Research on Thermal Fatigue Life Prediction Technology of PoP Laminated BGA Products

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Abstract. In this paper, a fast prediction method for thermal fatigue life of PoP laminated BGA Product was proposed. Firstly, the stress and strain of the solder joints of each layer of the laminated device in thermal fatigue test was determined by finite element simulation method. According to the research idea of relative stress and strain, the solder joints were divided into sensitive solder joints and reliable solder joints. Secondly, sensitive solder joint were connected with PCB traces through the internal pads, bonding wires, TSVs and reliable solder joints to form a daisy chain. Through real-time dynamic monitoring of the resistance change of the daisy chain in thermal fatigue test to judge whether the solder joints fail, and record the occurrence time of the first failure solder joint. Finally, the thermal fatigue life of the product was estimated by the Norris-Landzberg formula.

1. Introduction
With the light, thin, small and functional diversification of electronic products, ball grid array package (BGA) has become the most advanced packaging technology in integrated circuits[1-3]. Products based on BGA packaging technology have been fully penetrated into all sectors of the national economy. The failure of BGA packaging products will cause huge economic losses in various field of our country. According to statistics, more than 50% of the failures of BGA products are caused by welding assembly failure, and field failure studies show that 60% of the failure mechanisms can be attributed to thermal fatigue damage. How to calculate and analyze the residual stress in different solder joints of BGA products, so as to accurately predict the service life of solder joints, is one of the current research hotspots[1-3].

Package on package (PoP) is an innovative result of packaging industry. The vertical integration of two independent BGA products can significantly increase the system packaging density. It has many advantages such as convenient combination, flexible design and low signal delay[1-3]. Compared with single-layer BGA products, the research on thermal fatigue life of PoP laminated BGA products is almost blank. Although the process nature of PoP packaging products still belongs to surface mount technology (SMT), due to the more complex effects of temperature residual stress, warpage deformation and greater probability of solder ball defects, the relevant research results of single-layer BGA products cannot solve the technical problem of service fatigue life of PoP laminated BGA products[4].

In order to solve the technical problem of thermal fatigue life of PoP laminated BGA products, a 3D structure of solder joint reliability monitoring daisy chain structure is proposed, and a real-time online monitoring system for solder joint thermal fatigue life is designed. By dynamically monitoring the...
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resistance of each link of daisy chain, the failure solder joints can be quickly found, and the failure time can be recorded timely, which is simple and efficient[5].

2. Analysis of research methods for thermal fatigue life

The research on the reliability of SMT products usually focuses on two aspects, namely, the reliability of electronic components and the reliability of solder joints. As the solder joints of SMT products are the weakest link in the entire product, the failure of any solder joint may lead to the failure of the product. Therefore, the research on the reliability of products such as BGA products mainly focuses on the reliability of solder joints, especially the thermal fatigue life of solder joints.

According to different research objects, the research methods for thermal fatigue life of solder joints of BGA products can be divided into three categories[4][5][8]. The first one is to study the packaging system, which includes devices, solder joints and mounting substrate. This kind of analysis method usually uses simulation method to apply temperature cycling load on the packaging system to simulate its service state. Because it is practical to model a large number of solder joints with different sizes, the system modeling is usually simplified, or the mesh is simplified. In addition, the simulation analysis method cannot fully consider the influence of product assembly process, residual stress, device size and the location distribution of solder joints in the assembly process will affect fatigue life of the solder joint, so such modeling analysis cannot reflect the real situation of solder joint fatigue. The second category is to conduct research on the device, that is, to carry out temperature cycling test on device and auxiliary other means such as solder ball shear test for the device containing solder ball. This kind of method also does not consider the influence of product assembly process. The third type is to conduct research on the pure solder joint, which needs to simulate the solder joint sample, so the analysis results are not representative. Therefore, the current research methods on the thermal fatigue life of BGA products are more or less defective, and the related research on the thermal fatigue life of the solder joint of PoP laminated BGA products is even less. To sum up, the optimal method to study the thermal fatigue life of BGA solder joints is to apply physical thermal stress cyclic load to the research object of packaging system level.

The results show that the thermal fatigue damage of solder joints is mainly caused by the cyclic plastic strain of solder joints[6-8]. Based on the plastic strain theory, Coffin and Manson proposed and improved the prediction method based on the experimental data, and established the Coffin-Manson relationship between the load cycle and the plastic strain amplitude when fatigue failure occurs. However, the influence of time and temperature on life of the solder joint is ignored in this model. In order to overcome the above shortcomings, the EngelMaier-Wild model and the Norris-Landzberg model improved based on the Coffin-Manson formula are currently widely used. The EngelMaier-Wild model mainly considers the relative displacement between BGA product and the mounting substrate due to different coefficient of thermal expansion (CTE), which is suitable for the case where the shear force is the principle stress of solder joints. The model is mainly based on the finite element analysis, assuming that the assembly process is in an ideal state, without considering the effect of assembly process on the thermal fatigue life of solder joints. Therefore, this method can be used to quickly evaluate the thermal fatigue life of solder joints in the early stage of design, and judge whether the designed products meet the system-level working requirements. The Norris-Landzberg model is mainly based on the accelerated test results, combined with the service conditions to calculate the thermal fatigue life of solder joints, so this model is in line with the research idea of “apply physical thermal stress cyclic load to the research object of packaging system level”.

The Norris-Landzberg formula is a thermal fatigue life model based on physical temperature cycling test. Assuming that the plastic strain range is linearly proportional to the temperature range, the actual thermal fatigue life is calculated by using the maximum temperature, cycle frequency and other parameters of accelerated test and practical application conditions. The details are as follow.

\[ N_f = N_t \times A.F \]  

(1)

\( N_f \) is the predicted actual thermal fatigue life of solder joints, \( N_t \) is the number of cycles of the accelerated test, and \( A.F \) is the acceleration factor.
\[ AF = \frac{f_f}{f_f^m} \times \left[ \frac{\Delta T_f}{\Delta T_f} \right]^{-n} \times \exp \left[ \frac{H}{K} \left( \frac{1}{T_{max,f}} - \frac{1}{T_{max,t}} \right) \right] \] (2)

\( H \) is the activation energy of solder, \( \Delta T_f \) is the application temperature range of product service process, \( \Delta T_f \) is the test temperature range, \( K \) is Boltzmann constant, \( f_f \) is the temperature cycling frequency of product service process, \( f_f \) is the cycle frequency of physical simulation test. \( T_{max,f} \) is the highest temperature (unit: K) during service process, and \( T_{max,t} \) is the highest temperature of physical simulation test.

3. Design of Daisy Chain for Thermal Fatigue Life Monitoring of PoP Laminated BGA Products

3.1 Analysis of general monitoring methods
The thermal fatigue failure of BGA solder joints usually results in cracks or micro cracks, which are characterized by electrical connection open circuit or increased resistance[8][9]. In general, the life monitoring method of thermal fatigue life is to carry out temperature cycle test on the product to be examined, take out the product after reaching the predetermined cycle number, and determine whether the product is abnormal through auxiliary means such as electrical test. The result of electrical performance test determines whether to carry out further temperature cycling test or failure analysis used to determine whether it is solder joint failure. This kind of method can be called "interruption monitoring method". If the electrical characteristics of the product are abnormal, non-destructive inspections, such as visual inspection and X-ray inspection, are usually carried out first. Visual inspection can only detect the solder joints at the edge of the device, but not the solder joints hidden at the bottom of the device and the defects inside the solder joints. X-ray inspection uses X-ray projection characteristics to further detect the failure solder joints hidden at the bottom of the device, but it is likely that the defects with slight deformation but also affect the reliability of the product cannot be inspected. Further detections are destructive detection techniques, including dye penetration, sample preparation grinding, scanning electron microscope (SEM) observation and other analysis means, which can usually identify most of the solder failure joints, but destructive detection generally requires a large number of sample preparations, and the analysis process is expensive and time-consuming. As an organic whole, the thermal fatigue life of BGA products is marked by the failure of the first solder joint. Due to the limitations of the research methods, the “interruption monitoring method” usually cannot accurately located the first failed solder joint. In addition, the micro cracks of some failed solder joints increase under high temperature stress, and recover after unloading high temperature stress. Because the “interruption monitoring method” can only carry out static analysis of products, it cannot solve this problem.

Daisy chain is another important means to monitor the thermal fatigue life of BGA products. The internal pads of BGA products are connected by bonding wires, and then the external pads are connected by the printed circuit board (PCB) to form a network structure. The reliability of package welding is studied by monitoring the change of resistance value of the daisy chain. Because the solder joint is the weak link of the entire daisy chain, when the resistance value changes beyond a certain range, it can prove that the solder joint has quality problems. Daisy chain method can overcome the disadvantages of the “interrupt monitoring method”. However, at present, the daisy chain method only aims at the products with single-layer packaging structure, so this method cannot be directly applied to the PoP laminated BGA products in this paper.

3.2 Simulation and analysis of sensitive solder joints of PoP laminated BGA products
Due to the difference of CTE between the BGA product and the mounting substrate, the thermal deformation of the two is different when the temperature changes, resulting in stress. The figure below is the schematic diagram of a certain type of PoP laminated BGA product after assembly.
The vertical signal interconnection is realized by through silicon via (TSV). The TSV technology is relatively mature, and its reliability is much higher than that of BGA solder joint under the same stress[10-11]. The top device is welded and assembled with the bottom device through the top solder ball, and the assembled product is assembled to the mounting substrate through the solder ball of the bottom device. The material is shown in the table below.

| Structural name | material | Young modulus (GPa) | Poisson Ratio | CTE (ppm) |
|-----------------|----------|---------------------|---------------|-----------|
| device          | Si       | 129                 | 0.21          | 3.5       |
| Solder ball     | 63Sn37Pb | 43                  | 0.36          | 25.4      |
| pad             | Cu       | 58                  | 0.30          | 17.7      |
| Mounting substrate | FR4     | 7.0                 | 0.23          | 15.8      |

Through the finite element simulation method, the stress of the product shown in Fig.1 was analyzed under the condition of temperature cycling. The elastic-plastic model is used for the solder balls and pads, and the shell model is used for the mounting substrate. The results with the thermal load condition -55℃ is shown in Fig.2, where Fig.2 (a) is the product stress distribution diagram, and Fig.2 (b) is the diagram of stress distribution of the bottom solder balls.

![Figure 1. The diagram of assembly product.](image)

![Figure 2. Stress distribution diagram.](image)

Due to the different CTE of materials, the deformation of the assembled products will produce stress shown in Fig.2 during the temperature change process, and the edge stress of both the top layer device and the bottom layer device is larger than that of the middle region. Because the top layer device and the bottom layer device are made of silicon, the relative deformation between the top layer device and the bottom layer device due to CTE difference is less than the relative deformation between the bottom layer device and the mounting substrate, so this paper takes the bottom layer device as an example to
analyze. The device is a 20mm square. For the solder ball distribution surface of the bottom layer device, the coordinate system is established with its geometric center as the origin. For the interface with y=0mm, the result of stress-strain analysis is shown in the figure below.

![Figure 3](image1.png)

**Figure 3.** Division of sensitive solder joint and reliable solder joint.

Because the thermal fatigue life of BGA products is marked by the failure of the first solder joint, this paper adopts the research idea of relative stress, and the failure probability of high stress solder joint is greater than that of low stress solder joint. Assuming that the highest stress in the solder joints is $\sigma$, the solder joints with stress between $\sigma$ and $\sigma/N(N \geq 2)$ are considered as suspicious solder joints, that is, sensitive solder joints, and the solder joints with stress less than $\sigma/N$ are considered as reliable solder joints. If the sensitive solder joints are reliable during the temperature cycling test, the whole product is considered to be reliable in the application environment. In this paper, $N=2$ is chosen. Meanwhile, in order to facilitate the research and improve the reliability margin, the sensitive region is expanded and simplified to a rectangular ring as shown in Fig.3(c), whose length is 1/4 of the corresponding side length. Therefore, the research on thermal fatigue life of PoP laminated BGA products focuses on the sensitive solder joints in the rectangular ring.

### 3.3 Daisy chain design of PoP laminated BGA product

As the failure of any solder joint will lead to the failure of the product, the thermal fatigue life of PoP laminated BGA products must be evaluated for all solder joints.

According to the research content of *Chapter B*, this paper only need to consider sensitive solder joints, which can significantly reduce the workload, save monitoring resources and improve work efficiency. Because the edge solder joints of two stacked devices are sensitive solder joints and the middle region is reliable solder joints, the sensitive solder joints of the top layer device can be connected with the PCB lines through the internal pads of both the top layer device and the bottom layer device, bonding wires and reliable solder joints of both top solder joints and bottom solder joints to form a daisy chain network. Since the PoP laminated BGA product is connected with the PCB lines through the bottom solder balls, the final lead-out ends of the daisy chain are reliable solder joints in the middle region of the bottom device. This type of daisy chain is defined as the first type of daisy chain in this paper. Compared with the sensitive solder joints of the top layer device, the daisy chain of the bottom layer device can be completed only through the internal pads of the bottom layer device, bonding wires and sensitive solder joints of the bottom layer device, which is defined as the second type of daisy chain in this paper. The schematic diagram of the first type of daisy chain and the second type of daisy chain is shown in Fig.4.
3.4 Design of on-line monitoring system

In order to accurately monitor the thermal fatigue life of PoP laminated BGA products, an on-line monitoring system for the thermal fatigue life of solder joints is designed as shown in Fig.5, in which the high-temperature connector and high-temperature cable can withstand the high temperature above 150°C. The scheme can also be extended to other environmental reliability test, such as vibration reliability.

![Figure 5. On-line monitoring system.](image)

Figure 6 is the schematic diagram of daisy chain resistance on-line monitoring. Through dynamic monitoring the resistance change of the daisy chain in real time, the solder joints that failed in the thermal fatigue test can be quickly found. The change of resistance value of R1, R2 and Rn in local daisy chain can quickly locate the failure solder joint, provide corresponding information for the possible failure analysis test and assist product design improvement. Designers can carry out overall or partial combination daisy chain resistance monitoring such as R in Fig.6 as required, and achieve the purpose of assessing the reliability of regional solder joints. The reasonable use of the partial combination daisy chain resistance can also reduce the monitoring resources and the cost.

![Figure 6. On-line monitoring system.](image)

The position of the failed solder joint and the time of the first failure solder joint can be quickly located by the on-line monitoring system of thermal fatigue life. Then, according to the formula Norris-Landzberg and the actual service environment of the product, the thermal fatigue life can be calculated quickly.
4. Conclusion
This article extends the traditional daisy chain research method of solder joints reliability of single-layer BGA products to PoP laminated BGA package products. Through finite element simulation, the solder joints of PoP laminated BGA products are divided into sensitive solder joints and reliable solder joints, and the reliability of the products is studied by establishing a daisy chain network. Although this paper focuses on double-layer BGA devices, this method can also be applied to three or more layers of BGA package or other interconnected stack devices. Practice shows that this method is simple and efficient, and can quickly obtain the thermal fatigue life of laminated BGA products.

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