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Modeling Correlation for Solder Joint Fatigue Life Estimation in Wafer-Level Chip Scale Packages

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ABSTRACT

The wafer level chip scale package (WLCSP) has been widely used in mobile chipset applications since it provides a strong solution to satisfy the demands for smaller form factor, multifunctional and low cost devices. As WLCSP moves towards lower cost, higher performance and finer pitch designs to meet the increasing requirements of electronic products, there are a number of challenges in preventing package failure and enhancing reliability that need to be overcome. In general, the failure mode in WLCSP usually occurs near the solder joints and the package reliability becomes worse if the WLCSP design has a larger die size or smaller ball pitch. To evaluate the solder joint fatigue life, the Coffin-Manson equation is typically utilized. For the purpose of analyzing the solder joint fatigue life, the 2P2M WLCSPs which mean that there are two polymer layers and two metal layers (one under-bump-metallurgy (UBM) layer and one redistribution layer (RDL) on the passivated wafer) were examined in board level reliability (BLR) thermal cycling test (TCT; follows JEDEC standards for the temperature change from -40˚C to 125˚C). The three-dimensional (3D) finite element analysis (FEA) with rate dependent material nonlinearity behaviors was constructed to study the corresponding creep behaviors of Sn4.0Ag0.5Cu (SAC405) solder joints in four 2P2M WLCSP with different package size and ball pitch. By correlating the BLR TCT and simulation results, the fatigue ductility coefficient and the reciprocal of the fatigue ductility exponent in the modified Coffin-Manson equation for solder joint fatigue life in above WLCSP devices can be developed with the correlation of experimental and simulation results. With these equations, the solder joint fatigue life in these WLCSPs can be easily estimated through simulations without any evaluation of BLR TCT experiments. It is believed that the results not only provide an effective method to predict the package reliability life but also can save time and cost in the development stage.

I. INTRODUCTION

With the highly insatiable demands of high performance and lower cost requirements for handheld and portable electronic devices in the semiconductor industry, the wafer level chip scale package (WLCSP) is widely used in integrated circuit (IC) fabrication today. These insatiable demands have been pushing WLCSP designs aggressively towards die sizes larger than 5x5mm^2, solder pitches smaller than 400µm and lower prices [1-4]. A typical WLCSP structure in the semiconductor industry today includes four mask processes on the passivated wafer (2P2M WLCSP). The 2P2M WLCSP design includes one UBM layer, one RDL and two polymer layers. The first polymer layer (PBO1) is coated on the passivated wafer and then an opening is etched for electroplating RDL on the top surface of the PBO1 layer and connected to the Al pad. After plating RDL, the second polymer layer (PBO2) is coated to cover the RDL and on the top surface of PBO1 layer. After that, an opening is etched in the PBO2 layer followed by electroplating the UBM layer on the RDL pad to form the interconnections. The process flow for 2P2M WLCSP (with UBM layer) and associated solder joint cross-sectional images are illustrated in Fig. 1 [5].

For applications with larger than 5x5 mm^2 die sizes or less than 400µm ball pitch, the die I/Os can be increased to enhance the corresponding performance. With the increasing requirements of multifunctional, smaller form factor, lower cost and fine pitch package designs in WLCSP, a number of challenges need to be overcome, especially in terms of preventing the possible failures and enhancing the package reliability [6, 7]. Because the solder joint fatigue failure is the most common failure mode in WLCSPs, it is important to understand its fatigue behavior. From literature in industry publications [8-11], it is well known that the empirical Coffin-Manson equation has been widely adopted to evaluate the thermal fatigue life of solder joints in electronic packages. For the sake of understanding the solder joint reliability fatigue life, the BLR TCT that follows JEDEC standards for the temperature change from -40˚C to 125˚C was evaluated in 2P2M WLCSPs (with UBM layer and SAC405 solder joints) [12]. The experimental solder joint fatigue life of these WLCSPs can be obtained by Weibull distribution according to the BLR TCT results. In order to establish a modified Coffin-Manson equation for solder joint fatigue life prediction, the 3D finite element modeling with rate dependent material nonlinearity behaviors was utilized. The fatigue ductility coefficient and the reciprocal of the fatigue ductility exponent in the modified Coffin-Manson equation for SAC405 solder joints in 2P2M WLCSP can be obtained through the correlation of experimental and simulation results. Based on the present equations, the correlated thermal fatigue life for the utilization of SAC405 solder joints in the WLCSP with a UBM layer can be effectively estimated through the numerical modeling instead of evaluating the BLR TCT experiments. This study will be useful if high reliability and cost reduction are required in a larger die size and smaller ball pitch WLCSP during the development stage.

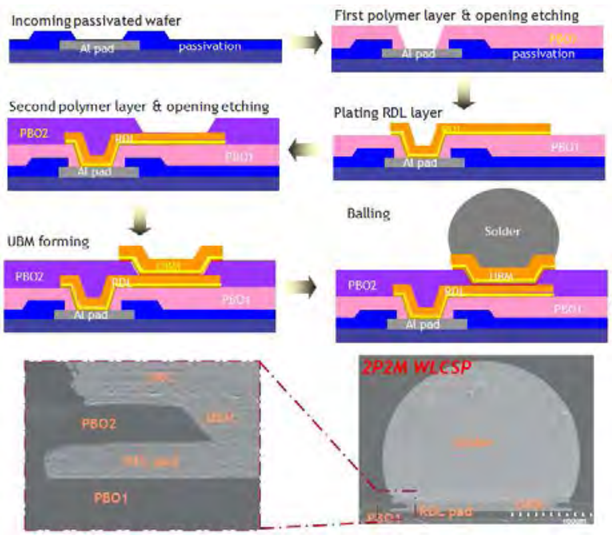


FIGURE 1. The process flow for 2P2M and associated cross-sectional images of solder ball structures [5].

II. BOARD LEVEL RELIABILITY THERMAL CYCLING TEST

The BLR TCT was completed according to JEDEC standard - JESD22-A104D for the temperature change from -40˚C to 125˚C (condition G). The printed circuit board (PCB) uses a built-up multilayer technology that incorporates microvias in a 1+6+1 stack-up that followed the JEDEC standard No.22-B111 [13]. The nominal thickness of the PCB was 1.0 mm with 132x77 mm dimensions that accommodated 15 components of the same type in a 3 row by 5 column format. The PCB pad design for perimeter I/O devices followed IPC-SM-782 guidelines and all component attachment pads were non-solder mask-defined (NSMD).

For the purpose of realizing solder joint fatigue life in the 2P2M WLCSP (with utilization of UBM layer), four test vehicles were introduced which included approximate die sizes of 4x4 mm^2 and 6x6 mm^2 as well as different ball pitches of 300µm and 400µm. The detailed geometrical dimensions are listed in Table 1. All the test vehicles are mounted with SAC405 solder joints that attached to the PCB.

TABLE 1. The dimensions of 2P2M WLCSP (with UBM layer)

Dimensions	Test Vehicles (2P2M WLCSP)			
	2P2M-TV1	2P2M-TV2	2P2M-TV3	2P2M-TV4
Die size (mm^2)	~ 4 x 4	~ 6 x 6	~ 4 x 4	
UBM size (µm)	240	240	170	190
UBM thickness (µm)	8.6			
PBO1 thickness (µm)	7.5			
PBO2 thickness (µm)	7.5			
PBO2 opening (µm)	210	200	140	160
RDL CD (µm)	250		180	200
RDL thickness (µm)	4			
Ball pitch (µm)	400		300	
Ball size (µm)	250		180	200
Ball count	100	151	144	144

Fig. 2 shows the probability plot of Weibull distribution for 2P2M WLCSP with SAC405 solder joints in BLR TCT (test condition G with soak mode 3 of 10-min dwell time). The results indicate that the first failure for 2P2M-TV1, TV2, TV3 and TV4 is 682, 417, 455 and 606 cycles, respectively and the corresponding characteristic life is 1013, 680, 587 and 876 cycles, respectively. The Weibull parameter η is the characteristic lifetime (63.2% failed) and β is the shape parameter. From Fig.2, it is observed that with increasing die sizes and/or decreasing ball pitches, the solder joint fatigue life decreases. Moreover, it was evident that the UBM size has a critical impact on the solder joint fatigue life. Larger UBM sizes and solder joints achieve good reliability results in fatigue life [14]. The results are in agreement with the physical phenomena. The corresponding reliability scanning electron microscope (SEM) results of the 2P2M WLCSPs are illustrated in Fig. 3. By examining the SEM photos in Fig. 3, it was determined that the solder crack initially occurred near the corner of the RDL pad and solder ball then propagated along the IMC layer. It did not, however, propagate perfectly along the interface of the RDL pad and IMC layer causing failure. Some cracks were found to have occurred at the solder ball that was adjacent to the PCB Cu pad and propagated along the top surface of PCB Cu pad (along the bottom IMC layer; as shown in Fig. 3(b), (c) and (d)).

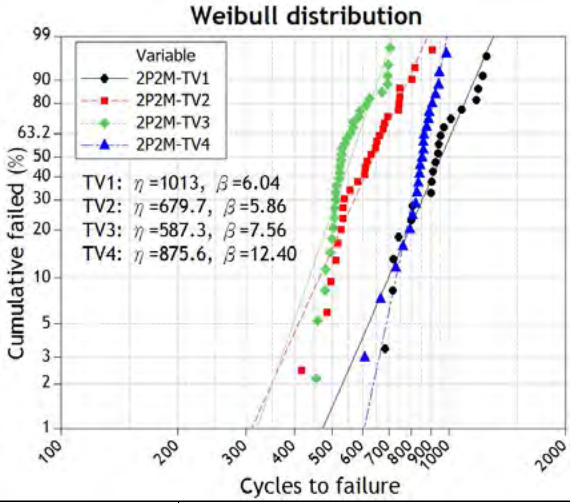
III. FINITE ELEMENT ANALYSIS FOR WLCSP

For the purpose of correlating the solder joint fatigue life through simulation and BLR TCT, the 3D quarter model was constructed in FEA due to the symmetry feature. The maximum creep strain and/or creep strain energy density is typically located on the outermost solder ball and this is always the critical place to drive the solder crack in WLCSP. To have a precise solution in the outermost solder ball area, dense meshes were used in this critical place. The quarter finite element models and the applied boundary conditions for 2P2M WLCSP are shown in Fig. 4, which are pure hexahedral element-meshed (with PCB size of 20x23 mm^2). The NSMD interconnects with solder resist opening (SRO) of 300µm and thickness of 30µm was utilized on the top surface of the PCB. The diameter of the Cu pad on PCB was 220µm and thickness was 25µm. The loading condition with five thermal cycles initially from 25°C to 125°C and down to -40°C were set in FEA, which consists of 10-min (soak mode 3) or 15-min (soak mode 4) dwell time with temperature extremes of 125°C and -40°C. The material properties in 2P2M WLCSP are listed in Table 2. In Table 2 E, ν, CTE and Tg are Young's modulus, Poisson's ratio, coefficient of thermal expansion and glass transition temperature, respectively. The creep constitutive equation (Garofalo-Arrhenius creep model) of SAC405 lead-free solder joint was described as [15-16]

$$d\varepsilon_{cr} / dt = C_1[\sinh(C_2\sigma)]^{C_3} e^{-(C_4/T)} , \quad (1)$$

where $d\varepsilon_{cr}/dt$ is equivalent creep strain rate, σ is the equivalent stress and T is the absolute temperature. C_1, C_2, C_3 and C_4 are material parameters which are defined as [16]:

$$C_1 = 1.15\times10^6\,(1/\sec),\; C_2 = 0.0335,\; C_3 = 7.5,\; C_4 = 8703.4\,(K).$$



Failure rate	Test Vehicle (2P2M WLCSP)			
	2P2M-TV1	2P2M-TV2	2P2M-TV3	2P2M-TV4
1st failure (cycles)	682	417	455	606
63.2% (cycles)	1013	680	587	876

FIGURE 2. Probability plot of Weibull distribution for SAC405 solder joint fatigue life in 2P2M WLCSP (with UBM layer).

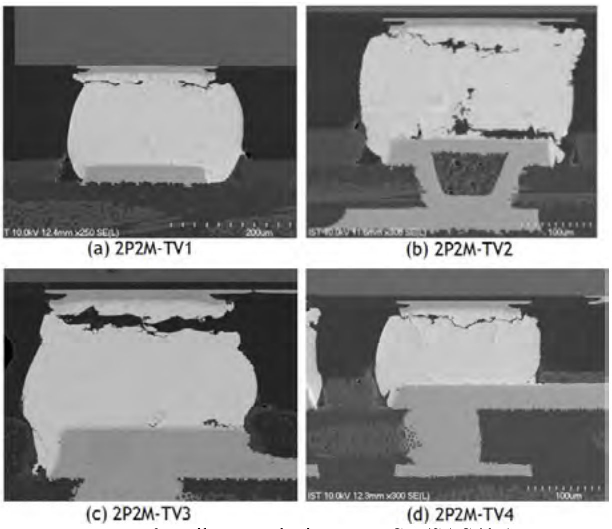


FIGURE 3. Failure results in BLR TCT (SAC405).

Fig. 5 illustrates the creep strain energy density plot for 2P2M-TV1 at the end of fifth thermal cycle. The result indicates that the maximum value occurs at the solder top interface of the outermost solder joint in the package. Fig. 6 shows the average element creep strain energy density and equivalent creep strain over the course of five thermal cycles for SAC405 solder joints in 2P2M WLCSP. The change in creep strain energy density was virtually invariant after the third thermal cycle and can be shown in most packages [9]. Hence, all the results are determined from the fifth thermal cycle. The results of the change in creep strain energy density (ΔW) and the change in equivalent creep strain ($\Delta\gamma$) at fifth thermal cycle for 2P2M-TV1, TV2, TV3 and TV4 are listed in Table 3.

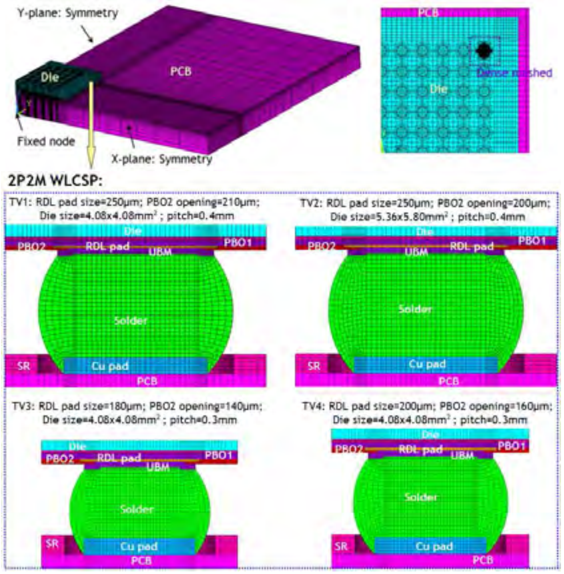


FIGURE 4. FEM and applied boundary conditions of 2P2M WLCSP

TABLE 2. Material properties in WLCSP.

Material	E (GPa)	ν	CTE (ppm/ °C)
Die	131	0.28	2.8
Low-k [17]	10	0.16	5
PBO1/PBO2 [18]	2.3	0.3	64
PCB Cu pad	110	0.34	17
Solder resist (SR) [19]	3.2	0.4	58/153 (Tg=105°C)
Solder (SAC405) [20]	46.625 @ -65°C 43.625 @ -25°C 39.875 @25°C 36.125 @ 75°C 32.375 @ 125°C	0.35	20.196 @ -65°C 20.876 @ -25°C 21.726 @25°C 22.576 @ 75°C 23.426 @ 125°C
RDL (Cu)	110	0.34	17
PCB	22	0.28	18.5
Passivation (SiN/USG)	137.5	0.206	1.907
UBM (Cu)	110	0.34	17

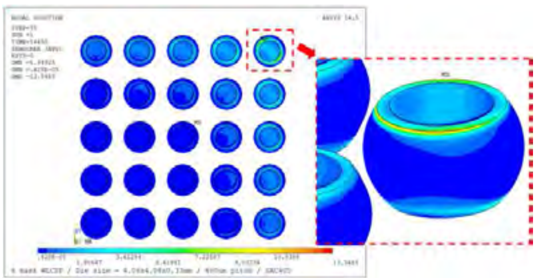


FIGURE 5. Creep strain energy distribution in 2P2M-TV1.

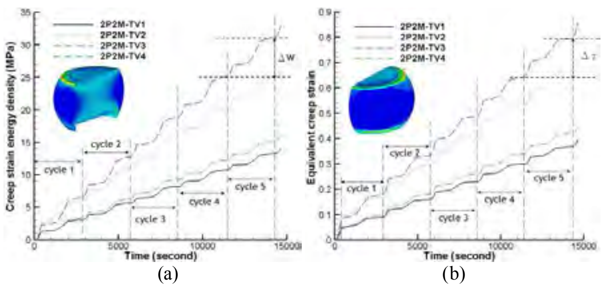


FIGURE 6. (a) Creep strain energy density; (b) equivalent creep strain during five thermal cycles for SAC405 solder joints in 2P2M WLCSP.

TABLE 3. The simulation result of ΔW and $\Delta\gamma$ in 2P2M WLCSP

Creep strain energy density (ΔW; MPa)	Test Vehicles (2P2M WLCSP)			
	TV1	TV2	TV3	TV4
	2.5383	4.6673	6.1175	2.9516
Equivalent creep strain ($\Delta\gamma$)	0.069140	0.122467	0.153659	0.079642

IV. MODELING CORRELATION AND CHARACTERIZATION

For the solder joint fatigue life correlation with simulation and BLR TCT results, there are two modified Coffin-Manson equations being utilized and can be expressed as

$$N_f = A_1(\Delta W)^{-n_1}; \quad (2)$$

$$N_f = A_2(\Delta \gamma)^{-n_2}; \quad (3)$$

where N_f is the average number of cycles to failure of the solder joint. The number of cycles until 63.2% cumulative failed is identical to the Weibull parameter η, which can be observed in Weibull distribution in Fig. 2. ΔW and $\Delta\gamma$ is the creep strain energy density and equivalent creep strain that changed in one cycle, respectively. A_1, A_2, n_1 and n_2 are coefficients that need to be determined by experiments. The equation (2) and (3) can also be expressed in a linear polynomial form as below.

$$\ln(N_f) = -n_1 \ln(\Delta W) + \ln(A_1); \quad (4)$$

$$\ln(N_f) = -n_2 \ln(\Delta \gamma) + \ln(A_2); \quad (5)$$

Fig. 7 shows the plots for the relationship of $\ln(N_f)$ based on BLR TCT results as well as $\ln(\Delta W)$ and $\ln(\Delta\gamma)$ that come from the simulation result. A linear regression trendline is added in the plot. From Fig. 7, it was found that the values of R^2 are larger than 0.99 which indicates that both simulation and reliability results are in a good approximation (the model with larger R^2 value is being more desirable). The coefficients of A_1, A_2, n_1 and n_2 can be obtained through Fig. 7 as -0.6016, -0.6591, 7.4553 and 5.1365, respectively. Thus, the correlated thermal fatigue life for SAC405 solder joints in 2P2M WLCSP can be expressed as

$$N_f = 1729(\Delta W)^{-0.6016}; \quad (6)$$

$$N_f = 170.1(\Delta \gamma)^{-0.6591}. \quad (7)$$

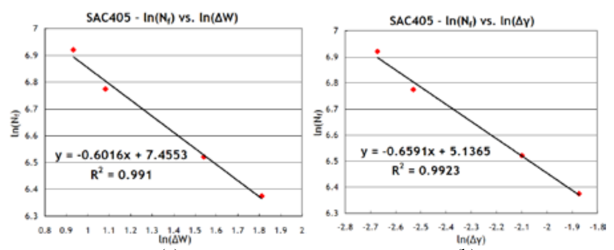


FIGURE 7. Correlation of SAC405 solder joint fatigue life in 2P2M WLCSP (a) $\ln(N_f)$ vs. $\ln(\Delta W)$; (b) $\ln(N_f)$ vs. $\ln(\Delta\gamma)$.

IV. CONCLUSIONS

The correlation of experiments in board level reliability thermal cycling test and finite element simulations for 2P2M WLCSP with SAC405 solder joints were studied in this paper. With the good approximation of this result, the modified Coffin-Manson equations for SAC405 solder joints fatigue life estimation in 2P2M WLCSP were obtained. Through the developed equations, the solder joint fatigue life in the WLCSPs with a UBM layer can be promptly calculated by simulations without any efforts on experimental evaluations. The result is valuable and useful if the adequate design for fine pitch and large die size WLCSP is demanded.

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