Reliability Research of TSV Micro Structure under Thermal and Vibration Coupled Load

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***Abstract*—Due to the advantages unmatched by traditional two-dimensional packaging technology, three-dimensional packaging technology has gradually attracted more and more attention from researchers and engineers, and is on the way to the market, but its degradation failure mechanism and reliability problems have not been systematically studied and solved. As one of the key structures of three-dimensional packaging, the degradation failure mechanism of through silicon via (TSV) under environmental and working load has not been fully elucidated. Previous studies only focused on the failure of TSV structures under thermal load, while ignoring the vibration load. Therefore, the reliability of the typical TSV structure under the thermal-vibration coupled load was studied in this paper. Based on numerical analysis, the time-history transient analysis of the typical TSV structure with the redistribution layer under thermal-vibration coupled load was performed. The analysis considered the combined effects of thermal load and vibration load and their mutual coupling effects. The maximum equivalent stress, elastic and plastic strain response of the structure were obtained, and the analysis of them was carried out. The effects of random vibration load and different thermal conditions on structural reliability were compared and analyzed, which could provide an important reference for the subsequent research of the degradation mechanism of TSV structure under thermal-vibration coupled load.**

Keywords—reliability; TSV; thermal and vibration coupled load; micro structure; finite element analysis (FEA)

I. INTRODUCTION

As Moore's Law gradually moves to the limit, 3D packaging technology is gradually gaining close attention in the scientific community and engineering[1]. Compared to traditional two-dimensional packaging technology, 3D packaging technology can achieve higher device performance with smaller package size, higher connection density, lighter quality, lower power consumption, and can implement heterogeneous integration[2]. One of the most critical technologies in 3D packaging technology is Through Silicon Via (TSV). The typical TSV microstructure is given in Fig.1, and it can be seen that a typical copper-filled TSV microstructure is made of silicon wafer, insulated layer, barrier layer, seed layer, TSV and redistribution layer (RDL).

With the development of technology, TSV-based 3D IC Integration is gradually moving from the laboratory to the market[2]. However, the degradation mechanism of TSV structure under environmental and working load has not been fully elucidated, and many reliability problems have not been solved. Therefore, the current TSV yield is very low and the cost is high. Besides, the research on reliability test and assessment of TSV microstructure is still in its infancy. The TSV-based three-dimensional package has a smaller package size and a higher connection density, and thus faces more severe challenges in heat generation and dissipation compared to conventional packages. In addition, the TSV structure is composed of many different materials and contains complex interfaces, and the coefficient of thermal expansion (CTE) of each material is different. For example, the thermal expansion coefficient of electroplated copper is 17.5×10^{-6}/°C, while the CTE of silicon is 2.5×10^{-6}/°C[3]. Therefore, under the thermal load, there will be large stress caused by thermal mismatch at the interface, causing interface cracks or delamination failure. In the manufacturing process, the TSV structure inevitably introduces many defects, such as voids, cracks in the process of electroplating copper, which cause stress concentration under service load and lead to reliability problems. As a plastic metal material, copper may suffer strain fatigue and creep problems under low-cycle thermal load. In addition, as an electrical connection structure, copper in the TSV structure gradually migrates over the dielectric layer into the silicon over time, causing electrical connection failure.

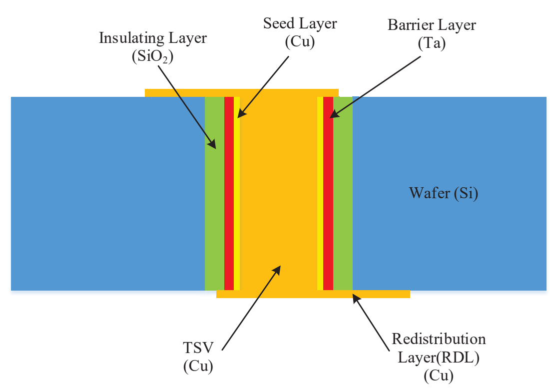

Figure 1. Typical Cu filled TSV micro structure

For the above reasons, the thermal load has been regarded as the main load affecting the reliability of TSV. The related research is mainly about thermal load, while the reliability related research of TSV structure under the vibration and shock

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load is rare. However, according to relevant literature reports, the vibration load is also an important environmental load that causes the failure of electronic devices, and about 20% of the failure of electronic devices is caused by vibration[4]. Under the vibration load, stress concentration occurs at the interface, flaws and cracks, which leads to delamination damage and crack propagation. In addition, metal materials also suffer high-cycle stress fatigue failure, namely vibration fatigue[5, 6]. On the other hand, previous research on the reliability of microelectronics and MEMS device packaging has focused on solder joint reliability[7], because solder joints are often seen as the weak point in the package structure. However, for a three-dimensional package structure based on the TSV structure, the first failure location may not be the solder joint but TSV structure[8]. In summary, it is necessary to conduct more in-depth reliability research on the TSV structure, especially the research on the degradation mechanism of the TSV structure under the thermal-vibration coupled load.

The current academic research on the reliability of TSV is mainly based on the FEA of the structure under the thermal load. Choa[8] et al. pointed out that for chips using TSV connections, the first failure location is the TSV structure. They used the FEA method to study the plastic strain, the fatigue phenomenon and failure position of TSV structure under thermal cyclic load. The influences of via size, the underfill material of the solder joint and the filling material of the through hole on the reliability of structure were investigated. Jing[9] et al. performed a thermal stress finite element simulation on the TSV structure on the BCB board, and explored the effects of different hole sizes, pitches, and BCB plate thickness on the Mises stress. The plastic yielding of the structure was used as the failure criterion. Liu[10] et al. used the sub-model analysis method to simulate the thermal stress of the three-dimensional stacked monolithic structure with TSV. It is pointed out that the thermal stress of the TSV structure in the actual package is smaller than that of the TSV in the free-standing wafer under the same thermal load. Ryu[11] et al. analyzed the influence of TSV on the adjacent surface stress distribution and TSV interface reliability by linear superposition method, and verified it by finite element analysis. At the same time, the influences of via diameter, wafer thickness, underfill and dielectric layer material were analyzed. Thakur[12] et al. performed a cooling analysis on the three-dimensional package containing TSV structure based on the 3D finite element model (FEM), and studied the effects of chip thickness, filling thickness, filling material, substrate thickness, process parameters and TSV aspect ratio on the chip interface stress.

Pan and Li[13] explored the effects of TSV size parameters, defect locations and defect types on thermal stress through a 3D finite element model. Dai[14] used the crack energy release rate as the parameter to investigate the effect of silicon anisotropy on the crack propagation of TSV structures. Rahangdale[15] explored the crack propagation of TSV structures under reflow, thermal shock and thermal cycling load based on the sub-model method.

The above research focuses on the analysis of stress, strain and crack propagation of TSV structures under thermal load such as thermal cycling and thermal shock, and mainly uses finite element methods. However, the reliability of TSV structures under the vibration load is rarely seen in the literature. Huang and Xiong[16] simulated the stress and strain distribution of TSV structure under random vibration load, but it is only a preliminary exploration. There are also literatures that are beginning to focus on the high frequency characteristics of TSV structures[17].

The reliability of package structure under the thermal and vibration coupled load has been reported in some literatures, but they are all aimed at solder joint[18-20], mainly adopting linear superposition model or progressive damage accumulation model. The linear superposition method does not consider the mutual coupling of thermal and vibration, and often differs far from the actual situation. The progressive damage accumulation model considers the mutual coupling relationship between thermal load and vibration load, but more in-depth theoretical research and experimental verification are still needed. Unfortunately, there is no relevant literature on the reliability of TSV structures under the thermal-vibration coupled load.

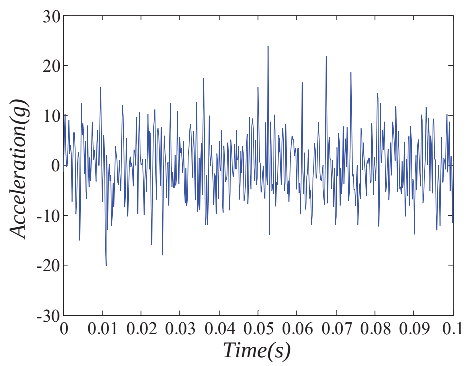
In this paper, the comprehensive effects of thermal and vibration load and their mutual coupling were considered. Based on the numerical analysis, the typical TSV structure with redistribution layer under thermal-vibration coupled load was analyzed by time-history transient analysis, and the stress and strain response were obtained. The effects of vibration load and thermal load of different parameters on the reliability of the TSV structure were compared and analyzed. The research results in this paper can lay a foundation and provide an important reference for the subsequent quantitative evaluation of the reliability of TSV structures under thermal-vibration coupled load. The full text are arranged as follows: Section 1 introduced the research background and reviewed the current research status; the basic concepts and theories were introduced in Section 2; Section 3 introduced the finite element modeling, including load parameters, materials and boundary conditions; the fourth part analyzed the simulation results; Section 5 summarized the full text and proposed the future research prospects.

II. Basic Concepts and Theories

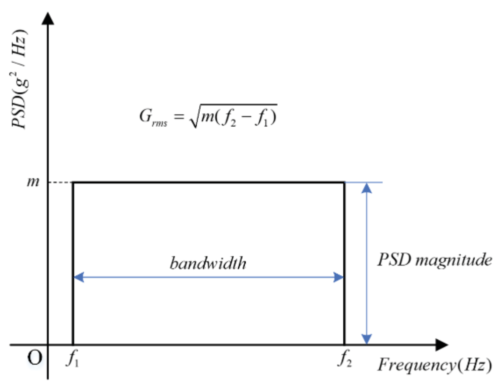
A. *Sinusoidal Vibration and Random Vibration*

Typical random vibration signals are shown in Figure 2[5]. Sinusoidal vibration is the simplest vibration signal and also a periodic deterministic signal, which can be represented by a sinusoidal function. The relevant parameters describing a sinusoidal vibration signal include: period(T), frequency(fr), amplitude(σ_a), maximum & minimum amplitude(σ_{max}, σ_{min}), average value(σ_{mean}), amplitude range($\Delta\sigma$), and stress ratio(R) et al. The random signal is different from the sinusoidal signal in the time domain. As shown in Fig.2(a), it appears as an irregular vibration, which is an aperiodic, uncertain signal that cannot be represented by an analytic function and thus cannot be described in the time domain. As shown in Fig.2(b), the description of the random vibration signal often adopts parameters in the frequency domain, including: bandwidth, power spectral density (PSD), minimum frequency(f_1), maximum frequency (f_2), root mean square(RMS) value(G_{rms})

et al. The vibration load carried by the structure during the service are random vibrations, so only random vibration load are considered in this paper.



(a) The time domain signal of a random vibration



(b) The PSD of random vibration

Figure 2. The random vibration[5]

B. *Spectral Analysis and Transient Analysis*

The random vibration signal is time-varying signal, then static analysis cannot be applied. Finite element analysis (FEA) has two methods for analyzing the response of a structure under random vibration load: spectral analysis and transient analysis.

Spectral analysis is a frequency domain method. It is necessary to perform the modal analysis first to obtain the structural modal shape and modal frequency, and then correlate the modal analysis results with the frequency domain spectrum of the random vibration signal to obtain the maximum response of the structure under the spectral signal. The analysis results of spectral analysis are not time-varying. Instead of time integration, the modal analysis results are linearized to approximate the peak of the structural response. Therefore, only linear problems can be processed with this method, which is quite different from the real situation, but it can greatly shorten the solution time and save the calculation cost.

Transient analysis is a time domain method that does not need perform modal analysis prior to transient analysis. The input load of the transient analysis can be any transient signal that changes with time, and the response sequence of the structure under time-varying transient load excitation can be obtained. Transient analysis considers the time integral and can analyze the nonlinear response of the structure, so it is closer to the real situation, and the analysis result is more reliable. However, the computational cost of transient analysis is large and needs high performance computing platform to support.

Obviously, transient analysis is superior in accuracy and applicability. With the support of high-performance computers, this paper chooses transient analysis as the main research method.

C. *Coupled Field Element*

Based on the finite element method, the stress, strain and deformation analysis of TSV in this paper need to consider the coupling effect of thermal and vibration load. In the previous literature, when dealing with thermal and vibration coupled load, simple linear superposition is often performed, and the interaction between the two is neglected, which leads to large errors and is inconsistent with the real situation. In this paper, the coupling field element in ANSYS software is selected for transient analysis. The thermal and vibration load can be loaded at the same time, and the coupling effect between the two is considered in the analysis process. In this paper, the PLANE 223 2D 8-node coupled field element and the SOLID 226 3D 20-node coupled field element were selected to handle 2D plane analysis and 3D analysis, respectively. Both elements can handle thermal-structure coupling field problems.

III. Finite Element Modeling

A. *Material Parameters*

As shown in Figure 1, the materials in a typical TSV structure include: electroplated copper (filling material), deposited copper (seed layer, redistribution layer), metal tantalum (isolation layer), silicon dioxide (insulation layer) and silicon (substrate). Since the seed layer and the isolation layer are very thin, much smaller than the other layer thicknesses, in order to simplify the model, the effects of the seed layer and the isolation layer are ignored.

TABLE I. Material Properties

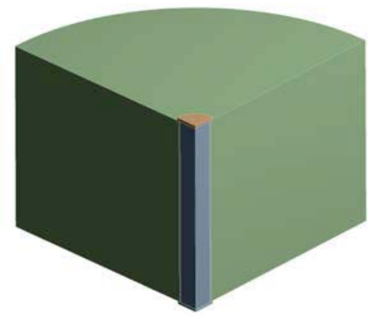
Materials	**Density /kg/m^3**	**Young's modulus /GPa**	**Poisson's ratio *v***	**CTE/ ×10^{-6}/℃**
Si	2300	129.62 (25°C) 128.43 (150°C)	0.28	2.81 (25°C) 3.11 (150°C)
SiO_2	2270	70	0.16	0.6
Cu (deposition)	8900	110	0.35	17
Cu (electroplate)	8900	70	0.34	18

Therefore, four material parameters are required for the analysis: deposited copper, electroplated copper, silicon dioxide, and silicon, as shown in Table I and Table II[3, 21], in which the electroplated copper is considered plastic, and the strain-free temperature is 25 °C.

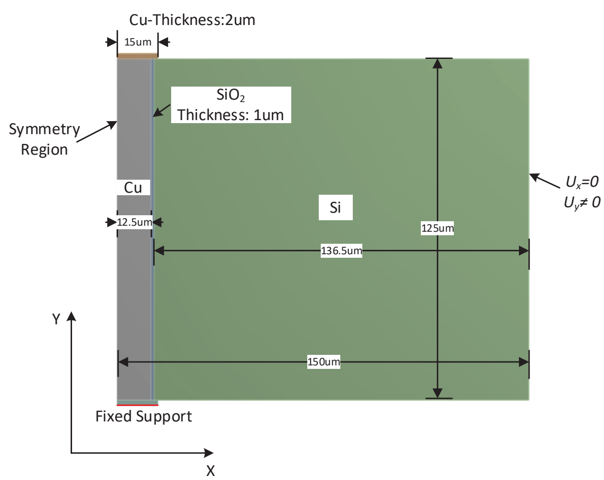
TABLE II. STRESS-STRAIN RELATIONSHIP OF ELECTROPLATE CU

Strain/ε	Stress (25°C) /MPa	Stress (125°C) /MPa
0.001	125	110
0.004	186	179
0.01	217	214
0.02	234	231
0.04	248	245

B. Model Dimensions and Boundary Conditions



(a) 3D model



(b) 2D model

Figure 3. The typical TSV model

The model of single TSV microstructure is shown in Figure 3. In order to simplify the calculation, a quarter model was established as shown in Fig.3(a), and Fig.3(b) shows the corresponding one-half 2D plane model. The seed layer and isolation layer are ignored in the model.

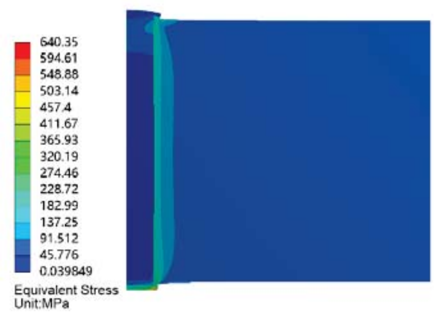
TABLE III. MODEL DIMENSIONS

Item	Dimensions/μm
TSV diameter	25
Thickness of SiO_2	1
Pitch	300
Thickness of RDL	2
Diameter of RDL	30

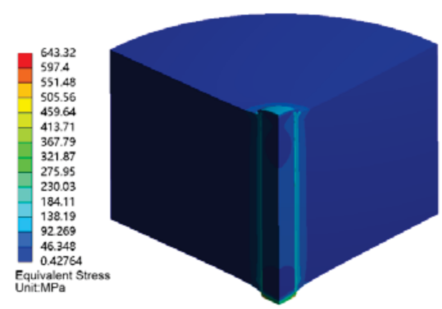
The 2D plane model can further reduce the computational complexity and improve the computational efficiency, but the equivalence of the 2D model and the 3D model needs further verification. The model dimensions are shown in Table III. The dimensions of the one-half model can also be seen in Fig.3(b). The model boundary conditions are given in Fig.3(b), and the fixed support was added to the bottom redistribution layer, while the displacement of the right end of the model in the x direction was constrained. The 3D model dimensions and boundary conditions are consistent with the 2D model. The quadrilateral mesh was selected to generate the meshing(the element size is 1μm).

C. 3D/2D modeling equivalence verification

As described in the previous section, this section verified the equivalence of the 2D model and the 3D model, by analyzing the stress under the heating load (-25 to 125°C) of the 3D model and the 2D model respectively. The mesh size was continuously reduced until the analysis results converge. The stress contour is shown in Figure 4.



(a) Equivalent stress of 2D model



(b) Equivalent stress of 3D model

Figure 4. The analysis results of 2D and 3D model

As shown in Fig.4, the maximum equivalent stress of the 2D model is 640.35 MPa, and the maximum equivalent stress of the 3D model is 643.32 MPa. The difference between the two is only 0.46%. It can be seen that the 2D axisymmetric plane model can be equivalent to the 3D model and greatly simplify the calculation.

D. Load Parameters

In this paper, the stress and strain analysis of a typical TSV structure under the thermal-vibration coupled load was carried out. The loaded thermal load is the heating or cooling load(with the duration of 3.2s), and the vibration load is the random vibration load. The specific parameters are shown in Table IV. The PSD spectrum of the vibration load of A2 is shown in Figure 5. The duration of vibration load is 3.2s. The Group A is to explore the influence of the RMS value and bandwidth on the solution results under the condition of heating load. The Group B is to study that under the cooling load. The load of group C is the control group, C1 and C2 are the individual heating and cooling load, respectively, while C3 is the single random vibration load, and the random vibration parameters are the same as A2.

TABLE IV. THE PARAMETERS OF LOAD

Item	Thermal load (3.2s)	Vibration load(3.2s)				
		PSD Magnitude/g	*RMS/g*	*Bandwidth/Hz*	*Minimum Frequency/Hz*	*Maximum Frequency/Hz*
A1	-25℃ to 125℃	1	6.72	45	5	50
A2	-25℃ to 125℃	1	9.75	95	5	100
A3	-25℃ to 125℃	1	13.96	195	5	200
B1	125℃ to -25℃	1	6.72	45	5	50
B2	125℃ to -25℃	1	9.75	95	5	100
B3	125℃ to -25℃	1	13.96	195	5	200
C1	-25℃-125℃	-	-	-	-	-
C2	125℃ to -25℃	-	-	-	-	-
C3	-	1	9.75	95	5	100

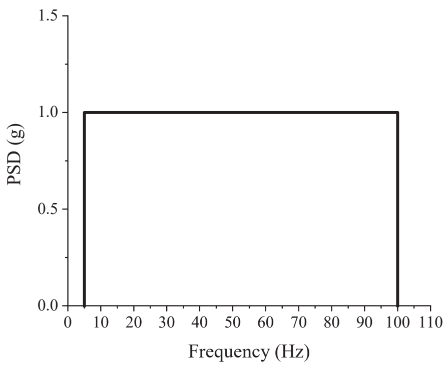


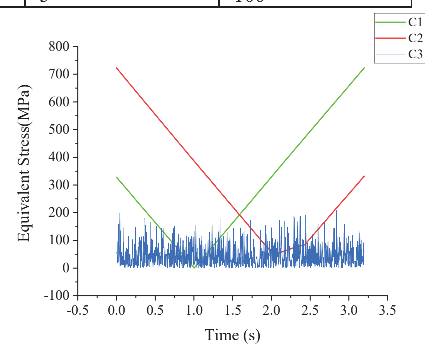
Figure 5. The PSD spectrum of A2

IV. RESULT ANALYSIS

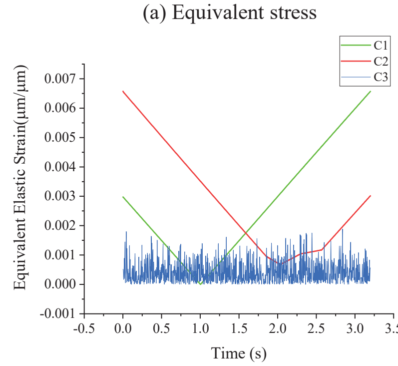
The load parameters in Section 3.4 were loaded into the model for solution, and the equivalent stress, elastic and plastic strain time-domain response of the structure were obtained.

A. Analysis of Solution Results under the Thermal Load or Vibration Load

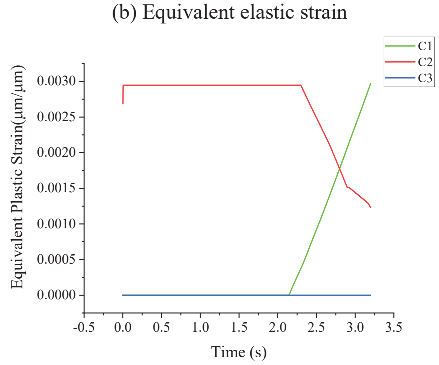
Fig.6(a), (b) and (c) respectively show the maximum equivalent stress, equivalent elastic strain and equivalent plastic strain of TSV structure under the heating, cooling or random vibration load. It can be seen that under the heating load of -25-125℃(C1), the structural thermal stress first decreases from about 300 MPa to the unstressed state, and there is a clear inflection point at 25℃, because the structural unstrained reference temperature was set to 25℃. As the temperature continues to rise, the thermal stress rises to around 730 MPa. During the cooling process (C2), the thermal stress first decrease from about 730 MPa to unstressed state and then rise to about 300 MPa, but the heating process and the cooling process are not symmetrical, because the plastic strain occurs at the high temperature as shown in Fig. 6(c). The thermal strain exhibits the same laws as thermal stress. The maximum equivalent stress and the maximum elastic equivalent strain of the structure under random vibration load are random signals, but much smaller than thermal stress and strain, and no plastic strain occurs.



(a) Equivalent stress



(b) Equivalent elastic strain



(c) Equivalentplastic Strain

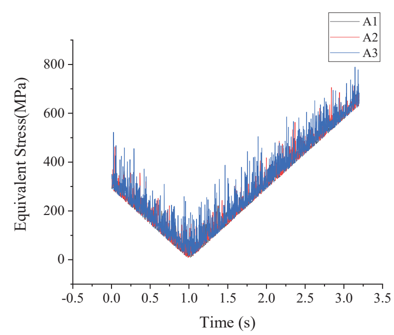
Figure 6. The simulation results of TSV under thermal load or vibration load

It can be seen that the thermal stress and strain of the TSV structure under the thermal load tend to be small in frequency but large in magnitude and plastic strain occurs, while the stress and strain under the vibration load tend to be higher in frequency but smaller in magnitude with no plastic strain occurred. Therefore, the structure often suffers from low-cycle strain fatigue under the thermal load and the high-cycle stress fatigue under the vibration load.

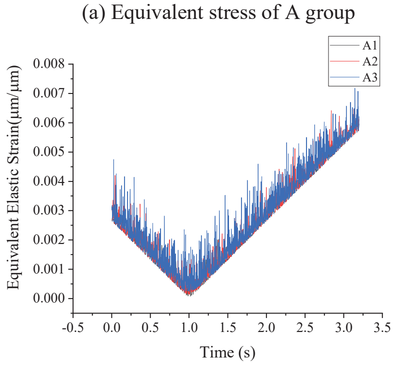
B. Analysis of solution results under thermal-vibration coupled load

Fig.7 shows the simulation results of the maximum equivalent stress, elastic strain and plastic strain of the TSV structure under the thermal-vibration coupled load. It can be seen from the figure that the trend of the maximum equivalent stress and elastic strain of the TSV structure under the thermal-vibration coupled load are consistent with the stress and strain under the thermal load alone, but the amplitude is higher. The amplitude change frequency, the maximum and average value are both greater than the thermal load or the vibration load alone. For example, the maximum equivalent stress of A1 reaches nearly 800 MPa, and the maximum equivalent stress of B1 has exceeded 800 MPa. This indicates that the life of the TSV structure under the thermal-vibration coupled load will be less than that under the thermal load or the vibration load alone. Therefore, it is unsafe to evaluate the reliability of the TSV structure by just considering thermal load alone. The accurate evaluation of the life of TSV structure requires full consideration of the combined effects of thermal and vibration load.

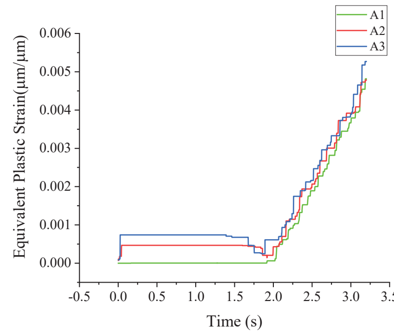
On the other hand, as can be seen from Fig.7, the maximum equivalent stress, elastic strain and plastic strain of A3 are the largest compared with A1 and A2, and A2 is the second, A1 is the smallest. And group B obeys the same rule:B3>B2>B1.



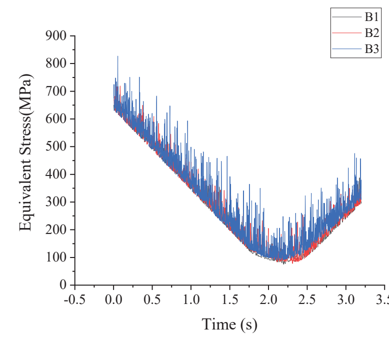
(a) Equivalent stress of A group



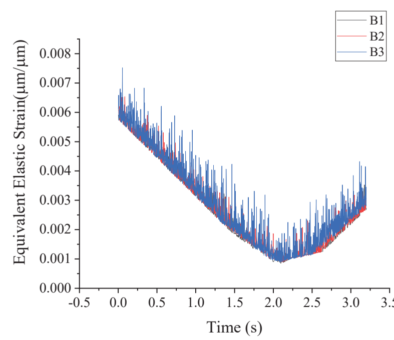
(b) Equivalent elastic strain of A group



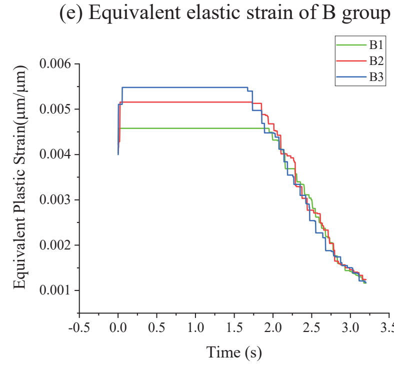
(c) Equivalent plastic strain of A group



(d) Equivalent stress of B group



(e) Equivalent elastic strain of B group



(f) Equivalent plastic strain of B group

Figure 7. The simulation results of TSV under thermal and vibration coupled load

This shows that when the thermal load is the same and the magnitude of the random vibration load PSD is kept constant, the larger the bandwidth or the RMS value of the vibration load, the larger the stress and strain of the TSV structure, so that the structural life is smaller.

V. CONCLUSIONS AND OUTLOOK

In this paper, the typical TSV microstructure of 3D integrated packaging technology was studied. Based on the coupled field finite element analysis, the stress and strain under the thermal-vibration coupled load were numerically analyzed. The following conclusions can be drawn:

(1) Under the thermal load (including heating, cooling, thermal cycling, thermal shock, etc.), the TSV microstructure tends to suffer low-cycle strain fatigue, and high-cycle stress fatigue is prone to occur under vibration load.

(2) The maximum equivalent stress, elastic strain and plastic strain of the TSV microstructure under the thermal-vibration coupled load are greater than the structure under thermal load or the vibration load alone, so the life of TSV under the thermal-vibration coupled load is smaller. Therefore, in the reliability evaluation of TSV structure, it is necessary to comprehensively consider the coupling effect of thermal and vibration load.

(3) When the thermal load conditions are the same and the PSD magnitude of the vibration load is constant, the larger the vibration load bandwidth or the RMS value, the smaller the structural fatigue life.

The above research results can provide important reference for the subsequent life evaluation and reliability test of TSV microstructure under the thermal-vibration coupled load. On the other hand, the research in this paper is only a preliminary exploration. In order to evaluate the life of TSV structure under the thermal-vibration coupled load, there are still many aspects that need further research, such as failure mechanism and damage accumulation criterion of electroplated copper. In addition, the influence of different parameters of thermal and vibration load on the reliability of TSV structure requires more comprehensive research.

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