STUDY ON APPLICATION OF STRAIN MEASURING TECHNOLOGY IN BOARD LEVEL ASSEMBLY PROCESS

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ABSTRACT
The board level assembly technology which contains soldering and assembling is the key link in the manufacture of electronic products. The quality and reliability of board level assembly process directly affects the quality and reliability of the whole products. This has to consider the impact of the strain on the soldering and assembling process. With the high density package and assembly prevails, and the materials at the transformation of environmental protection laws and regulations, the strain-induced damages in board level assembly process are frequent.

It is well known that the excessive strain can result in various failure modes for different package types, surface finishes, or laminate materials. Such failures include solder joint cracking, trace damage, laminate related adhesive failure (pad lifting) or cohesive failure (pad **c**rater) and substrate cracking. Therefore, characterization of PCBA strain in worst-case is critical to the reliability assurance for electronic products. The application of strain gage test had been improved to be one favorable and effective method to discriminate the hazardous process.

Based on the conversion principle between strain and resistance change, strain gage test is a kind of effective measuring technology, which can be used in the fields such as theoretical verification, quality inspection and scientific research. However, the study on strain measurement for PCBAs in electronic industry has just started, and there are still many unsolved puzzles, whether about strain gage selection or about measurement methodology. To address these problems, this study conducted a deep analysis of the basic principle for strain gage test technology combining with strain-induced damage phenomena of PCBAs. Then the strain gage test was applied to PCBA reliability evaluation during a typical mechanical assembly process. And systematic analysis for some critical problems during this process was conducted, such as the strain gage selection technology, specific operation method and strain data analysis method.

Key words: strain measuring technology, board level assembly process, strain-induced damage

INTRODUCTION
The application of strain gage test for controlling the warpage of printed circuit board (PCB) had been improved to be one favorable and effective method to discriminate the hazardous process. However, along with the increasing of interconnect density and the embrittlement of halogen-free of PCB substrate, the probability of damage resulted from warpage also increased. Otherwise the thermal stress from multiple soldering process and mechanical stress form assembling and working bring the challenges to the component undoubtedly [1,2]. Recently, a great deal of PCB assembly manufacturers required to operate under the special strain level from the client or the component supplier. In this case, the study for the strain distribution on the PCB by means of strain gage methodology gets the wide attention more and more.

Characterization of the worst case for PCB assembly (PCBA) strain is critical due to the susceptibility of components to strain induced failures. Excessive strain can result in various failure modes for different types [3, 4], surface finishes, or laminate materials. Such failures include solder joint cracking, trace damage, laminate related adhesive failure (pad lifting) or cohesive failure (pad crater) and substrate cracking.

The strain gage test [5] allows the objective analysis of the strain and strain rate levels to which a surface mount component may be subjected during PCBA assembly, test and operation.

PCBA strain measurement includes application of strain gages to the printed circuit board near the specified components, followed by subjecting the instrumented board to various test, assembly, and handling operations. Steps which exceed strain limits are deemed excessive and re identified so that corrective actions can be made. The strain limits may come from the customer, component supplier or internal best known practices.

TEST METHOD
The typical PCBA strain gage test procedure includes the following four steps.

Step 1： Select strain gage sensor
A strain gage is a device whose electrical resistance varies in proportion to the amount of strain in the device. The IPC/JEDEC-9704 [6] guideline document recommends using three-element stacked rosette strain gages for PCB strain gage tests. A rosette strain gage (see Figure 1) consists of three independent strain gages stacked on top of each other. Unlike a wire strain gage, which can measure strain in only

one direction, a rosette strain gage measures the full state of strain on the surface of a part. In other words, it can measure not only the two extensional strains, e_x and e_y, but also the shear strain, g_{xy}, with respect to some given x-y axis system.

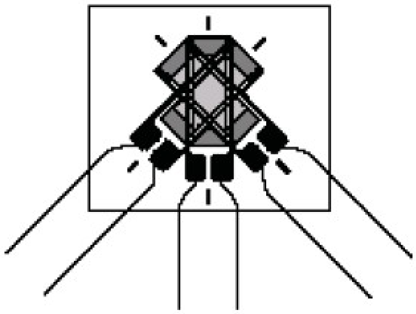


Figure 1: Three-Element Stacked Rosette Strain Gage

According to the IPC/JEDEC-9704 guideline, details of the recommended strain gage are as follows:

- Three-element stacked rectangular (0°/45°/90°) rosette strain gage
- 1.0 to 2.0 mm, 2 nominal, gage sensor size
- 120 or 350 W strain gages
- Lead wire attach pads located at or lead wires attached on one side of strain gage

Step 2： Prepare PCB for Test and Mounting Strain Gages

Typically, the test boards are not required to be electrically functional, but they must mechanically represent the latest design. The IPC/JEDEC-9704 guideline recommends that measure any BGA device with a package body size equal to or larger than 27 by 27 mm (see Figure 2). This includes selecting the location at which are going to mount the strain gages. If there is no space to mount a strain gage on the board, it might have to make space on the PCB by removing already mounted components on the test board.

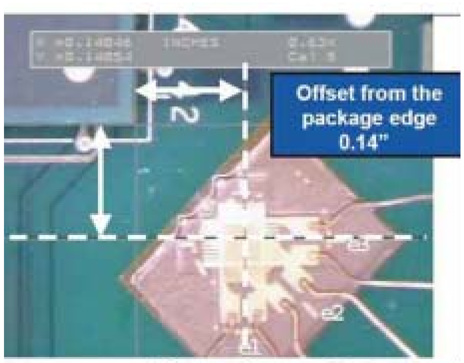


Figure 2: Recommended Gage Placement for BGA Components (IPC-9704)

Board preparation is a critical part of the instrumentation process. Proper board preparation helps ensure the proper bonding of strain gages; this, in turn, improves reading accuracy. It also should perform strain gage attachment in accordance with instructions the strain gage and adhesive suppliers provide. Note that strain gages require the use of specially formulated adhesive systems, and strain gage suppliers typically provide this information. It can find additional details about board preparation, strain gage attachment, and wire routing in the IPC/JEDEC-9704 guideline document.

Step 3: Measure Strain

After preparing the board and mounting the strain gages, the third step in PCB strain gage testing is connecting the sensors to data acquisition instrumentation and running the actual test. The length of the test may vary - it can typically run for 5 to 10 seconds while data is recorded. IPC/JEDEC-9704 recommends paying attention to the following parameters while running the test:

Scan frequency (sampling rate): the rate at which data is sampled in the units of number of samples per second (Hz). For PCB strain gage tests, a minimum scan frequency of 500 Hz is recommended, although typical scan frequencies range from 500 Hz to 2 kHz.

Sampling Resolution: refers to the number of bits of the analog-to-digital converter (ADC) in the data acquisition hardware. The higher the resolution, the smaller the input signal changes that can be detected and the more accurate the measurement carries. For PCB strain gage tests, a minimum sampling resolution of 12 to 16 bits is recommended.

Number of Channels: the number of available monitoring channels limits the number of measurements in one pass. At least 12 measurement channels are required to monitor four stacked rosettes mounted at all corners of a BGA chip, and at least three channels are required to measure one stacked rosette. While it can make multiple passes if there are insufficient channels, it must monitor all three gages in any stacked rosette at the same loading to avoid any strain calculation errors during analysis.

Simultaneous Sampling: it must monitor all three gages in a stacked rosette at the same loading and in the same pass. The data acquisition device dictates how can take these measurements. Two of the common techniques are multiplexing and simultaneous sampling. Data acquisition devices that offer multiplexing feature one ADC and sample channels sequentially. For PCB strain gage tests, sequential sampling may result in miscalculated strain values. Data acquisition devices with simultaneous sampling offer an individual ADC per channel, resulting in measurements taken on all channels at the exact same time and eliminating any errors in strain calculations.

Bridge Completion and Excitation Voltage each of the three individual gages in a stacked rosette is a quarter-bridge gage that requires bridge completion and excitation voltage – both of which are provided by the data acquisition instrumentation – to function. Bridge completion for a quarter-bridge strain gage sensor includes providing three of the four arms of a

Wheatstone bridge (see Figure 3), where the gage acts as the fourth arm.

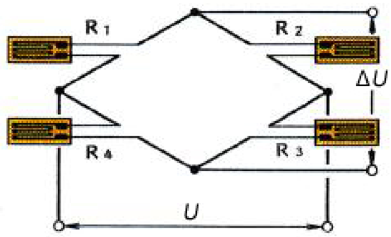


Figure 3: Wheatstone Bridges

Step 4: Analyze and Report Data
Once it have acquired the raw strain data, it can begin the last step of the PCB strain gage test – analyzing this data to calculate resultant stresses (maximum and minimum) induced on the board during the test. We can complete this analysis online during the test or offline after the test has finished and have collected all of the data.

Analysis details vary with the particular strain limit criteria we are using. Many strain limit criteria may require obtaining strain rates or principal strain calculations using Mohr's circle equations. According to the IPC-9704 guideline, at a minimum, it should provide the peak values of the principal or axial strain (maximum and minimum) for each step monitored.

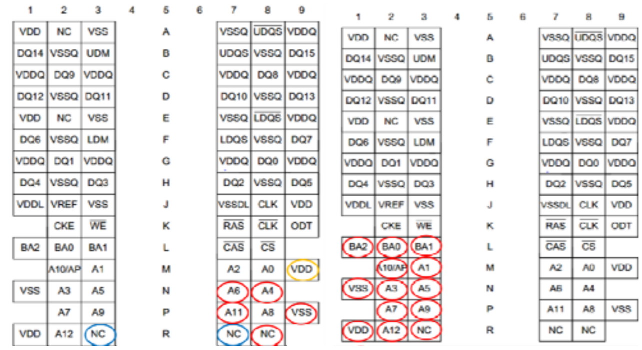
A common way to report data is with a strain versus strain-rate chart, where the y-axis represents maximum allowable principal strain and the x-axis represents strain rate. Strain rate is the change in the absolute value of strain between consecutive readings.

APPLICATION OF STRAIN GAGE TEST IN PCBA MANUFACTURING PROCESS

A typical case of strain damage evaluation for PCBA assembly process was analyzed as follows, focusing on the application of the strain gage technology as well as on the basic thinking about solving such problems.

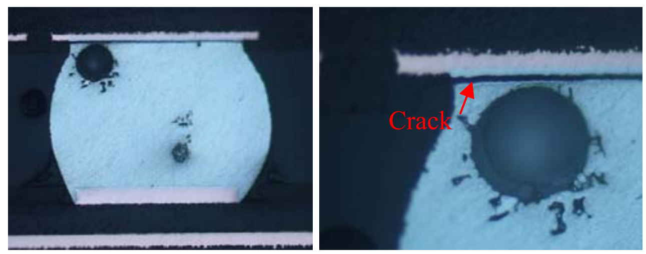
Testing Samples and Background
The failure sample board was designed for daughter-mother board structure. The daughter board which made-up design for the four sub-boards layout, reflowed and then mounted on the motherboard by hand soldering. The failure BGA located at the edge of the daughter board.

The cross section analysis showed that cracks were found in failure BGA solder joints. The failure solder joints matrix map was detailed in Figure 4. The principal crack mode was the crack between solder ball and BGA pad. Pad crater was detected in few solder joints. All the cracks occurred in BGA corner position where the stress was more centralized. The representative cross section views were shown in Figure.5.

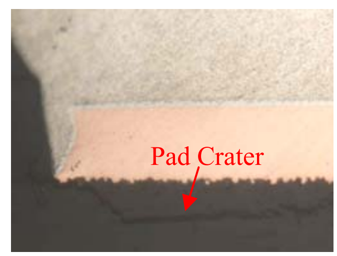


(a) Top Side (b) Bottom Side

Figure 4: Matrix Map of BGA Failure Solder Joints



(a) Cracking Between Solder Ball and BGA Pad



(b) Pad Crater

Figure 5: Representative Section Views of Cracking Solder Joint

Furthermore, the SEM inspection results showed that the cracking was between intermetallic compound (IMC) and nickel layer of BGA pad. The IMC layer either in BGA component side or in PCB pad side was uniform and continuous, with moderate thickness which directed the soldering process was desirable. The representative SEM views were shown in Figure 6. In addition, BGA package was found no evidence of significant deformation, and the height of BGA solder balls was uniform. It can exclude the influencing factors resulted from soldering thermal stress.

Therefore, it has reason to suspect that the stress came from the assembly mechanical stresses. The typical high-risk stress step comprises V-cut separation, shield, covered, tighten, split cover and so on. The above processes need to be through the strain measuring technology one by one investigation and analysis [7].

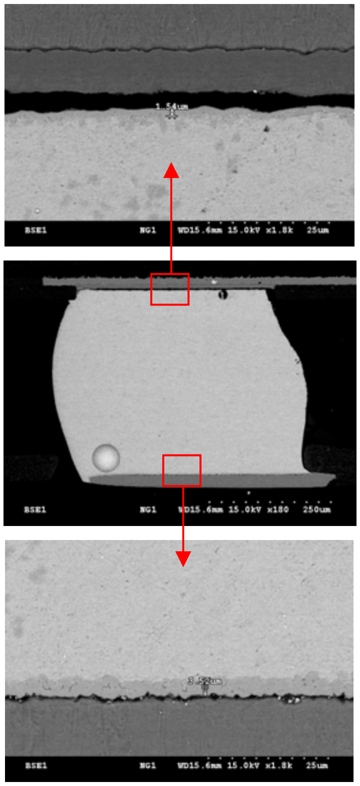


Figure 6: Representative SEM Views of Cracking Solder Joint

Testing Procedures

(1) Strain gage selection

Considering the character of the PCBA samples in this strain gage testing case, the information of the strain gages selected is listed as follows: gage type (three elements stacked rectangular (0°/45°/90°) rosette strain gage), dimension (5mm*5mm), gage resistance (350 Ω).

(2) Strain gage attachment

Quarter-bridge connection was applied for this test. The gage placement is with the gage substrate edge no more than 1.0mm away from each end of the component, aligned along the component length, as shown in Figure 7.

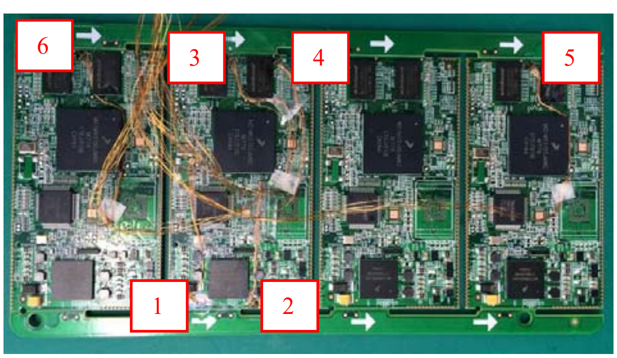


Figure 7: Gages' Placement

(3) Strain measurement

For the typical mechanical assembly process (thread locking process), the scan frequency was chosen as 500Hz. The excitation voltage was chosen as 2V for the PCB material. Three monitoring channels and six monitoring channels were used in one pass for case 1 and case 2, respectively.

(4) Data analysis

Data analysis is the last step for strain measurement. Depending on the criteria, the peak values (maximum and minimum) of the principal or diagonal strain should be given for each step monitored. The maximum and minimum principal strains can be obtained by Strain Mohr circle analytical method, and the computation formula is as follows.

$$\left(\varepsilon_{max},\ \varepsilon_{min}\right) = \frac{\varepsilon_{0^\circ}+\varepsilon_{90^\circ}}{2} \pm \frac{\sqrt{2}}{2}\cdot\sqrt{(\varepsilon_{0^\circ}-\varepsilon_{45^\circ})^2+(\varepsilon_{45^\circ}-\varepsilon_{90^\circ})^2} \qquad (1)$$

After the data analysis step, a comprehensive analysis and risk assessment should be conducted for the PCBA samples, in order to propose the corresponding improvement measures.

Results and Suggestion

According to the above measurement steps, after preparing PCBA samples and connecting the strain gages to the data acquisition instrument, the high-risk steps were conducted for the PCBA samples one by one and the strain-time data was obtained for the testing points, respectively.

Depending on the second strength theory, the maximum principal strains were calculated by Strain Mohr circle analytical method (see Eq. (1)). Table 1 detailed the specific data analysis results for the different steps. The variation of maximum principal strain with time of V-cut separation were shown in Figure 8.

The test results indicated that V-cut separation was the highest risk process for strain-induced damage. The maximum strain value of V-cut separation (above 6000μE) was even more than 10 times the industry standard (600μE). Obviously, it is necessary to change the board separation method to eliminate the influence of the over stress.

Table 1: Strain Gage Test Results

Step	Max. Strain Value (μE)					
	1	2	3	4	5	6
V-cut Separation	6507	362	3555	1602	6181	5242
Shield	-	-	115	94	-	-
Cover	-	-	190	234	-	-
Tighten	-	-	156	35	-	-
Split Cover	-	-	152	108	-	-
Note	"-": strain effect can be ignored.					

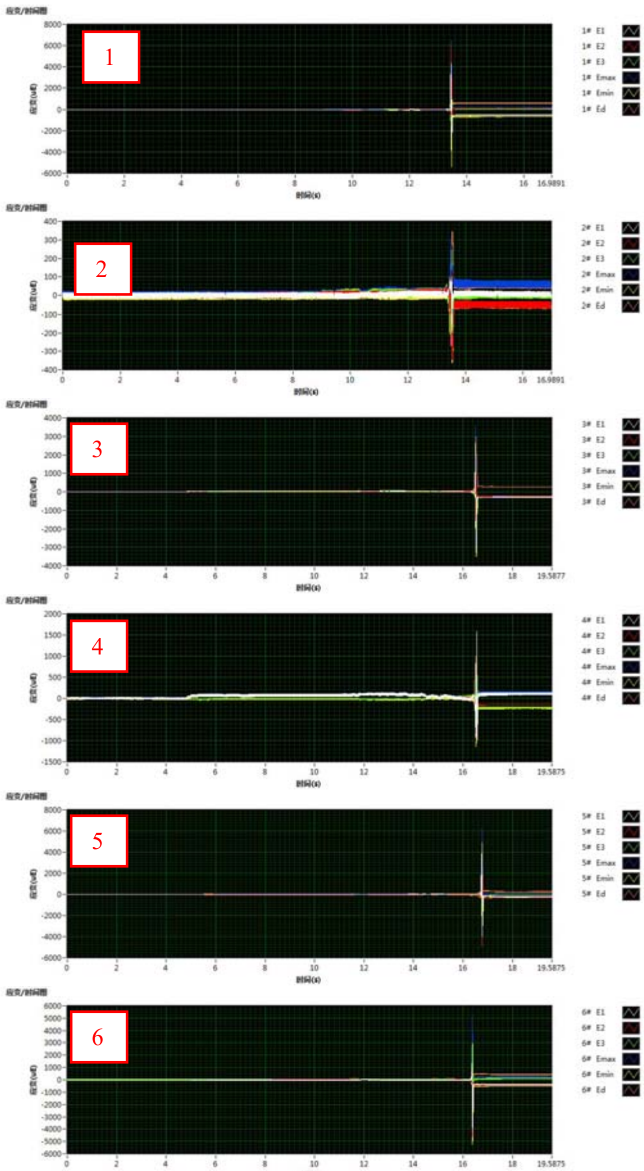


Figure 8: Variation of Maximum Principal Strain with Time

Modify the PCB design from the V-cut slot to stamp hole, as shown in Figure 9. Then prepared the sample and connected the strain gage to the data acquisition instrument, the strain gage test started with board separation process. The variation of maximum principal strain with time was shown in Figure 10. The result showed that the maximum strain reduced to about 700µE significantly.

Figure 9: Stamp Hole Design

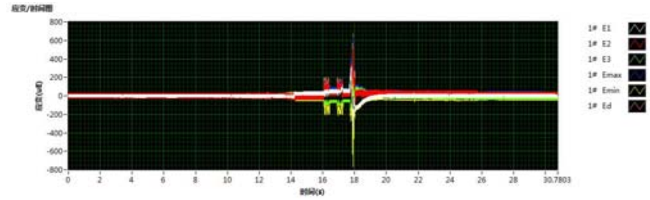


Figure 10: Variation of Maximum Principal Strain with Time (Stamp Hole Separation)

The use of machinery board separation (see Figure 11) to place manual board separation method, the stain-induced damage further declined. The variation of strain with time was shown in Figure 12.

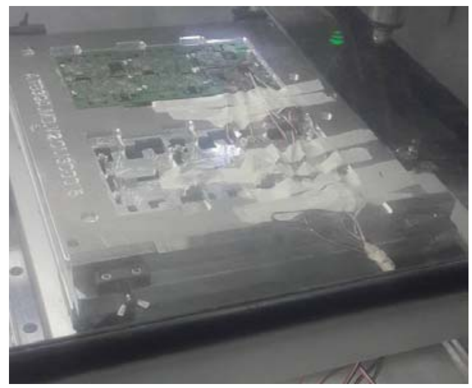


Figure 11: Machinery Separation

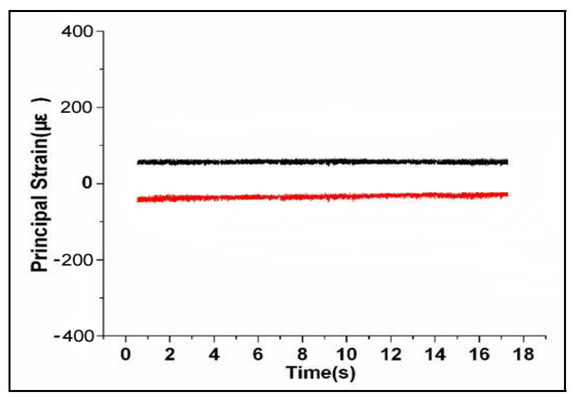


Figure 12: Variation of Maximum Principal Strain with Time (Machinery Separation)

Obviously, by the stain measurement technology, the root cause for solder joint cracking failure was found, the high – risk process was identified and corrected based on the failure cause and then was validated effectively with the aid of strain gage test. Thus the quality risk was avoided, and the products' reliability was guaranteed.

CONCLUSION

PCBAs and components deformation control using strain gage measurement is proven beneficial to the electronic assembly industry, which can be used as a method to identify and improve manufacturing operations that may pose a high risk for interconnect damage.

This article studied on the application of strain measuring technology in PCBA reliability evaluation, such as the strain gage selection technology for PCBA, specific operation method of strain gage tests during PCBA assembly process and strain data analysis method. Accordingly, electronic process related technical personnel can quickly and reliably establish related evaluation scheme, and continue to identify and control the risky PCBA manufacturing process.

The study on strain measurement for lead-free PCBAs in electronic industry has just started and there are still many unsolved puzzles. Facing to this new and challenging research field, there are many more to explore for PCBA strain/stress damage mechanism and evaluation method.

ACKNOWLEDGEMENTS
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