

Effect of Thermal Cyclic Loading on Stress-Strain Response and Fatigue Life of 3D Chip Stacking Structure

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Effect of thermal cyclic loading on stress-strain response and fatigue life of 3D chip stacking structure

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Abstract In this paper, the thermo-mechanical reliability of IMCs (Ni_3Sn_4 , Cu_3Sn , Cu_6Sn_5) solder joints and Sn-3.9Ag-0.6Cu solder joints were investigated systematically in 3D chip stacking structure subjected to an accelerated thermal cyclic loading based on finite element simulation and Taguchi method. Effects of different control factors, including high temperature, low temperature, dwell time of thermal cyclic loading, and different IMCs on the stress-strain response and fatigue life of solder joints were calculated respectively. The results indicate that maximum stress-strain can be found in the second solder joint on the diagonal of IMC solder joints array, for Sn-3.9Ag-0.6Cu solder joints array the corner solder joints shows the obvious maximum stress-strain, these areas are the crack propagated locations. The stress-strain and fatigue life of solder joints is more sensitive to dwell temperature, especially to high temperature, increasing the high temperature, dwell time, or decreasing the low temperature, can reduce the stress-strain and enlarge the fatigue life of solder joints. The optimal design in the 3D IC structure has the combination of the $\text{Cu}_6\text{Sn}_5/\text{Cu}_3\text{Sn}$, 373K high temperature, 233K low temperature, and 10min dwell time.

Key words 3D IC, Taguchi method, control factors, fatigue life

1 Introduction

With the development of chip technology, the use of Moore's law in microelectronic industry may approach the limit, three-dimensional integrated circuits (3D-IC) technology can overcome the limitations of the Moore's law with the advantage of high density integration, high performance and low power consumption^[1-3]. Therefore, the chip stacking in 3D IC has attracted considerable attention in electronic industry, different bonding technology have been developed to ensure the chip (or wafer) vertical stacking, among the bonding technology, TLP bonding with solder has been proposed as an effective method to implement low temperature bonding and high temperature service.

Talebanpour^[4] used Sn3.0Ag0.5Cu as interconnection materials in 3D structure with 260°C reflow temperature and aging to obtain total IMC ($\text{Cu}_6\text{Sn}_5/\text{Cu}_3\text{Sn}$). Chu^[5] investigated Cu/Sn/Cu and Ni/Sn/Ni solder joints for low temperature stable transient liquid phase (TLP) bonding, Cu_6Sn_5 , Cu_3Sn , Ni_3Sn_4 , Ni_3Sn_2 can be detected respectively. Chen^[6] investigated the Cu/Sn3.5Ag/Cu and Cu/Sn3.5Ag/Cu15Zn based on TLP bonding, Cu_6Sn_5 and $\text{Cu}_6(\text{Sn}, \text{Zn})_5$ were found in the solder joints, it is found that the Cu_6Sn_5 can weaken the bond reliability resulting from its homogeneous grain structure and brittleness, the Zn can effectively modify the homogeneous grain structure into interfolded structure to enhances the bond reliability. In 3D IC structure, the reliability of complete IMC solder joints under thermal cycling loading, have been consider as an important research aspect, the finite element code can be used to calculate the stress-strain response and fatigue life of IMC solder joints. Tian^[7] researched the stress analysis and structure optimized of IMC joints in 3D

package with finite element simulation, it is found that the resin thickness played the most important role but the resin hardness played the least important role in affecting the stress in the IMC joint.

In this paper, the IMCs and Sn-3.9Ag-0.6Cu solder joints have been considered in 3D IC, the effect of high temperature, low temperature, dwell time of thermal cyclic loading, and different IMCs on the solder joints reliability during thermal cyclic loading was studied using finite element method and Taguchi method. The results can provide an effective way to evaluate the reliability of IMC and Sn-3.9Ag-0.6Cu solder joints in 3D IC.

2 FEM analysis

In 3D ICs, the most significant elements of the enabling technology for handling and double-sided processing of extremely thin chips are the temporary bonding and debonding processes at lower temperature and higher throughput^[8]. A common 3D device is shown in Fig.1, the two chips are bonded to form IMCs solder joints using TLP bonding, then the assembly is soldered on BT substrate with Sn-3.9Ag-0.6Cu alloy using reflow soldering bonding, meanwhile, during the second bonding, the first-level IMCs solder joints will not be molten and keep stable state. As the process of thermal cycling test is very time consuming and costly, finite element simulation is widely accepted in analyzing the mechanics and reliability of materials and structures like an electronic package especially during the design stage^[9]. Finite element method has been proposed by many researchers to calculate the stress-strain and to predict the reliability of solder joints. The quarter symmetric FEA model of the 3D IC was utilized because of the symmetry both in the geometry, which can reduce the computational time. The quarter models have been utilized in BGA, CSP, WLCSP and QFP devices successfully in finite element simulation to calculate the fatigue life of solder joints under thermal cycle loading^[10-12].

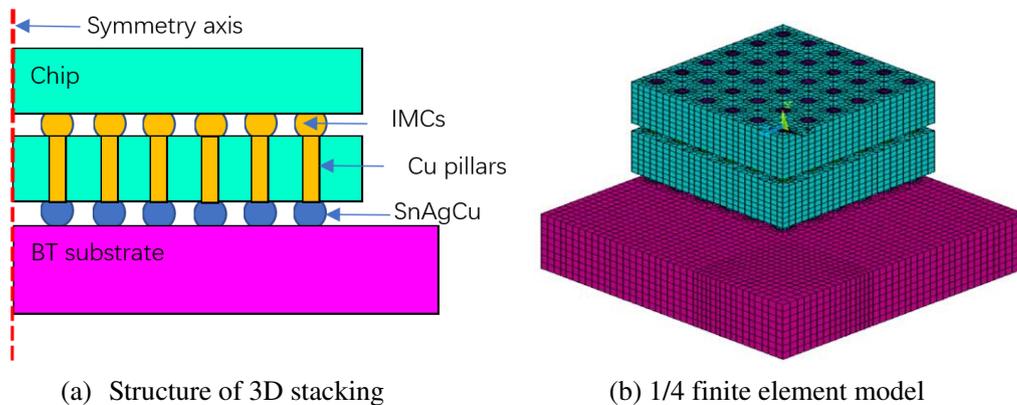


Fig.1 Finite element model of 3D IC

The finite element model of the 3D IC is shown in Fig.1 (b), the model consists of chips, IMCs/Sn-3.9Ag-0.6Cu solder joints, TSV Cu pillars, BT substrate and Cu/Ni pads. SOLID186 with 20-node hexahedral element was selected to model the complex geometry to calculate the stress-strain response, and sweep mesh method was utilized in modeling. Since the focus is on the solder joints, finer meshes are used to model the 3D assembly, Fig. 2 shows the IMCs solder joints and Sn-3.9Ag-0.6Cu lead-free solder joints array. Meanwhile, the displacement boundary conditions are considered respectively, zero displacement constraints of vertical direction of the cross-area were applied to the cross-sections of the quarter model, namely all nodes on the symmetric surface ($X=0$, $Z=0$) were fixed in the corresponding directions (X , Z), and the node at the origin ($X=Y=Z=0$) was

constrained in all three directions.

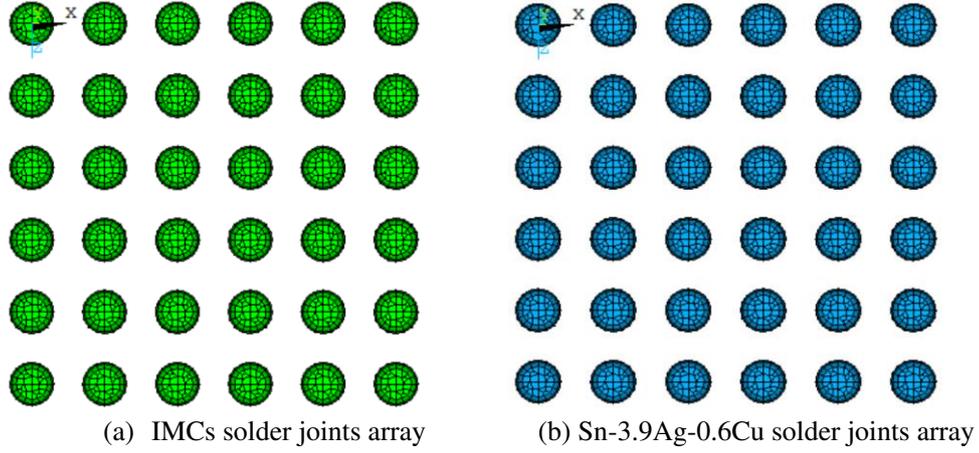


Fig.2 Finite element model of solder joints array

Table 1 shows the material parameters of the chip, IMCs solder joint, Ni/Cu pads and BT substrate in 3D assembly, these material parameters are assumed to be isotropic, linearly elastic and independent of temperature except for those of Sn-3.9Ag-0.6Cu solders^[13]. It was well demonstrated that creep plays a very important role in deformation behavior of materials at homologous temperatures close to and above 0.5 if the loading rate is slow enough for creep deformations to occur^[14]. The Sn-3.9Ag-0.6Cu lead-free alloy is subjected to high homologous temperatures (0.61) at room temperature. Therefore, the creep response may be considered as the main deformation of solder joints in service. In the finite element simulation, Garofalo-Arrhenius model was employed extensively to describe the steady-state creep of lead-free solder alloys^[15], Eq.(1) shows the creep model to calculate the creep behavior of Sn-3.9Ag-0.6Cu solders.

$$\frac{d\gamma}{dt} = C \left(\frac{G}{T} \right) \left[\sinh \left(\omega \frac{\tau}{G} \right) \right]^n \exp \left(-\frac{Q}{RT} \right) \quad (1)$$

where $\frac{d\gamma}{dt}$ is the creep shear strain rate, G is the shear modulus, T is the absolute temperature, ω is the stress level, n is the stress exponent, R is the gas constant, C is the materials constant.

If the solder materials obey the von Mises criterion, the creep equation can be rearranged and expressed as^[16]

$$\dot{\epsilon} = C_1 \left[\sinh(C_2 \sigma) \right]^{C_3} \exp \left(-\frac{C_4}{T} \right) \quad (2)$$

where $\dot{\epsilon}$ is the equivalent creep strain rate, σ is the equivalent stress, T is the absolute temperature. C_1 , C_2 , C_3 and C_4 are the materials constants, which are given in Table 2 for SnAgCu solder.

Table 1 Parameters of materials

Materials	E/MPa	μ	CTE/ $\times 10^{-6} K^{-1}$
Sn-3.9Ag-0.6Cu	43700-22.3T	0.4	20.9
Chip	163000	0.28	2.5
BT	26000	0.39	15
Cu	117000	0.23	16.6
Ni	207000	0.31	13.1

Cu_3Sn	143000	0.3	18.2
Cu_6Sn_5	124000	0.3	19.0
Ni_3Sn_4	134000	0.33	13.7

Table 2 Parameters of creep

Materials	C_1	C_2	C_3	C_4
Sn-3.9Ag-0.6Cu	441000	5E-9	4.2	5412

In evaluation of electronic device, accelerated thermal cycling tests are often utilized to speed up the thermal fatigue failure process assess the reliability of lead-free solder joints under cyclic temperature variation. According to the thermal cycling testing^[17], temperature from 218K to 398K was proposed to evaluate the reliability of IMCs and Sn-3.9Ag-0.6Cu lead-free solder joints in 3D IC, and duration of thermal cycle is 60min, including 15 min dwell at 218K and 398K, which was shown in Fig.3. In order to analyze the parameters on the reliability of solder joints, high temperature, low temperature, dwell time of thermal cyclic loading are considered in finite element simulation, during the analyzing, the variation of high temperature, low temperature and dwell time are considered, the duration of thermal cycle still is 60min. In addition, it is assumed that no stress occurs at the initial temperature and at all nodes in the 3D assembly are loaded a uniform temperature distribution in the finite element simulation.

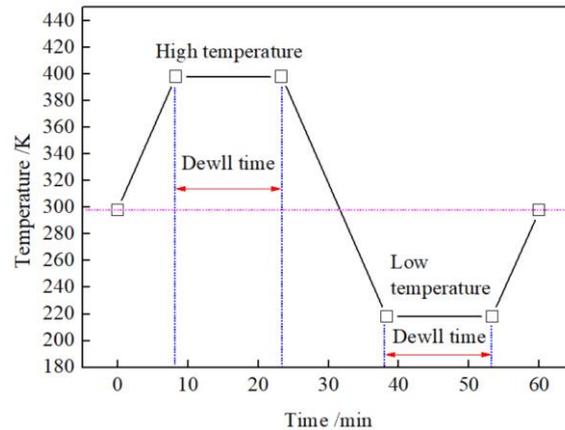


Fig.3 Temperature profile of thermal cyclic loading

3 Results and discussion

Fig.4 plots the von Mises stress and von Mises total mechanical strain of IMCs solder joints in 3D assembly, the maximum strain-strain is obtained in the second IMC solder joint of the chip oriented diagonally, which demonstrate that the diagonal position is more critical than the rectangular one. However, the stress-strain response of IMC solder joints is different with that of Sn-3.9Ag-0.6Cu solder joints. Fig.5 show the von Mises stress and von Mises total mechanical strain of Sn-3.9Ag-0.6Cu solder joints in the array, the findings show that the von Mises stress and von Mises total mechanical strain obviously with the increase of distance to neutral point, the maximum stress and strain occurred on the outer solder joint, and concentrated on the top surface of corner solder joint near the chip, the area may be the failure location of 3D assembly. In WLCSP device, Wu^[18] also found that the dangerous zone is the corner of the solder joint near the chip pad side, in addition, the crack extend in the location from experimental result, which demonstrates that the stress-strain response calculated can predict the failure location of solder joints.

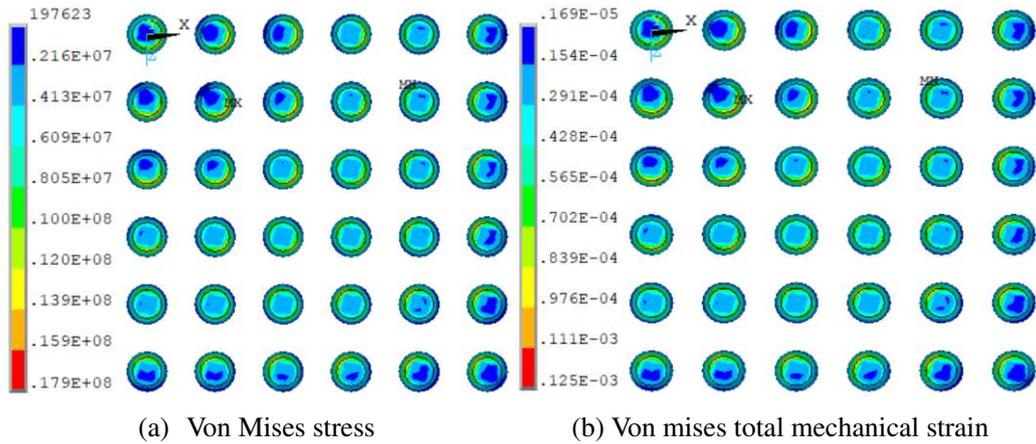


Fig.4 Stress-strain response of IMCs solder joints after thermal cyclic loading

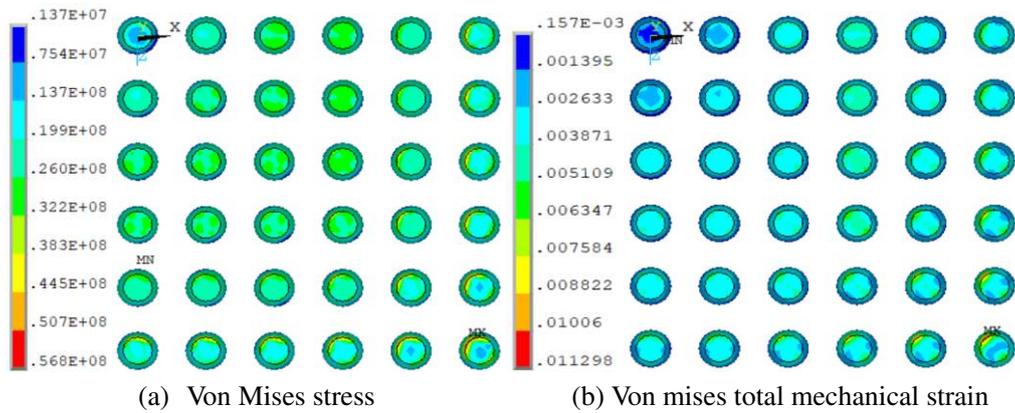


Fig.5 Stress-strain response of Sn-3.9Ag-0.6Cu solder joints after thermal cyclic loading

Fig.6 shows the deformed shapes (500X) of the 3D assembly after three thermal cycles, the maximum displacement can be found in the Sn-3.9Ag-0.6Cu solder joint array, it can be found with the increasing of the distance with the center solder joints, the displacement increases obviously, the displacement mainly concentrates at corner solder joints in the 3D assembly, due to the mismatch of thermal expansion coefficient between chip and substrate, the solder joints are subjected to very lager deformation. In WLCSP device, Lau^[19] found the same phenomena in WLCSP device with Sn-2Ag-36Pb and Sn-3.5Ag solders under thermal cycle loading.

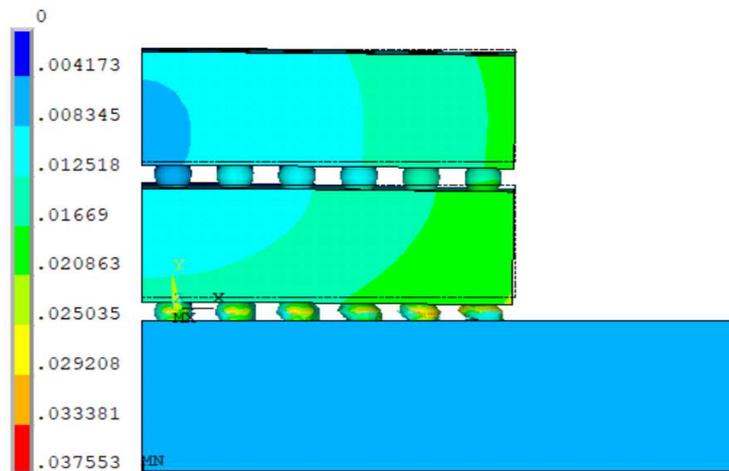


Fig.6 Displacement vector sum (500X)

The Taguchi method is widely used to analyze the factor level combination and to assess effect factor, so the method is selected in our research to determine the effect of different control factors on the reliability of solder joints in the 3D assembly. In 1980, Taguchi's introduction of robust design to several major American industries, including AT & T, Ford and Xerox, resulted in significant quality improvements in product and manufacturing process design^[20]. For Taguchi method, the orthogonal array (OA) and signal-to-noise (S/N) ratios are the main instruments for economically conducting and analyzing an experiment^[21]. The idea of orthogonal arrays is to get the statistic information and robust process conditions during shorter time by using fewer analyses. With the consideration of control factors and their levels, the $L_9(3^4)$ orthogonal array is to be used in the optimized experiment to minimize the creep strain $\Delta\varepsilon$. The robust design (or quality) characteristics can be classified into three different types: 1) Nominal-the best, 2) smaller-the-better, and 3) larger-the-better^[22]. In 3D assembly, the design of the chip stacked structure, the stress-strain of the solder joints has to be minimized, the smaller-the-better criteria is suitable to describe the experimental results. The signal-to-noise (S/N) objective function for the quality characteristic of smaller-the-better type was computed as shown in Eq.(3):

$$S/N = -10\log\left(\frac{\sum_{i=1}^r y_i^2}{r}\right) \quad (3)$$

where r is the total number of measurements, y_i is the i th measurement data, and S/N is the signal-to-noise ration in decibel.

In the finite element simulation, the $r=1$ and $y = \Delta\varepsilon$, so the $\frac{\sum_{i=1}^r y_i^2}{r} = \Delta\varepsilon^2$, therefore, the

Eq.(3) can be transforms to

$$S/N = -10\log(\Delta\varepsilon^2) \quad (4)$$

The four selected control factors and their levels applied in this study are tabulated in Table 3. these control factors contain high temperature, low temperature, dwell time of thermal cyclic loading, and different IMCs. And the control factors all show three levels. Cu_6Sn_5 , Cu_3Sn and Ni_3Sn_4 IMCs were selected in this paper, these IMCs show higher melting temperature than Sn-based alloys.

Table 3 Control factors and levels

Control factors		Level 1	Level 2	Level 3
A	IMC	Cu_6Sn_5	Cu_3Sn	Ni_3Sn_4
B	High Temperature	423K	398K	373K
C	Low Temperature	233K	218K	213K
D	Dwell time	15min	12.5min	10min

The Taguchi method can effectively find out the optimal condition of production to ensure the consistency and get the best quality control with the lowest cost^[23]. In order to obtain the optimal parameters of the 3D assembly, the main experiment is carried out to analyze the control factors and levels within Taguchi method. Table 4 shows the simulated creep strain ($\Delta\varepsilon$) and the S/N ration for each experiment cells on the $L_9(3^4)$ orthogonal array. It is found that with the variation of high temperature, low temperature, dwell time of thermal cyclic loading, and different IMCs, the creep strain ($\Delta\varepsilon$) and S/N ratio change significantly. The smaller value of creep strain ($\Delta\varepsilon$) demonstrated

that the more reliability of Sn-3.9Ag-0.6Cu solder joints in 3D assembly. And the evaluation of Sn-3.9Ag-0.6Cu solder joints is based on the quality factor $\Delta\varepsilon$.

Table 4 Main experiment

EXP.	Factor and level				Quality	
	A	B	C	D	$\Delta\varepsilon$	S/N
1	1	1	1	1	0.0842156667	21.49
2	1	2	2	2	0.0705263333	23.03
3	1	3	3	3	0.0557870000	25.07
4	2	1	2	3	0.0833843333	21.58
5	2	2	3	1	0.0706106667	23.02
6	2	3	1	2	0.0562143333	25.00
7	3	1	3	2	0.0838226667	21.53
8	3	2	1	3	0.0695220000	23.16
9	3	3	2	1	0.0570686667	24.87
Average						23.19

Fig.7 shows the S/N ratio response diagram of the four control factors, magnitudes of the control factors response and ranks are summarized in Table 5. According to the S/N response diagram, the greater is the S/N ratio, the smaller is the variation of equivalent creep strain, the effect of four factors is different, the contribution degree of the four factors is Factor B (High Temperature) > Factor D(Dwell time) > Factor C(Low Temperature) > Factor A(IMCs), the most important factor is the high temperature, which demonstrates that the reliability of the Sn-Ag-Cu solder joints in 3D assembly can be influenced mainly by high temperature of thermal cycles loading, other three parameters have small impact on the reliability, especially for IMCs, we should enhance the reliability of Sn-Ag-Cu solder joints based on the optimal design. And the optimal parameters match is A1/2B3C1D3, namely the optimal design in the 3D assembly has the combination of the Cu₆Sn₅/Cu₃Sn, high temperature at 373K, low temperature at 233K, Dwell time at 10min. Moreover, it is imperative to illustrate that when the levels are varied, the optimal set of the control factors and rank then change obviously. The effect deviation of factor (IMCs) on S/N repose is very small and negligible.

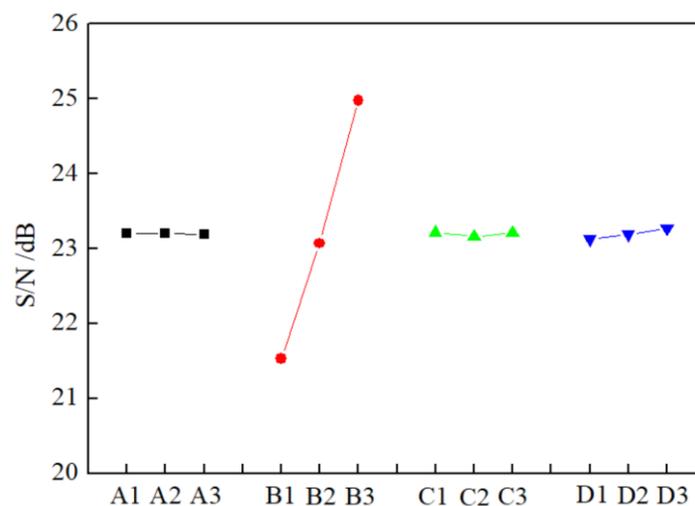


Fig.7 S/N response diagram

Table 5 S/N response and rank

	Factor and level			
	A	B	C	D
Level 1	23.20	21.53	23.22	23.13
Level 2	23.20	23.07	23.16	23.19
Level 3	23.19	24.98	23.21	23.27
Effect	0.01	3.45	0.06	0.14
Rank	4	1	3	2

For the two different temperature profiles of thermal cycle loading, the durations of thermal cycle are all 60min, only high temperature, low temperature, dwell time are different, based on the finite element simulation combined with Taguchi method, only high temperature can affect the reliability of solder joints, when high temperature (T) changes obviously, the ramp rate ($r = T / s$) will also vary. Therefore, in this paper, high temperature and ramp rate have same effect, only high temperature was selected as a analyzed parameter.

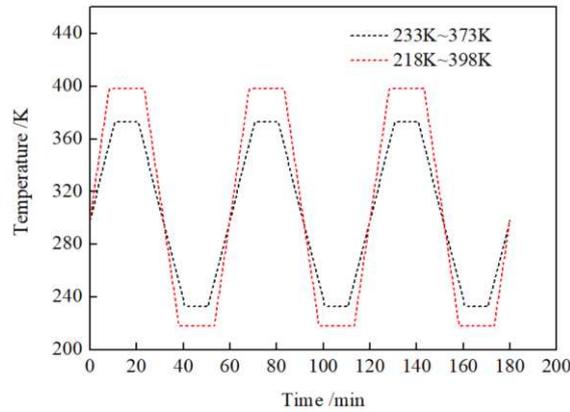


Fig.8 Two different temperature profiles of thermal cyclic loading

Fig.9 shows the history of von Mises stress and equivalent creep strain history at the corner Sn-3.9Ag-0.6Cu solder joints of the 3D assembly, respectively. It is found that the von Mises stress and equivalent creep strain history of Sn-3.9Ag-0.6Cu solder joints under 218K~398K loading is higher than that of solder joints under 233K~373K loading, which demonstrates that the decrease of high temperature can decrease the von Mises stress and equivalent creep strain history under thermal cycling. Moreover, low stress can be found in the von Mises stress curve during the high temperature stage of the thermal cyclic loading, while high stress appears in the low temperature stage. Due to creep effect stress relaxation happens both at the high and low temperature dwell stage. For the second and third thermal cycle, the Sn-3.9Ag-0.6Cu solder joints reach a stabilized cyclic pattern where the highest stress is experienced at the beginning of the low temperature dwell and the lowest stress at the end of the high temperature dwell because of the viscous behavior of the solder joints. Meanwhile it is observed that both equivalent creep strain increase as the temperature cycle proceeds, and the thermally induced cyclic creep deformation tends to accumulate as the number of the thermal cycle increase. The creep strain of Sn-3.9Ag-0.6Cu solder joints under 218K~398K loading higher than that of solder joints under 233K~373K loading, which can be attributed to the enhancement of creep strain with the increase of high temperature. Moreover, the high temperature increases, the ramp rate will increase significantly, the equivalent creep strain will be boosted.

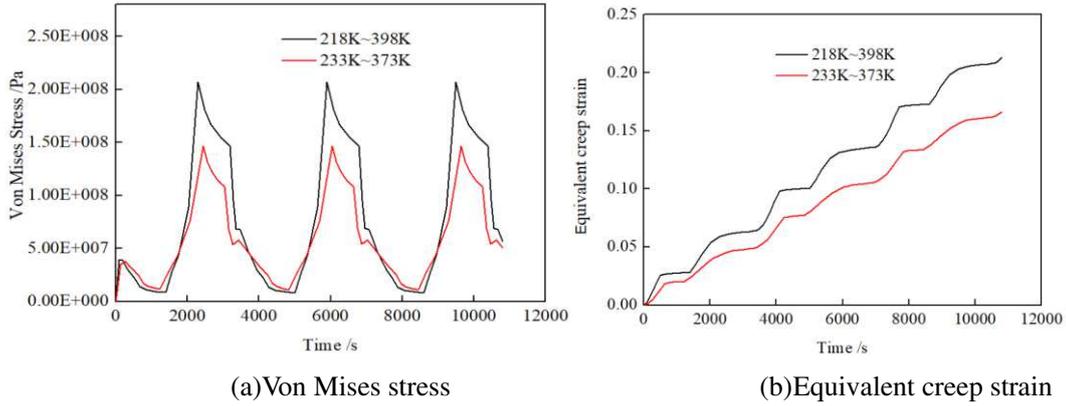


Fig.9 Stress-strain response of Sn-Ag-Cu solder joints

With the finite element simulated data, combining the fatigue life equations of the solder joints, the Sn-3.9Ag-0.6Cu solder joints in 3D assembly can be calculated effectively. A number of fatigue life prediction models have been proposed in the literature, and the prediction equations based on accumulated creep strain show obvious superiority. Syed^[24] suggested that creep is the primary damage mechanism for Sn-Ag-Cu solder during thermal cycling and can be used to simulate the material's behavior, so the creep deformation can be considered in the life prediction model. Fatigue life prediction equation of Sn3.9Ag-0.6Cu solder joints based on accumulated creep strain is as follows^[25]:

$$N_f = (0.0405\Delta\varepsilon)^{-1} \quad (5)$$

Where N_f is the number of cycles to failure, $\Delta\varepsilon$ is the accumulated creep strain per cycle.

The fatigue lives of Sn-3.9Ag-0.6Cu under 218K~398K and 233K~373K loading in the 3D assembly based on the creep strain are 347.4 cycles and 445.5 cycles, which demonstrates that the increase of high temperature of the thermal cycles loading can increase the equivalent creep strain and reduce the fatigue life of Sn-3.9Ag-0.6Cu solder joints in 3D assembly. Fig.10 shows the crack of solder joint in experiments (380cycles, 218K~398K), the results have a good agreement with the simulated result predicts the failure location. Due to the mismatch of thermal expansion coefficient between chip and substrate, the solder joint is subjected to creep strain, when the accumulated creep strain reaches a critical value, the crack may initial and propagate.

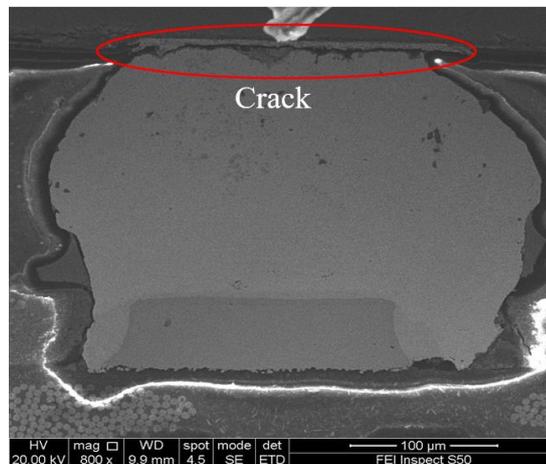


Fig.10 The crack of corner solder joints

4 Conclusion

The stress-strain response of IMCs (Ni_3Sn_4 , Cu_3Sn , Cu_6Sn_5) solder joints and Sn-3.9Ag0.6Cu solder joints in 3D assembly was investigated using finite element simulation and Taguchi method. It is found that the high temperature is most important factor among all the four control factors (high temperature, low temperature, dwell time of thermal cyclic loading, and different IMCs), and the stress-strain response and fatigue life of the Sn-3.9Ag-0.6Cu solder joints in 3D assembly can be influenced mainly by high temperature of thermal cycles loading, other three parameters have small impact on the reliability, especially for IMCs.

Availability of data and materials

All data and materials have been presented in this manuscript.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

Zhang Liang analyzed and interpreted the patient data in this paper, and was a major contributor in writing the manuscript. Zhong Su-juan was responsible for revising the grammar of the manuscript. All authors read and approved the final manuscript.

Acknowledgments (Not applicable)

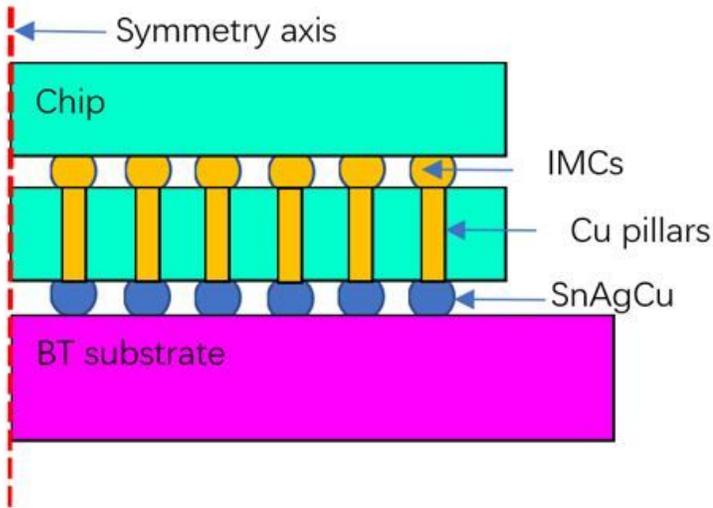
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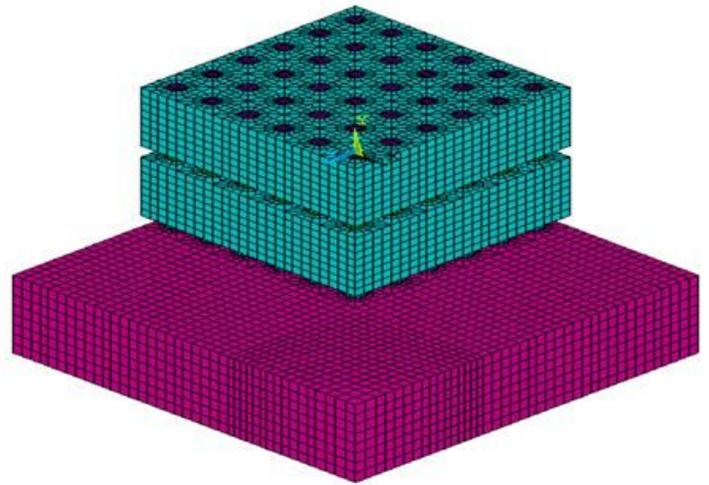
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Figures



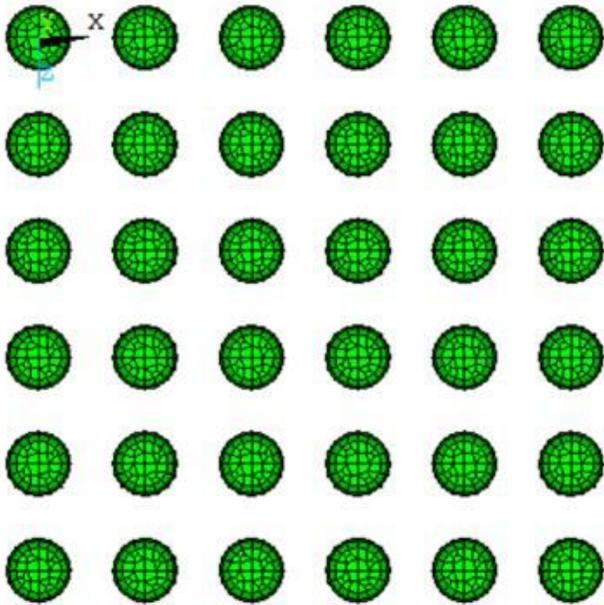
(a) Structure of 3D stacking



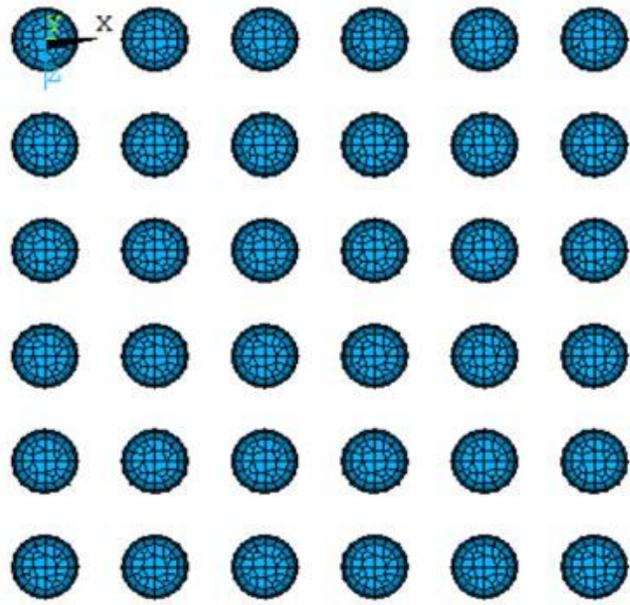
(b) 1/4 finite element model

Figure 1

Finite element model of 3D IC



(a) IMCs solder joints array



(b) Sn-3.9Ag-0.6Cu solder joints array

Figure 2

Finite element model of solder joints array

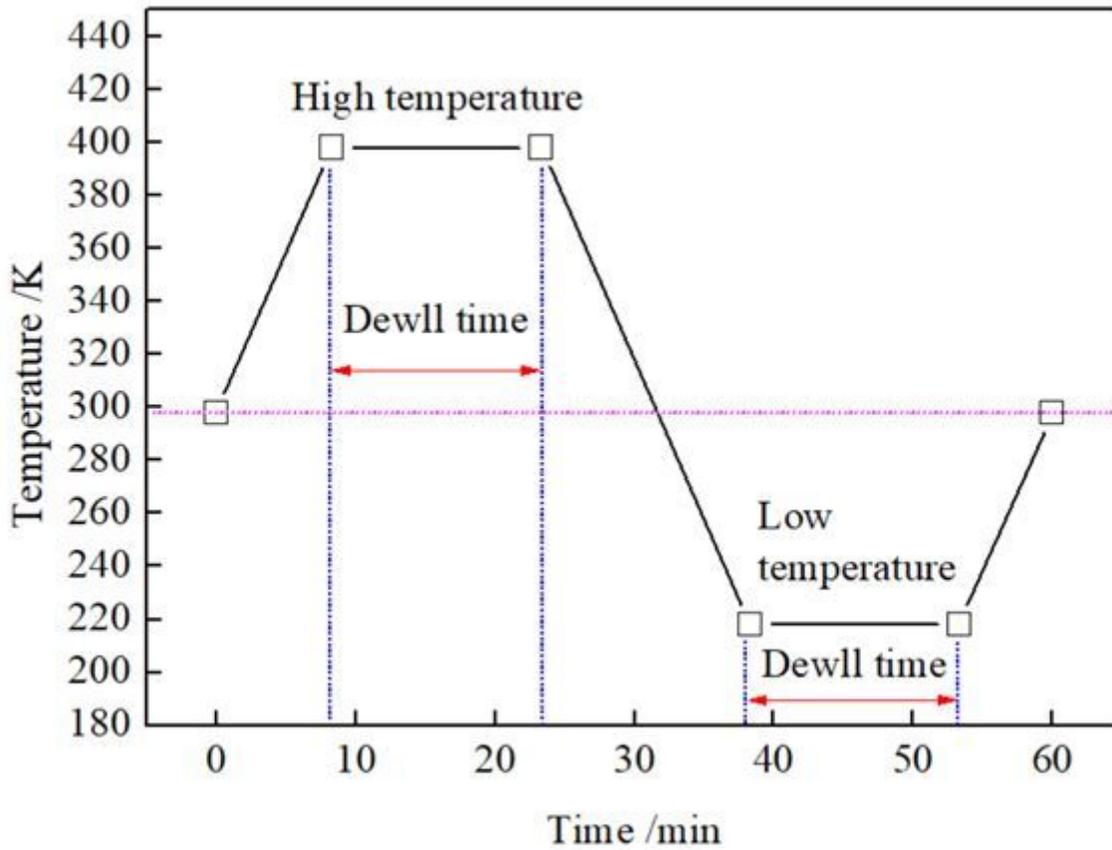


Figure 3

Temperature profile of thermal cyclic loading

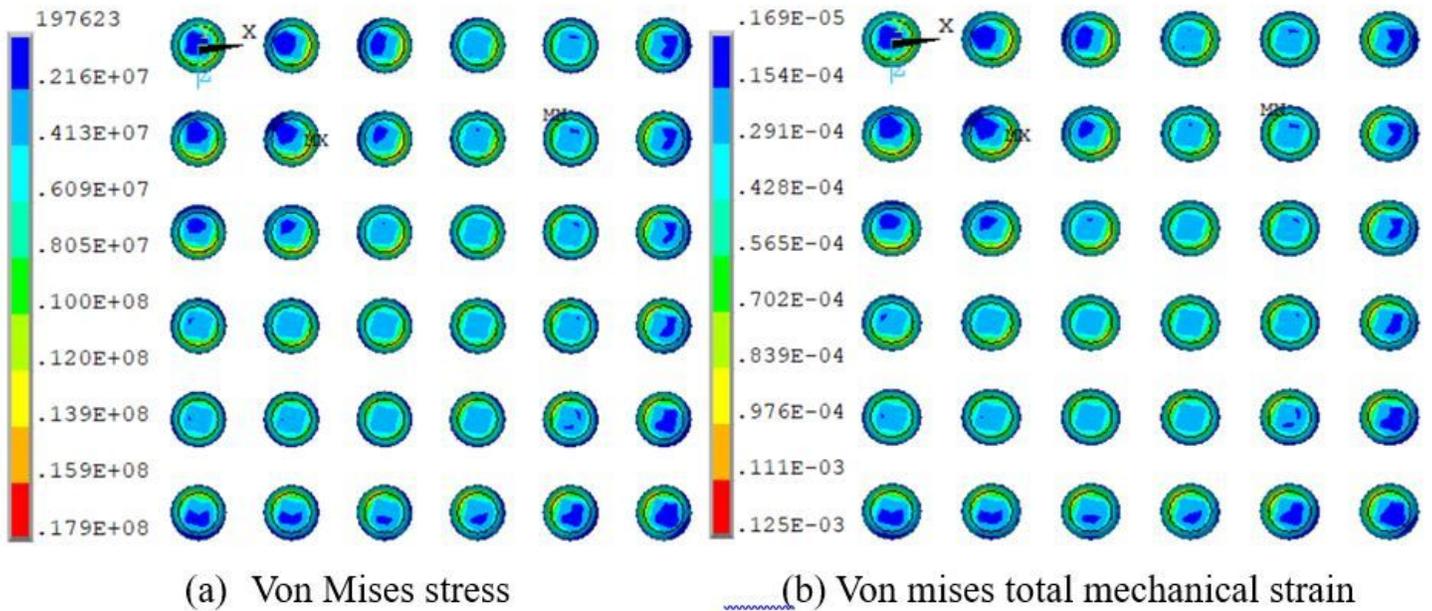


Figure 4

Stress-strain response of IMCs solder joints after thermal cyclic loading

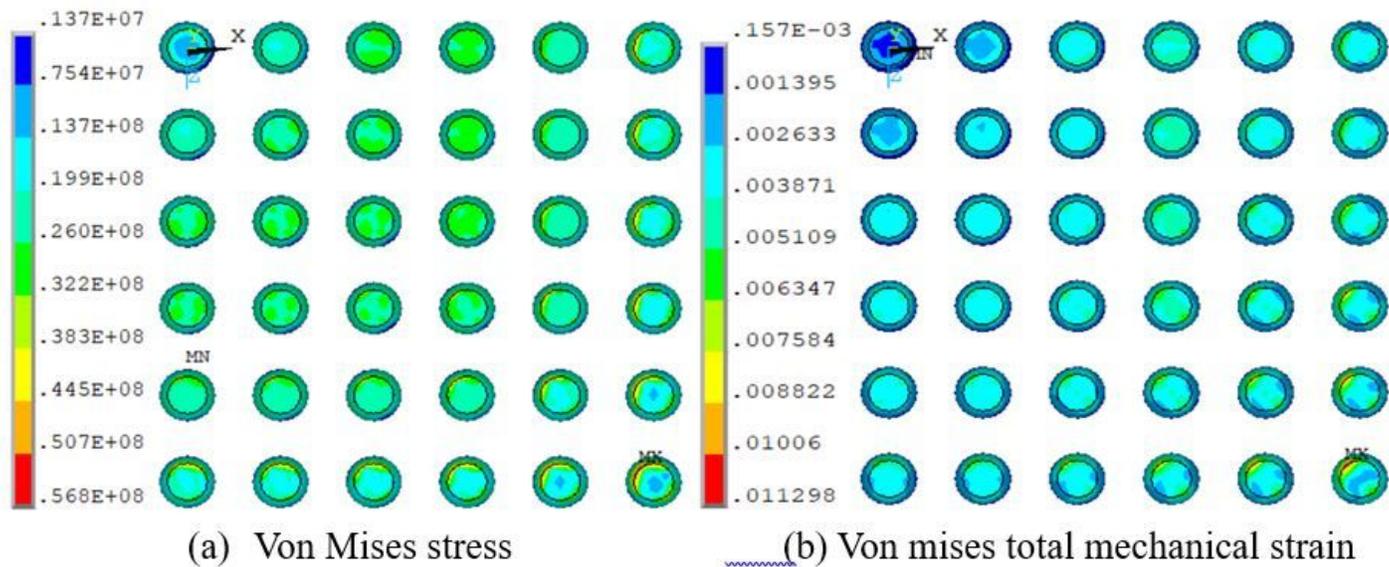


Figure 5

Stress-strain response of Sn-3.9Ag-0.6Cu solder joints after thermal cyclic loading

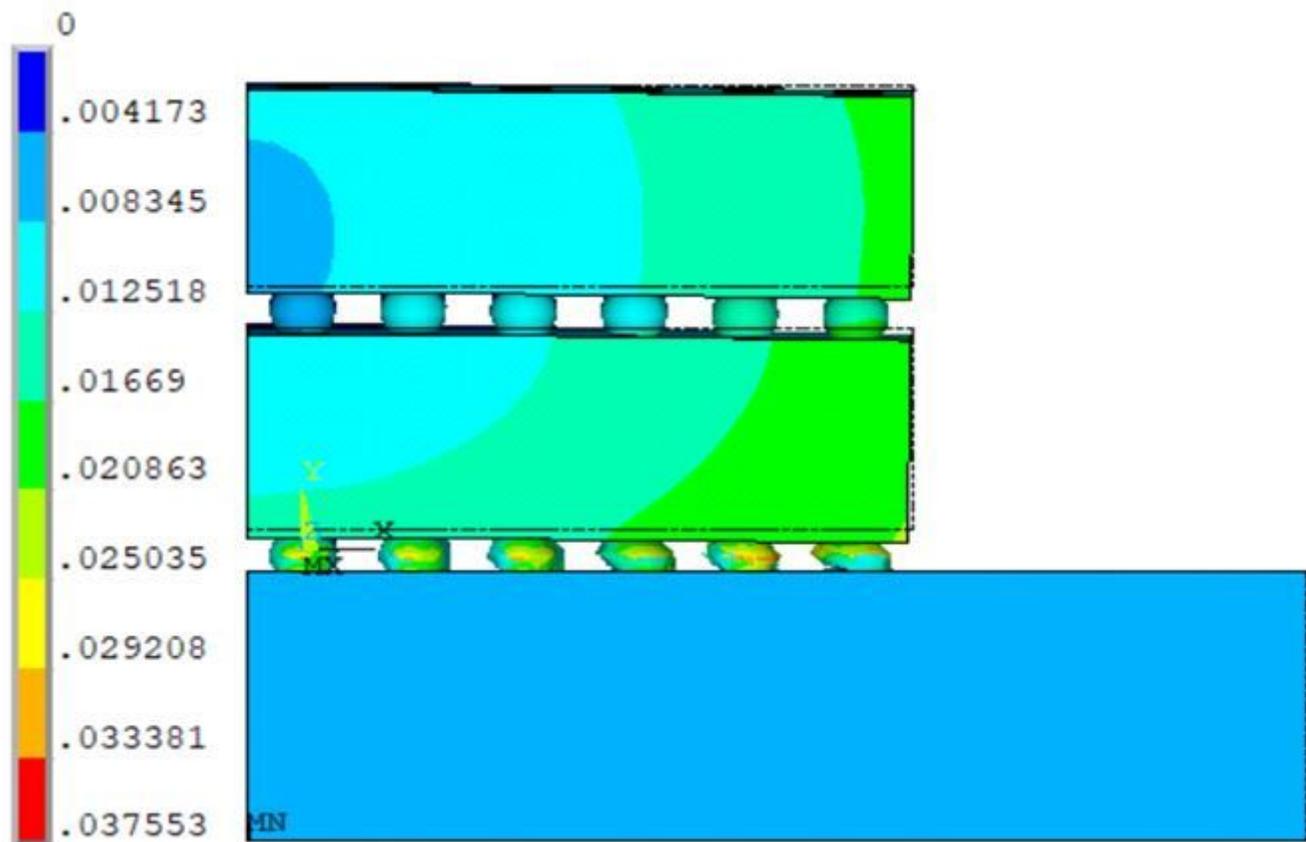


Figure 6

Displacement vector sum (500x)

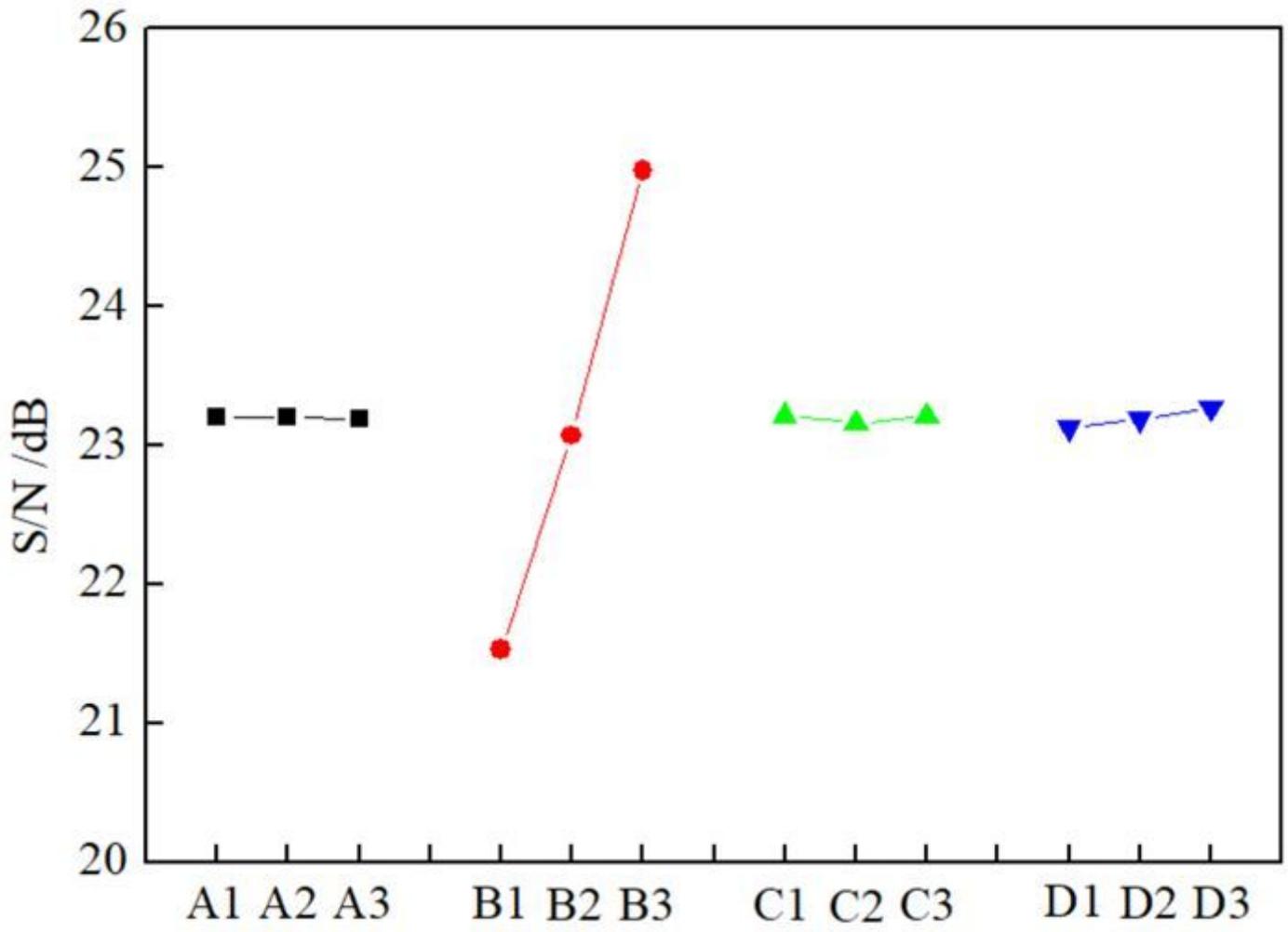


Figure 7

S/N response diagram

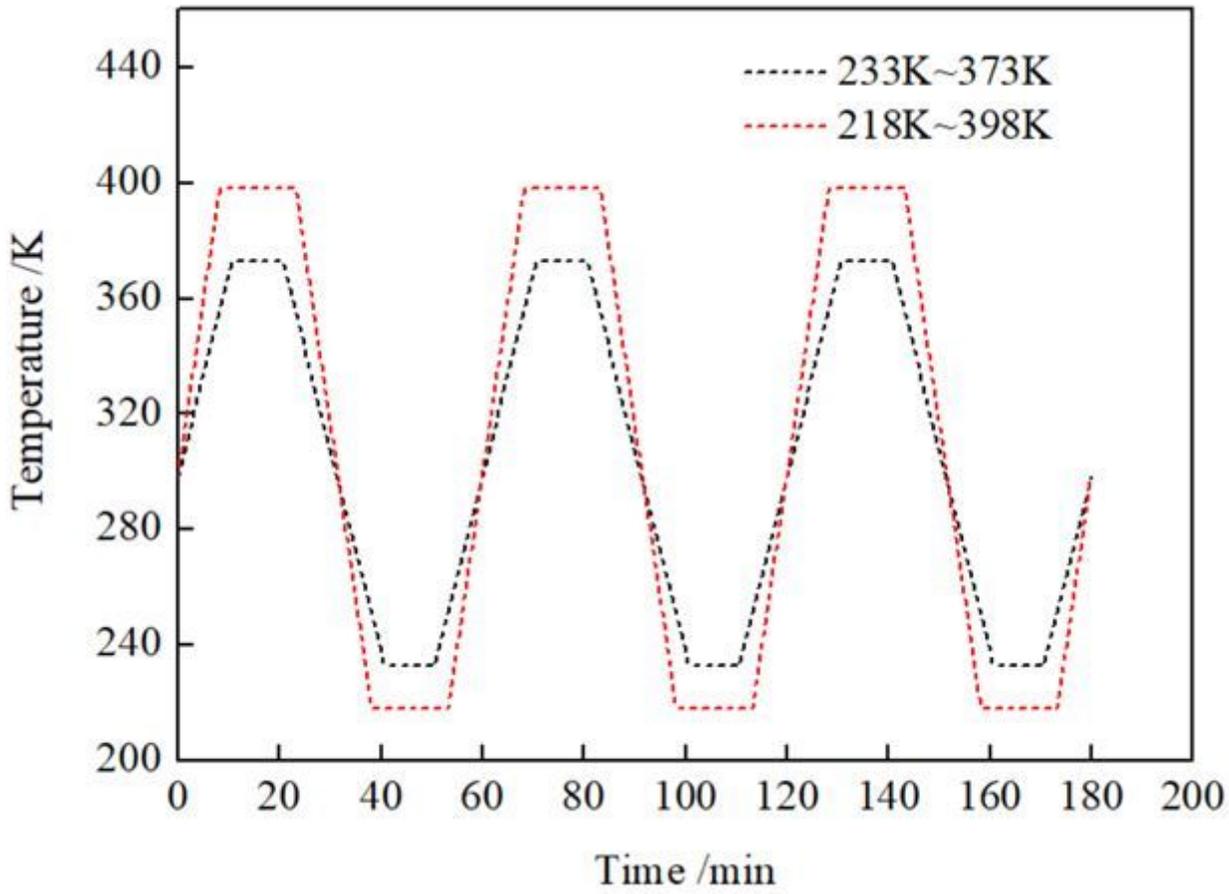


Figure 8

Two different temperature profiles of thermal cyclic loading

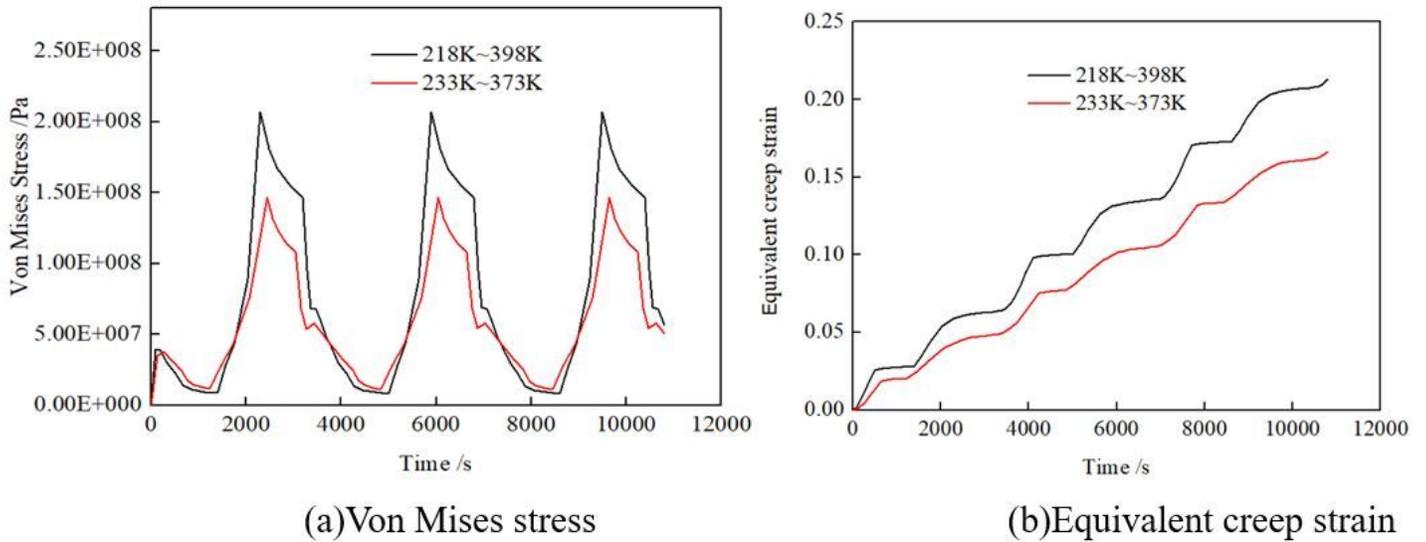


Figure 9

Stress-strain response of Sn-Ag-Cu solder joints

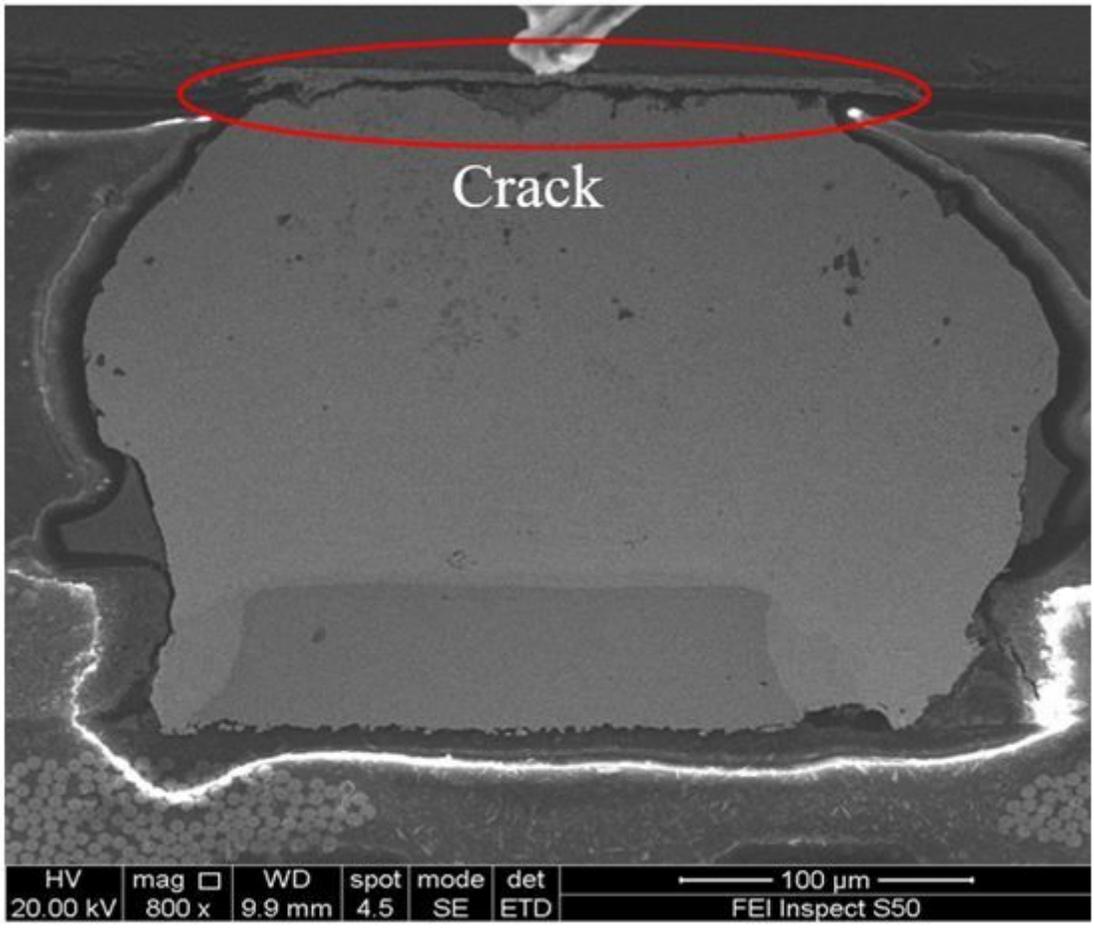


Figure 10

The crack of corner solder joints