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## Research

**Keywords:** Nano silver, Fatigue life, Simulation, Elemental Analysis, Materials Testing

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# Prediction of mechanical properties and fatigue life of nano silver paste in chip interconnection

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**Abstract:** The simulation of nano-silver solder joints in flip-chips is performed by the finite element software ANSYS, and the stress-strain distribution results of the solder joints are displayed. In this simulation, the solder joints use Anand viscoplastic constitutive model, which can reasonably simulate the stress and strain of solder joints under thermal cycling load. At the same time this model has been embedded in ANSYS software, so it is more convenient to use. The final simulation results show that the areas where the maximum stresses and strains occur at the solder joints are mostly distributed in the contact areas between the solder joints and the copper pillars and at the solder joints. During the entire thermal cycling load process, the area where the maximum change in stress and strain occurs is always at the solder joint, and when the temperature changes, the temperature at the solder joint changes significantly. Based on comprehensive analysis, the relevant empirical correction calculation equation is used to calculate and predict the thermal fatigue life of nano-silver solder joints. The analysis results provide a reference for the application of nano-silver solder in the electronic packaging industry.

**Key words:** Nano silver; Fatigue life; Simulation; Elemental Analysis; Materials Testing.

## 1. Introduction

Nano-silver paste is a promising electronic packaging interconnect material, which can overcome some of the shortcomings of alloy solder.

1. Metal silver has a very high thermal conductivity (410W/m·K). Some studies have shown that the thermal conductivity of nano-silver paste after sintering can reach 229W/m·K, which can meet the heat dissipation requirements of high power density packaging systems.

2. At the same time, due to the size effect of nanometers, the melting point and sintering temperature of nano silver particles are much lower than the melting point

and sintering temperature of bulk silver. Surface-melted nanoparticles are sintered together by the action of liquid capillary forces to finally form a sintered material with a melting point similar to that of the bulk material. Nano silver paste sintered joints can be obtained at lower processing temperatures and work at higher temperatures to avoid remelting during the package interconnection process. This feature is very suitable for multi-level packaging [1-3].

3. The nano silver paste sintered joint consists of a single structure. After continuous aging experiments, the shear strength is basically unchanged. Nano-silver particles can effectively pin dislocations and limit crack growth, extending solder joint fatigue life.

There are few studies on the application of nano-silver paste to flip-chip interconnects. In this paper, the flip chip is used as the object to study the chip interconnection of nano silver paste. Nano-silver is a viscoplastic material and is described using Anand's unified viscoplastic constitutive model. The finite element method was used to simulate the thermal cycling loading process, and the stress-strain state and cycle failure times of the nano-silver paste solder joints were predicted and analyzed.

The flip chip used in this article was customized at Wuxi Huajin Semiconductor Company. The upper chip contains 54 nano silver solder joints with a diameter of 100  $\mu\text{m}$ , and the bottom plate is a silicon substrate, as shown in Figure 1.

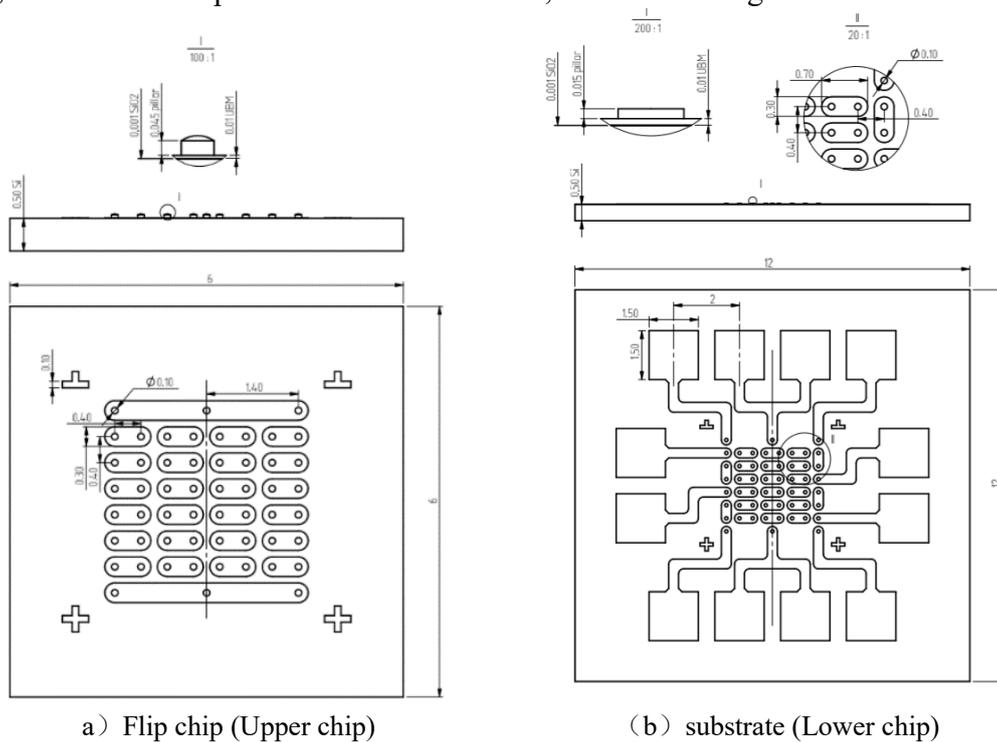


Fig.1 Flip chip and substrate

## 2. Finite element analysis

### 2.1 Anand constitutive equation and parameter fitting

The Anand model is a viscoplastic model of metal thermal work proposed by Anand and Brown [4]. Suitable for describing large viscoplasticity and small elastic deformation. The relationship between the saturation stress and the strain rate of the viscoplastic Anand model is as follows:

$$\sigma^* = \frac{s'}{\xi} \left[ \frac{\dot{\varepsilon}_p}{A} \exp\left(\frac{Q}{RT}\right) \right]^n \sinh^{-1} \left\{ \left[ \frac{\dot{\varepsilon}_p}{A} \exp\left(\frac{Q}{RT}\right) \right]^m \right\} \quad (1)$$

The relationship between stress and strain at different temperature and strain rates:

$$\sigma = \sigma^* - \{(\sigma^* - cs_0)^{(1-\alpha)} + (\alpha - 1)[(ch_0)(\sigma^*)^{-\alpha}] \dot{\varepsilon}_p\}^{\frac{1}{(1-\alpha)}}, \alpha \neq 1 \quad (2)$$

The above equation contains the nine parameters of the Anand constitutive equation:

$A, \frac{Q}{R}, \xi, s', n, m, \alpha, h_0, s_0$ , According to the formula derivation, they are constant, activation energy / gas constant, stress multiplier, saturation value coefficient of deformation impedance, strain rate sensitivity, strain rate sensitivity index, strain hardening parameter, strengthening coefficient, and initial value of deformation impedance. The parameters of the constitutive equation model of nano-silver are calculated through formula deduction, which are listed in Table 1 [5].

Tab .1 Anand model parameters of nanosilver

A	Q/R	m	n	$\xi$	$s'$	$h_0$	$s_0$	$\alpha$
9.81	5709	0.6572	0.00326	11	67.389	15800	2.768	1

### 2.2 ANSYS finite element model

In order to facilitate the study of thermal fatigue effects of solder joints, the model needs to be simplified. Due to the symmetry, a quarter of the chip can be used as the research object, which contains 12 solder joints. The model is shown in Figure 2. The material parameters of each component are listed in Table 2 and Table 3 [6].

Tab.2 material properties of each component

Ingredient	Young's Modulus	Poisson's ratio	Thermal expansion coefficient
Silicon	131	0.3	2.8
Copper column	110	0.34	16.4
Nano Ag	as follows	0.38	19.9

Tab.3. Young's Modulus of Nano Silver at Different Temperatures

temperature (°C)	-50	0	25	60	120	150
Young's Modulus	9.00	8.00	6.25	4.50	2.65	1.60

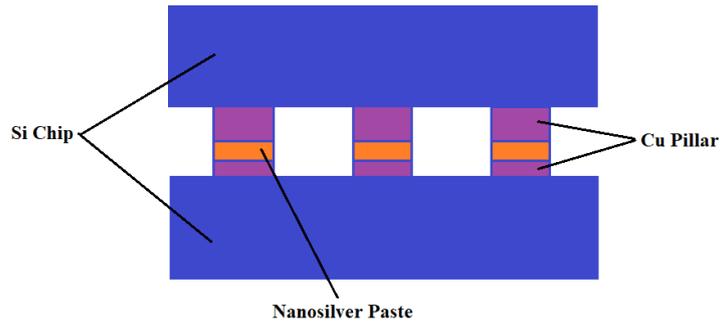


Figure 2 Schematic diagram of the finite element model

### 2.3. Meshing

Because the size of the mesh division will have a greater impact on the calculation time and the final analysis result. In order to make the effect of the mesh division on the basis of satisfying the calculation accuracy and save the calculation time, there are differences in the meshing of different parts. This time, the mesh of the model is divided into 0.005 using the size controller for the solder joints and copper pillars, and 0.02 is used for the chip controller. All of them are mapped grids, which are divided into 1334400 grid cells Figure 3 shows the meshing situation.

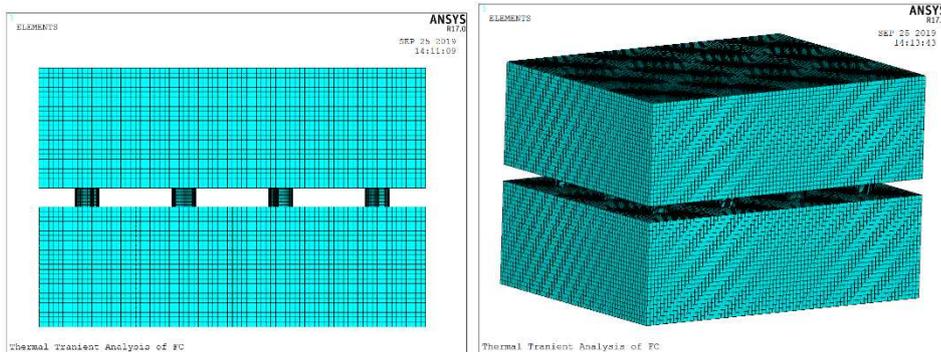


Figure 3 Meshing

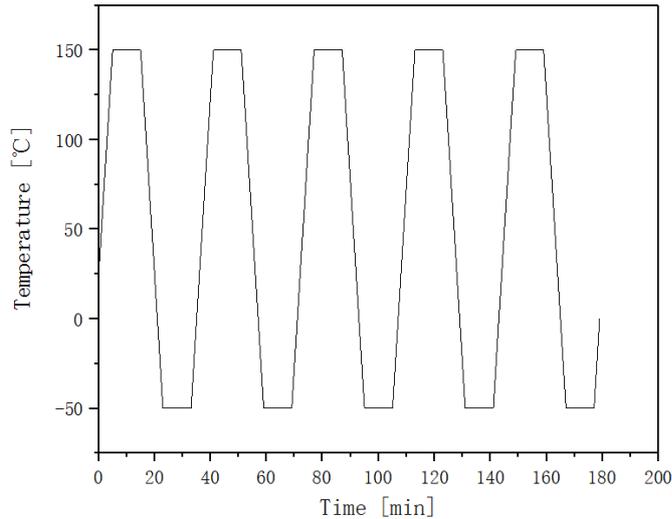


Figure 4 Temperature cycling load

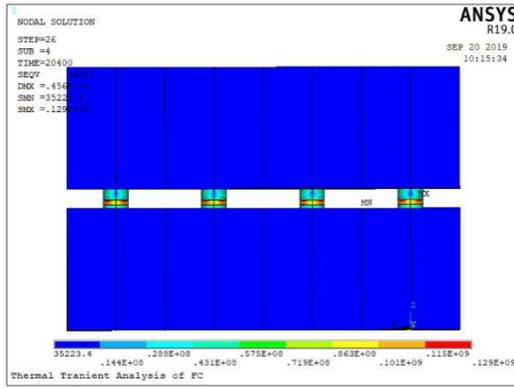
## 2.4. Loading loads and boundary conditions

The thermal cycling load is determined according to various conditions that may be encountered during service. The temperature range is  $-50\text{ }^{\circ}\text{C}$  to  $150\text{ }^{\circ}\text{C}$ , the temperature rise and fall rate is  $25\text{ }^{\circ}\text{C} / \text{min}$ , and it is maintained for 10 minutes when it rises to the highest temperature and 10 minutes when it is lowered to the lowest temperature. The cycle period is 36min. According to existing research, the stress and strain of solder joints show periodic changes during thermal cycling. After loading for several cycles, the results will stabilize. This model calculates 5 cycles<sup>[7]</sup>, as shown in Figure 4.

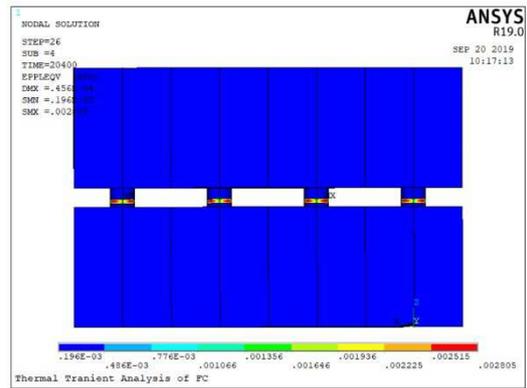
The base plate is mounted on a tooling fixture. The bottom surface of the lower chip can be imposed with zero displacement constraints in all directions, and the two symmetrical surfaces of the upper chip can be imposed with unidirectional zero displacement constraints.

## 2.5. Stress and strain analysis

The simulation lasted for 20400 seconds. After the simulation, check the stress and strain diagrams of the entire chip using the POST\_26 post-processing program. It can be seen that there is basically no obvious stress and strain on the chip part, as shown in Figure 5.

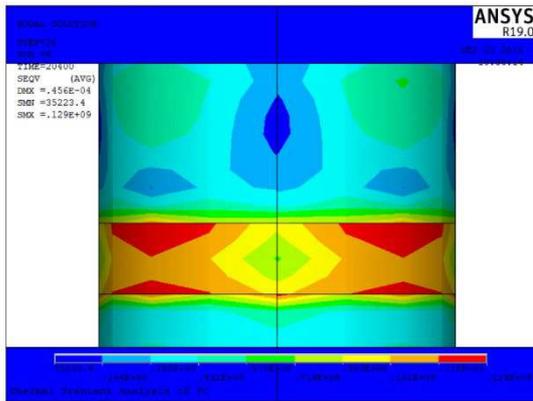


(a) Chip equivalent stress diagram

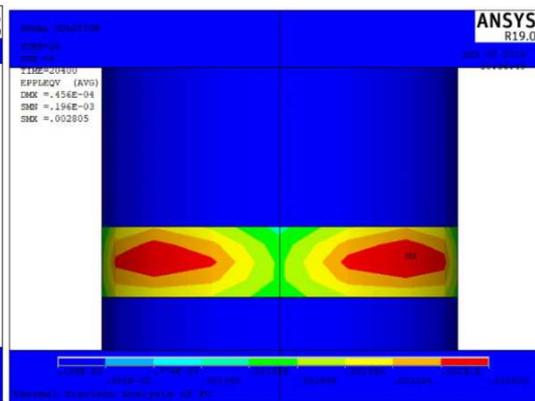


(b) Chip equivalent strain diagram

Figure 5 Stress and strain diagram of the chip after the simulation is completed



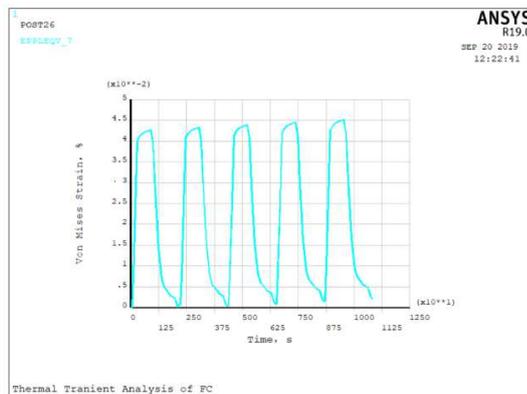
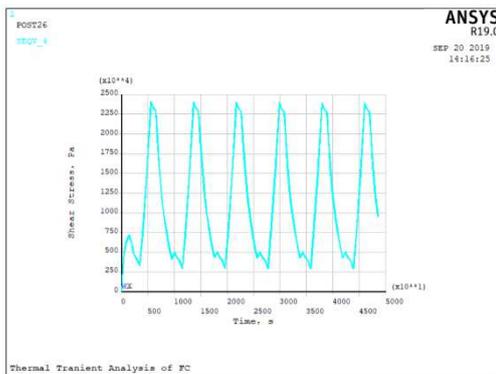
(c) Magnified equivalent stress of solder joint



(d) Magnified equivalent strain of solder joint

Figure 6 Stress-strain diagram of solder joints after simulation technology

Enlarge the stress-strain diagram at the solder joint. As shown in Figure 6, it can be seen that the outer part of the solder joint where contact with the upper and lower copper pillars generates a large stress, while the interior of the solder joint generates a large strain. The strain is gradually extended from the center of the solder joint to the periphery with the load of the temperature cycle. When it reaches the contact surface with the upper and lower copper pillars, stress deformation occurs due to the different material properties of the two. It can be speculated that if the simulation is continued, fatigue cracking will occur at the interface between the solder joint and the upper and lower copper pillars, which will cause the chip to fail.



- (a) Curve of equivalent stress of solder joint over time      (b) Curve of equivalent strain of solder joint over time

Fig. 7 Equivalent stress-strain curve of solder joint

In order to more clearly analyze the stress and strain of the solder joint under the thermal cycling load, a node in the middle of the solder joint is now selected as the research object, and the stress and strain curve is drawn for analysis. As shown in Figure 7, the curve of the equivalent shear stress of the joint at the middle of the solder joint over time. In the figure, the horizontal axis represents time, and the vertical axis represents the numerical value of the stress change of the node. It can be seen that the equivalent shear stress of the node changes periodically with the progress of the thermal cycle.

It can be seen from Fig. 8 that the viscoplastic strain energy density of the solder joint gradually increases with time, and the increase in each cycle is basically the same.

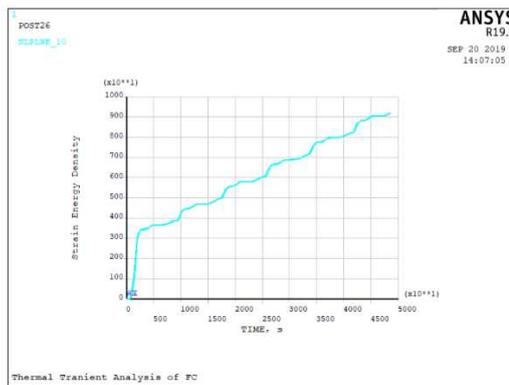


Fig. 8 Curve of strain energy density of solder joints over time

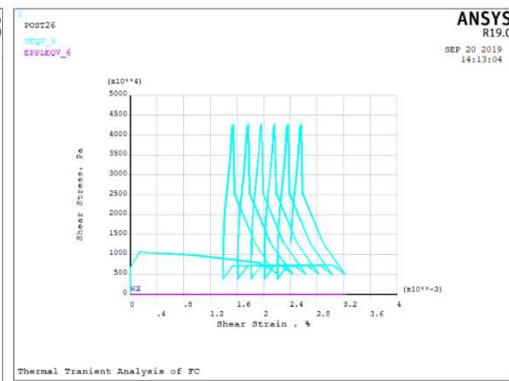


Fig. 9 Stress-strain hysteresis curve of solder joints

The stress-strain hysteresis curve of the internal node of the solder joint is shown in Figure 9, where the horizontal axis represents the equivalent shear strain of the internal node of the solder joint and the vertical axis represents the equivalent shear stress of the node. It can be seen from the figure that as the temperature cyclic load is loaded, the stress-strain hysteresis curve moves to the right, and the interior of the solder joint is undergoing cumulative plastic deformation.

## 2.6. Fatigue life prediction

In the case of loading thermal cycle load, the stress and strain behavior of solder joints is very complicated, and factors such as time, temperature, and solder all affect the performance of solder joints. In general, plastic strain is the root cause of cracking of solder joints until failure. Therefore, we use the strain fatigue model Manson-Coffin to predict solder joint life.

Fifties of last century, the relationship equation  $N_f \sim \Delta \varepsilon_p^{-\beta}$  proposed in the

famous paper published by Coffin and Manson [8,9]. It relates the fatigue life  $N_f$  to the magnitude of the inelastic strain  $\Delta\varepsilon_p$  applied. The index  $\beta$  is found to be very common in pure metallic materials and very close to 2, it has nothing to do with their microstructure. When the plastic strain amplitude is large, this law applies to the definition of low cycle fatigue state (LCF) [10]. In the low cycle thermal cycle, the fatigue life ( $N_f$ ) and the nonlinear strain amplitude ( $\Delta\varepsilon_p$ ) have the following relationship regardless of the residence time:

$$N_f = C (\Delta\varepsilon_p)^{-\beta} \quad (3)$$

In the formula,  $N_f$  is the fatigue life,  $C$  and  $\beta$  are the constant numbers of the sample, and  $\Delta\varepsilon_p$  is the inelastic strain amplitude.

Above we introduced a method for predicting thermal fatigue life—C-M empirical equation based on strain range. However, since this equation only deals with the influence of the magnitude of the strain amplitude on the thermal fatigue life, it does not take into account the influence of temperature on it, thus reducing the credibility of its predicted life, so there are limitations. In order to solve this problem and make the results of life prediction more accurate, Engel-Maier's C-M correction equation becomes a more accurate one of many derivative equations:

$$N_f = \frac{1}{2} \left( \frac{\Delta\gamma}{2\varepsilon_f'} \right)^{\frac{1}{c}} \quad (4)$$

Among them,  $\Delta\gamma$  represents the equivalent plastic shear strain range  $\Delta\gamma = \sqrt{3}\Delta\varepsilon$ , and  $\varepsilon_f'$  represents the fatigue toughness coefficient (take 0.325) [11].  $C$  stands for the fatigue toughness index, which can be determined by the following formula.

$$C = -0.442 - 6 \times 10^{-4} T_m + 1.74 \times 10^{-2} \ln(1 + f) \quad (5)$$

In the formula,  $T_m$  is the arithmetic mean of high and low temperatures, and  $f$  is the number of loads per unit time. The Engel-Maier correction formula not only reduces the number of model parameters, but also simplifies its structure. Because of the influence of temperature, the result of this formula is relatively accurate. It is widely used in calculating the thermal fatigue life of solder joints.

Through the comparison and calculation of the strain range of each node in the central part of the solder joint by the ANSYS program, the node with the maximum strain range can be obtained. The equivalent plastic strain range of the node = 0.0082, and the plastic shear strain range =  $1.42 \times 10^{-2}$ . The average temperature of the temperature cyclic loading load is  $T_m = (150-50)/2 = 50$  °C, and each thermal cycle is 36 min. The temperature cycle frequency  $f = 1.67$  cyc/h can be calculated and substituted into Equation (5), and it can be calculated  $C = -0.455$ , substituting the above data into Equation (4), the fatigue life of the silver tin solder joint can be calculated  $N_f = 2166$  weeks.

### 3. Conclusion

(1) The Anad unified viscoplastic constitutive model is used to model the nano-silver paste solder. The simulation results obtained can provide a certain reference for the chip interconnection of nano-solder.

(2) With the finite element simulation of thermal cycling loading, the stress and strain inside the solder joint are gradually accumulated, and the increase in plastic deformation will lead to the ultimate failure of the solder joint.

(3) Using the C-M correction formula, the finite element method was used to calculate the thermal fatigue life of the solder joint at 2166 weeks when the diameter of the solder joint was 0.1 mm and the height was 0.02 mm.

### Declarations

- Ethics approval and consent to participate

The study received approval from the institutional review board of Guilin University of Technology.

- Consent for publication

All authors consent for publication

- Availability of data and material

All data and materials are available.

- Competing interests

All authors declare no competing financial interests.

- Funding

Not applicable.

- Authors' contributions

All authors approved the final version.

- Acknowledgements

Not applicable.

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# Figures

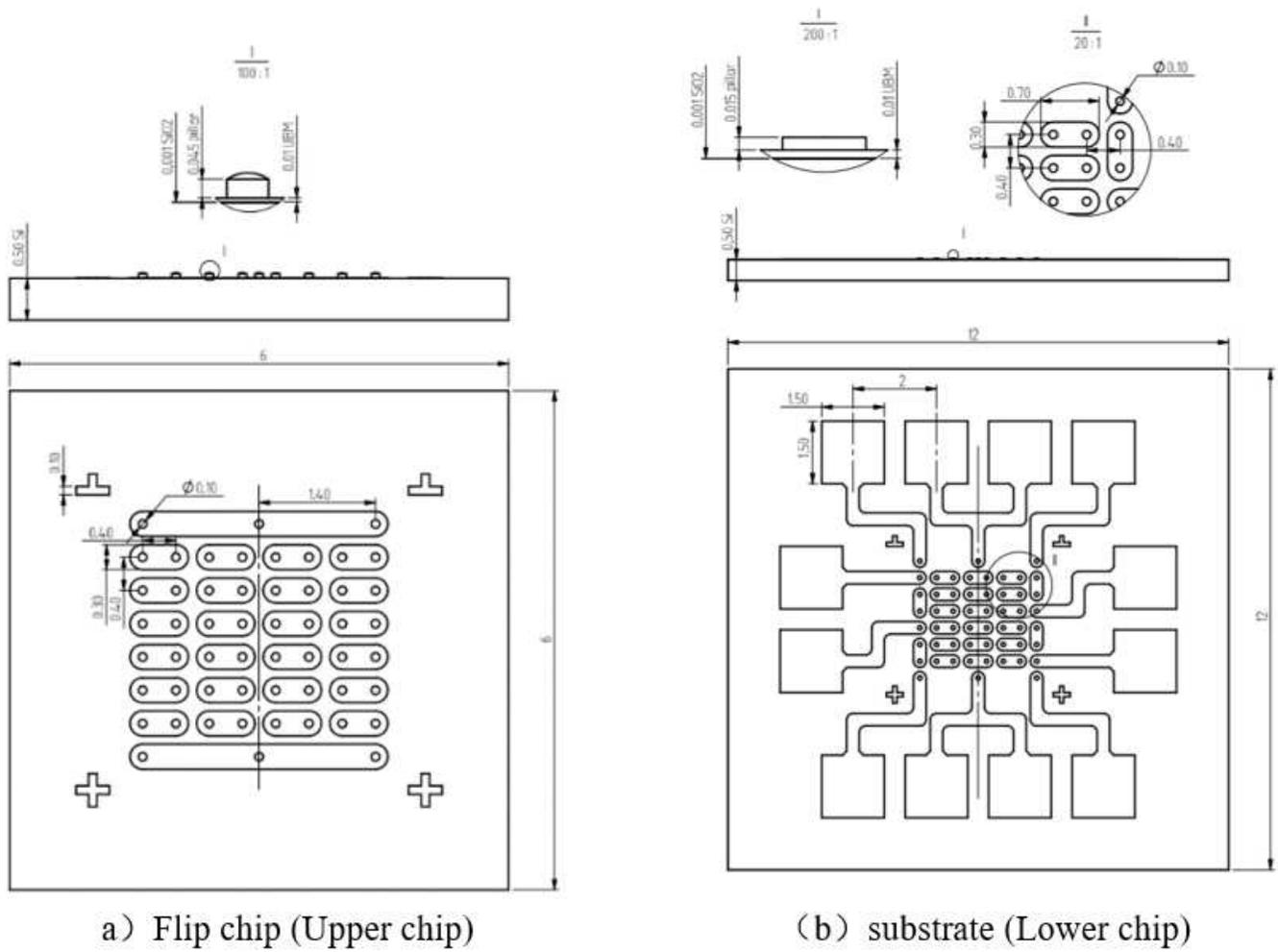


Figure 2

Flip chip and substrate

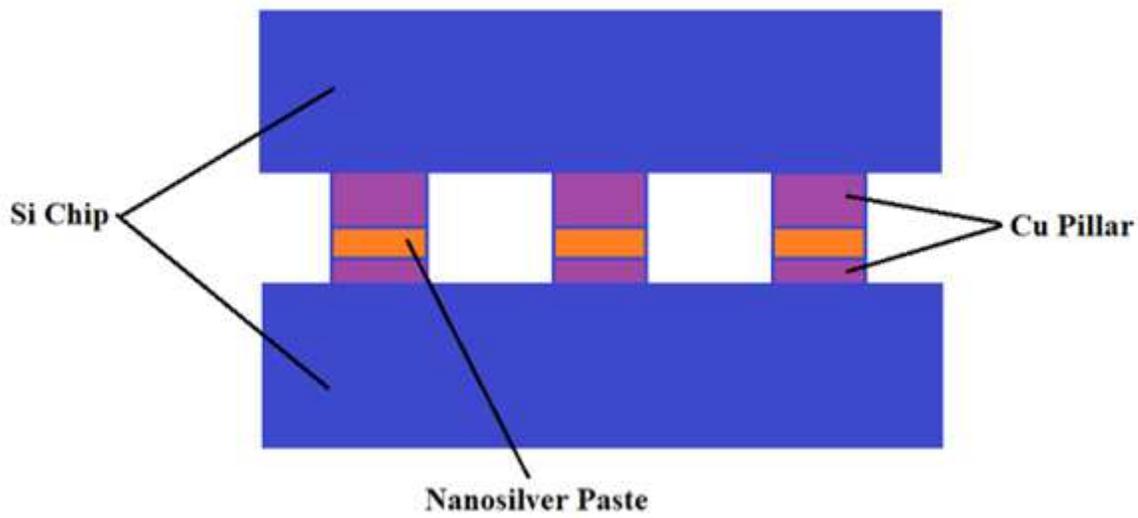


Figure 4

Schematic diagram of the finite element model

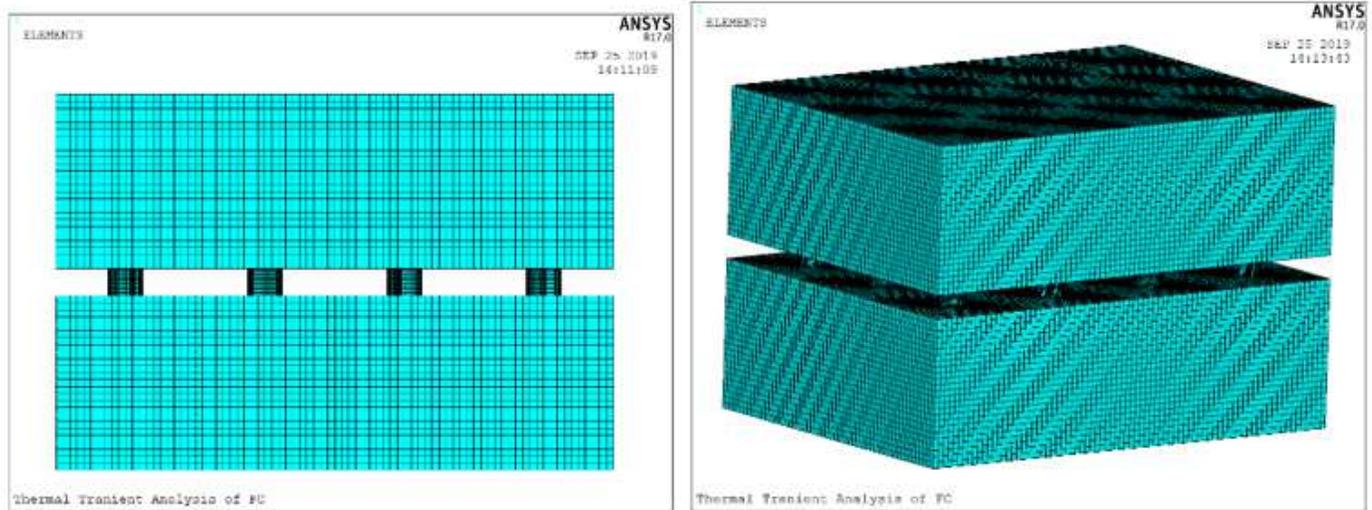


Figure 6

Meshing

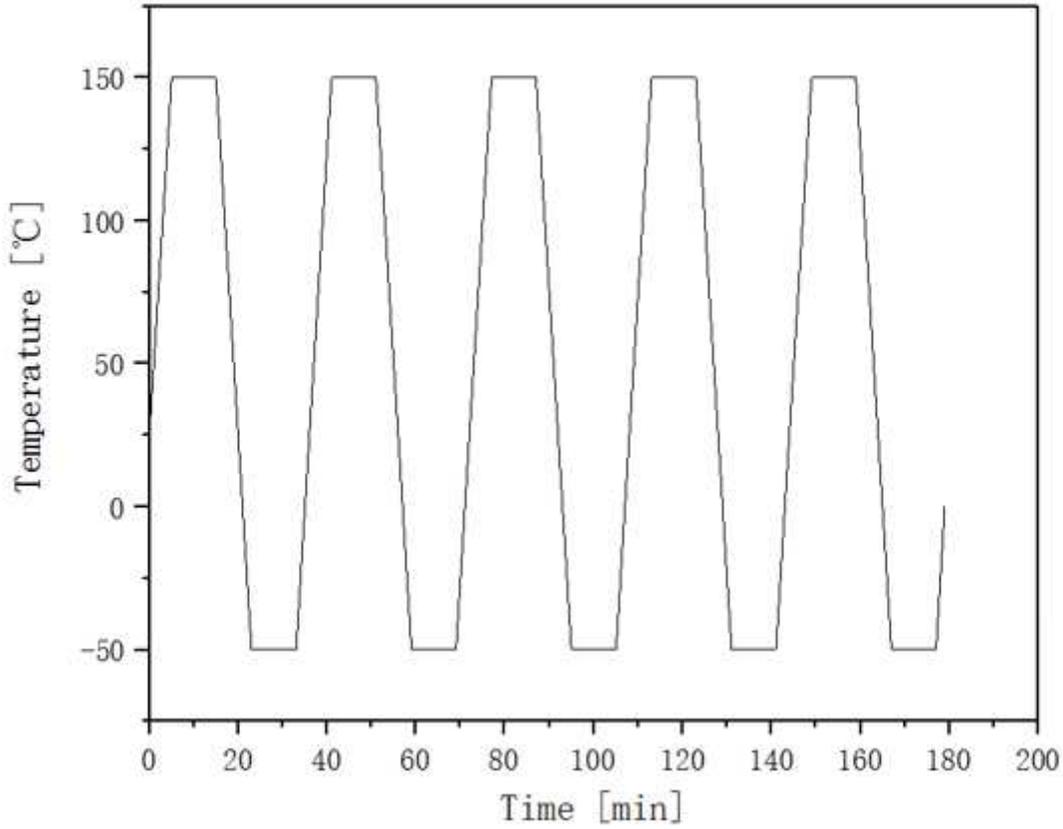
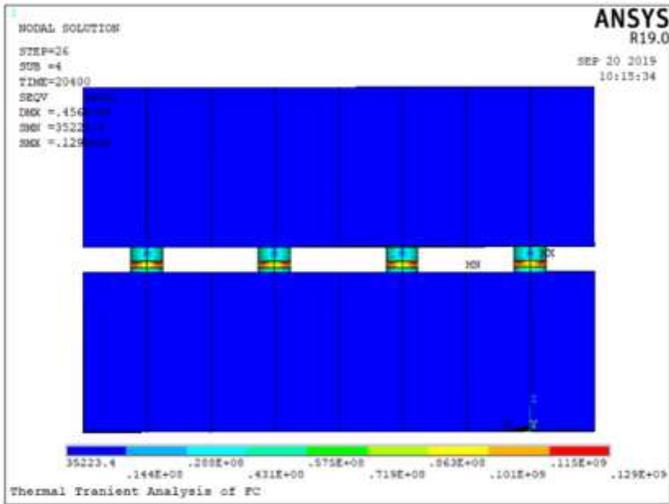
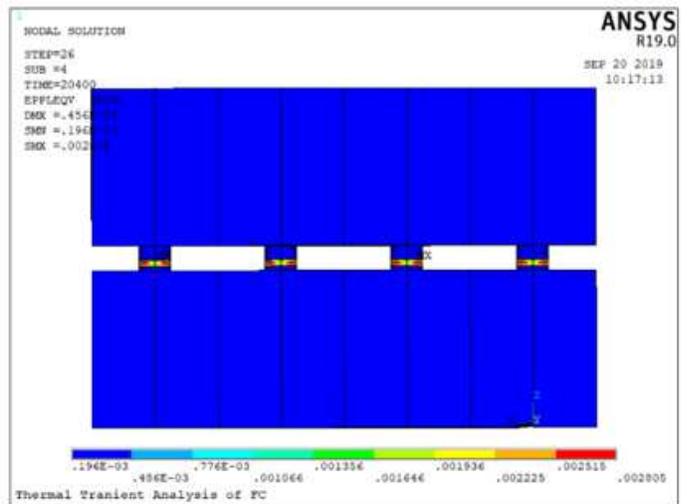


Figure 8

Temperature cycling load



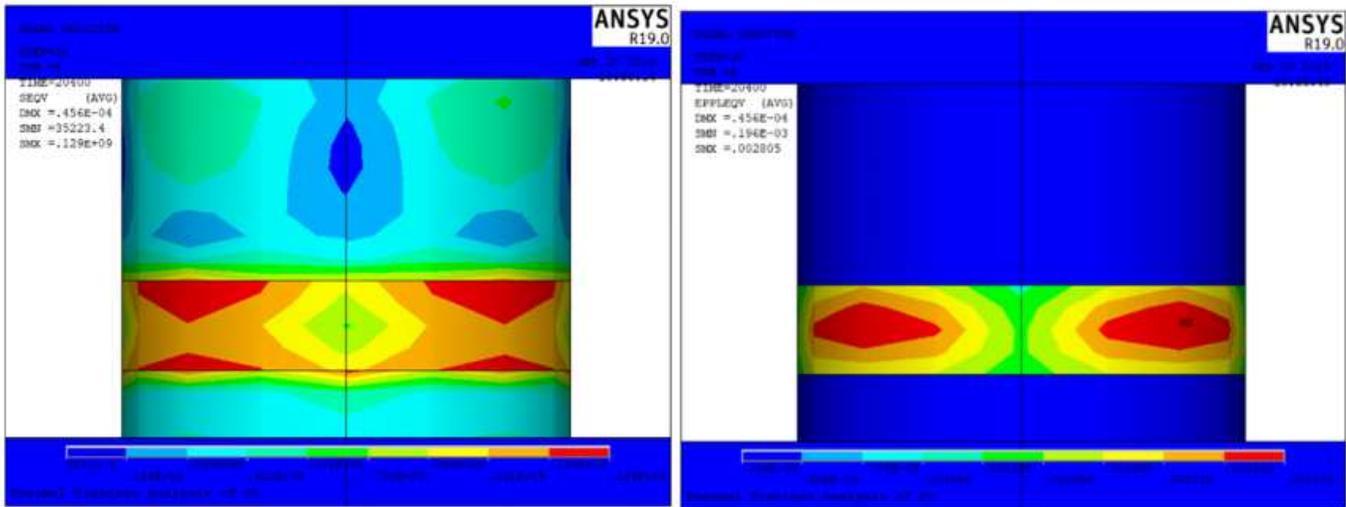
(a) Chip equivalent stress diagram



(b) Chip equivalent strain diagram

Figure 10

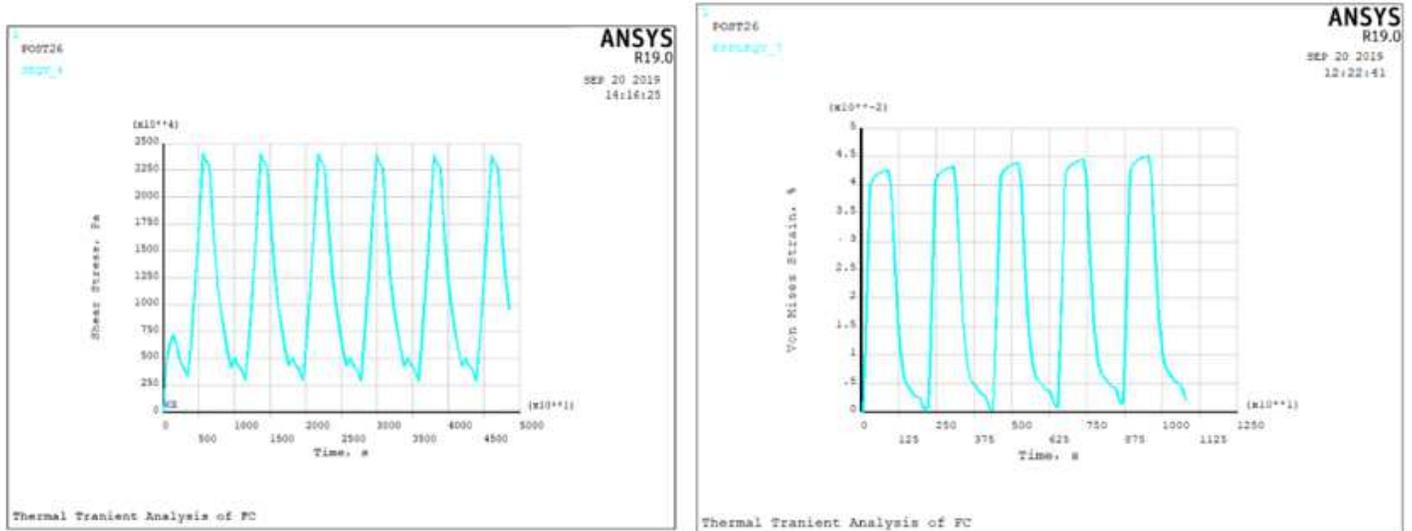
Stress and strain diagram of the chip after the simulation is completed



(c) Magnified equivalent stress of solder joint (d) Magnified equivalent strain of solder joint

Figure 12

Stress-strain diagram of solder joints after simulation technology



(a) Curve of equivalent stress of solder joint over time

(b) Curve of equivalent strain of solder joint over time

Figure 14

Equivalent stress-strain curve of solder joint

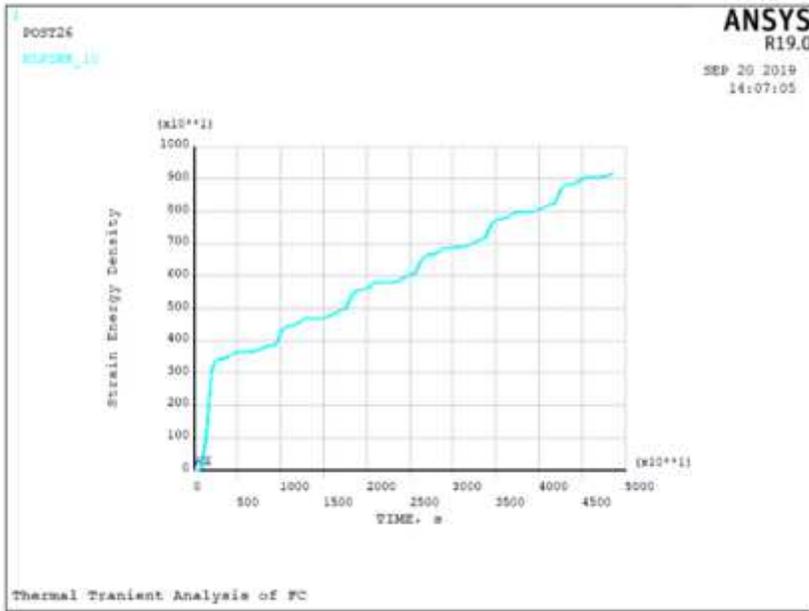


Figure 16

Curve of strain energy density of solder joints over time

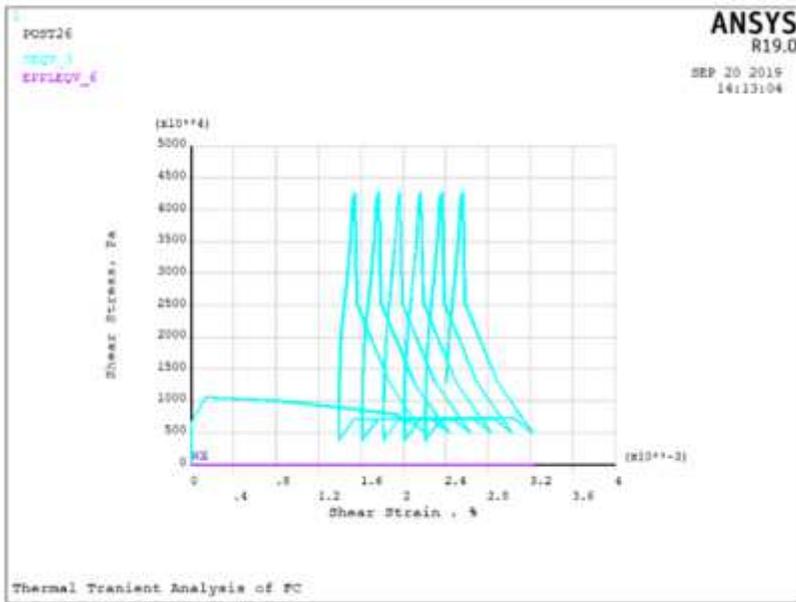


Figure 18

Stress-strain hysteresis curve of solder joints