

Process capability study and thermal fatigue life prediction of ceramic BGA solder joints

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Abstract

The design and process capability of board-level assembly of ceramic ball grid array (CBGA) packages with respect to their reliabilities were investigated. Two types of FEM models were built for elastic and elastic–plastic–creep analyses, respectively. The effect of PCB material, PCB thickness, and the thickness of ceramic substrate on solder joint deformation was discussed. It was shown that the variation in assembly process would cause the highest stress in the joints change by 10% from the mean value. The failure location and fatigue life under the temperature cycling condition were also studied. It was concluded that the prediction was close to the first failure in the test and would be seen as a conservative estimation. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: BGA; FEM; Fatigue life prediction; Solder joints; Process capability

1. Introduction

BGA is becoming very popular in the electronic industry as it offers many advantages over conventional surface mount components [1–5], such as smaller size, higher pin count, and higher yield in assembly. Among various types of BGAs, CBGA shows excellent electric and thermal performance but the joint reliability may be the potential setback. This is due to a large difference in the coefficient of thermal expansion (CTE) of the ceramic substrate and that of the Fr-4 printed circuit board (PCB). Thus, it is very important for designers to understand the effect of design parameters on the reliability performance. On the other hand, the confidence of our study will have to be linked with the operation window in the assembly process. The process capability analysis exposes the effect of process variation on the joint integrity.

To an end user, the design variables, which might affect the stress and strain distributions in solder joints, include PCB material, PCB thickness and ceramic substrate thickness. CBGA

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mechanical packages without an actual chip inside are often used for the qualification test. Therefore, whether the existence of the actual chip affects the testing results is a concern to users as well. Here, these parameters will be studied first. The assembly process variation results in the variation of solder joint geometry and size. These are the root causes of inconsistency in the failure of these joints. In this paper, we will determine the scale of variation experimentally and apply the finite element method (FEM) to analyze the effect of such variation on the stress and strain distributions in the solder joints of CBGA packages. In the design parameter study and the process capability study, the design of experiment (DOE) technique will be adopted to form the parameter matrices of simulation. Three-dimensional linear elastic analyses will be performed to determine the comparative effect of each parameter.

In order to have a better understanding of the applicability of the FEM technique on failure and life prediction, the elastic–plastic–creep model of CBGA solder joints will be established. The strain range approach will be adopted to predict the thermal cycling fatigue life of the interconnected joints. The prediction will then be compared with the testing results. In this paper, our discussion will focus on CBGA 256, i.e., the CBGA package with 256 pin counts. The software package MARC from Marc Analysis Research Corporation is used for the finite element analysis.

2. Package design and process capability study

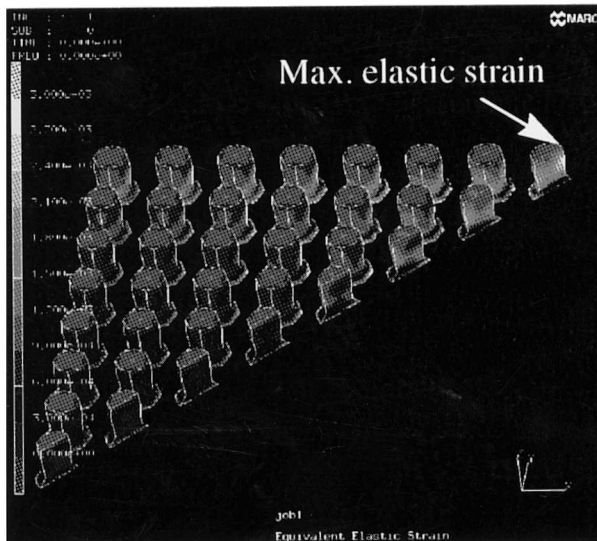
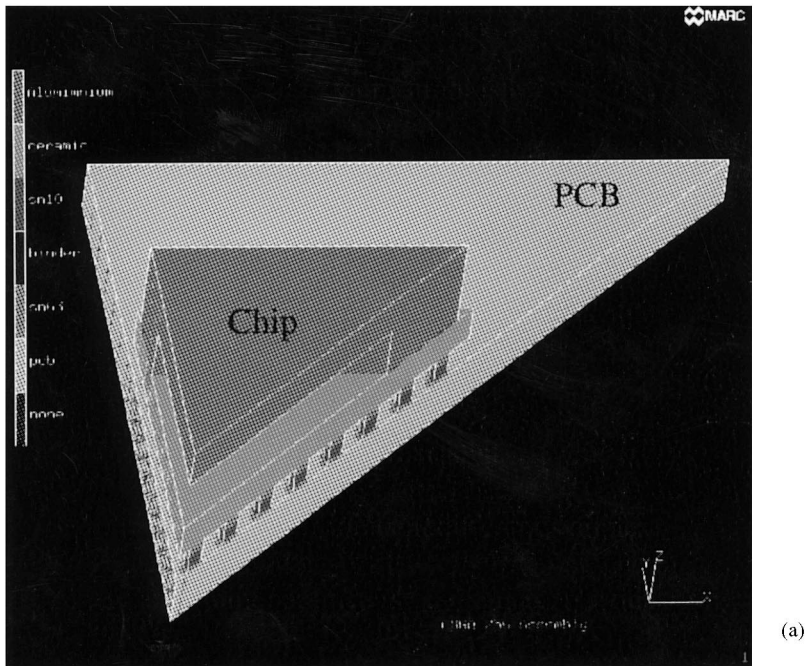
The interconnected joints in CBAG 256 are formed with a high lead (Sn10/Pb90) solder ball attached to the ceramic substrate through eutectic (Sn63/Pb37) solder. In the assembly process, eutectic solder paste is printed to the soldering pads on PCB. After placing CBGA 256 packages onto the corresponding locations on the PCB, the whole assembly is sent to reflow. During the reflow process, the solder paste melts first with the increase in temperature and then solidifies with the drop of temperature. After the cleaning and testing, the assembly process is completed.

In the service condition, the temperature changes with the power on/off, which results in the thermal stress in the interconnect solder joints and may cause failure after a certain period of time. Thermal cycling test is commonly used to accelerate the damage caused by the thermal stress in solder joints to assess the reliability. The typical thermal cycling condition is from -40°C to 125°C , which is used as the basis for our discussion.

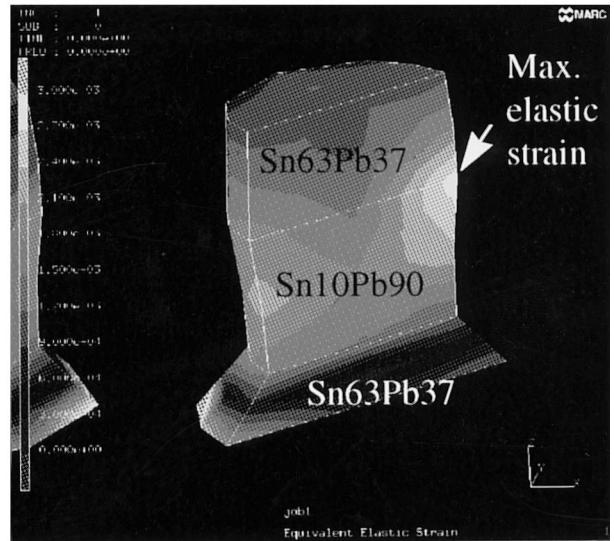
FEM analyses will be arranged into two DOE matrices in order to analyze separately the effects of various design parameters on the stress and strain in solder joints and the assembly process capability.

2.1. FEM model for CBGA 256 solder joints

Fig. 1a shows the FEM model used in the simulation. Due to the axis symmetry, only $\frac{1}{8}$ of the assembly was taken into consideration. Six different materials were considered in the model: ceramic layer, die, aluminum encapsulation, high lead solder, eutectic tin–lead solder and PCB. Total of 1032 twenty-node and 3-D solid elements were used. The nodes on the y -axis were fixed in the x -axis direction. The nodes on the diagonal line ($x = y$) were fixed in the diagonal direction. The initial temperature was 298 K and then changed to 398 K with thermal loading. The material properties are given in Table 1.



(b)



(c)

Fig. 1. FEA model and the elastic strain distribution in the solder joint. (a) FEA model; (b) the maximum strain is located in the corner joint; (c) high lead solder in the corner joint.

Table 1
Material properties used in the FEM modeling

Material	Solder Sn63/Pb37	Solder Sn10/Pb90	PCB Fr-4 (Bt)	Ceramic	Al alloy	Seal	Die
Young's modulus (GPa)	30.6	9.877	16.82 (22.45)	296.8	148	0.002	127
Poisson's ratio	0.35	0.40	0.39 (0.195)	0.30	0.344	0.48	0.30
CTE (ppm/K)	24.5	29	14.5 (14.6)	6.8	5.3	2000	2.8

Note: CTE = Coefficient of thermal expansion.

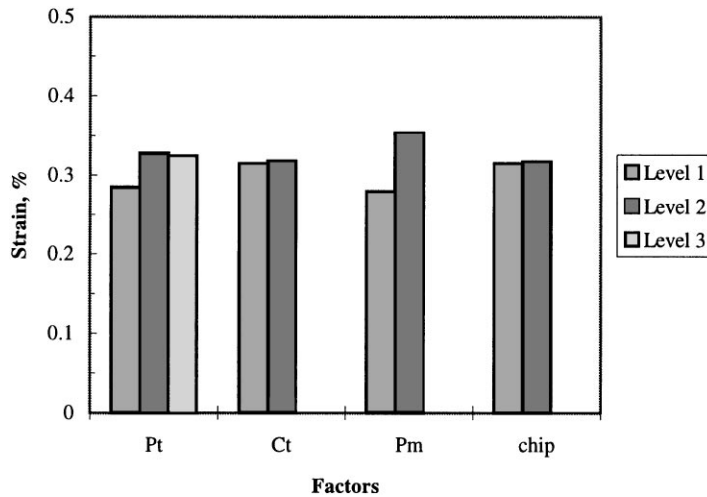


Fig. 2. Maximum elastic strain in the corner joint.

2.2. Design parameters study

The design parameters considered included the PCB material, the thickness of the PCB, the ceramic substrate thickness, and the existence or non-existence of die. These variables are listed in Table 2 and arranged in L_8 (4×2^4) experiments based on the DOE techniques [6]. The linear elastic analysis for each set of parameters in the L_8 matrix was performed. It was found that the stress and strain patterns do not change in all cases, but the highest values of stresses and strains vary with different parameter settings.

Fig. 1b shows a typical strain distribution in the solder balls. The maximum equivalent elastic strain occurs in the corner ball. In an enlarged picture of the corner ball as shown in Fig. 1c, it is found that the maximum strain concentrates at the high lead solder. The readings of the maximum strains for different levels of factors are used as the response of the DOE study and plotted in Fig. 2. It can be seen that PCB material has a significant effect on the elastic strain. A higher elastic strain was obtained using Bt as compared to that using Fr-4. This is because the CTE of Bt material

Table 2
Factorial design ($L_8(4 \times 2^4)$)

Factors	Details	Level 1	Level 2	Level 3
Pt	PCB thickness, (mm)	0.45	1.6	2.25
Ct	Ceramic thickness (mm)	1.2	1.4	
Pm	PCB materials	Fr 4	Bt	
Chip	Chip (die) inside	No	Yes	

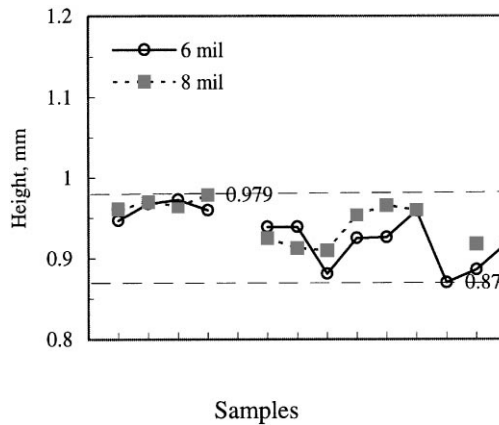
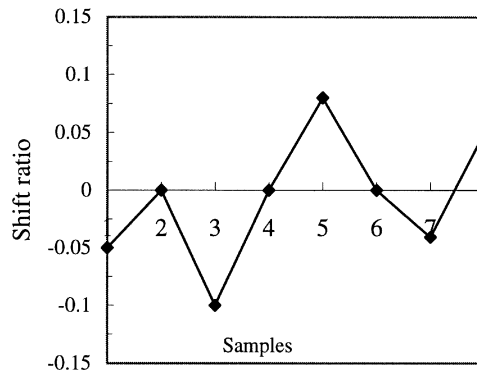


Fig. 3. Distribution of solder joint height with different thickness of stencil

chosen in the experiments is higher than that of Fr-4. The elastic strain is about 0.28% with PCB thickness of 0.45 mm and increases to 0.32% when the thickness goes up to 1.6 mm. It remains at the same level if the thickness increases further. This is because the thicker the PCB, the higher the overall board stiffness. A thicker board, therefore, may result in a higher strain in the solder joints. However, the strain increases little when increasing the PCB thickness from 1.6 to 2.25 mm. This shows that the effect of thickness on the deformation of solder joints becomes less once it reaches a certain value. The ceramic thickness and existence of die have no effect on the strain values. This indicates that the mechanical CBGA sample can simulate the actual CBGA packages in terms of deformation and joint failure in temperature cycling tests.

2.3. Process capability study

The strains in a solder joint are dependent on the shape and size of the joint besides the thickness and material of PCB as well as those of the package. The final solder joints after assembly may have different shapes due to process variation. Some joints may have a large misalignment as well resulting from the tolerance of the placement machine. Fig. 3 shows the joint height for samples obtained from the experimental runs with different stencil thickness for solder paste printing [3]. It is shown that the height varies from 0.87 to 0.97 mm. The misalignment of a solder joint may look



Distribution of solder ball shift ratio.

Fig. 6. Shift ratio of solder joints in different samples.

Table 3
Process capability study of FEA for CBGA 256

Factors	h (mm)	D (mm)	Shift ratio
Level 1	0.87	1	− 0.1
Level 2	0.92	0.85	0
Level 3	0.97	0.7	0.1
Experiment	h	d	Shift ratio
1	0.87	1	− 0.1
2	0.87	0.85	0
3	0.87	0.7	0.1
4	0.92	1	0
5	0.92	0.85	0.1
6	0.92	0.7	− 0.1
7	0.97	1	0.1
8	0.97	0.85	0
9	0.97	0.7	− 0.1

ratio means that the corner solder joint shifts inwards to the center of the packages, while a positive ratio stands for outward shifting. It is noted that if a corner joint shifts outwards, the opposite corner joint shifts inwards. Another major factor affecting the strain is the joint diameter. The joint diameter may also vary since different solder paste volume is applied. Therefore, three major process assembly factors, height, diameter and shift ratio, are considered and these parameters are arranged in the second DOE matrix as shown in Table 3.

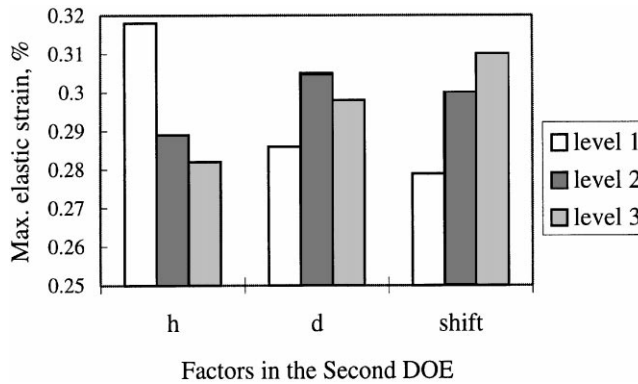


Fig. 7. Effect of joint parameters on the maximum elastic strain.

The FEA results of the second DOE are shown in Fig. 7. From Fig. 7, the following can be observed:

1. The strain decreases by $\frac{1}{10}$ when increasing the joint height from 0.87 to 0.92 mm. It decreases slowly when the height increases further after 0.92 mm. This shows that the joint height should be no less than 0.92 mm.
2. The strain may decrease with the joint diameter once the diameter is greater than a certain value, which is 0.85 mm in this study. As seen from Fig. 7, the solder joint diameter does not affect the strain greatly. When the diameter changes from 0.7 to 1.0 mm, the strain varies in the range from 0.285% to 0.305%. Normally, the bigger the diameter, the lower the strain. However, the strain has a lower value at a smaller diameter ($d = 0.7$ mm). It is noted that the diameter of the soldering pad is fixed in the study. Therefore, decreasing the joint diameter may assist increasing the flexibility of the joint, which can absorb some strain from the eutectic solder. However, there is a limit for reducing the joint diameter as the high lead solder would be weaker if the diameter is too small.
3. The strain increases about 3.3% when the joint shifts outward about 0.1 from the center, indicating that the shifted solder joints are harmful to the fatigue life. However, the effect is not critical if its shift ratio is within ± 0.1 , as what we found in the experiments [3].

3. Elastic–plastic–creep analysis and solder joint fatigue life prediction

In a typical temperature cycling test, the solder joints of CBGA packages are subjected to cyclic stress and strain. Since the test temperature is well above half of the melting temperature of the eutectic solder, creep deformation would be an important factor for the failure of joints.

As discussed above, the highest stress occurs at the corner joint of CBAG 256. In order to calculate more accurately the stress and strain at the possible failure location, the refined mesh around the corner joint is used.

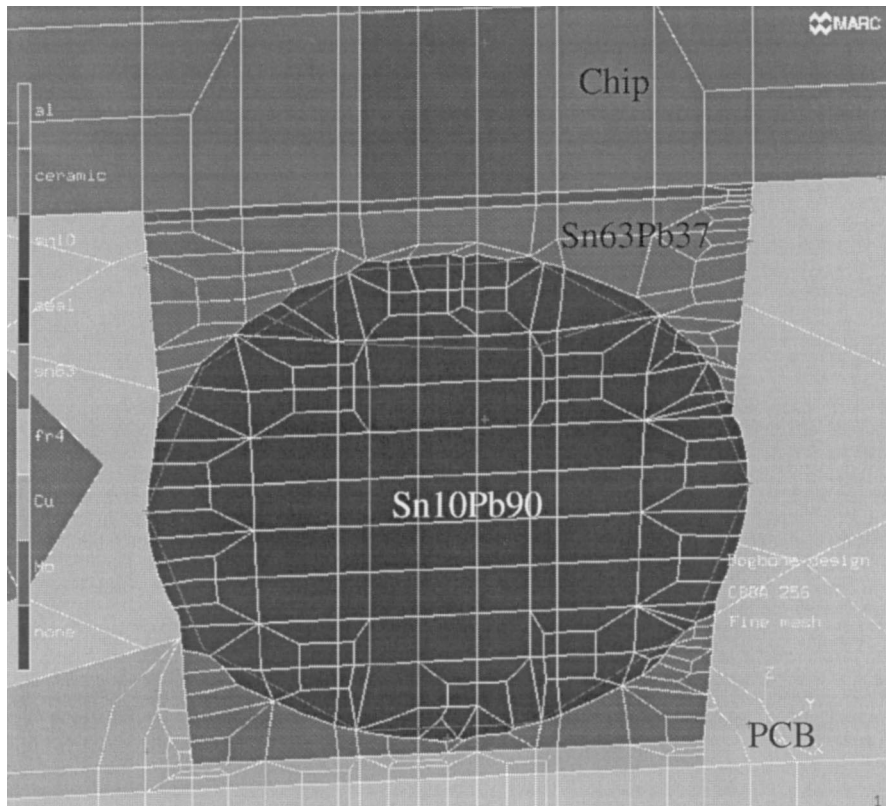


Fig. 8. Fine mesh of corner joint for FEA modeling.

3.1. Elastic–plastic–creep simulation

The fine mesh around the corner joint is shown in Fig. 8. In this model, 2500 3-D isoparametric elements are used. The elastic–plastic behavior of two types of solder at different temperature may be characterized by the following equations [1].

$$\varepsilon_p = k_1 \left(\frac{\tau}{G} \right)^{k_2} \quad (1)$$

$$G_{\text{sn63}} = 13\,300 - 55.85(T - 273), \quad (2)$$

$$E_{\text{sn63}} = 30\,600 - 79.78(T - 278), \quad (3)$$

$$E_{\text{sn10}} = 9877 - 98.5(T - 278), \quad (4)$$

where τ is the shear stress and coefficient $k_1 = 1.21 \times 10^{13}$ and $k_2 = 5.58$; G is the shear modulus and E stands for the Young's module; the subscript sn63 stands for Sn63/Pb37 solder and sn10 for Sn10/Pb90 solder.

Table 4
Creep properties of Pb/Sn solder

	G_0 (GPa)	G_1 (GPa/K)	C_4 (K/s/MPa)	n	α
Eutectic solder (Sn63Pb37)	13.1	0.0558	8.28	3.3	1300
High lead solder (Sn10Pb90)	19.6	0.0670	0.454	5.5	1500

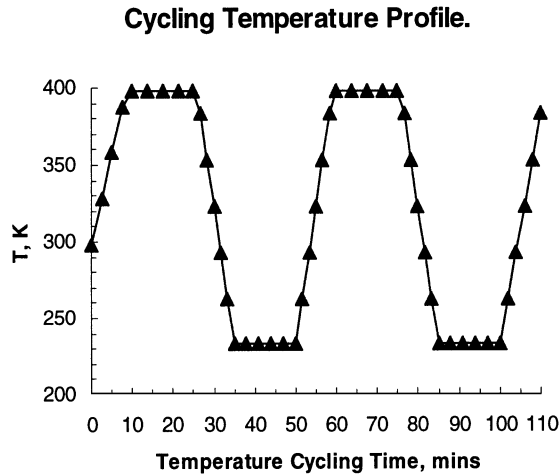


Fig. 9. Temperature profile used in the elastic–plastic–creep analysis.

The creep model proposed by Robert Darveaux et al. [1] was adopted in this study. In this model, the stable-state creep strain rate is defined by

$$\frac{d\epsilon_c}{dt} = C_4 \frac{G}{T} \left[\sinh \left(\alpha \frac{\sigma}{G} \right) \right]^n \exp \left(\frac{-Q}{kT} \right), \quad (5)$$

where $G = G_0 - G_1(T - 273)$ is the shear modulus, k is the Boltzmann's constant, T is the absolute temperature, σ is the applied stress, Q is the activation energy for the deformation process, n is the stress exponent, α and C_4 are material constants. The values of these parameters of the materials are listed in Table 4.

In the test, the temperature cycling profile followed that shown in Fig. 9, in which the temperature varies from -40°C to 125°C with a dwell time of 15 min at the extreme temperatures. The creep strains accumulated during heating and cooling were ignored in the simulation in order to simplify the study. The plastic and creep strain distributions in the corner joint when heated to 125°C are shown in Fig. 10. From Fig. 10a, it can be seen that the highest plastic strain concentrates at the interface between the eutectic solder and ceramic substrate. It is noted that the highest

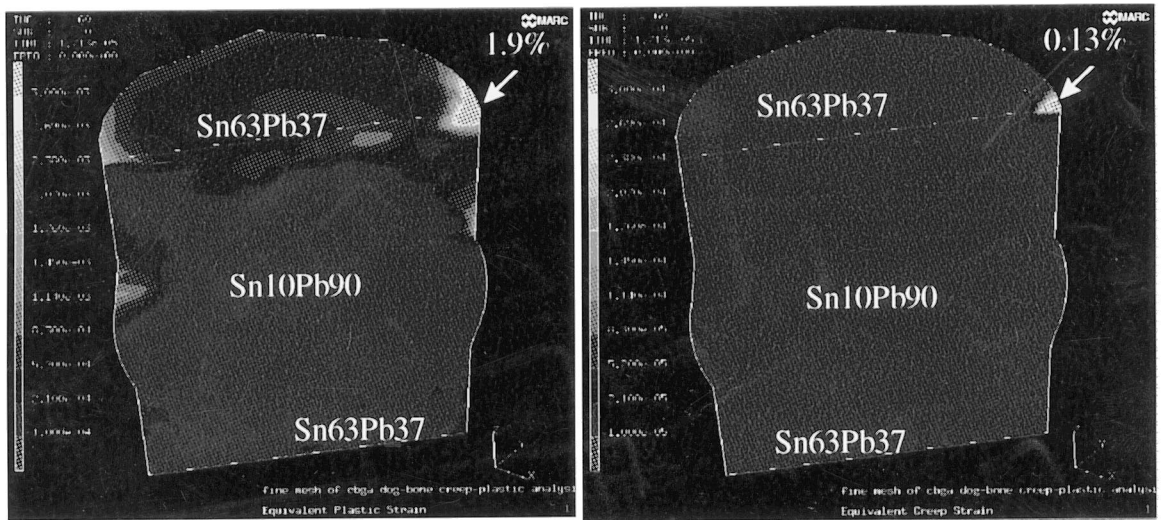


Fig. 10. Maximum strain distribution at 125°C for CBGA 256 solder joints. (a) Equivalent plastic strain; (b) Equivalent creep strain.

creep strain also concentrates at the same location as shown in Fig. 10b. As the combination of plastic strain and creep strain dominates the crack initiation and propagation, it appears that the solder joint would be easily cracked from the interface close to the ceramic substrate. In the thermal cycling test, it was confirmed that cracks occurred in the eutectic solder near the interface close to the package substrate [3]. Variations of the plastic strain for one-and-a-half temperature cycles are shown in Fig. 11. The results show that the plastic strain is higher at -40°C than that at 125°C . It decreases with time increasing even though the temperature remains unchanged at the highest temperature (125°C). This is because the creep deformation of the solder joint helps to release the plastic deformation. The creep strain increases with the time. It increases with the number of cycles as well, showing that the creep strain does not form a closed loop in a cycle, as shown in Fig. 12, in which the variations of the plastic strain and creep strain with respect to the stress are plotted for the first one-and-a-half cycles. The variation of the von Mises stress vs. the plastic strain during the temperature cycling forms a hysteresis loop which shows the stress relaxation at the highest temperature and hardening at the lowest temperature. The trend for the von Mises stress–creep strain, however, is not clear.

3.2. Fatigue life prediction with comparison to temperature cycling test

The ranges of the maximum plastic strain and creep strain at the critical location are summarized in Table 5. These ranges are calculated from one whole temperature cycle excluding the first half-cycle, as shown in Fig. 11. The fatigue life can be predicted using the following equations [7–9]:

$$\frac{1}{N} = \frac{1}{N_p} + \frac{1}{N_c}, \quad (6)$$

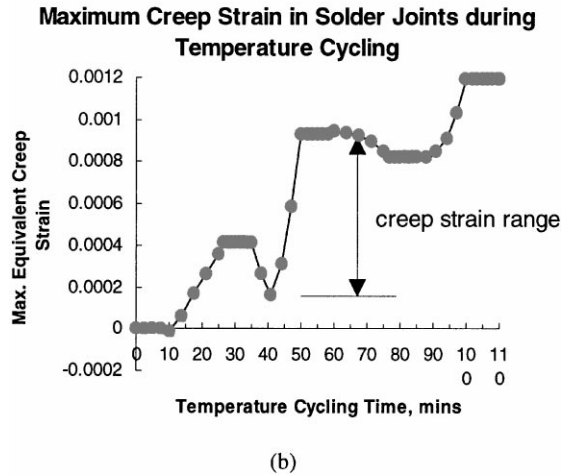
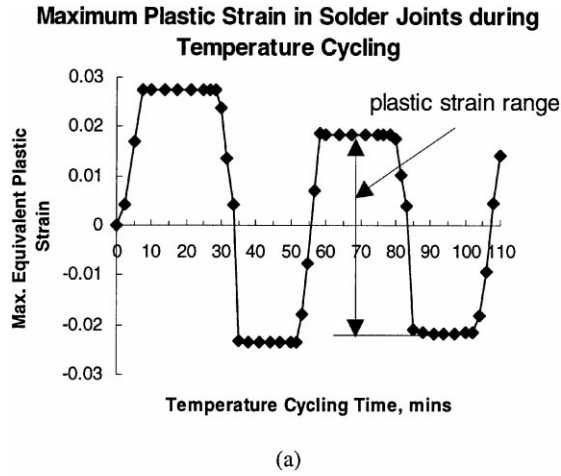


Fig. 11. Variations of plastic strain and creep strain with the temperature during temperature cycling. (a) plastic strain; (b) creep strain.

and

$$N_p = \left(\frac{1.36}{\sqrt{3}\Delta\epsilon_p} \right)^{1/0.5}, \quad (7)$$

$$N_c = \frac{8.9}{\sqrt{3}\Delta\epsilon_c}, \quad (8)$$

where N represents the fatigue life of the solder joints subject to cyclic plastic strain and creep strain; and N_p and N_c stand for the fatigue life subject to cyclic plastic strain or to creep strain alone. $\Delta\epsilon_p$ and $\Delta\epsilon_c$ stand for plastic strain range and creep strain range, respectively. The strain ranges can be determined from Fig. 12, i.e., $\Delta\epsilon_p = 4.02\%$ and $\Delta\epsilon_c = 0.037\%$. After substituting

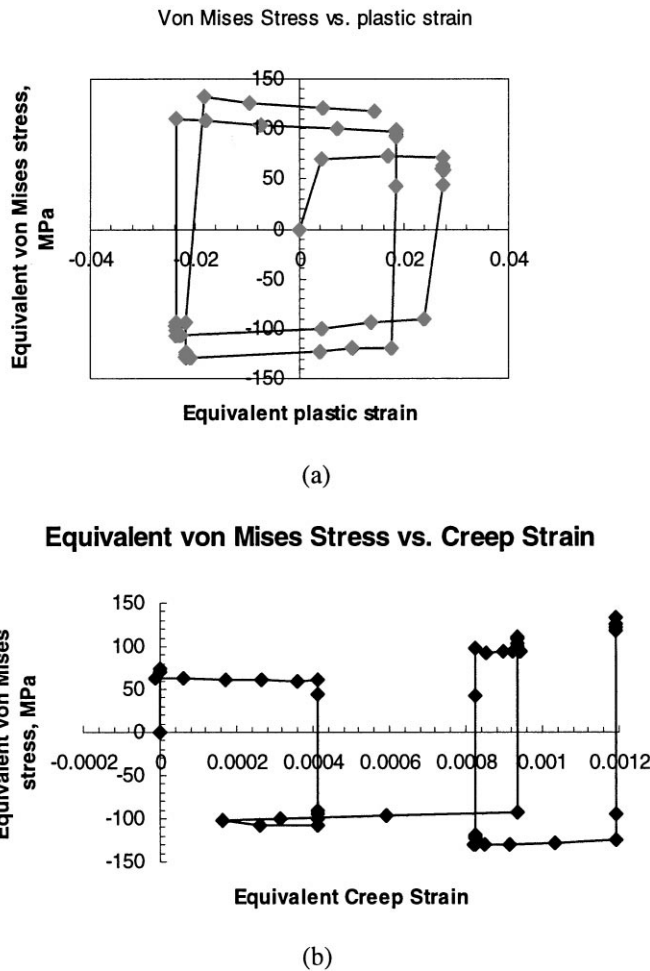


Fig. 12. Stress–strain hysteresis loops during temperature cycling. (a) Equivalent plastic strain; (b) Equivalent creep strain.

Table 5

Comparison of predicted life with test results

Strain range	Predicted fatigue life (cycles)	Characteristic life in test (cycles)	First failure in test (cycles)
4.02% (plastic) 0.037% (creep)	371	771	433

these values into the above equations, $1/N_p = 0.0026$, $1/N_c = 0.000072$ and the fatigue life is then obtained as $N = 371$ cycles. As shown in Table 5, the characteristic life of CBGA 256 solder joints from the thermal cycling test is 771 cycles [3], which is at 63.2% of failure. The first failure of 44 components in the test occurred at 433 cycles [3]. The failure was determined by the measurement

of electrical resistance. When the resistance approaches the infinite, the circuit is open and the package is considered failed. Then, the failure in the test would mean a crack cutting through the whole width of the solder joint, as found from the cross-sectional SEM observation of the failed samples [3]. It is noted that the plastic and creep strain ranges in the calculation are at the specific location, i.e., in the eutectic solder close to the ceramic interface. The other areas of the solder joint sustained much lower strain. Therefore, the failure life predicted here is the crack initiation life. The actual fatigue life of the whole corner solder joint should also include the crack propagation life. That is to say, the fatigue life obtained by Eqs. (6)–(8) may give a conservative prediction for the assembly.

It is noted that for CBGA 256 solder joints, the failure is dominated by the plastic deformation in the eutectic solder. The creep deformation contributes only slightly to the failure of the joint. This is different from plastic BGA packages, where the creep deformation dominates the failure of solder joints.

4. Conclusions

1. The PCB material and its thickness play important roles in the deformation of CBGA 256 solder joints. Using a material with a CTE close to the ceramic and reducing PCB thickness can help to reduce the strain in the CBGA 256 solder joints. The thickness of the ceramic substrate and the CBGA package with or without die have no significant effect.
2. Variation in the assembly process will result in different shapes and sizes of solder joints. Such differences will give rise to the variation of the maximum equivalent strain. It was shown that this variation is within 10% of the center value for the current process.
3. The maximum plastic strain as well as maximum creep strain concentrates at the eutectic solder close to the BGA ceramic substrate, suggesting the cracks would initiate and propagate from that location in the temperature cycling test. This is consistent with the cross-sectional observation of the tested samples.
4. The predicted fatigue life is 371 cycles for CBGA 256 solder joints, in comparison with the first failure of 433 cycles in the test. The prediction may be seen as a conservative estimation since the crack growth was not considered in the calculation.

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