Wave Soldering Coupled Thermal-mechanical Simulation of Multi-layer Ceramic Capacitors

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Abstract. In this paper, the thermal-mechanical coupling finite element analysis of MLCC wave soldering with heat conduction and heat convection is calculated, and the steady-state temperature field and transient temperature field as well as the stress distribution of MLCC are obtained. Using the finite element analysis method of indirect thermal-mechanical coupling, the stress analysis is carried out with the temperature field as the boundary condition, and the thermal-structural coupling model is established. By analyzing the thermal stress of MLCC, the weak parts sensitive to thermal stress are determined, which provides a useful reference for solving the reliability problem of MLCC wave soldering.

Keywords: Wave Soldering, Thermal-mechanical Coupling, Thermal Stress, Weak Parts.

1. Introduction

Multi-layer Ceramic capacitors (MLCC) are characterized by small size, high capacitance and excellent electrical properties. They are widely used in circuits. MLCC is adopted to replace the traditional tantalum electrolytic capacitor, which not only reduces the PCB board area, but also greatly improves the product performance [1]. However, the reliability of MLCC in wave soldering is a long-standing problem. The rise and fall of temperature during welding and the thermal expansion difference between MLCC components can cause thermal stress [2]. Therefore, it is particularly important to determine the stress distribution caused by thermal shock and thermal cycle. In this paper, finite element analysis is used to evaluate the thermal stress and find out the relevant weak parts, so as to provide technical support for the reliability analysis of MLCC.
2. Steady-state thermal stress analysis

2.1. Modeling of the MLCC
The high temperature generated by MLCC during wave soldering will cause thermal stress to the components, and to influence the parameters and the Reliability of MLCC [3]. MLCC, as a key component in the circuit board, the load is complex and prone to failure [4,5]. The overall modeling of MLCC adopts the solid model, and the grid adopts the solid unit and divides the hexahedral mesh, and encrypts the key contact area. The geometric and finite element models of MLCC are shown in Fig. 1.

![Fig. 1 MLCC's geometric models (a) and (b), finite element models (c).](image)

2.2. Simulation results of the MLCC
In the process of MLCC wave soldering, the bottom of MLCC is in contact with the solder, resulting in a temperature of 245 °C, while the rest of the surface is in contact with air, generating thermal convection. Since the internal components of MLCC are solid configurations, the internal heat transfer is realized by heat conduction. Therefore, the method of steady-state thermal stress analysis was
adopted to conduct thermal analysis and mechanical analysis on the high temperature of MLCC welding. The steady-state temperature field is solved by the thermal analysis entity unit SOLID70, and the distribution of temperature field is shown in Fig. 2(a). According to the results of the temperature field, the thermal stress is calculated by converting the thermal element into the corresponding structural element. The structural stress cloud diagram is shown in Fig. 2(b).

(a) Distribution of steady-state temperature

(b) Distribution of thermal stress

Fig. 2. Distribution of temperature and stress for MLCC
3. Transient thermal stress analysis
During MLCC peak welding, the time required for solder consolidation to cool to room temperature (25°C) is 200s [6]. After MLCC welding, when it enters an external storage environment with a low temperature (such as room temperature of 25°C), temperature redistribution will be formed between MLCC and the external environment through convection and heat conduction between components on MLCC. The process is a transient thermodynamic problem, and eventually thermal equilibrium and temperature equilibrium will be reached as time goes by. The whole dynamic process is solved by transient thermal stress analysis.

3.1. Thermal analysis
The temperature distribution during the consolidation period of MLCC solder extraction (time gradient 10s, 20s, 80s, 200s) is shown in Fig. 3.
(b) Temperature field at 20s

(c) Temperature field at 80s
3.2. Mechanical analysis

The uneven temperature distribution will lead to thermal stress of components. MLCC is placed in an external environment with a temperature of 25°C. The calculation results of thermal stress and thermal strain after 10s and 200s are shown in Fig. 4.
Thermal strain distribution of whole model
(a) Stress-strain distribution of MLCC at 10s

Thermal stress distribution of whole model
Thermal strain distribution of whole model
(b) Stress-strain distribution of MLCC at 200s

Fig. 4. Stress-strain distribution of MLCC

4. Conclusions
In this paper, the steady-state and transient thermal-structure coupling analysis and calculation of MLCC are carried out by ANSYS. The steady-state calculation results of wave soldering are shown in Fig. 2. As can be seen from Fig. 2(a), the highest temperature area of MLCC is the bottom surface in contact with the solder, with a value of 245 ℃, which gradually decreases from the bottom to the top. The lowest temperature area is the top surface of the end electrode, with a value of 241 ℃. It can be seen from Fig. 2(b) that the stress is mainly concentrated in the area of the end electrode bottom in contact with the solder, and the stress value is 4.5GPa. The transient calculation results of the cooling process of wave soldering are shown in Fig. 3 and 4. It can be seen from Fig. 3 that during the whole cooling process, the larger MLCC temperature area is concentrated on both sides of the dielectric. The overall temperature difference is not large, and with time the temperature difference is smaller and smaller, the overall temperature gradually tends to balance. It can be seen from Fig. 4 that the maximum von-Mises stress-strain occurs at the tip Angle of the terminal electrode after thermal stabilization (200s), where the stress is 5.93MPa and the strain is $1.10 \times 10^4$. It can be seen that there is a large thermal stress-strain on the contact surface of solder and capacitor, and the thermal stress-strain on the contact surface of electrode is much larger than that on the contact surface of dielectric. In addition, the thermal stress-strain of the terminal electrode is much greater than that of the dielectric. The main reason is that the thermal expansion coefficient of the terminal electrode assembly is much larger than that of the dielectric. At the same time, due to the large thermal response at the bottom of the electrode, a large thermal deformation occurs, resulting in a large thermal stress-strain at the bottom of the electrode.

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