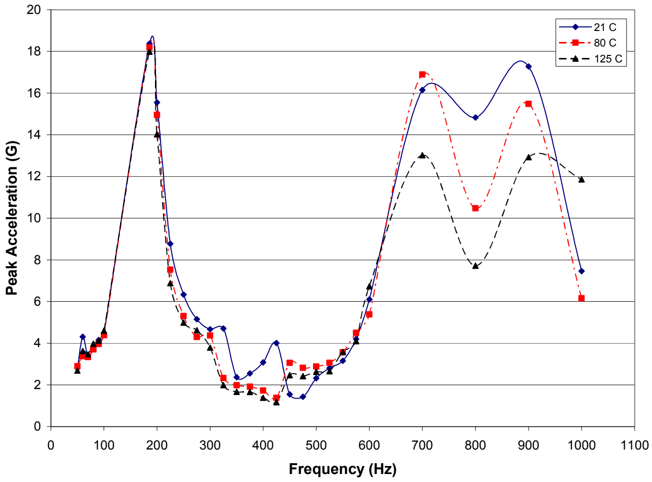

Figure 5: Vibration response at location 5 (center of board) under different temperatures

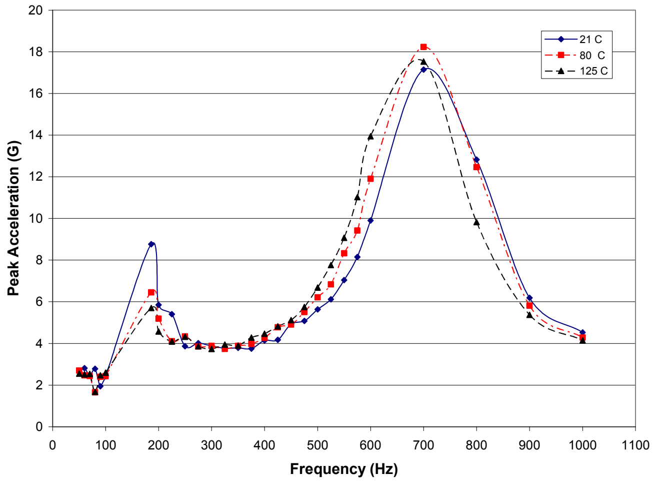

Figure 6: Vibration response at location 7 (clamp fixture) under different temperatures

To investigate the effect of glass transition temperature on the vibration response, vibration tests were also carried out at 160 °C (T_g is 130 °C for FR4) with frequency range from 100 Hz to 200 Hz. This is the range at which the first mode frequency occurred as shown in Figure 5. The test results are drawn on Figure 7. It is seen that FR4 PCB assembly has a different vibration response below T_g (130 °C) and above T_g (130 °C) with first mode natural frequency shifting dramatically. Specifically the first mode frequency changes from 190 Hz at 21ºC to 110 Hz at 160ºC. The reason is that elastic modulus of FR4 PCB decreases significantly below T_g and this reduces the stiffness of the PCB and hence the decrease in the first mode frequency.

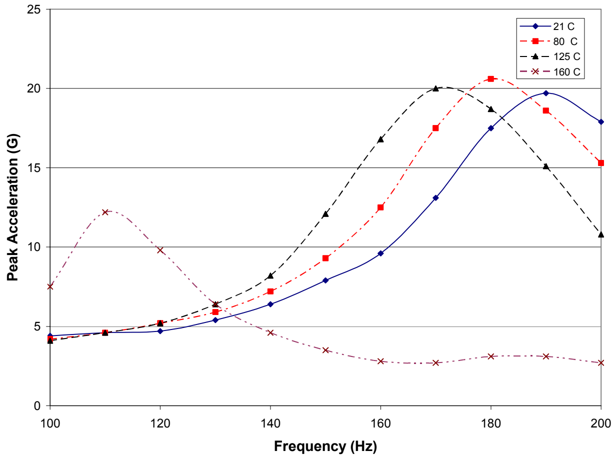

Figure 7: Vibration response at location 5 (center of board) below T_g and above T_g

5. Conclusions

This study shows thermomechanical properties, such as elastic modulus and thermal expansion coefficients, of the PCB materials have a direct impact on the solder joint durability. The durability of solder joint simulation under temperature cycling shows PI board provides a better interconnect durability than FR4 and high T_g FR4 due to less CTE mismatch between board and components. Random vibration simulation results indicate that PI assembly has better solder joint durability than FR4 assembly possibly due to higher elastic modulus of PI (and higher stiffness) compared to FR4. Tests are being carried out to validate these results.

The paper also addresses the effect of temperature on the vibration response of the FR4 printed circuit board assemblies. The experiment results show that vibration response of the PCB assembly is dependent upon temperature. For example, the first mode frequency shifts from 190 Hz at 21ºC to 110 Hz at 160ºC, when FR4 PCB temperature is above T_g. This is attributed to the decrease in elastic modulus (and hence decrease in stiffness) of FR4 PCB above Tg. The data from this study will help the study on interconnect durability under combined temperature cycling and vibration loading conditions.

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