

Finite element modeling of printed circuit board for structural analysis

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ABSTRACT

Printed circuit boards having unfavorable deflection have been considered for a better mechanical design. During reflow process, pcb has experienced a range of the temperature between ambient temperature and peak temperature in furnace. Out of plane deflection is generated due to the property mismatch of material composition. Combination degree of board and copper plating will be researched for further investigation of trouble cause and design improvement.

The soldering effect and mounting components weight are ignored considering input data complexity. And a set of real pcb has been exposed in reflow process and the deflection data for comparison are collected. In this study, setting up the analysis procedure and a finite element model for board deflection was focused.

INTRODUCTION

The demand for structurally reliable pcb has grown as electronic products are asked more functions, less weight and smaller sizes. It gives certain limitations and critical requirements. The unfavorable pcb deflection can ask extra effort for pcb design. Multi-media portable electronic products such as personal digital assistance and cellular phone, etc. are asking more and more. And finally new breakthrough is needed. Before looking for the improvement, a source of problem and theoretical approach for main causes are sought. Several studies have been carried out to show a behavior of the bonded materials due to a mismatch of thermal and mechanical properties. The first solution, based on beam theory, was given by Timoshenko (1925). The problem of edge effects was first addressed by Aleck (1949). The more recent solutions include elasticity solution of Kuo(1989) and Lee(1991). The finite element solutions of this problem are discussed by Lau(1989). Pao(1991) tries to develop an analytical approach of multilayered stacks. His approach, which is based on an extension of Suhir's bimetal thermostat model(1986, 1988) provides a system of coupled linear second order differential equations used in solving for the interfacial stresses.

The purpose of this paper is to develop a proper finite element model describing a pcb structural instability and its boundary conditions. And the real examples from one of electronic industries (LG Electronics Inc.) are introduced. 0.4mm thickness 2 sided surface mounted pcb has been experienced large out-of plane deflection in audio assembly. A mechanical grip like cross bar is used to keep the board straight. This compulsion can

create unexpected stresses on pcb. Pcb's mounting thin QFP or thin SOP face double trouble due to a board deflection and package popcorning in CD-ROM. This pcb has a specified deflection limit in Fig.1 for a pick and place machine and after reflow. Over this limit range, inspection system will show an error message meaning potential defects.

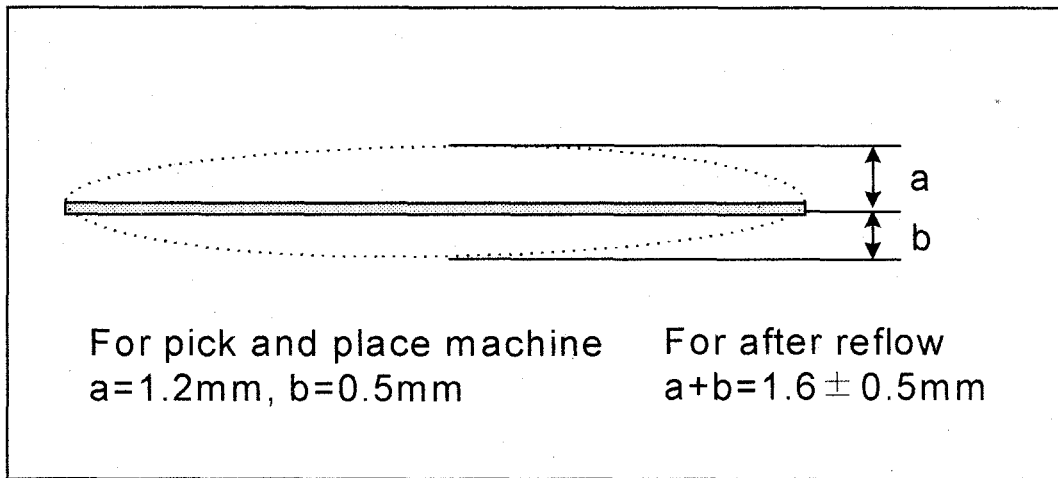


Fig.1 deflection limit for a pick and place machine and after reflow (courtesy of CD-ROM objective business unit, LG Electronics, Inc. 1996)

PROBLEM DEFINITION

Thermal stress and strain distribution of copper plated pcb which is an orthotropic woven glass fiber and phenolic composite assembly subjected to a typical IR reflow were investigated. The objective is to find out the main causes of warpage, or out-of-plane pcb deflection and suggestions to improve pcb against deflection. Generally warpage is a result of the induced thermal stresses and the laminate asymmetry. It can be calculated by classical lamination theory using lamina material properties. Integration of the curvature-deflection relations

$$\kappa_x = - \frac{\partial^2 W}{\partial x^2}$$

$$\kappa_y = - \frac{\partial^2 W}{\partial y^2}$$

$$\kappa_s = - \frac{2 \partial^2 W}{\partial x \partial y}$$

yields the out-of plane deflection W

$$W = - \frac{1}{2} (\kappa_x x^2 + \kappa_y y^2 + \kappa_s xy) + \text{rigid body motion}$$

An ideal model of plated pcb without discontinuities or irregularities was assumed to develop finite element model in a 3-dimensional orthotropic analysis. Non-linear orthotropic properties for Cem-3 board were modeled as piecewise linear, with three data points describing the changes in each material constant with temperature. See Fig.2 for temperature profile. Thermocouple attached on the area of interest catches the temperature

when it passes through the reflow furnace. It is thin enough to consider as a constant temperature through thickness.

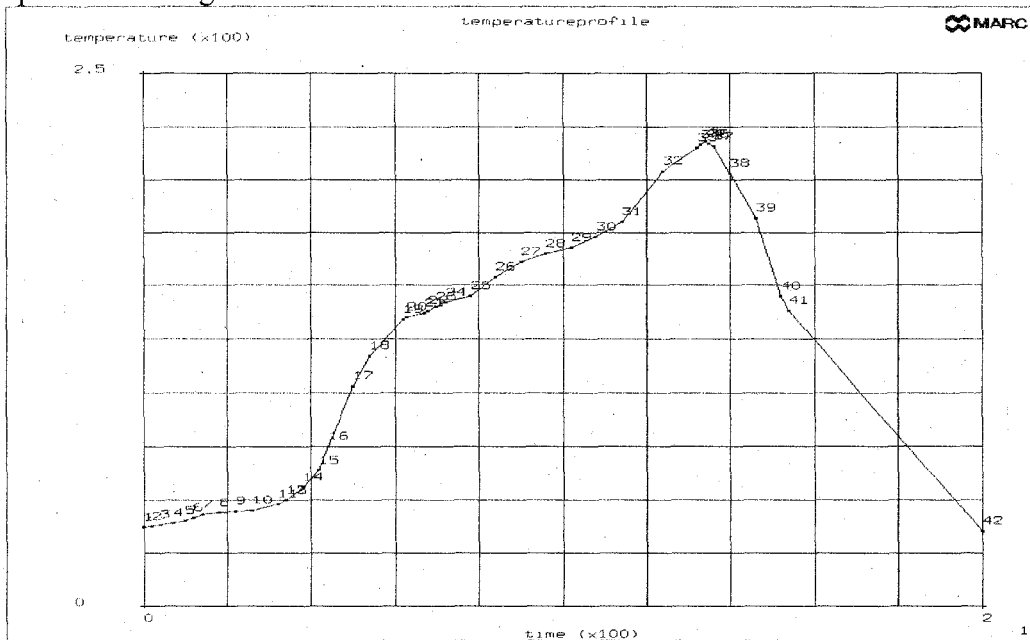


Fig.2 Reflow Temperature Profile

A nonlinear finite element model based simulation methodology, has been developed by Marc, the commercial fem program for predicting the deflection of pcb subjected to thermal shock because it is noted that pcb treated involves significant nonlinear deformation, e.g. creep and plasticity, in a general reflow temperature environment.

Comparatively simple model is introduced to check the modeling reliability and influencing factors for design at the beginning. 3 different reliable boundary conditions are applied. The first condition is about a quarter of pcb. It has a couple of symmetric planes which assume no normal displacement and slope at the interface after thermal load application. And there is no out of plane displacement where pcb lies on. See Fig. 3a. 2nd condition shows a cantilever style plate modeling half board in Fig. 3b. One side is restrained about displacements and rotations in all direction. Others are free. 3rd condition is about a board attached perpendicularly to a light beam simulating no extra restraints exist. See Fig. 3c. After satisfaction for modeling reliability, more complicated and realistic model of Cem-3 board is developed for comparison with empirical result and for introduction of design guide. Cem-3 board is the commercial name of woven glass fiber in phenolic resin and is used as TV tuner printed circuit board. Board material, phenolic laminates, is made of 2 to 3 plies of fine glass and 50-65% weight resin content. The degree of cure and fiber alignment of board as well as these compositions should have influenced thermal and mechanical properties and elastic fields significantly. No single set of properties and conditions can be used effectively to compare different samples of board. A study like this, the calculated values of stresses/strains are valid only for boards with properties close to the ones used here.

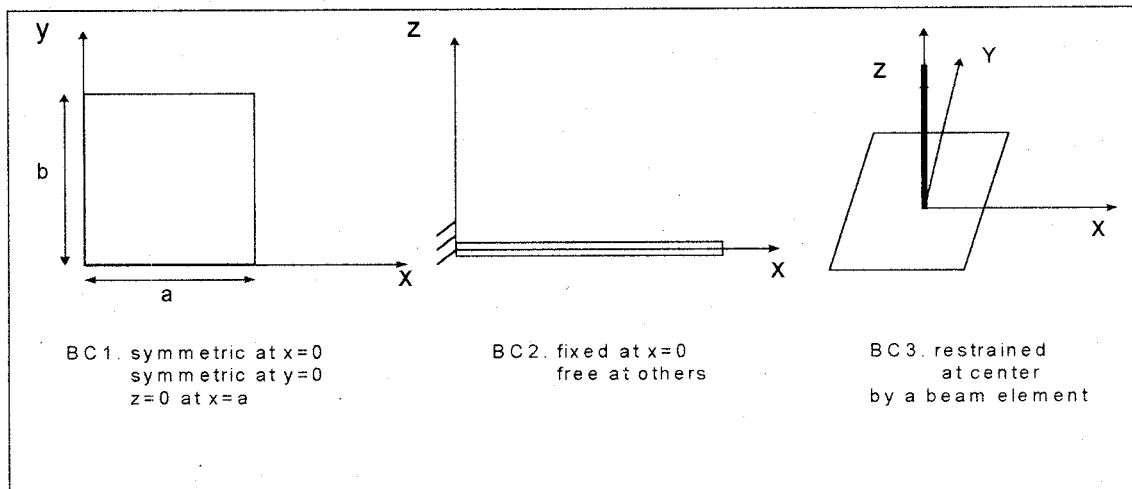


Fig.3a, b and c 3 different boundary conditions

MATERIALS AND PREPARATION

In the most general case the stress and strain components are related by the generalized Hooke's law as follows:

$$\sigma_{ij} = C_{ijkl} \epsilon_{kl} \quad \text{where } i,j,k,l = 1,2,3$$

The number of independent elastic constants is reduced to nine when the reference system of coordinates is selected along principal planes of material symmetry, i.e., in the case of a specially orthotropic material.

The subscripts 2 and 3 and 5 and 6 in the material constants are interchangeable due to cross ply fibers, i.e.,

$$C_{12} = C_{13}, \quad C_{22} = C_{33}, \quad C_{55} = C_{66}$$

The relations above show that an orthotropic material is characterized by only 6 independent elastic constants.

For this study it is assumed that the pcb material is orthotropic Cem-3. Temperature dependent thermal and mechanical properties for fem structural analysis exhibit in Table 1. These data are collected from tests assisted by CALCE electronic packaging research center in University of Maryland. Impressions for Cem-3 test are as follows.

- coefficient of thermal expansion measured by Thermo-mechanical analysis machine with furnace

- 1) out-of-plane CTE tells a complex dependence on temperature. Below the glass transition temperature (T_g), 130-150°C, it is a hard, glassy state turning into a soft rubbery state above T_g as expected.
- 2) In case of in-plane CTE measurement, a proper specimen fixture is essential to drive right result especially for the prepared specimen which has about 1mm thickness. After failure of several tests, in-plane CTE was measured and this test says that T_g does not influence the characteristics of CTE in plane.
- 3) A sample once tested in Tma shrinks in thickness (0.3%). It seems to be due to pcb

moisture evaporation during test.

4) CTEs are averaged with at least 10 test result.

- out-of plane elastic modulus at room temperature by scanning acoustic microscope

1) $E = v^2 \rho$

2) where ρ is a density and weight over volume and v is a velocity.

$$\rho = 1.090 / 600.56 \text{ (g/mm}^3\text{)} = 1814.972 \text{ Kg/m}^3$$

$$v = 0.914 / 594 * 10^{-9} \text{ (mm/s)}$$

$$E = 4.297 \text{ Gpa}$$

- temperature dependent in-plane elastic modulus and Poisson's ratio by UTM and standard test method for tensile properties of polymer matrix composite materials (Designation : D3039/D3039M - 95a)

- temperature dependent in-plane and out-of plane shear modulus by UTM and standard test method for shear properties of composite materials by the V-notched beam method (Designation :D5379/D5379M-93)

1) laminates composed only of woven-fabric filamentary laminae with warp direction oriented either parallel or perpendicular to the loading axis

2) 2 to 3 layers of stacking up bare material was bonded in autoclave for shear modulus specimen.

- Bare material is not easy to measure out-of plane modulus and Poisson's ratio in high temperature simulating reflow process. It is too flexible to keep straight when the force applies. The sample itself starts to burn and change the color and melt as it is heated up. The phase of material must be changing. Bonding process in autoclave is required to prevent specimen from failure.

2 finite element models were developed for numerical analysis. One is a simplified model to find out whether it satisfies modeling reliability and physical intuition. And this FE preliminary model is also employed to determine the relationship between deflection and copper thickness and location. Another model was to show a real pcb and its behavior.

In electronic packaging, materials with different thermal and mechanical properties are bonded together to form complicated structures, such as transistor stacks or plated printed circuit boards. The bonding interfaces of such structures near the free edge suffer high stress concentration due to the mismatch of properties of bonded materials and can create a source of crack initiation. This mismatch can also produce out-of plane unfavorable deflection and make a less contact area of solder between copper plated pcb and surface mounted packages and occur a debonding which causes a electrical malfunction. Understanding the nature of interfacial stresses and out-of plane displacement in such electronic systems plays an important role in achieving higher reliability. Here, this study

focuses on the troublesome displacement, its cause and prevention.

Property	Phenolic Fiber Glass			Copper
	25	100	200	
T (°C)	25	100	200	
ρ (Kg/m ³)	1814	1814	1814	8940
Ex(Gpa)	19.42	15.14	14.42	103.42
Ey(Gpa)	19.42	15.14	14.42	103.42
Ez(Gpa)	3.42	0.864	0.096	103.42
ν_{xy}	0.25	0.27	0.46	0.3
ν_{xz}	0.16	0.18	0.48	0.3
ν_{yz}	0.16	0.18	0.48	0.3
Gxy(Gpa)	6.8	4.6	4.33	39.71
Gxz(Gpa)	1.44	0.44	0.133	39.71
Gyz(Gpa)	1.44	0.44	0.133	39.71
α_x (ppm/C)	19.48	15.52	12.5	17.00
α_y (ppm/C)	19.48	15.52	12.5	17.00
α_z (ppm/C)	37.68	50.16	260.8	17.00

Table 1. Thermal and mechanical properties

FINITE ELEMENT MODELING

Fig.8b is a three dimensional finite element model of copper clad pcb in TV tuner and Table 2 is a list of pcb fem dimension data.

catalog	dimension
width	63.8mm
length	114.5mm
thickness	1.00mm
copper thickness	0.035mm
element type	4 node quadratic thick shell
number of element	9064

Table 2 TV tuner pcb dimension

Exact description of copper pads consumes too much time for modeling and computing for not much benefit. A method is introduced for simplifying complex 3-D geometries so that the commercial fem codes can be conveniently used in thermal design analysis. It starts with adding all copper pad area manually and calculating volume by multiplying thickness and spreading it at different locations. The applicability of this method has been

investigated next by selecting suitable example. It could be much easier if electric cad data includes the area dimension of pads on pcb. Runs of simulation said that different simplified models including copper pads show slight max. deflection changes ($\pm 0.15\%$) as long as same amount of copper exists and the copper does not locate where the stress concentrates. See Fig. 5.

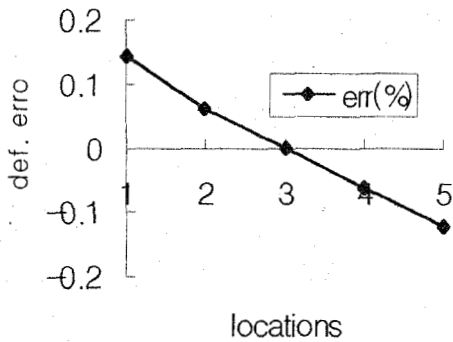


Fig.5 deflection error at different copper locations

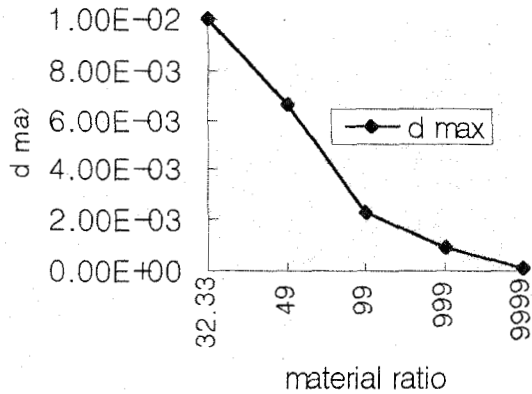


Fig. 6 max deflections with material thickness ratio(pcb/copper)

Fig. 6 describes bimaterial thermal effect depending on thickness ratio. Copper roles the pattern on surface of pcb and its min. thickness ratio (pcb/copper) is about 32.33. The thinner copper plate is, the less deflection happens. This is an expected behavior of bimaterial considering the mismatch of coefficient of thermal expansion.

RESULTS AND DISCUSSION

1) empirical measurement of pcb deflection

Procedure includes - measure the bare board - reflow - cooling to room temperature

- measure the deflections at 6 points. See Fig.7. - repeat with 20 samples

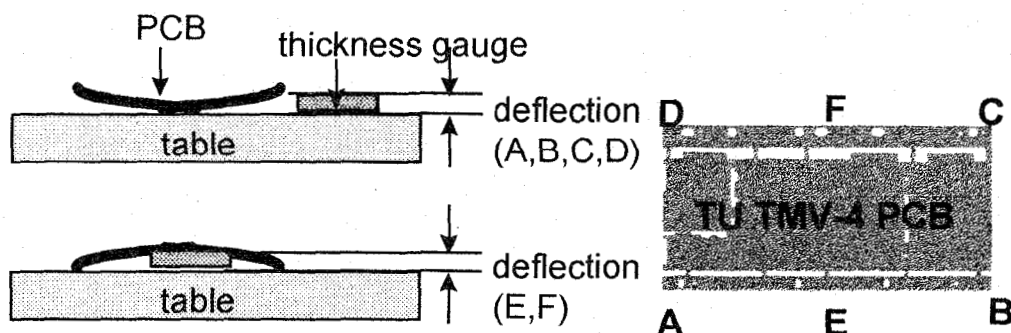


Fig. 7 deflection measuring gauge and locations

Pcb with slight opposite curvature has been provided. Measuring the bare board before reflow is necessary for exact deflection due to thermal loading. The average deflection out of 20 boards is shown as follows.

(Unit: mm)

	A	B	C	D	E	F
Bare pcb	0.18	0.21	0.18	0.18	0.16	0.15
After reflow	-0.54	-0.23	-0.42	-0.37	-0.44	-0.41
Total def.	0.72	0.44	0.60	0.55		
Simulation	0.688	0.39	0.57	0.34	*	*

Max. deflection of board after reflow is about 0.72mm at A. It shows concave on copper after reflow from convex and a hyperbolic paraboloid or saddle-shaped surface. It exposes to a room atmosphere before measurement and cooling down to room temperature can flex the board down a bit. So the deflection during reflow is assumed to be bigger than the one in table.

2) Numerical analysis

Temperature dependent nonlinear thermo-mechanical analysis has been proceeded simulating IR reflow process. Reflow process takes totally 154 seconds from entrance to exit. It experiences temperature distribution in Fig. 2 during this period. And Fig. 8 shows pcb displacement by fem analysis. This result is addition of thermally and mechanically induced displacement considering reflow heat and board weight. There is about 6% difference in max. deflection between empirical and numerical result. That can be explained as follows. Real pcb is covered with solder resistor on surface of copper clad pcb while fem model has only copper pads and a board.. Additionally 3D geometry simplifying process approximates simulating real board behavior. And holes in pcb will introduce less thermal stress when the board expands. It leaves more deformation in plane but less in out-of plane. Higher computational facility is required to develop fem solid model describing above all. The cooling process out of reflow furnace will definitely influence the characteristics of polymer pcb and cooling rate during process plays a major role on board reaction. More intensive studies are requested for detail subjects influencing board behavior.

CONCLUSION

It results the effect of mismatch of thermal material properties. Numerically driven saddle shaped deflection and direction match fairly well with empirical results. Boundary conditions and pcb models as well as problem definition have been proved as reasonable

choices for finite element analysis. Theoretical understanding of the copper clad pcb's thermal behavior can give flexibilities in pcb design and it means various approaches for improvement. Cooperation of empirical and theoretical approach will develop new design concept in limited time. The ability of an engineer or circuit board designer to predict structural integrity accurately will be multiplied with numerical analysis and empirical assessment system.

This reflow simulation and test did not produce deflection enough to cause structural defect in TV tuner. However, the model considered for multi-media portable products can have a different aspect because of severe design limitation. Failure by pcb deflection may arise during product life time, not during reflow or manufacturing. It will obviously shorten product life. Good quality with full proof of life time can be considered as a goal of research and development in electronic industries.

With satisfaction of reflow simulation design guide and assessment system should be prepared for design completion. This is not an easy but essential task to be followed. The experimental and finite element method will help to reduce stress from developing an engineering definition.

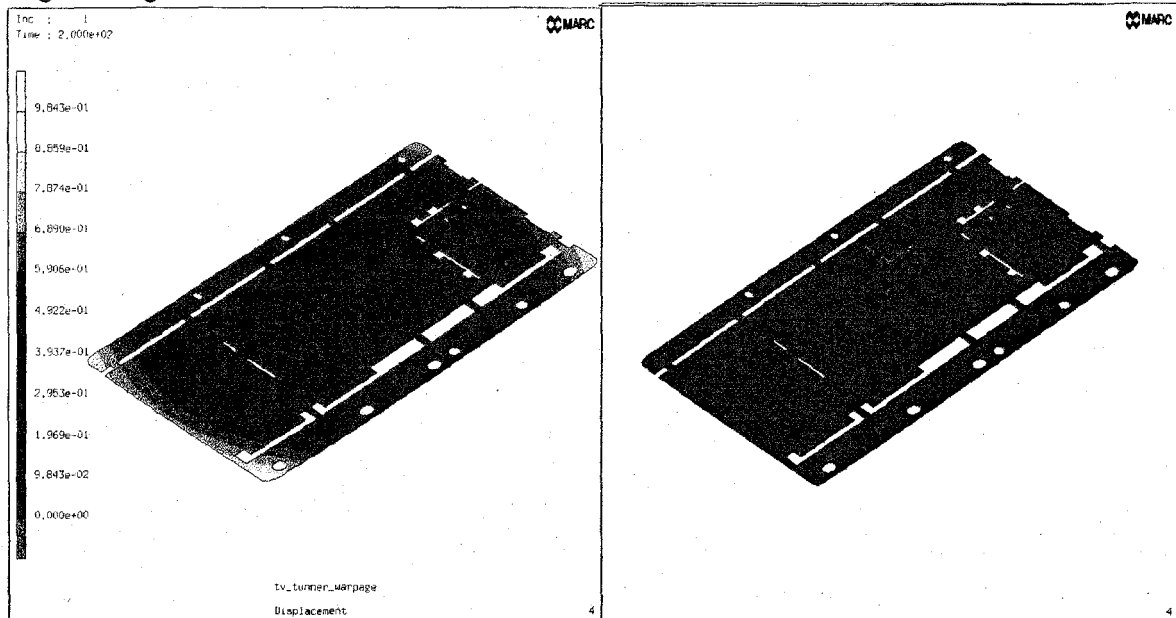


Fig. 8a,b Pcb deflection numerical model and result

This preparatory study will be continued for understanding and developing structural integrity and reliability of routable substrates. Effect of copper plating in dead space, shape and size of cut-out are to be studied as influencing factors to board behavior by finite element analysis. And combining unfavorable pcb deflection with popcorning package will be investigated because packages commonly mounted to a board by solder bumps which

electrically and mechanically connect the package to the board can express popcorning during reflow.

ACKNOWLEDGMENT

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