Pad Cratering Evaluation of PCB

Dongji Xie*, Ph.D., Dongkai Shangguan*, Ph.D. and Helmut Kroener**
*FLEXTRONICS, San Jose, CA
** Multek, Schongau, Germany
email: Dongji.xie@flextronics.com

Abstract

Pad cratering in the PCB is a new failure mode encountered in electronic assemblies, particularly in lead-free products. The failure mechanisms and root causes are not yet fully understood, and lack appropriate industry standard tests for PCB qualification with regard to pad cratering. This paper reviews major publications and research reports on various PCB materials from industry studies in this field. Various PCB tests, such as flexural strength test and pad strength test, have been studied. It is recommended that the qualification of the PCB can be done in two stages: PCB board level and PCBA product level. From those results, a new qualification method is suggested for screening out PCB pad cratering failures.

Introduction

Pad cratering in the PCB (printed circuit board) is one of the major failure modes encountered in electronic assemblies and has become more prevalent as the industry moves to lead-free soldering. It impacts the production yield as well as long term reliability. Pad cratering is defined as a separation of the pad from the PCB resin/weave composite or within the composite immediately adjacent to the pad. It triggers failures only if the crack propagates into a copper trace or conduction pad and makes the circuit open or intermittent.

Pad cratering starts from cracking of the laminate. The crack may initiate from the intersection of the solder, copper pad and laminate as shown in Fig. 1, as this is a stress concentration point for crack initiation. The crack may propagate from the interface of the epoxy to the glass bundle under certain stresses.   In this case, as the stress may concentrate on the other side of the perimeter of the pad, the crack may propagate through the pad and create a total pad cratering.   According to Roggerman et al, the propagation of the crack through the glass reinforcement and along the glass-resin interface takes a significant amount of time and stress to become a complete failure [1].
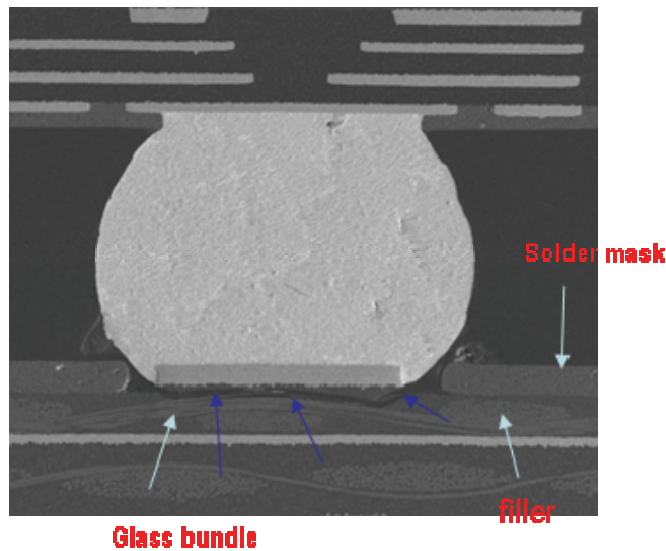

Fig. 1 Pad cratering occurred in the BGA assembly during functional test in the production line.

Root Causes of Pad Cratering

Pad cratering has been widely seen in drop and shock tests as one of the major failure modes, giving an impression that pad cratering only occurred in drop and shock tests or other mechanical tests. In reality, pad cracking could actually occur under thermal stress or thermomechanical stress, especially for large BGAs (body size >30mm).   Fig. 1 is an example taken from production with no mechanical stress test.

Testing for Pad Cratering

There are three levels of tests related to pad cratering: PCB materials, soldered PCB (pad-solder level), and system level. The PCB material is associated with the raw materials (such as epoxy resin, filler and fiber), and the layer structure and

fabrication process. The test methods at the PCB level are mostly defined by IPC TM650 in various tests including modulus, flexural strength, peel strength, fracture toughness, etc.   Modulus and flexural strength are basic mechanical properties of the laminate. They are dependent on the resin content and curing system.   Peel strength test is to test the copper clad adhesion to the laminate.   The fracture toughness is not a standard IPC test yet so that it is unavailable in most materials data sheets.

The pad-solder level test includes ball shear [2, 3], ball pull [3] and pin pull [3,4], which are being drafted in a new IPC standard (IPC 9708). Those tests are used to test the adhesion of the pad to the solder and pad to the laminate as well as the strength of the bulk laminate. The comparison of those three test methods are listed in Table 1. The ball shear test is the most convenient to execute and it represents the stressing from thermal cycling in the field. However, the failure mode is not consistent as it may fail in the solder depending on the pad condition and test set-up.   The pin pull test[3] is performed by soldering a pin to the pad and can be done hot (up to 180C) or cold (at the room temperature).   This method is attractive because it can get very high percentage of failures of laminate cracking (>90%). The ball pull test is between the ball shear test and the pin pull test.   For a comparison study of the various laminate materials, all three types of tests may be useful. The challenge is to define the pass/failure criteria.

Table 1 Pad strength test comparison.

Test method	(a). Ball Shear	(b) Ball Pull	(c) Pin Pull
Specimen	Soldering ball	Soldering ball	Soldering Pin
Machine Setup	easy	medium	hard
Error from testing	medium	medium	low
Test execution cost	Low	Low	High
Pad cratering detect percentage	30~97% (Flextronics, [2]), 0~50% (Intel,[5])	0~50% (Intel, [5])	>90%(CISCO method, [3])
Simulate field stress	Preferable	Less preferable	Less preferable

(a)   (b)   (c)
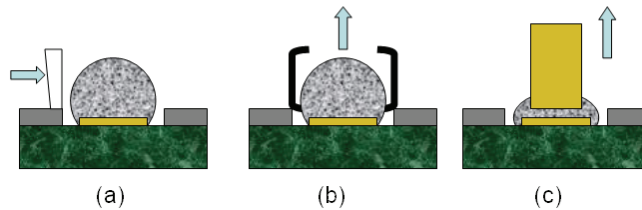
       The system level tests are non-standard tests and performed at the product level, which includes PCB, component, solder joints, and box build. The BGA pads could perform much differently under different loading conditions even if the PCB materials and design are the same.   The test method at this level is limited because of complexity. The test methods used most widely include cross sectioning, dye and pry after thermal cycle stressing, and/or drop and vibration tests. These tests are more representative of the field usage and hereby more realistic, but at the same time more complex.

Strength of FR4 and Modeling
       Flexural strength is mostly used in the evaluation of the PCB materials subject to a bending stress. According to IPC TM-650 2.4.4 [6], the bending strength is a maximum stress of the sample at the breaking point using Equation 1.

$$\sigma_b = \frac{3PL}{2wt^2}$$

(1)

where, σ_b is the flexural strength;
P is the bending force;
L is the length span of the sample;
w is the width; and
t is the board thickness.

The flexural strength for epoxy is usually above 75kpsi at room temperature for FR4 cured with either Dicy or phenolic novolac, as shown in Fig. 3 [7]. In Fig. 3, IS402, FR406 and ED130UV are standard FR4 materials used for tin-lead process while FR404, IS410 and FR408 are lead-free compliant materials using non-Dicy FR4. It clearly shows in Fig. 3 that these non-Dicy materials have a lower flexural strength at the room temperature.

However, the flexural strengths from both groups of materials are very close to each other over 100C.   As the flexural strength is highly dependent on the resin content (RC%) and the type of the filler, the flexural strength of phenolic novolac resin could be higher than that of a Dicy resin. For example, Phenolic1 has a flexural strength over 100kpsi [8].

How important is the flexural strength to pad cratering? Is the higher flexural strength better for pad cratering resistance? From the pin pull test results performed by Mudasir et al [3], there is no clear correlation between the flexural strength and pin pull force as shown in Fig. 4.   In Fig. 4, pad strength is represented by Average Pull Strength for pads built with various FR4 materials.   The flexural strength values are taken from the materials data sheet by individual suppliers [3].   The Decomposition Temperature is also plotted for reference.

There are possibly several reasons for the lack of correlation. One reason is that the flexural strength is a global performance of the whole section of the PCB (including the impact of reinforced fiber materials), while the pad strength by the pin pull test measures only a localized area. To depict the layer structure of the PCB, Fig. 5 shows a typical prepreg layer on the outer layers, which is composed of resin layers and fiber layer in-between. If we concentrate on the pad underneath, the FEA model can simplify the rest of the layers as a block composite model.   The loading and boundary structure are illustrated in Fig. 5b.   The yield point of epoxy is 60MPa at 25C[2] and the other materials properties are shown in Table 1.   The maximum stress and strain observed in the prepreg will increase with the bending force (P) or stress (σ_b) as shown in Fig. 6. It is shown that the strain at the prepreg layer is much higher than that at the core PCB layer regardless of the bending directions.   The strain increases significantly when the bending stress passes 300MPa.   As 500MPa is a value for the flexural strength for most FR4, the strain at the prepreg is >10% which is significant in this case. The strain at the PCB is about 3%. From this analysis, the prepreg will crack much sooner than the core PCB. From Fig. 6, it is also concluded that the strain at the prepreg layer is high if the prepreg layer is at the outer surface during the bending. This is important as deformation of the BGA corner pads during reflow soldering is most likely.   This is to be discussed further in this paper.
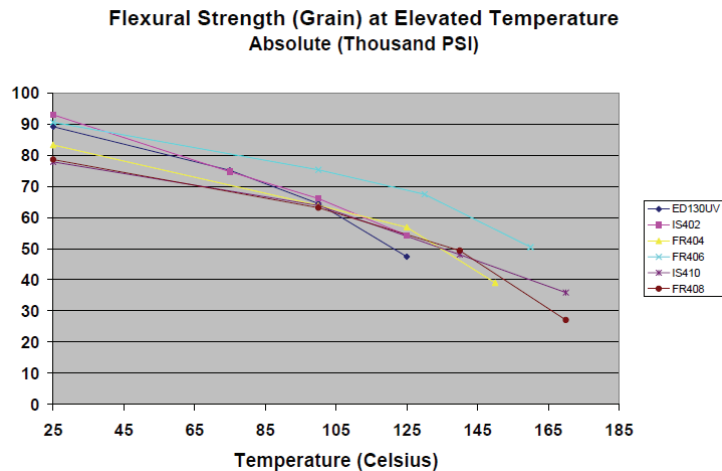

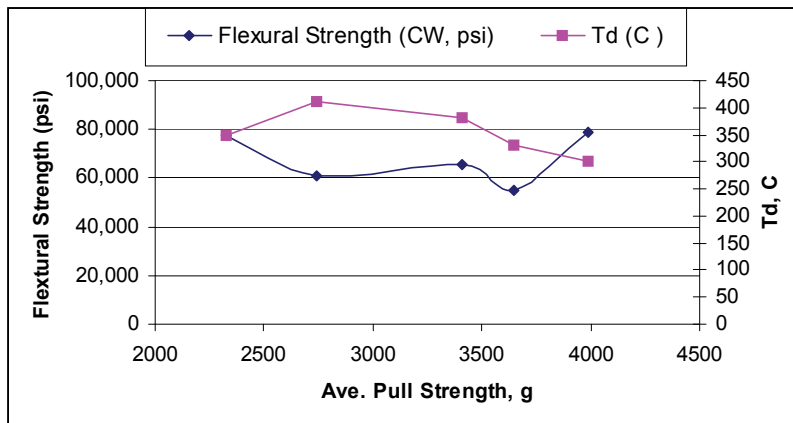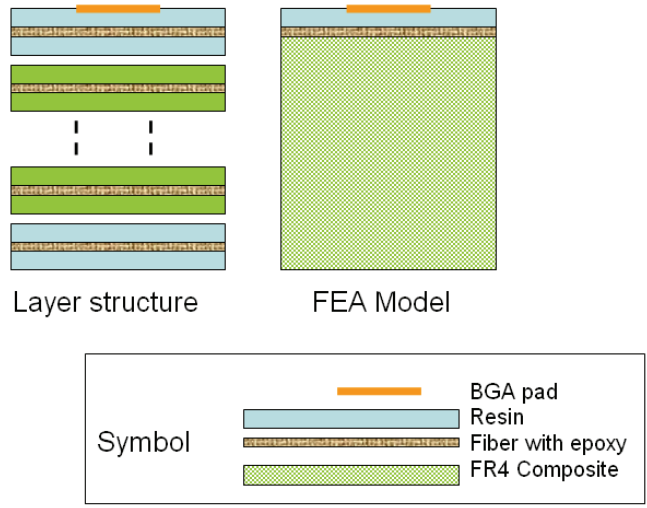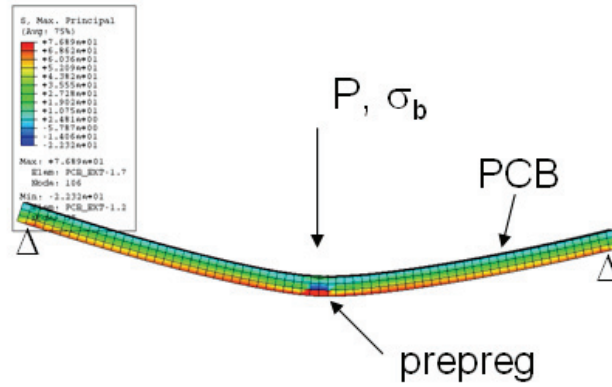Fig. 3 Flexural strength of FR4 laminate. (courtesy of Isola Group, [3])

Fig. 4 Flexural strength vs. pad pull force. (original data are from Madasir et al [2].)

Layer structure   FEA Model

Symbol		
		BGA pad
		Resin
		Fiber with epoxy
		FR4 Composite

(a)

(b)
Fig. 5 FEA model for flexural strength test. (a) schematic layer structure; (b) bending model.

Table 1. Material properties use in FEA.

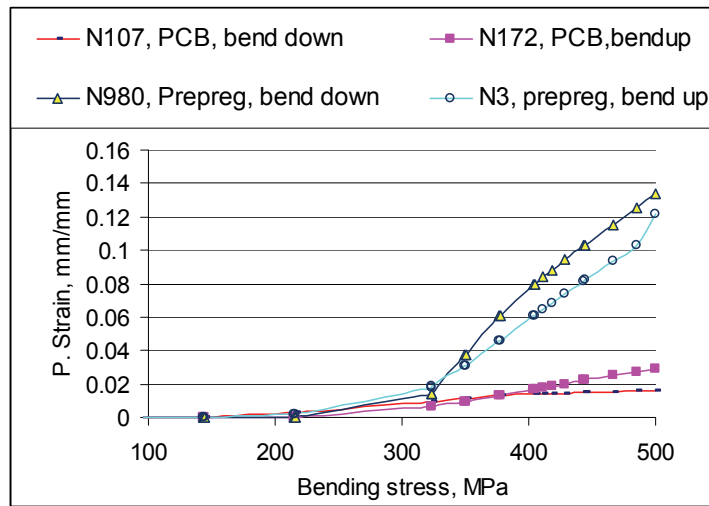| Material Layer	Type	Young's modulus,Mpa	Poisson' ratio	Yield Point, Mpa	CTE, ppm/C at 25C
PCB	FR4	25,000	0.18	60	16 (x,y)
BGA pad	Cu	128,000	0.29	NA	17
Solder	SAC	44,400	0.36	25.2	23
Prepreg	Epoxy	12,500	0.29	60	14 (x,y)
fiber	E-glass	150,000	0.11	NA	10 (x,y)

Fig. 6 Plastic strain vs. bending stress in the flexural test for PCB.

Pad Strength Test by Pin Pull
As discussed earlier, the pad may fail at the laminate using the pin pull test.   Interestingly, a trend is clear when plotting the pad strength by the pin pull test with the pad size as shown in Fig. 7, where the pin pull test data have been calibrated for Dicy and phenolic epoxy [3]. Both epoxy resins are high Tg materials.   As shown in Fig. 7a, the pin pull force increases with the pad size linearly. Dicy cured resin has a higher pull force than phenolic resin. When changing the pull force to the pull strength (defined as the pull force per pad area) and replotting as shown in Fig. 7b, the strength does not change significantly with the pad size but is not constant either. To summarize the results from Fig. 7a and 7b, the pin pull force is one dimensional parameter which is different from the pad strength, similar to the peel force as in the peel test [9].   Fig. 7c shows a comparison of the peel force vs. pin pull force. The peel force may be estimated using equation 2 with a typical peel strength of 9lb/in for Phenolic1 [9].

$$F_p = \sigma_L * 3.14 * d \tag{2}$$

where, F_p is the peel force at a pad size of d, and σ_L is the peel strength for laminate materials.

It is noted that the peel force is scaled at 5 times to be comparable to the pin pull force. It shows that the slope of both trend lines are close to each other. This also shows that the pin pull force is approximately 5 times as large as the peel force. In other words, the laminate may crack at a force approximately 5 times as large as the forces for copper delamination. That is, delamination should occur earlier than pad cratering. This could be a reason that more pad delamination is found for some field return units. However, this is in conflict with the pin pull test result for the fresh build! Two possibilities exist:
a) The peel force could be a minimum value which a copper clad has to meet.   The actual peel force is much bigger.
b) This could be a main reason: there is a size and shape effect when comparing round pads vs. a long strip. Usually the strip will peel off easier in a rectangular format rather than round shape which means the peel force by Equation 2 is conservative. This is worthy of further studies.

To summarize, the pin pull test may cover the peel test in the BGA pad area, which can include the integrity of a system which includes three elements:
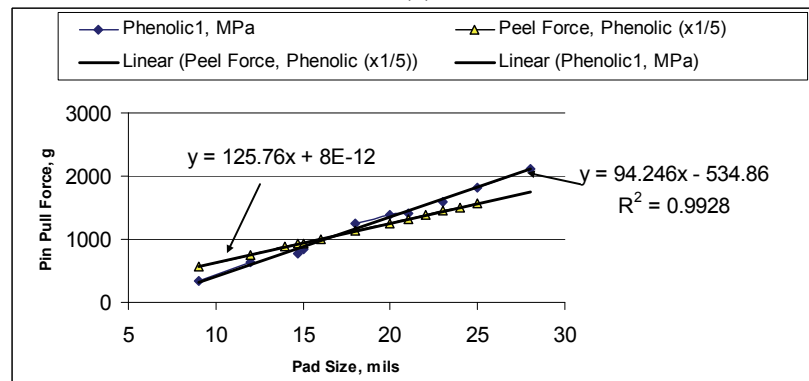a) pad;
b) prepreg;
c) reinforcement layer.

The pad strength will be determined by the adhesion of the interfaces between them as well as the strength of the prepreg. Both the adhesion and strength of prepreg will be affected by the thermal and mechanical stresses from reflow, board handling and field. This is to be discussed in the next section.
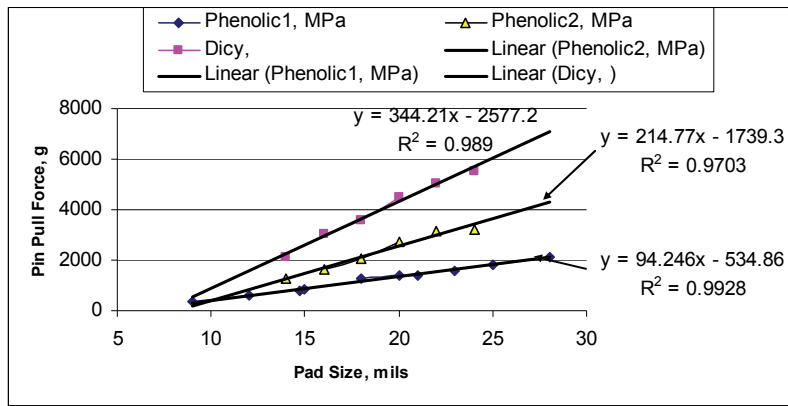
(a)
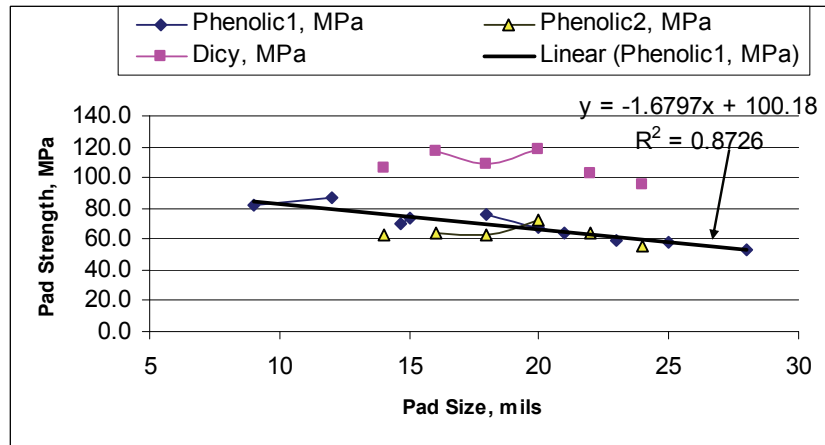
(b)

(c)

Fig. 7 Pad strength by Pin pull test for a typical Dicy and phenolic epoxy materials. (a) Pull force vs. pad size for different laminate materials. (b) Pad strength vs. pad size, (c) Comparison between pad pull force and peel force, using 9lb/in as the peel force . Date source: [3, 9].

Reflow Soldering Test

Reflow test is often used to simulate the stressing from the SMT process especially for lead-free where the reflow temperature can be as high as 260C. As a part of PCB qualification for lead-free, the PCB is usually required to pass 5~10 cycles of reflow.   Similar tests were used to stress the pad to determine the impact of the reflow on the pad strength. The results from pad strength test indicate that the impact of the reflow test is insignificant for bare PCB without component [3,7]. On the other hand, it does show some impact from the soldering if BGA components are present[1], because of the impact of the thermal stress induced from the thermal mismatch. There is no stress in the pad area if no component is mounted on the pad. The larger the BGA, the higher the thermal stress.

To illustrate the BGA impact on pad cratering, an FEA model has been created as shown in Fig. 8. Only a diagonal slice of BGA assembly is employed and the focus is to study the stress at the corner joint. The loading simulates reflow up to 217C where the solder starts to solidify and the thermal stress is initiated from that point and reaches the maximum at the room temperature. This is followed by a bending test which simulates the ICT or mechanical handling in the process. The bending uses a PCB strain up to 2000ue and the bending direction could be bending up or down as shown in Fig. 9. To study the impact of the solder mask, both a solder mask defined pad (SMD) and a non-solder mask defined (NSMD) pad are employed. The pad area for soldering is kept the same (0.5mm diameter). The SMD pad size is 0.6mm with a solder mask opening of 0.5mm. The BGA has a body size of 40x40mm. The results are shown in Fig. 10.

The dotted line in Fig. 9a depicts the deformation contour of the PCB after the reflow process. It is noted that the corner pad is a turning point for the PCB to change from concave in the area underneath the BGA to convex outside the BGA. This shape is important as it determines the impact of bending for the later processes. In Fig. 9, bending down will aggregate the deformation and create a larger stress at the corner pad as shown in Fig. 10. On the other hand, the bending does not cumulate the strain if the bending is upward. It is also shown from Fig. 10 that SMD design will help reduce the strain and stress at the prepreg layer significantly as compared to NSMD design. The arrows in Fig. 10 shows the aggregated strain from reflow soldering for the prepreg layer, which shows that the strain for the NSMD design is much higher than that for SMD. The strain at the prepreg is significant and at risk for the NSMD design even though the PCB strain is at 500ue in bending (according to IPC9704). That may explain why the prepreg may crack during reflow and mechanical handling even though the handling follows the specification. Further studies are underway to explore the structure and materials impact for various PCB and BGA.
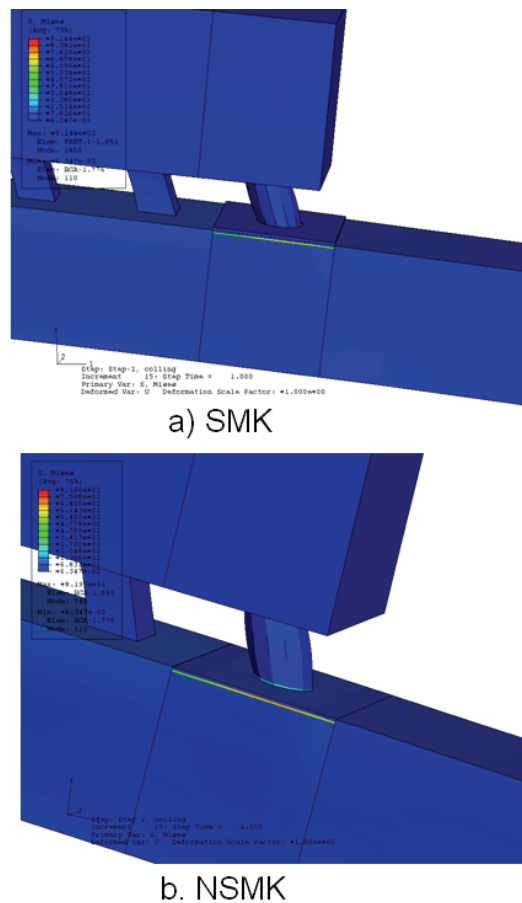

a) SMK

b. NSMK

Fig.8 Reflow and bending impact on the pad stresses for different solder mask design (SMD vs. NSMD).

a. After reflow

b. Bend down 1mm
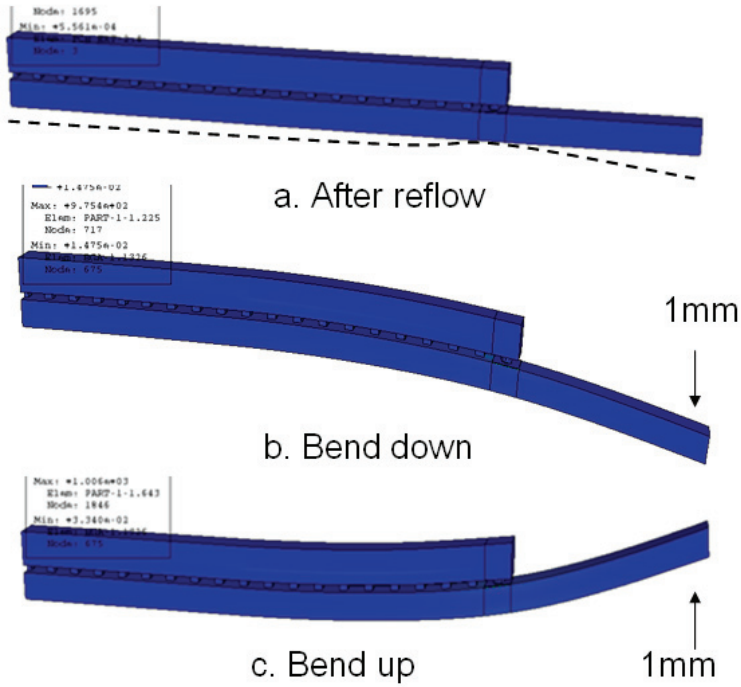
c. Bend up 1mm

Fig. 9 Deformation of BGA during reflow and bending test.
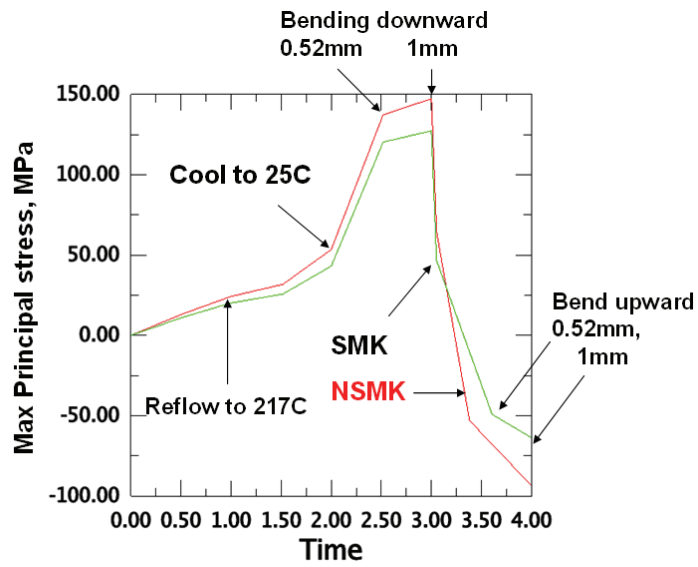

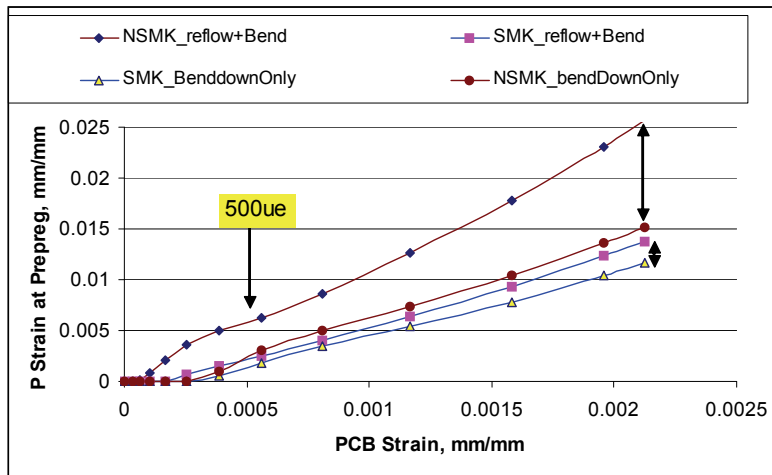**Fig. 10 Max. stress in prepreg layer (SMD vs. NSMD).**

Fig. 11 PCB strain vs. max. strain at the prepreg layer for two processes: (a) reflow plus bending and (b) bending only.

System Level PCB Qualification for Reflow and Handling

        To get a product without pad cratering, we have to ensure that no laminate cracking initiated during PCB assembly including reflow and handling.   That means that the PCB should be tested together with BGA components and fixtures such as heatsinks. Fig. 11 is a simplified process for screening out the pad cratering risks due to reflow and handling. The PCB starts with proper board handling and baking. The second step is a standard SMT process involving paste printing and followed by BGA mounting and multiple reflows. Bending test is then performed at 500~1000ue. The BGA is then removed following rework procedures. Steps 6 to 8 involve attaching solder balls and/or copper pins. Dye penetration is to ensure that all pre-cracks are recorded from pad strength test. Control samples may be used as reference.   To include the impact of the stress test and/or field application, accelerated stress tests using thermal cycling, moisture aging and mechanical shock may also be included.
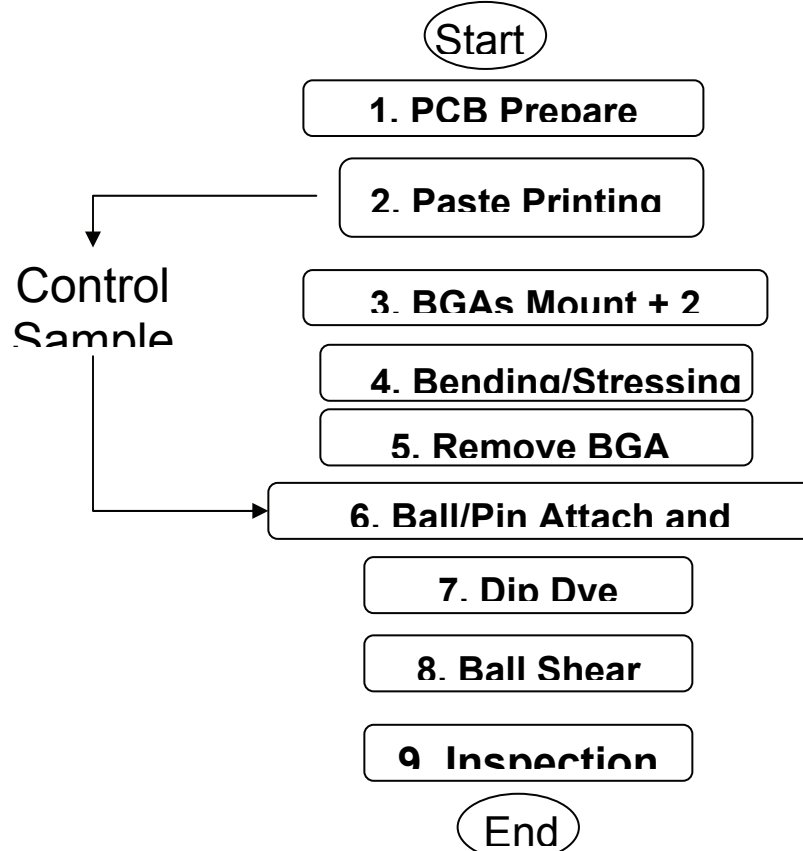

Fig. 11 Flowchart of a new PCB qualification method for pad cratering risk evaluation.

Summary
Pad cratering occurs from the cracking of the laminate and/or prepreg materials. Several tests can be used at the PCB materials level, board level, and system level. The flexural strength is not sensitive enough for capturing pad cratering because the prepreg layer normally fails earlier than the core PCB. Three types of board level testing on the pad strength can be used: ball shear, ball pull, and pin pull. Among them, the pin pull test may capture more pad cratering modes than ball shear and pull tests. The pin pull test is similar to the peel test for BGA pads and can be used as a good indicator of pad health. The prepreg may crack even if the PCB strain is controlled under 500ue. Solder mask defined pads are preferred in the prevention of pad cratering as it provides more contact area and hereby reduces the stress in the prepreg layer. A new system level PCB qualification process is suggested to mitigate the pad cratering risk. The qualification test uses actual PCBA and simulates multiple reflows and board handling as well as stresses in the field.

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