Settling Studies of Underfill Particles for Flip-Chip Solder Interconnections

Chiang-Ho Cheng, An-Shik Yang, Chih-Jer Lin, and Chun-Ta Chen

***Abstract*—In view of the flip-chip on board packaging method, an underfill encapsulant material is dispensed along one or two adjacent sides of the chip. The capillary force then draws the underfill beneath the chip to fill the gap between the integrated circuit (IC) chip and substrate. These shear stresses are imposed on the solder interconnections owing to a significant mismatch of coefficient of thermal expansion (CTE) between the IC chip and substrate. Hence, this underfill is required to specifically harmonize the CTE value of the solder for minimization of the stresses caused by the thermal inconsistency between the IC chip and substrate. This paper aims to conduct the micromechanical analysis using the Eshelby equivalence inclusions principle and Mori-Tankaka's average stress field concept for investigating the equivalence thermolelastic of underfill filler particles. In calculations, the finite element method (FEM) software ANSYS is used to simulate the inhomogeneity of underfill fillers, such as settling of filler particles, for appraising the reliability of flip chip solder interconnections. We further probed if the reliability of flip chip solder interconnections could be influenced by the predicted volume fractions of underfill fillers.**

***Keywords*—flip chip, underfill, micromechanical, reliability**

I. Introduction

In recent years, along with the fast development of the electronic products, under the needs (higher speed, higher effect, smaller size and lower price) of the market, electronic packaging I/O count continuously increasing, therefore, how to increase the I/O counts of the unit area in the limited space is a major research subject now. Flip chip (FC) package is the most form to save space and highest density packaging technique now. In the 1960s, IBM developed the Flip chip bonding, also called as C4 (Controlled Collapse Chip Connection). This bonding technology was the area array solder bump, rather than the wire bonding and the tape automated bonding (TAB) technique which could only provide the peripheral solder bump. For this reason, flip chip bonding has been the most hopeful method of high density packaging but it has a fundamental problem of fatigue failure in solder joints due to the thermal stress caused by a CTE mismatch between the integrated circuit chip and carrier substrate, that problem becomes more serious with the increasing chip size and smaller size of solder joints. Therefore, the chip cracking and interfacial delamination between the underfill and chip were investigated in many studies [1–3]. Most of these researches focused on the fatigue and creep phenomenon in the solder joint induced by the plastic strain alternation and accumulation [4–5]. The underfill and solder bump material behaviors will influence the solder joint reliability and produce certain phenomena that can be simulated. Suryanarayana [6] studied to enhancement in fatigue life of the flip chip package with the different encapsulation. Which paper indicated that reliability of no settling underfill was more than settling underfill. Gektin [7] researched on the enhancement of the height of the solder ball to increase the fatigue life of the flip chip package. The Rinne [8] studied the effect of the solder reliability in flip chip package used different material.

Now, the primary technique of flip chip package is using underfill between the silica chip and the substrate to enhance the fatigue life of solder joints. Because of the CTE of the epoxy of the underfill is too large (about 75 ppm/℃), so add a large number of fillers, such as silica (SiO_2) particles to decrease the CTE. Usually, the filler particles decrease the CTE, thermal shrinkage, and moisture absorption of package and increase the elastic modulus, thermal conductivity and viscosity, etc., in proportion to the amount of filler particles used. Especially the thermoelastic modulus have significant influence on the thermal stress and strain of flip chip package and thus the understanding about the effect of shape, kind, and volume percentage of filler on the above material constants is very important. Additionally, because of the law of gravity, the underfill will produce a settling phenomenon that is the more filler particles near the substrate much than near the IC chip. A typical settling of silica particles in an epoxy matrix is illustration in Fig. 1. The settling of particles leads to a variation of thermoelastic modulus of the underfill from the die side to the carrier substrate side of the flip chip. Therefore, the focus of the work in this paper is to understand and quantify the impact of the underfill settling on the thermomechanical reliability of the solder interconnects.

II. Equivalent Thermoelastic Modulus

Drab [9] discovered that because of the laws of gravity, the underfill would have a settling phenomenon. He [10] observe that the grains of the silica filler particles look like spheroid, therefore, the combination of the underfill of flip chip package is composite material. We assume that it composed

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Chiang-Ho Cheng is with the Department of Mechanical and Automation Engineering, Da-Yeh University, Changhua, 515, Taiwan (phone: (886) 4-8511888 ext. 2119; e-mail: chcheng@mail.dyu.edu.tw).

An-Shik Yang is with the Department of Energy and Refrigerating Air-Conditioning Engineering, National Taipei University of Technology, Taipei, 106, Taiwan (e-mail: asyang@ntut.edu.tw).

Chih-Jer Lin is with the Institute of Automation Engineering, National Taipei University of Technology, Taipei 106, Taiwan. (e-mail: cjlin@ntut.edu.tw).

Chun-Ta Chen is with the Department of Mechatronic Technology, National Taiwan Normal University, Taipei, 106, Taiwan, (e-mail: chenct@ntnu.edu.tw).

of homogenous and continuous matrix fill the discontinuous filler. General the matrix of the underfill of the flip chip package is pure epoxy, the primarily inclusion of filler is the silica which is a isotropic material (material property show as Table I), with the theory of the micromechanical this study computes out the equivalent thermolelastic modulus of the underfill by the concept of the equivalent inclusion principle of the Eshelby [11] and the average stress field of the Mori-Tankaka [12]. Which the effective elastic modulus $\mathbf{C}^*$ and effective coefficient of thermal expansion $\boldsymbol{\alpha}^*$ are expression as follows: [13]

$$\mathbf{C}^* = \mathbf{C}_0 \cdot [\mathbf{I} + f_1\,\mathbf{A}\cdot\mathbf{F}]^{-1} \tag{1}$$

$$\begin{aligned}\alpha^* = \alpha_0 - f_1\,\mathbf{A}\cdot\mathbf{H}\cdot(\mathbf{I} + f_1\,\mathbf{B})^{-1}\cdot[\,f_1\,\mathbf{B}\cdot(\mathbf{C}_0 - \mathbf{C}_1)^{-1}\cdot\mathbf{C}_1 \\ \cdot(\boldsymbol{\alpha_1} - \boldsymbol{\alpha_0})] + f_1\,(\mathbf{A}\cdot\mathbf{H}\cdot\mathbf{S} + \mathbf{I})\cdot\mathbf{C}_0^{-1}\cdot\mathbf{C}_1\cdot(\boldsymbol{\alpha_1} - \boldsymbol{\alpha_0})\end{aligned} \tag{2}$$

Where $\mathbf{A} = (\mathbf{I} - \mathbf{C}_0^{-1}\cdot\mathbf{C}_1)$ (3)

$$\mathbf{F} = [\,(\mathbf{I} - \mathbf{S}\cdot\mathbf{A}) + f_1\,(\mathbf{S} - \mathbf{I})\cdot\mathbf{A}\,]^{-1} \tag{4}$$

$$\mathbf{H} = (\mathbf{I} - \mathbf{S}\cdot\mathbf{A})^{-1} \tag{5}$$

$$\mathbf{B} = (\mathbf{S} - \mathbf{I})\cdot\mathbf{A}\cdot\mathbf{H} \tag{6}$$

The capital English boldface letter represent fourth order tensor; the lower case Greece boldface letter represent second tensor; subscripts 0, 1 represent two types of different materials of matrix (pure epoxy) and filler particles (silica) respectively; f_1 represent the volume fraction of the matrix for filler particles; **C** and α represent elastic modulus and coefficient of thermal expansion respectively; **S** and **I** represent Eshelby tensor and fourth order identity matrix respectively; Eshelby tensor depend on the configuration of inclusions. Appendix is the Eshelby tensor when inclusions configuration are sphere.

The underfill will produce the settling phenomenon by the effect of the law of gravity. Therefore we consider three different types of underfill of silica filler particles fill in pure epoxy. First, the filler particles are diffused in matrix homogenously which without settling phenomenon, also consider the filler particles with the phenomenon of settling. The beginning is 20% pure matrix and 80% composite material of underfill, and then is 50% pure matrix and 50% composite material of underfill, illustrate in Fig. 1. Assume the filler particles are homogenous distribute in pure epoxy.

In view of the silica filler particles distributed in the volume fractions of 0.3, 0.5 and 0.7 respectively, we can compute the effective material properties of the underfill as presented in Table II. This study examines the parameters of three types of particles in three different volume fractions, respectively.

TABLE I
THE MECHANICAL PROPERTY OF UNDERFILL

	Yonug's Modulus (MPa)	Poisson's Ratio	Coefficient of Thermal Expansion (ppm/℃)
Pure Epoxy	2500	0.35	75
Silica	71000	0.2	0.6

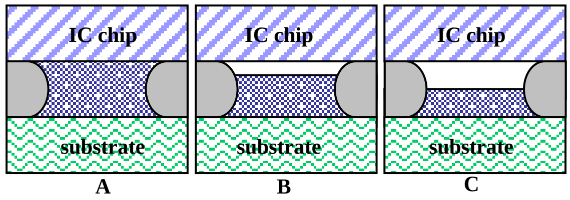

Fig. 1. Three different types of underfill of silica filler particles fill in pure epoxy. A: without settling phenomenon, B: 80% settling height, C: 50% settling height.

TABLE II
THE EFFECTIVE MECHANICAL PROPERTY OF THE DIFFERENT FILLER PARTICLE VOLUME FRACTION FILL IN UNDERFILL

	Yonug's Modulus (MPa)	Poisson's Ratio	Coefficient of Thermal Expansion (ppm/℃)
0.3	4440.9	0.344	41.9
0.5	6863.8	0.338	26.5
0.7	11884.9	0.326	14.5

III. FINITE ELEMENT SIMULATE

A schematic drawing of diagonal cross-section of flip chip package composed of FR-4 substrate, silicon chip, underfill and solder bumps is shown in Fig. 2. [14] The numerical model was two-dimensional (2D) with the plane strain assumption and only one-half of the cross-section was modeled due to geometry symmetry. The silica chip is 3.51 mm in length, 0.64 mm in thickness. The substrate material is FR-4, which is 5.82 mm in length, 0.7 mm in thickness. The solder material is assumed 63wt%Sn/37wt%Pb, which is 0.16 mm in diameter, 0.15 mm in height, and 0.52 mm in pitch. The underfill consider settling phenomenon in analysis, therefore the finite element model of underfill divided into the above layer and the below layer two layers. If the underfill has not settling phenomenon, the above layer and the below layer have the equivalent material properties, which are the composite material of the silica fill in the epoxy. Its material properties are the effective material properties of composite material calculate by the micromechanical. If the underfill has settling phenomenon, the above layer is pure epoxy, the below layer are composite material. Table III [15] lists the material properties using in the analysis in the study. The finite element meshes for the overall numerical model is show as Fig. 3. The symmetrical boundary conditions were applied along the left edge of the model. The left bottom corner was constrained in the vertical direction to prevent body motion. The material property of the solder ball is elastic-plastic, which is relation with the temperature. Fig. 4 illustrates the relations of different temperatures effects on the stress-strain curves.. Other materials are all linear elastic and isotropic, and independent of in variety temperatures. In accordance with standard of fatigue test of JESD22-A104-A [16] of JEDEC (Joint Electron Device Engineering Council). The loadings of temperature are form - 40 ℃ to 125 ℃ in the analysis. Fig. 5 shows the thermal cycle numerical analysis history in this study. The thermal cycle temperature ranged from −40 to 125 ℃ with a ramp rate of 8.25℃/min and a dwell time of 10 min at the peak temperature.

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TABLE III
THE MECHANICAL PROPERTY OF THE MATERIAL OF FLIP CHIP

	Yonug's Modulus (MPa)	Poisson's Ratio	Coefficient of Thermal Expansion (ppm/℃)
IC chip	131000	0.3	2.8
FR-4 substrate	22000	0.28	18
63Sn37Pb solder	36300	0.35	25

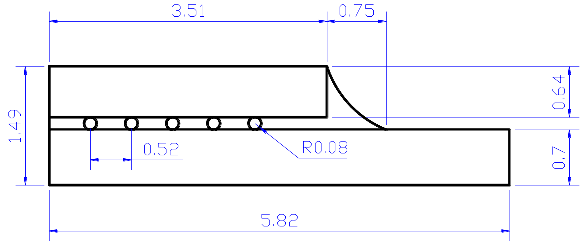

Fig. 2. The dimensions of the numerical model.

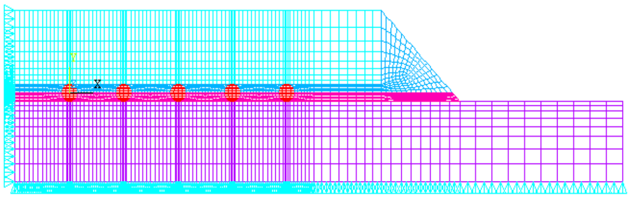

Fig. 3. Finite element meshes for the overall numerical model.

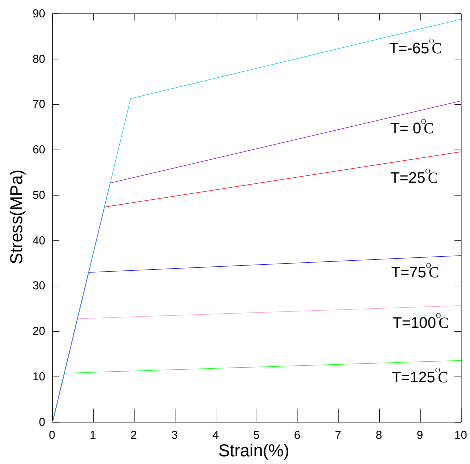

Fig. 4. Temperature-dependent stress–strain curves of solder ball.

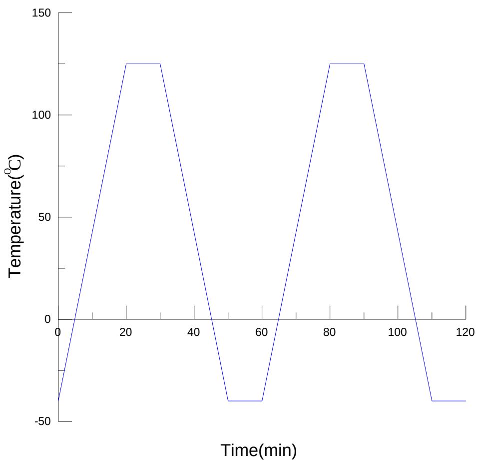

Fig. 5. Thermal cycle history of the numerical analysis of this study.

IV. THEORY OF RELIABILITY

Flip chip package receives a loading of the periodic thermal cycle, which is caused the materials tension and compression stress over and over to failure of thermal fatigue. The fatigue failure is takes the largest plastic shear strain place, usually. Hence, we obtained the largest plastic shear strain of the solder using the finite element analysis software ANSYS by a temperature cycle in the study. And the Coffin-Manson [16-18] relationship was also employed to predict the fatigue life of the flip chip package :

$$N_f = C(\gamma_p)^\eta \tag{7}$$

Where N_f represent the number of cycle to failure of the solder connections, and γ_p represent inelastic strain range. For 63Sn37Pb solder, Solomon fit his data at –50, 35 and 125 ℃ into the relation of Coffin-Manson and obtained the average values as $C = 1.2928$ and $\eta = -1.96$. The applied inelastic strain range in equation (7) is replaced by the corner plastic shear strain to serve as a simplified reliability estimate [19-23].

V. RESULTS AND DISCUSSION

This study used the micromechanical theory in conjunction with the finite element analyses software ANSYS to simulate and investigate the underfill effect on the flip chip packaging reliability. Applying the 2-D analysis model, the shear strain is the primarily factor causing the fatigue failure. Hence, we adopted the range of the plastic shear strain as an indicator to predict the reliability of the solder ball. Because the fatigue failure is usually occurred at the outmost region of solder balls, we focus on the crucial issue where the solder ball connects with other materials, as shown in Fig. 6. The points A and D are expressed as the junction place of the IC chip and underfill with the points C and F specified accordingly as the junction place of the substrate and underfill, whereas the points B and E are denoted as the settling place of underfill.

First, the settling phenomenon is not observed when the volume fraction of silica filler particles for the underfill is 0.5. Figure 7 illustrates the plastic shear strain of 0.5 silica volume fraction without settling phenomenon occurred at 1800 and 3600s. Afterward, in Fig. 8 showing the plastic shear strain range for all measurement points, it can be found that the curve A has the largest plastic shear strain range. When the volume fraction of the silica is 0.5, the associated reliability of the solder ball is 19577 cycles. Table IV demonstrates the predicted reliability of different volume fractions of the silica filler particles in the underfill. When the settling phenomenon of filler particles takes place, it is observed that the silica filler particles volume fraction of the underfill is 0.5. Figures 9 and 10 present the plastic shear strain diagram of the solder ball for 80% to settling height and the plastic shear strain range diagram for all measurement points, respectively. In addition, Figs 11 and 12 show the plastic shear strain diagram of the solder ball for 50% to settling height and the plastic shear strain range diagram for all measurement points. Tables V and 6 are the predicted solder ball reliability for different volume fractions of silica filler particles in the underfill with the

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settling process of filler particles taken place. The fatigue failure places of the solder balls also take place at the point A. When the silica filler particles in the underfill is 80% settling height, the solder ball reliability is about over 2,000 cycles. When the silica filler particles in the underfill are 50% settling height, the solder ball reliability is about over 1,000 cycles.

Besides, in Figs. 13 and 14, we discover the effect of silica volume fraction on the settling phenomenon of underfill for determining the solder ball reliability. With no finding of the settling phenomenon of underfill, an increase in the volume fraction of silica filler particles can enhance the solder ball reliability. On the other hand, if the settling phenomenon of underfill takes the place, the growing silica volume fraction tends to reduce the solder ball reliability.

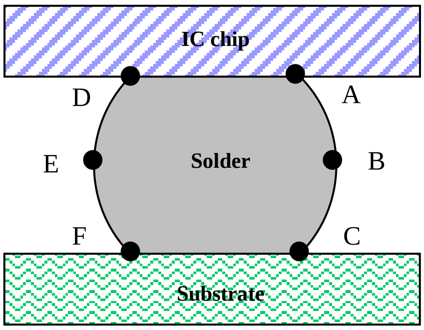

Fig. 6. The measuring points of the solder ball

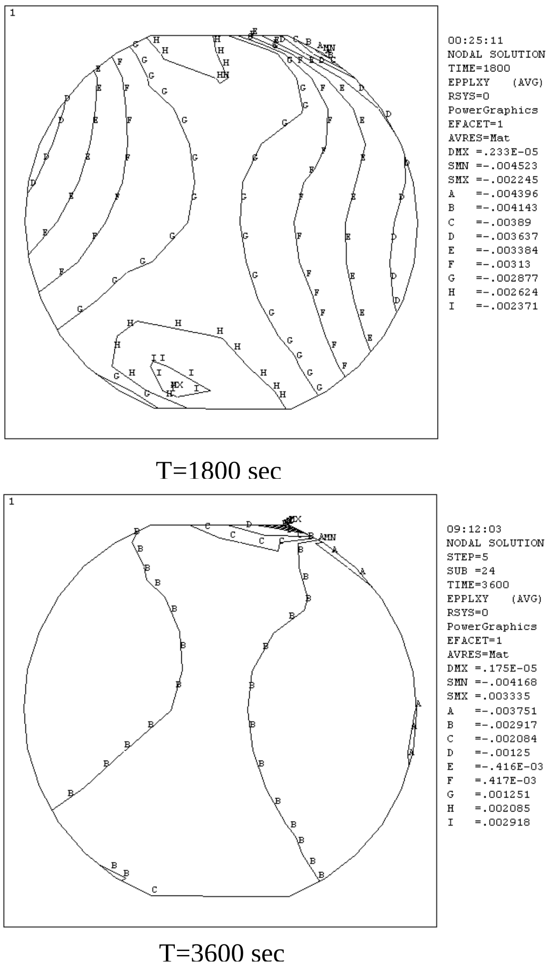

Fig. 7. The plastic shear strain of 0.5 silica volume fraction and without settling phenomenon at 1800 and 3600 sec.

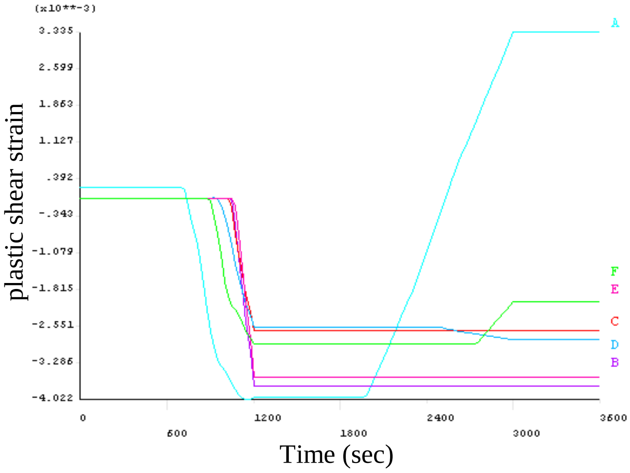

Fig. 8. The plastic shear strain range for all measurement points of 0.5 silica volume fraction and without settling phenomenon

TABLE IV
PREDICTED RELIABILITY OF THE SILICA FILLER PARTICLES AT WITHOUT SETTLING PHENOMENON

Volume Fraction	Plastic Shear Strain(%)	Reliability(cycles)
0.3	1.2778	6650
0.5	0.7366	19577
0.7	0.5089	40414

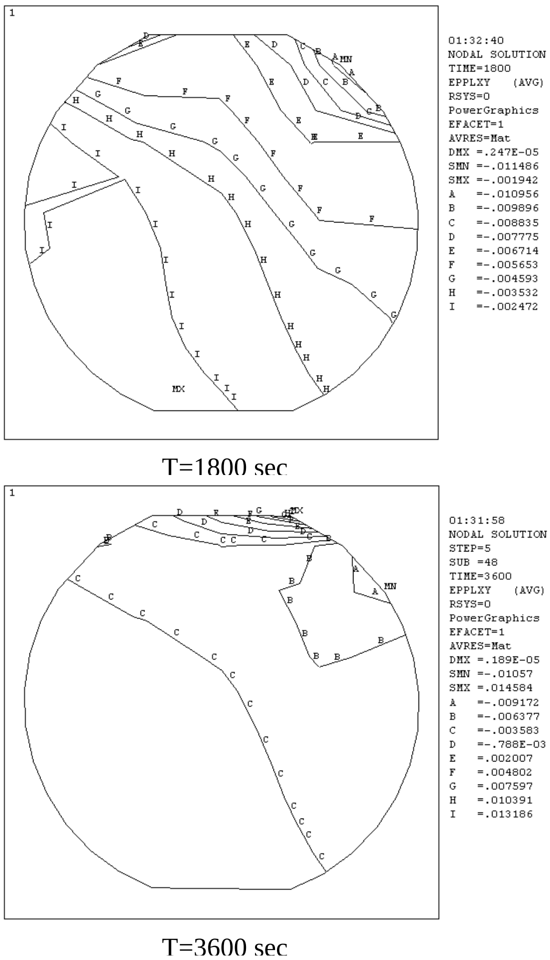

Fig. 9. The plastic shear strain of 0.5 silica volume fraction and 80% settling height at 1800 and 3600 sec.

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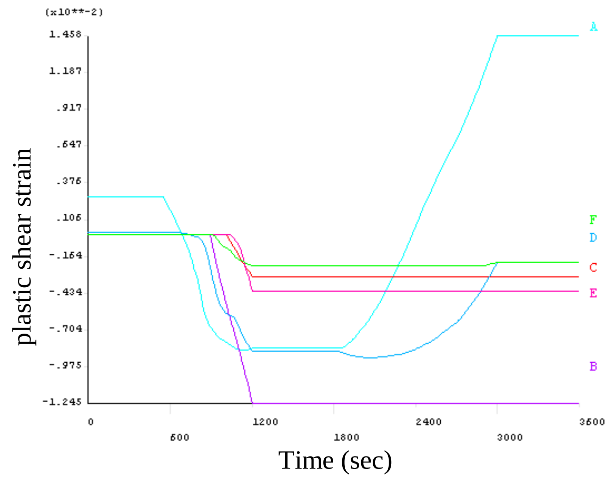

Fig. 10. The plastic shear strain range for all measurement points of 0.5 silica volume fraction and 80% settling height.

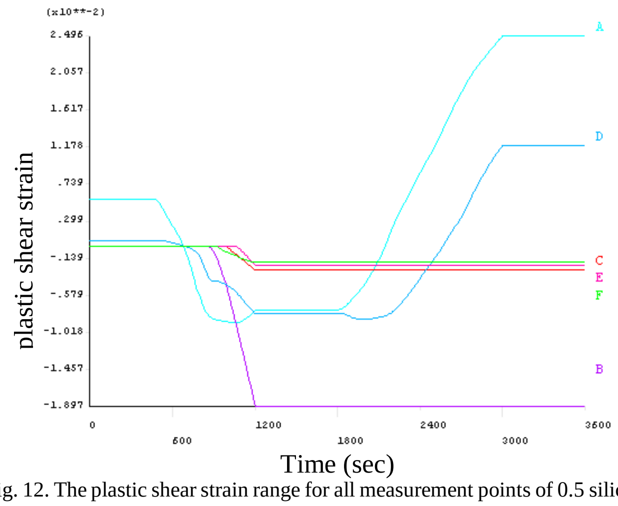

Fig. 12. The plastic shear strain range for all measurement points of 0.5 silica volume fraction and 50% settling height.

TABLE V
PREDICTED RELIABILITY OF THE SILICA FILLER PARTICLES UNDER 80% SETTLING HEIGHT

Volume Fraction	Plastic Shear Strain (%)	Reliability(cycles)
0.3	2.2251	2242
0.5	2.2932	2114
0.7	2.3360	2038

TABLE VI
PREDICTED RELIABILITY OF THE SILICA FILLER PARTICLES UNDER 50% SETTLING HEIGHT

Volume Fraction	Plastic Shear Strain (%)	Reliability(cycles)
0.3	3.1521	1133
0.5	3.2463	1070
0.7	3.2990	1036

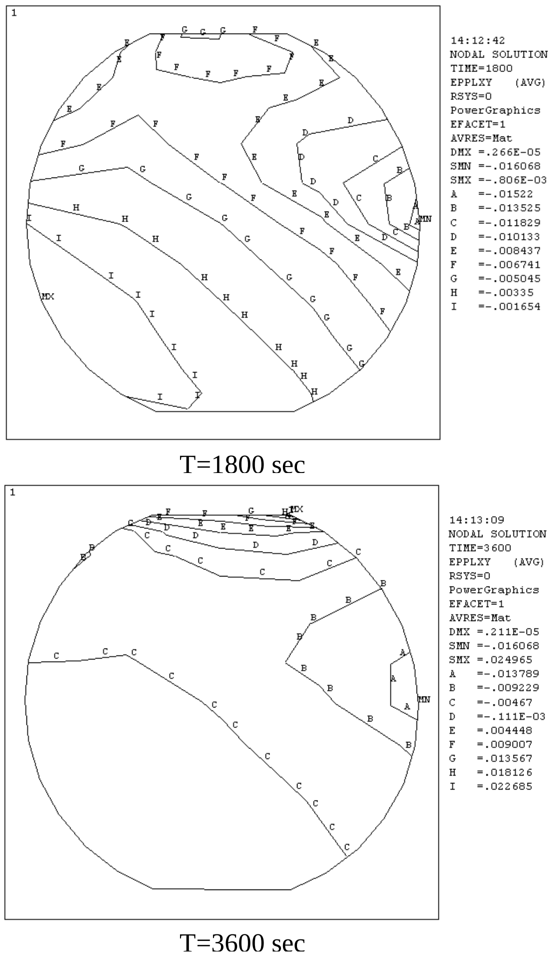

Fig. 11. The plastic shear strain of 0.5 silica volume fraction and 50% settling height at 1800 and 3600 sec.

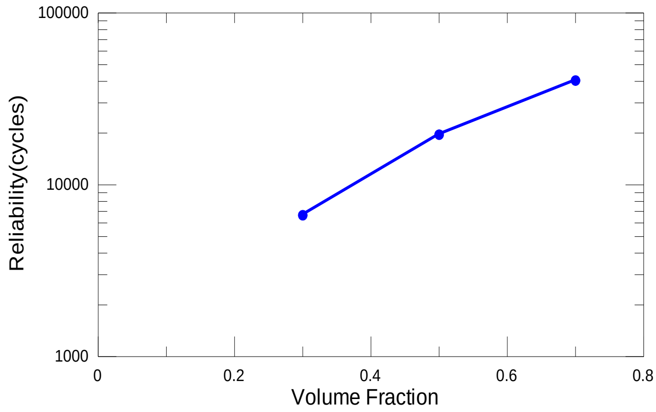

Fig. 13. The silica volume fraction and reliability relations of without settling.

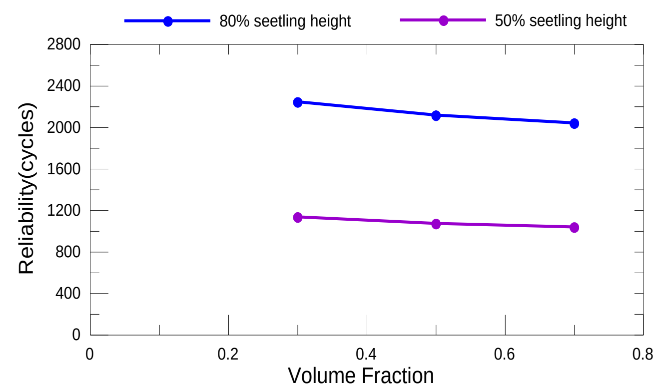

Fig. 14. The silica volume fraction and reliability relations of 80% and 50% settling height

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VI. CONCLUSION

This study has discovered the significant influence of the volume fraction of underfill filler particles on the solder ball reliability for determination of the fatigue life of the flip chip package. The inducible conclusion from the analyses is given as follows:

1) With no finding of the settling event of the underfill, the reliability of solder balls can be substantially improved by adding the silica volume fraction.
2) As the settling phenomenon of the underfill occurs, the increases of the silica volume fraction and the ration of the above pure epoxy layer to the underfill can decrease the solder ball reliability.

Therefore, it is very important to avoid the happening of the settling event of the underfill for enhancement of the flip chip package reliability.

APPENDIX

For spherical inclusion, the components of Eshelby's tensor S_{ijkl} are given by

$$\begin{aligned} S_{1111} = S_{2222} = S_{3333} &= \frac{7-5\upsilon_0}{15(1-\upsilon_0)} \\ S_{1122} = S_{2233} = S_{3311} &= \frac{5\upsilon_0-1}{15(1-\upsilon_0)} \\ S_{1212} = S_{2323} = S_{3131} &= \frac{4-5\upsilon_0}{15(1-\upsilon_0)} \end{aligned} \tag{A-1}$$

where ν_0 is the Poisson's ratio of matrix (epoxy).

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