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Stress Analysis for Chip Scale Packages with Embedded Active Devices under
Thermal Cycling

by

Hyunwook Yeo

A thesis submitted in partial fulfillment of the
requirements for the degree of

Master of Science
in
Mechanical Engineering

Thesis Committee:

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Abstracts

One of the main challenges in the electronics manufacturing and packaging development is how to integrate more functions inside the same or even smaller size. To meet the demand for higher integration, the interest toward passive and active component embedding has been increasing during the past few years. One of the main reasons for the growing interest toward embedded active components, in addition to demand for higher packaging density, is the need for better electrical performance of the component assemblies. However, it is little known how embedded IC and passives affect the reliability of IC packaging.

Solder joints have been used in the electronic industry as both structural and electrical interconnections between electronic packages and printed circuit boards (PCB). When solder joints are under thermal cyclic loading, mismatch in coefficients of thermal expansion (CTE) between the printed circuit boards and the solder balls creates thermal strains and stresses on the joints, which may finally result in cracking. Consequently, the mechanical interconnection is lost, leading to electrical failures (such as hard/intermittent open, parametric failure), which in turn causes malfunction of the circuit or whole system.

When a die is embedded into a substrate, Young's modulus of the die is larger than one of the core of the substrate and the CTEs of the die is smaller than those of the substrate. As a result, mismatch in coefficients of thermal expansions (CTE) between the substrate with the embedded device and the solder balls may increase.

In the present study, the stress of chip scale packages (CSP) with an embedded die under thermal cycling conditions is evaluated using the finite element method. The viscoplastic model for solders including matrix dislocation mechanism and grain boundary sliding model developed by Yi *et al.* (2002) is employed.

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Chapter 1. Introduction

One of the main challenges in the electronics manufacturing and packaging development is how to integrate more functions inside the same or even smaller size. The electrical performance and the number of functions of every new product generation are increasing while the size and the weight of the products are decreasing. To meet this, the semiconductor industry is going toward 14 nano m process, which means that more transistors can be integrated into the same silicon area. This allows either to reduce the size of the IC or to increase the functionality and performance of the same size IC components. At the same time, there is also an interest to increase the packaging density even more by using 3D assembly, e.g. die stacking or package stacking. In both case the outcome is the same, the number of the contacts in same area is increasing and causing challenges for the packaging, assembly and substrate technologies.

To meet the demand for higher integration, the interest toward passive and active component embedding has been increasing during the past few years. Several institutes and companies have announced that they are developing technologies for embedding active and passive components. One of the main reasons for the growing interest toward embedded active components, in addition to demand for higher packaging density, is the need for better electrical performance of the component assemblies. Embedded passive components in printed circuit boards have been shown

to reduce space requirements by 30% or more, achieve better HF signal integrity and also allow for cost reductions. In the reference (Yi *et al.*, 2013), low cost and high performance duplexers have been developed for WiMAX front-end modules with multi-layered organic substrates and a new organic substrate manufacturing process has been proposed in order to improve the tolerance of embedded passives in organic substrates. The dual band front-end module for mobile devices includes a power amplifier die with a switch and has a very small package form factor.

Work on embedded active components is ongoing and is expected to achieve these same results and should additionally allow higher interconnect density and a dramatic functionality increase while maintain key PCB attributes of component and interconnects. However, this new technology itself may prove insufficient and/or non-optimal without considering the system level impacts of the specific military and/or consumer design. What is also needed to further these design goals are both the fundamental technology improvements (such as embedded active discrete chips), as well as novel and appropriate system level integration of the chips into the specific devices. As the complexity and requirements of systems increase, this system level integration will become more and more important.

Solder joints have been used in the electronic industry as both structural and electrical interconnections between electronic packages and printed circuit boards (PCB). When solder joints are under thermal cyclic loading, mismatch in coefficients of thermal expansion (CTE) between the printed circuit boards and the solder balls creates thermal strains and stresses on the joints, which may finally result in cracking (Zhong

and Yi, 1998; Zhong and Yi, 1999; Zhong *et al.*, 2002). Consequently, the mechanical interconnection is lost, leading to electrical failures (such as hard/intermittent open, parametric failure), which in turn causes malfunction of the circuit or whole system. Such failure mechanism is called thermal fatigue. Thermal fatigue is a major failure mechanism of solder joints and plays an important role in determining the reliability of electronic packages. Figure 1 shows a typical solder joint fatigue crack after being subjected to a thermal cycling test. Many efforts have been spent on predicting thermal fatigue lifetime to assess product reliability, especially in the product design and development stage.

Thermal fatigue happens mostly at solder joints, thus it hinders the reliability of the product. The ability to predict thermal fatigue life accurately is valuable to industry because it saves time and cost for product development and optimization. In order to predict thermal fatigue life accurately, an appropriate constitutive model and finite element analysis are required.

Phenomenal-based models are often used to establish the constitutive relationship of materials. The mechanical behavior of solders is viscoplastic because its deformation is rate-dependent. Thermal stresses in electronic packages are often beyond yield strengths of solders and the solder joints deform plastically. The plastic strain may consist of two components: the time-independent plastic deformation and the time-dependent creep deformation.

Figure 1-1 Cross section of solder balls after 1000 thermal cycles (-40 to 150 °C) where the arrow indicates the crack (Zhong and Yi, 1999).

In the past, many constitutive models were proposed for solders (Morris *et al.*, 2003; Darveaus and Banerji, 1992; Yi *et al.*, 2002; Joo and Yu, 2002; Wieses and Meusel, 2003). However, though many experimental studies show the strong influence of microstructure on solder mechanical properties, this phenomenon was not considered in most constitutive relationships. Yi *et al.* (2002) had established a constitutive relationship to take the microstructural grain size effect into account. In this model, matrix dislocation mechanism and grain boundary sliding are considered.

In the present study, the stress in solder joints of chip scale packages (CSP) with an embedded die under thermal cycling conditions is evaluated using the finite element

method. The viscoplastic model for solders including matrix dislocation mechanism and grain boundary sliding model developed by Yi *et al.* (2002) is employed.

Chapter 2. Analysis

2.1 Constitutive Relationships for Solders

The general form of the constitutive equation usually expresses the total strain rate

$\dot{\epsilon}_{ij}^{total}$ as the sum of the elastic $\dot{\epsilon}_{ij}^e$, time independent plastic strain rate $\dot{\epsilon}_{ij}^{pl}$, and time-dependent creep strain rate $\dot{\epsilon}_{ij}^{cr}$:

$$\dot{\epsilon}_{ij}^{total} = \dot{\epsilon}_{ij}^e + \dot{\epsilon}_{ij}^{pl} + \dot{\epsilon}_{ij}^{cr} \quad (i, j = 1, 2, 3) \quad (2.1)$$

In a unified model, the plastic and creep strain rates are unified as one inelastic term

($\dot{\epsilon}_{ij}^{in}$) which is calculated by the same equations. Therefore, the total strain can be

defined as

$$\dot{\epsilon}_{ij}^{total} = \dot{\epsilon}_{ij}^e + \dot{\epsilon}_{ij}^{in} \quad (2.2)$$

According to Yi *et al.* (2002), there are two deformation mechanisms to account for

$\dot{\epsilon}_{ij}^{in}$, so that

$$\dot{\epsilon}_{ij}^{in} = \dot{\epsilon}_{ij}^{mc} + \dot{\epsilon}_{ij}^{gb} \quad (2.3)$$

Finally,

$$\dot{\epsilon}_{ij}^{total} = \dot{\epsilon}_{ij}^e + \dot{\epsilon}_{ij}^{mc} + \dot{\epsilon}_{ij}^{gb} \quad (2.4)$$

where $\dot{\epsilon}_{ij}^{mc}$ is the creep strain rate due to the matrix dislocation and $\dot{\epsilon}_{ij}^{gb}$ is the creep

strain rate due to the grain boundary sliding, respectively.

Power law is used to model the deformation mechanism due to matrix dislocation (Yi *et al.* 2002).

$$\dot{\varepsilon}_{ij}^{mc} = C^{mc} \frac{E(T)}{T} \exp\left(\frac{-\Delta H^{mc}}{kT}\right) \left(\frac{|\mathbf{S} - \mathbf{X}^{mc}|}{D_0}\right)^{n^{mc}} \frac{s_{ij} - x_{ij}^{mc}}{|\mathbf{S} - \mathbf{X}^{mc}|} \quad (2.5)$$

The strain rate due to grain boundary sliding is given by a similar form of the equation.

The grain size effect is introduced to the equation by a term $\frac{1}{d^n}$, where d is the initial

grain size in the solder material:

$$\dot{\varepsilon}_{ij}^{gb} = C^{gb} \frac{1}{d^n} \frac{E(T)}{T} \exp\left(\frac{-\Delta H^{gb}}{kT}\right) \left(\frac{|\mathbf{S} - \mathbf{X}^{gb}|}{E(T)}\right)^{n^{gb}} \frac{s_{ij} - x_{ij}^{gb}}{|\mathbf{S} - \mathbf{X}^{gb}|} \quad (2.6)$$

with

$$|\mathbf{S} - \mathbf{X}^{mc}| = \sqrt{\frac{3}{2}(s_{ij} - x_{ij}^{mc})(s_{ij} - x_{ij}^{mc})} \quad (2.7)$$

$$|\mathbf{S} - \mathbf{X}^{gb}| = \sqrt{\frac{3}{2}(s_{ij} - x_{ij}^{gb})(s_{ij} - x_{ij}^{gb})} \quad (2.8)$$

In the above, $\mathbf{X}$ is the dynamic hardening back stress tensor, x_{ij} is the index notation for $\mathbf{X}$, $\mathbf{S}$ is the deviatoric stress tensor, s_{ij} is the index notation for $\mathbf{S}$ and given by

$$s_{ij} = \sigma_{ij} - \frac{1}{3} \sigma_{kk} \delta_{ij} \quad (2.9)$$

C and n are the material constants, ΔH is the activation energy, k is the Boltzman Constant which is equal to 8.617×10^{-5} eV/K, T is the temperature in Kelvin, D_0 is the isohardening drag stress, $E(T)$ is the Young's Modulus which is a function of

temperature. Superscript 'gb' and 'mc' denotes the parameters for grain boundary sliding and matrix dislocation, respectively. User-defined viscoplastic constitutive model is implemented to ABAQUS through a subroutine UMAT and semi-implicit time integration scheme is used. Large deformation analysis with the thermo-viscoplastic constitutive law has been performed and the subsequent interval is determined by ABAQUS solver. User-defined viscoplastic constitutive model is implemented to ABAQUS through a subroutine UMAT and semi-implicit time integration scheme is used. Large deformation analysis with the thermo-viscoplastic constitutive law has been performed and the subsequent interval is determined by ABAQUS solver.

Chapter 3. Verification Studies

Verification studies for Isothermal linear elasticity and non-isothermal linear elasticity are designed and conducted to check the accuracy of the result obtained by using the ABAQUS with the user-defined material subroutine (UMAT).

3.1. Linear Elastic Analysis

3.1.1. Isothermal Isotropic Linear Elasticity

A cantilever beam structure with a dimension of 10x1x1 (m) is considered. A surface traction (1000Pa) is applied at the right free end with left end fixed. Based on the Simple Beam Theory, the tip deflection of the cantilever beam is given by

$$\delta = \frac{FL^3}{3EI} \quad (3.1)$$

where F= Force acting at the tip of the beam, L= Length of the beam (span),

E=Modulus of elasticity and I= Area moment of inertia, respectively.

Area moment of inertia of a rectangular with a base width of b and height h is

$$I = \frac{bh^3}{12} \quad (3.2)$$

The analytic result the tip deflection of the cantilever beam is 3.419e-5m with E = 117 GPa. The finite element result of deflection (U_2) obtained with an isotropic isothermal elasticity UMAT designed in this study is 3.41e-5 m as shown in Figure 3-1. The analytic result agrees very to finite element one with UMAT and these results are tabulated in Table 3-1.

Figure 3-1 Deflection (U_2) of cantilever beam analyzed with UMAT

Table 3-1 Deflection (U_2) of cantilever beam

	Simple beam theory	FEA (ABAQUS)	FEA with UMAT (ABAQUS)
Tip deflection	3.419×10^{-5} (m)	3.41×10^{-5} (m)	3.41×10^{-5} (m)

3.1.2. Non-Isothermal Linear Elasticity

A beam structure with fixed both ends is considered. The dimension of the beam is $4 \times 1 \times 1$ m. Thermal loading, $\Delta T = 1$ degree C, is applied. In this case, the uniform temperature change through the beam is assumed.

Figure 3-2 Beam with $U_x = U_1 = 0$ displacement boundary condition

Theoretically, thermal displacement, thermal strain, and thermal stress can be obtained as

$$\Delta\delta = \alpha L (T_F - T_0) \quad (3.3)$$

$$\varepsilon^* = \Delta\delta / L = \alpha (T_F - T_0) \quad (3.4)$$

$$\sigma = E(\varepsilon - \varepsilon^*) = -E \alpha (T_F - T_0) \quad (3.5)$$

where ε = total strain, ε^* = thermal strain, σ = thermal stress, α = coefficient of thermal expansion, T_F = final temperature and T_0 = initial temperature respectively.

With $E = 1$ Pa, $\nu=0.3$, $\alpha=1$, $T_F=2$, $T_0=1$ for convenience, the thermal strain is 1 and thermal stress is -1 Pa since the total strain is zero. Exactly same results were obtained by using ABAQUS. The thermal strain of 1 and thermal stress of -1 are calculated as shown in Figure 4-3. All results are tabulated in Table 3-2.

Figure 3-3 Thermal stress and strain result applied UMAT

Table 3-2 Thermal stress and strain

	Theoretical Result	ABAQUS	ABAQUS with UMAT
Thermal Strain	1	1	1
Thermal Stress	-1	-1	-1

The thermal stress and thermal strain results of using isotropic non-isothermal elasticity UMAT are agree to CAE result and theoretical result.

Chapter 4. Finite Element Analysis of Embedded Ball Grid Array Packages under Thermal Cycling

Linear elastic and viscoplastic behaviors of solders are considered for the eBGA and the chip scale package (CSP) with an embedded chip to study the deformation and stresses during thermal cycle loading. The finite element formulation based on the viscoplastic constitutive relationship presented in the previous chapter is employed to analyze thermo-mechanical behaviors of solders.

4.1. Finite Element Model

4.1.1. Geometries and Mechanical Properties

Two different geometries are considered for this study. One is the eBGA and the other is the chip scale package (CSP) with the eBGA. They are illustrated in Figure 4-1.

Figure 4-1 eBGA and CSP with eBGA

A plane strain condition is considered which simplifies the problem to two-dimensional one. Half of the model is constructed due to geometric symmetry about the vertical axis. Figure 4-2 illustrates the FEA model for the CSP with the eBGA.

An 8-node biquadratic plane stress quadrilateral element with reduced integration (CPS8R in ABAQUS) is used.

Figure 4-2 Geometry of half model for CSP with eBGA

The geometry and mechanical properties of the CSP with the eBGA used for the present study are given in Tables 4-1 and 4-2, respectively. BT (Bismaleimide Triazine) and PCB are elastic and orthotropic because of their laminar structures. The mechanical properties in the x and z-directions are identical, but are different from those in the y-direction. The substrate consists of several layers with various materials including build-up layer, Cu layer, Core, and solder mask as shown in Figure 4-3. In addition, a die is embedded in the middle of the substrate. The remaining materials are assumed to be elastic and isotropic (Morris *et al.*, 2002; Yi *et al.*, 2005).

Solder Mask : 20μm	
Cu : 20 μm	
Build up : 40 μm	
Cu : 20 μm	
Build up : 40 μm	
Cu : 20 μm	
Build up : 40 μm	
Cu : 20 μm	
Embedded Die : 130μm	Core : 130μm
Cu : 20 μm	
Build up : 40 μm	
Cu : 20 μm	
Build up : 40 μm	
Cu : 20 μm	
Build up : 40 μm	
Cu : 20 μm	
Solder Mask : 20μm	

Figure 4-3 Cross section of substrate

Table 4-1 Geometry of CSP with eBGA

Materials	Full dimension LengthxWidthxThickness (mm)	Additional information
Mold compound	10 x10 x 0.76	Angle : 120°
Die (upper)	7.0 x 7.0 x 0.38	
Embedded die	6.8 x 6.8 x 0.13	
Substrate	12 x 12 x 0.57	
PCB	12 x 12 x1.57	
Solder ball	Diameter : 0.3mm Standoff height : 0.25mm Bond pad opening: 0.1mm	Total numbers of solder balls : 576 Pitch : 0.4mm

Table 4-2 Material properties of CSP with eBGA (Yi *et al.*, 2012; Chu, 2006).

Material	Young's modulus (MPa)	Poisson's ratio	CTE (ppm/K)	Additional information
Mold compound	15000	0.25	16.0	
Die	131000	0.28	2.6	
Solder mask	2549	0.29	55	
Copper layer	121000	0.35	17	
BT Build-up layer	x, z=26000 y=11000	xz=0.11 xy, zy=0.3	x, z=15 y=40	G _{xy} =8250 (MPa) G _{yz} =8250(MPa) xz=11712(MPa)
Core	x, z=26000 y=11000	xz=0.11 xy, zy=0.3	x, z=15 y=40	G _{xy} =8250(MPa) G _{yz} =8250(MPa) G _{xz} =11712(MPa)
Solder ball Sn3Ag0.5Cu (SAC305)	74419-110T(K)	0.36	24.,Temp< 218K 25.6, 218K<Temp<300K 27.9, 300K<Temp<398K	See Table 4-3
PCB	x, z=18000, y=7380 Mpa	xz=0.11 xy, zy=0.39	x, z=14.5 y=67.2	G _{xy} =5535(MPa) G _{yz} =5535(MPa)

Sn-3Ag-0.5Cu is employed for solders. Although there are numerous studies on the creep data of SnAgCu solders published, few was found suitable to use for curve-fitting purpose for the GM constitutive model. Firstly, creep data of solder joint (instead of bulk solder) is preferred since solder joints behave differently compared

with bulk solders. Secondly, creep data with several grain sizes at various temperatures and strain rates are required in order to obtain the full set of model parameters. A Pb-free solder, Sn3Ag0.5Cu, reported by Morris *et al.* (2003) is considered. As its creep data was obtained from actual solder joints rather than from bulk solders, it is expected to predict the thermo-mechanical of solder joints accurately. In their study, the experiment for the SAC solder reported by Morris *et al.* (2003) was conducted by applying a constant shear force to shear a specimen with nine solder joints of thickness 160 μm . This composition of alloy is considered in this study due to its gaining popularity. However, as the grain size data was not reported, the parameters for grain boundary deformation mechanism could not be determined.

Table 4-3 Creep data for Sn-3Ag-0.5Cu at various temperatures (Chu, 2006)

60°C		95°C		130°C	
τ (MPa)	$\dot{\gamma}^{\text{total}}$ (1/s)	τ (MPa)	$\dot{\gamma}^{\text{total}}$ (1/s)	τ (MPa)	$\dot{\gamma}^{\text{total}}$ (1/s)
5.44	1.0×10^{-8}	5.44	8.0×10^{-8}	3.6	1.5×10^{-8}
7.25	1.5×10^{-8}	7.25	7.0×10^{-7}	4.5	3.0×10^{-8}
9.07	3.0×10^{-8}	9.07	2.0×10^{-6}	5.44	2.5×10^{-6}
10.88	1.0×10^{-7}	10.88	1.0×10^{-5}	7.25	1.2×10^{-5}
12.7	2.0×10^{-6}	12.7	4.0×10^{-5}	9.07	3.5×10^{-5}
15	4.0×10^{-6}	-	-	10.88	2.0×10^{-5}

The strain rates at various temperatures and stresses are given in Table 4-3. The steady state stresses are obtained for various temperatures and the corresponding secondary creep strain rates are extracted. A summary of model parameters is given in Table 4-4.

Table 4-4 Material parameters of Sn-3Ag-0.5Cu (Chu, 2006)

Material parameters	Values
C^{mc}	4.0×10^{-6}
D_0	1.0
n_{mc}	6.7
ΔH^{mc} (eV)	0.697
H^{mc} (MPa)	$8885 - 21T(K)$
r^{mc}	500
$E(T)$ (MPa)	$74419 - 110T(K)$
ν	0.36

*Experimental conditions: 60 – 130°C, with strain rates ranging from 10^{-8} to 4×10^{-5} /s.

The predicted steady state stresses are calculated in this study and the creep curves are constructed. Comparison is made between the predicted steady state stresses and the experimental data. The discrepancies are found to be within 10%, showing that the model gives a good estimation of the experimental data. These set of parameters work best in the range of 60 – 130 °C with shear strain rates ranging from 10^{-8} to 4×10^{-5} /s.

4.1.2. Temperature Cycles

The temperature profile has an important effect on solder joint deformation since solder behavior is rate-dependent and the creep is a time-dependent strain. The temperature profile of thermal cycling has a strong influence on solder deformation. Fast temperature ramp rate increases the strain and stress as solder behavior is rate-dependent. The dwell time is also another factor because it allows creep to develop. Therefore, the choice of temperature profile affects the reliability of solder balls significantly.

The temperature profile of thermal cycling chosen in the present study consists of $T_{\text{initial}}=25^{\circ}\text{C}$ (298K), $T_{\text{high}}=125^{\circ}\text{C}$ (398K), $T_{\text{low}}=-40^{\circ}\text{C}$ (233K), dwell time=10mins, and ramp rate($10^{\circ}\text{C}/\text{min}$).

A common standard used by the electronic packaging industry is JEDEC. With standards, comparisons can be made between test results performed by different parties. Temperature profile used in this present study corresponds to ‘Condition G’ from the JEDEC standard which is commonly used by industry to conduct solder joint reliability studies. Temperature profile is plotted in Figure 4-4.

Figure 4-4 Temperature profile used for the FEA simulation

4.1.3. Finite Element Modelling

The coordinate system (1, 2, 3) is interchangeably used with the coordinate system (x, y, z), and the 3 axis (z axis) is out-of-plane. The boundary conditions are set as fixed ($U_1=U_2=U_3=0$) at the left bottom point of PCB and symmetry about the vertical axis ($U_1=0$) along left line of the chip scale package with eBGA. The stress-free state is considered at $T_{\text{initial}}=25^{\circ}\text{C}$ (298K).

Half of model is constructed due to geometric symmetry about the x axis. Linear elastic and viscoplastic behaviors of solders are considered. In addition, the eBGA and

the chip scale package with the eBGA are studied. The eBGA consists of 14,352 elements and 44,354 nodes, while the chip scale package with the eBGA has 21,947 elements and 67,209 nodes.

4.2. Linear Elastic FEA Results

4.2.1. eBGA

As shown in Fig 4-5, one thermal cycle is considered.

Figure 4-5 Thermal cycle applied for linear elastic FEA

Figure 4-6 Y displacement (U_2) of eBGA

Figure 4-7 Variation of maximum displacement in the y-direction during thermal cycling

As shown in Figs. 4-6 to 4-7, for positive temperature change ($\Delta T > 0$), the eBGA assembly bends upward (U-shape) because of the mismatch of CTEs among the materials, while it bends downward for negative temperature changes ($\Delta T < 0$). The results agree with the results published in the reference (Yi *et al.*, 2005). The maximum displacement in the y-direction of the eBGA package is obtained at the edge of the eBGA. For $\Delta T = 100$ and -65 degree C, the maximum displacements are 0.01576 mm and -0.0102 mm, respectively.

Figure 4-8 Normal stress S_{11} in eBGA

Figure 4-9 Normal stress S_{11} in substrate at step1 (T_{high})

Figure 4-10 Variation of the normal stress S_{11} through the thickness of substrate at step1(T_{high})

As shown in Figs. 4-8, 4-9, and 4-10, for positive temperature change ($\Delta T > 0$), the embedded die is in tension, while the surrounding of embedded die is in compression along the x axis since the surrounding of embedded die tries to expand more than the

embedded die and these two parts are held together. The opposite is observed at $\Delta T < 0$ as shown in Fig 4-8. These agree with the results published in the reference (Yi *et al.*, 2012).

As shown in Fig. 4-10, the maximum tensile stress S_{11} in the substrate at step1(T_{high}) is 115.028MPa and is observed at the bottom of the embedded die. The surroundings of the embedded die in the substrate are in compression and high compressive stresses are observed in the copper layers. The maximum compressive stress in the copper layer at step1 (T_{high}) is -74.3921MPa, which is observed at the first copper layer from the top. The maximum compressive stress of other surroundings except copper layers is -11.2614MPa, which is observed at the first solder mask layer from the top.

Figure 4-11 von Mises stress (S_{mises}) in eBGA at step1(T_{high})

Figure 4-12 von Mises stress (S_{mises}) in embedded die at step1(T_{high})

As shown in Figs. 4-11 and 4-12, the highest von Mises stress (S_{mises}) is observed at the contact area between the embedded die and the core. Actually, the die corner and the core corner experience the highest von Mises stress at both high and low temperatures. This is because geometric discontinuities and stress concentration happen in these corners. The high von Mises stress at the die corner may exceed the adhesive strength between the build-up layer and the die surface, resulting in delamination. This agrees to the well-known die corner delamination phenomenon seen in industry during reliability test (Yi *et al*, 2005). The von Mises stresses of the embedded die corner and all solder balls in eBGA at step1(T_{high}) are tabulated in Table 4-5.

Figure 4-13 Shear stress S_{12} in eBGA at step1 (T_{high})

Figure 4-14 Shear stresses S_{12} in embedded die corner and solder joint at step1 (T_{high})

As shown Figs. 4-11 and 4-12, high shear stresses S_{12} are observed in the embedded die corner and the solder joint. The maximum shear stress S_{12} in the eBGA exists at the embedded die corner and is 50.9775MPa. Also, the 9th solder joint from the x

origin has the highest shear stress S_{12} of -16.51MPa among solder joints. The shear stresses S_{12} of the embedded die corner and all solder balls in the eBGA at step1 (T_{high}) are tabulated in Table 4-5.

Figure 4-15 Shear Stress S_{12} in Solder Joints

As shown in Fig 4-15, the positive and negative shear stress is developed in the solder joint during thermal cycles. The shear stress near the right corner of the solder ball is compressive at T_{high} , while it is tensile at T_{low} . The distribution of shear stress in solder joint is almost diagonally symmetric.

Table 4-5 Shear stress and von Mises Stress of embedded die corner and all solder balls in eBGA at Step1 (T_{high})

Solder	Shear Stress (S_{12}) (MPa)	von Mises Stress (S_{mises}) (MPa)
1 st Solder Ball	-13.91	33.51
2 th Solder Ball	-14.20	33.99

3 th Solder Ball	-13.89	32.01
4 th Solder Ball	-14.91	35.24
5 th Solder Ball	-15.33	36.03
6 th Solder Ball	-14.88	34.10
7 th Solder Ball	-15.43	35.22
8 th Solder Ball	-15.67	35.43
9 th Solder Ball (near the end of embedded die)	-16.51	37.15
10 th Solder Ball	-13.72	31.56
11 th Solder Ball	-12.34	27.90
12 th Solder Ball	-10.94	24.60
The Upper corner of embedded die	50.98	116.46
The lower corner of embedded die	-49.91	115.06

Note that stresses in solder joints are measured at the most upper right element.

As seen from Table 4-6, the shear stress and the von Mises stress in the solder ball tend to increase except the 3th solder ball and the 6th solder ball as the distance in the x-direction increases until the 9th solder ball. Then, those stresses in the 10th ~12th solder joints decrease as the x distance increases. Namely, the highest stress among the solder joints occurs in the 9th solder joint, which is near the end of the embedded die.

The shear strain in the solder join can be expressed as

$$\gamma = \frac{l}{2h} (\alpha_s - \alpha_p) \Delta T \quad (3.6)$$

where γ = the shear strain, α_s = the coefficient of thermal expansion(CTE) of substrate, α_p = the coefficient of thermal expansion(CTE) of PCB, l = the length, h = the height of solder, and ΔT =temperature difference.

According to the equation above, the shear stress S_{12} of solder joint is proportional to the distance from origin. Therefore, it is reasonable that the 9th solder joint has the highest shear stress in the eBGA.

During thermal cycling, the various stresses including the normal stress, the shear stress, and the von Mises stress in the right corner of 9th solder ball are plotted in Figs. 4-16 and 4-17. The stresses of solder joints are proportional to temperature change linearly and don't change during dwelling.

Figure 4-16 Normal stresses (S_{11} and S_{22}) and shear stress (S_{12}) during thermal cycling

Figure 4-17 von Mises stress (S_{mises}) during thermal cycling

4.2.2. Chip Scale Package with eBGA

The linear elastic response of the chip scale package with the eBGA is analyzed with ABAQUS. In this case, one thermal cycle that is described in the previous section is considered.

Figure 4-18 Y displacement (U₂) in CSP with eBGA

As seen in Fig. 4-18, for positive temperature change ($\Delta T > 0$), the eBGA assembly bends upward (U-shape) due to the thermal expansion/mismatch among the materials, while it bends downward for negative temperature changes ($\Delta T < 0$). These agree with the results of previous eBGA case. The maximum displacement in the y-direction of

the CSP with eBGA package is obtained at the edge of the CSP which is the same location with previous eBGA. For positive temperature change $\Delta T=100$ degree C, it is 0.02006mm and is increased by 27.3% when compared with the eBGA. For negative temperature change $\Delta T= -65$ degree C, it is -0.01297mm and is 27.15% larger when compared with the eBGA.

Figure 4-19 Normal stress in the x direction of CSP with eBGA

As plotted in Fig. 4-19, for positive temperature change ($\Delta T > 0$), the upper die and the embedded die are in tension, while the surroundings of the upper die and the embedded die are in compression along the x axis since the surroundings of those dies expand more than those die. The opposite is observed at $\Delta T < 0$ as shown in Fig 4-19. These agree with the results of the previous eBGA.

Figure 4-20 von Mises Stress (S_{mises}) of CSP with eBGA at step1(T_{high})

Figure 4-21 von Mises stress (S_{mises}) near embedded die corner at step1(T_{high})

As shown in Figs. 4-20 and 4-21, the highest von Mises stress (S_{mises}) is observed at the contact area between the embedded die and the core. This agrees with the result of the previous eBGA. The von Mises stresses of the embedded die corner and all solder balls in the CSP with the eBGA at step1 (T_{high}) are tabulated in Table 4-7.

Figure 4-22 Shear stress S_{12} of CSP with eBGA at step1(T_{high})

As illustrated in Figs. 4-22 and 4-23, high shear stresses S_{12} are observed in the embedded die corner and the solder joint. For the CSP with eBGA, a maximum shear stress of -52.19MPa exists at the embedded die corner. Also, the 9th solder joint has the highest shear stress among the solder joints and the shear stress value is -16.61 MPa. The shear stresses of the embedded die corner and all solder balls in the CSP with eBGA at step1 (T_{high}) are tabulated in Table 4-6.

Figure 4-23 Shear stresses in embedded die corner and solder joint at step1(T_{high})

Table 4-6 Stresses in eBGA and CSP

Location	eBGA		CSP with eBGA		Shear Stress (S_{12})		von Mises Stress (S_{mises})	
	S_{12} (MPa)	S_{mises} (MPa)	S_{12} (MPa)	S_{mises} (MPa)	Difference	Percent (%)	Difference	Percent (%)
1 st Solder	-13.91	33.51	-15.01	36.37	-1.10	7.91	2.86	8.52
2 th Solder	-14.20	33.99	-15.01	36.36	-0.81	5.67	2.38	7.00
3 th Solder	-13.89	32.01	-14.47	33.92	-0.59	4.22	1.91	5.96
4 th Solder	-14.91	35.24	-15.02	36.39	-0.12	0.78	1.15	3.27
5 th Solder	-15.33	36.03	-15.06	36.41	0.27	-1.78	0.37	1.03

6 th Solder	-14.88	34.10	-14.42	33.62	0.46	-3.09	-0.47	-1.39
7 th Solder	-15.43	35.22	-14.77	34.13	0.66	-4.29	-1.09	-3.09
8 th Solder	-15.67	35.43	-15.11	34.29	0.56	-3.59	-1.14	-3.22
9 th Solder	-16.51	37.15	-16.61	37.10	-0.10	0.62	-0.05	-0.13
10 th Solder	-13.72	31.56	-13.19	30.43	0.53	-3.85	-1.13	-3.57
11 th Solder	-12.34	27.90	-10.68	24.55	1.65	-13.40	-3.35	-12.02
12 th Solder	-10.94	24.60	-7.89	23.53	3.05	-27.90	-1.08	-4.37
Upper corner of Embedded Die	50.98	116.46	41.41	96.32	-9.57	-18.77	-20.14	-17.29
Lower corner of Embedded Die	-49.92	115.06	-52.19	116.24	-2.28	4.56	1.18	1.03

As seen from Table 4-6, in the CSP with eBGA, the maximum shear stress and von Mises stress among the solder joints are also observed at the 9th solder joint, which is similar to the eBGA. As shown in Table 4-6, the magnitudes of those stresses at the 9th solder joint for both eBGA and CSP are almost identical. The shear stress and the von Mises stress in the 1st solder joint of the CSP with eBGA is about 8.5% higher than one of the eBGA. However, the shear stress and the von Mises stress in the 11th solder joint and the 12th solder joint of the CSP with eBGA are less compared with those of the eBGA. The shear stress in the 11th solder is 1.65MPa which is 13.4% less than one of the eBGA, while the shear stress in the 12th solder is 3.05MPa which is 27.9% less.

In addition, the shear stress and the von Mises stress at the upper corner of embedded die decreases by about 18%. Adding the upper die makes the stress at the upper corner of the embedded die decrease.

Figure 4-24 Normal stress (S_{11} , S_{22}) and shear stress (S_{12}) during thermal cycling

During thermal cycling, the various stresses including the normal stress and the shear stress in the right corner of 9th solder ball are plotted in Figs. 4-24. The stresses of the solder joint are proportional to temperature change linearly.

4.3.Viscoplastic FEA Results

4.3.1. eBGA

The viscoplastic response of the eBGA is analyzed with ABAQUS. In this case, four thermal cycles loading is considered.

Figure 4-25 Y displacement (U_2) in eBGA

Figure 4-26 Maximum displacement in the y-direction during thermal cycling

As illustrated in Figs. 4-25 and 4-26, for positive temperature change ($\Delta T > 0$), the eBGA assembly bends upward (U-shape) because of the thermal expansion mismatch among the materials, while it bends downward for negative temperature changes ($\Delta T < 0$). It agrees with the previous linear elastic result of the eBGA.

The maximum y-displacement in the eBGA is obtained at the edge of the eBGA which is the same location with the previous linear elastic case. For positive temperature change($\Delta T > 0$), it is changed from 0.01555mm at the start of the first hot(T_{high}) dwell to 0.0151mm at the end of the fourth hot(T_{high}) dwell. The result of the previous linear elastic case which is 0.01576mm, for the viscoplastic case, it gradually decreases from 1.33% to 4.19%. For negative temperature change($\Delta T < 0$), the maximum y-displacement in the eBGA is changed from -0.01052mm at the start of the first cold(T_{low}) dwell to -0.01085mm at the end of the fourth cold(T_{low}) dwell. For the linear elastic case, it is -0.0102mm, while, for the viscoplastic case, it increases in the negative direction from 3.14% to 6.37%.

Figure 4-27 von Mises stress of eBGA at step1 (T_{high})

Figure 4-28 von Mises stress near embedded die corner at step1 (T_{high})

As shown in Figs. 4-27 and 4-28, the highest von Mises stress (S_{mises}) is observed at the contact area between the embedded die and the core. This agrees with the results of the previous linear elastic response. The von Mises stresses of the embedded die corner and all solder joints in eBGA at step1 (T_{high}) are tabulated in Table 4-8.

Figure 4-29 Shear stress of eBGA at Step3(T_{low})

Figure 4-30 Shear stress in embedded die corner at step1 (T_{high}) and step3 (T_{low})

Figure 4-31 Shear stress in solder joint at step1 (T_{high}) and step3 (T_{low})

As shown in Figs 4-29 to 4-31, the viscoplastic shear stress in the eBGA is smaller than one for the linear elastic case. However, the distributions of shear stress in the

solder joints and the embedded die corner are similar to those for the linear elastic case.

The shears stresses at the embedded die corner and all solder joints in the eBGA at step1 (T_{high}) are tabulated in Table 4-7.

Table 4-7 Stress comparison with linear elastic response of eBGA at step1(T_{high})

Solder	Linear elastic case		Viscoplastic case		Shear stress (S_{12})		von Mises stress (S_{mises})	
	S_{12} (MPa)	S_{mises} (MPa)	S_{12} (MPa)	S_{mises} (MPa)	Difference	Percent (%)	Difference	Percent (%)
1 st Solder	-13.91	33.51	-5.20	9.71	8.71	-62.60	-23.80	-71.02
2 th Solder	-14.20	33.99	-5.34	9.99	8.86	-62.37	-24.00	-70.62
3 th Solder	-13.89	32.01	-5.33	10.09	8.56	-61.64	-21.92	-68.47
4 th Solder	-14.91	35.24	-5.62	10.78	9.29	-62.33	-24.46	-69.41
5 th Solder	-15.33	36.03	-5.74	11.29	9.59	-62.57	-24.74	-68.66
6 th Solder	-14.88	34.10	-5.59	11.50	9.29	-62.44	-22.59	-66.26
7 th Solder	-15.43	35.22	-5.76	12.08	9.67	-62.70	-23.14	-65.71
8 th Solder	-15.67	35.43	-5.86	12.31	9.82	-62.63	-23.12	-65.25
9 th Solder	-16.51	37.15	-5.74	13.25	10.77	-65.22	-23.90	-64.33
10 th Solder	-13.72	31.56	-5.45	12.88	8.26	-60.24	-18.68	-59.18

11 th Solder	-12.34	27.90	-5.45	11.11	6.89	-55.85	-16.79	-60.17
12 th Solder	-10.94	24.60	-5.23	9.64	5.71	-52.24	-14.96	-60.80
Upper corner of Embedded Die	50.98	116.46	50.82	116.06	-0.16	-0.31	-0.40	-0.35
Lower corner of Embedded Die	-49.92	115.06	-49.84	114.79	0.07	-0.15	-0.26	-0.23

As seen from Table 4-7, in viscoplastic case, the maximum von Mises stress among solder joints is also observed at the 9th solder. In the viscoplastic case, the von Mises stress in the solder joints tends to increase as the distance in the x-direction increase until the 9th solder. Afterward those stresses in the solder joints decrease as the x distance increases. This is similar to the linear elastic case. The magnitudes of viscoplastic shear stresses in solder joints of the eBGA are 52.24% ~65.22% of those for the linear elastic case. The von Mises stresses in the solder joints are 59.18% ~71.02% less compared with those for the linear elastic case. However, the magnitudes of those stresses at the embedded die corner are almost identical. The shear stresses at the die corner are 0.31% and 0.15% less and von Mises stresses are 0.35% and 0.23% less. During thermal cycling, the various stresses including the normal stress, the shear stress, and the von Mises stress in the right corner of the 9th solder ball are plotted in Figs. 4-32 to 4-35.

Figure 4-32 Variation of shear stress S_{12} during thermal cycling

Figure 4-33 Variation of normal stress S_{11} during thermal cycling

Figure 4-34 Variation of normal stress S_{22} during thermal cycling

Figure 4-35 Variation of von Mises stress (S_{mises}) during thermal cycling

As plotted in Figs. 4-32 to 4-35, the viscoplastic stresses in the eBGA are nonlinear and the magnitudes of stresses relax during dwelling.

During the temperature ramp up, the magnitudes of stresses decrease due to reduction of Young's modulus of the solder. The von Mises stress (S_{mises}) in the right corner of the 9th solder ball decrease from 33.17MPa to 7.89MPa when temperature increases from 233K to 308K, but it increases from 7.89MPa to 11.92MPa for when temperature increases further from 308K to 398K. During the cool or hot dwell period, the magnitudes of stresses decrease as stress relaxation occurs. The von Mises stress (S_{mises}) decreases from 11.92MPa to 8.03MPa during the hot dwell period (398K).

During the temperature ramp down, the magnitudes of stresses increase due to increase of Young's modulus of the solder. The von Mises stress (S_{mises}) in the right corner of the 9th solder ball increases from 8.03MPa to 35.21MPa, which is maximum, when temperature decreases from 398K to 233K.

During the cold dwell, cycle, the magnitudes of stresses decrease because of stress relaxation. As shown in Figure 4-32, the behavior of shear stress in the right corner of the 9th solder ball is very similar to one of the von Mises stress.

4.3.2. Chip Scale Package with eBGA

The viscoplastic response of chip scale package with eBGA is analyzed with ABAQUS. In this case, four thermal cycles loading is considered.

Figure 4-36 Y displacement (U_2) of CSP with eBGA

Figure 4-37 Maximum displacement in the y-direction during thermal cycling

From Figs. 4-36 and 4-37, for positive temperature change ($\Delta T > 0$), the chip scale package with the eBGA assembly bends upward (U-shape) because of the thermal expansion mismatch among the materials, while it bends downward for negative temperature changes ($\Delta T < 0$). It agrees with the previous linear elastic result of the chip scale package. The maximum y-displacement in the CSP with eBGA is obtained at the edge of the eBGA which is the same location with the previous linear elastic

case. For positive temperature change ($\Delta T > 0$), it is changed from 0.019952mm at the start of the first hot (T_{high}) dwell to 0.019821mm at the end of the fourth hot (T_{high}) dwell. The result of the previous linear elastic case which is 0.02006mm, for the viscoplastic case, it gradually decreases from 0.0539% to 1.191%. When it is compared with the result of the previous viscoplastic response of the eBGA, it increases by 28.31% at the start of the first hot (T_{high}) dwell and 31.265% at the end of the fourth hot (T_{high}) dwell. For negative temperature change ($\Delta T < 0$), the maximum y-displacement in the CSP with eBGA is changed from -0.013144mm at the start of the first cold (T_{low}) dwell to -0.0132256mm at the end of the fourth cold (T_{low}) dwell. The linear elastic case, it is -0.01297mm, while, for the viscoplastic case for the CSP with eBGA, it increase in the negative direction from 1.34156% to 1.9707%. When it is compared with the result of the previous viscoplastic case of the eBGA, it increases by 24.94% at the start of the first hot (T_{high}) dwell and 21.89% at the end of the fourth hot (T_{high}) dwell.

Figure 4-38 von Mises stress of CSP with eBGA at step1(T_{high})

Figure 4-39 von Mises stress near die corner at step(1)(T_{high})

As shown in Figs. 4-38 and 4-39, the highest von Mises stress(S_{mises}) is observed at the contact area between the embedded die and the core. This agrees with the results of the previous linear elastic response. The von Mises stresses of the embedded die corner and all solder joints in the CSP with eBGA at step1(T_{high}) are tabulated in Table 4-8.

Figure 4-40 Shear stress S_{12} of CSP with eBGA S_{12} at step3(T_{low})

Figure 4-41 Shear stress S_{12} in embedded die corner at step1(T_{high}) and step3(T_{low})

Figure 4-42 Shear Stress S_{12} in Solder Joint at step1(T_{high}) and step3(T_{low})

As shown in Figs 4-40 to 4-42 the viscoplastic shear stress(S_2) in the CSP with eBGA is smaller than one for the linear elastic case. However, The distributions of shear stress(S_{12}) in solder joints and embedded die corner similar to those for linear elastic case. The shears stresses of the embedded die corner and all solder joints in the CSP eBGA at step1(T_{high}) are tabulated in Table 4-8.

Table 4-8 Stress comparison with the linear elastic case at step1(T_{high})

Solder	Linear elastic case		Viscoplastic case		Shear stress (S_{12})		von Mises stress (S_{mises})	
	S_{12} (MPa)	S_{mises} (MPa)	S_{12} (MPa)	S_{mises} (MPa)	Difference	Percent (%)	Difference	Percent (%)
1 st Solder	-15.01	36.37	-5.21	9.85	9.80	-65.30	-26.52	-72.91
2 th Solder	-15.01	36.36	-5.22	9.90	9.79	-65.20	-26.46	-72.77

3 th Solder	-14.47	33.92	-5.15	9.81	9.33	-64.45	-24.11	-71.09
4 th Solder	-15.02	36.39	-5.26	10.08	9.76	-64.98	-26.31	-72.30
5 th Solder	-15.06	36.41	-5.31	10.21	9.75	-64.75	-26.20	-71.96
6 th Solder	-14.42	33.62	-5.20	10.02	9.22	-63.92	-23.60	-70.18
7 th Solder	-14.77	34.13	-5.44	10.35	9.32	-63.13	-23.79	-69.68
8 th Solder	-15.11	34.29	-5.70	10.65	9.41	-62.30	-23.64	-68.94
9 th Solder	-16.61	37.10	-5.89	12.39	10.72	-64.56	-24.71	-66.60
10 th Solder	-13.19	30.43	-5.36	11.87	7.83	-59.35	-18.56	-60.98
11 th Solder	-10.68	24.55	-4.94	9.20	5.74	-53.77	-15.35	-62.53
12 th Solder	-7.89	23.53	-4.01	11.38	3.88	-49.20	-12.15	-51.65
Upper corner of Embedded Die	41.41	96.32	41.27	96.01	-0.14	-0.33	-0.31	-0.32
Lower coner of Embedded Die	-52.19	116.24	-52.13	116.02	0.06	-0.12	-0.22	-0.19

As seen from Table 4-8, in the viscoplastic response of the CSP with the eBGA, the shear stress and the von Mises stress in the solder tend to increase except the 3th solder and the 6th solder as the distance in the x-direction increases until the 9th solder. Then those stresses in the solder joint decrease as the x distance increases. This is similar to the linear elastic case.

The viscoplastic shear stresses in the solder joints of the CSP with eBGA are 49.2% ~65.3% less than the linear elastic ones, while the von Mises stresses of solder joints are 51.65% ~71.91% less. However, the magnitudes of those stresses at the embedded die corner are almost identical to the elastic ones. The differences of the shear stresses and the von Mises stress near the corner of the die are about 0.25% and 0.3%, respectively. During thermal cycling, the various stresses including the normal stress, the shear stress, and the von Mises stress in the 9th solder ball are plotted in Figs. 4-43 to 4-46.

As plotted in Figs 4-43 to 4-46, the viscoplastic stresses in the CSP with eBGA are nonlinear and the magnitudes of stresses decrease during dwelling.

During the temperature ramp up, the magnitudes of stresses decrease due to reduction of Young's modulus of SAC305. The von Mises stress (S_{mises}) in the right corner of the 9th solder ball decrease from 32.37MPa to 7.66MPa when temperature increases from 233K to 308K, but it increases from 7.66MPa to 11.20MPa for when temperature increases further from 308K to 377K. When temperature increases from 377K to 398K, the von Mises stresses (S_{mises}) decrease slightly from 11.20MPa to 11.05MPa. During the cool or hot dwell period, the magnitudes of stresses decrease as stress relaxation occurs. The von Mises stress (S_{mises}) decreases from 34.64MPa to 32.8MPa for 600 seconds during the cool dwell period (233K).

Figure 4-43 Variation of shear stress S_{12} during thermal cycling

Figure 4-44 Variation of normal stress S_{11} during thermal cycling

Figure 4-45 Variation of normal stress S_{22} during thermal cycling

Figure 4-46 Variation of von Mises stress (S_{mises}) and during thermal cycling

During the temperature ramp down, the magnitudes of stresses increase due to increase of Young's modulus of the solder. The von Mises stress (S_{mises}) in the right corner of the 9th solder ball increases from 7.27MPa to 34.64MPa, which is maximum, when temperature decreases from 398K to 233K.

During the cold dwell, cycle, the magnitudes of stresses decrease because of stress relaxation. As shown in Figure 4-43, the behavior of shear stress in the right corner of the 9th solder ball is very similar to one of the von Mises stress.

Chapter 5. Conclusions

In the present study, the thermal-mechanical behavior of the solder balls in the eBGA and the CSP with eBGA has under thermal cycling is successfully studied by the finite element analysis. The linear elastic and viscoplastic material behaviors of the solder are considered.

For positive temperature change ($\Delta T > 0$), both of the eBGA and the CSP bend upward (U-shape) because of the mismatch of CTEs among the materials, while those bend downward for negative temperature changes ($\Delta T < 0$).

The maximum displacement in the y-direction of the eBGA package is obtained at the edge of the eBGA. Based on the linear analysis, the maximum displacements in the y-direction of the eBGA for $\Delta T = 100$ degree C and $\Delta T = -65$ degree C are 0.01576 mm and -0.0102 mm, respectively.

For the CSP with the eBGA, the maximum displacement in the y-direction is 0.02006mm for $\Delta T = 100$ degree C and is increased by 27.3% when compared with the eBGA, while it is -0.01297mm for $\Delta T = -65$ degree C and is increased by 27.15%.

For positive temperature change ($\Delta T > 0$), the tensile normal stress along the x direction is developed in the embedded die, while the compressive normal stress is observed in the substrate around the embedded die since the surrounding of the embedded die tries to expand more than the embedded die. The opposite is observed for $\Delta T < 0$.

For the linear elastic analysis, the maximum shear stress and von Mises stress are observed at the 9th solder joint in both the eBGA and the CSP. The magnitudes of those stresses at the 9th solder joint for both the eBAG and the CSP are almost identical.

For the viscoplastic analysis, the creep is observed. The y-displacement in the eBGA is -0.01052mm after temperature decrease and then it was further increased during the cool dwell period. The maximum y-displacement is -0.01085mm at the end of the fourth cold (T_{low}) dwell, which is 6.37% large compared with the elastic one.

The viscoplastic shear stresses of solder joints in the CSP with eBGA are 49.2% ~65.3% smaller than the linear elastic ones. The von Mises stresses based on the viscoplastic analysis is 51.65% ~71.91% smaller than the linear elastic ones.

The viscoplastic stresses in the eBGA and the CSP are highly nonlinear and relax during dwelling. During the temperature ramp up, the magnitudes of stresses decrease due to reduction of Young's modulus of the solder.

In the CSP, the von Mises stress (S_{mises}) in the right corner of the 9th solder ball decrease from 32.37MPa to 7.66MPa when temperature increases from 233K to 308K, but it increases from 7.66MPa to 11.20MPa for when temperature increases further from 308K to 377K. When temperature increases from 377K to 398K, the von Mises stresses (S_{mises}) decrease slightly from 11.20MPa to 11.05MPa. The von Mises stress (S_{mises}) decreases from 34.64MPa to 32.8MPa for 600 seconds during the cool dwell period (233K).

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