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Variation of Thermal Cycling Life Prediction of PBGA Microprocessor Components with Substrate Properties

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Abstract
The modern trend is to decrease the size of microprocessor components, at the same time, the number of I/O of the silicon chip microprocessors have been greatly increased over the last few years, which means high BUS speed, high amount of heat generation and much more elevated temperature operation. Plastic ball grid array (PBGA) is one of the most widely used microprocessor components in electronic packaging industries. Due to the complex nature of the configuration of the package, when subjected to temperature fluctuation, thermal stresses are developed inside the package. Severe stresses may develop when the packages are exposed to harsh environments e.g. spaceship, automobile etc. where extreme fluctuation of temperature may occur. So the PBGA packages are often subjected to thermal cycling which ultimately causes fatigue failure in solder balls of the package. The thermal cycling life of a PBGA package may depend on the properties of its constituent materials. Particularly this study aims at investigating the effects of substrate mechanical properties on the prediction of thermal cycling life of the critical solder joint in a PBGA package. In experiments, it has been found that from package to package there is significant variation in elastic modulus of the Bismaleimide-Triazine (BT) substrate material. Finite element analysis results show that there is large degradation in thermal cycling life of the solder ball for a package with low elastic modulus BT material when it is compared with the results that obtained for higher value of elastic modulus.

Keywords: plastic ball grid array (PBGA), solder, thermal cycling life, mechanical properties, finite element method

INTRODUCTION

Modern microprocessors are often exposed to harsh environments where these are subjected to extreme change of temperatures. Finite element simulations of Accelerated Life Testing (ALT) for the PBGA assemblies are normally performed using thermal cycling, where the test assemblies are subjected to harsh changes in temperature over a much shorter period of time than the expected field exposure of the parts. This process also allows the determination of various characteristics of the packaging architecture during its life cycle, i.e. critical locations, failure modes, stress levels, etc. For the accurate prediction of the life of the PBGA packages, it is important to use the correct mechanical properties of the constituent materials rather than the standard properties. Variation of the mechanical properties of a constituent material may also result in the variation of the predicted life of the package. The orientation of different layers in a typical microprocessor is shown in Figure 1. The substrate material is placed just above the solder ball layer. These solder balls are also attached to the printed circuit board (PCB) at the bottom side (not shown in figure). During thermal cycling, the deformation and failure of the solder balls largely depends on the mechanical properties of the substrate layer. From package to package, due to the variation in package architecture, orientation of copper layers in the substrate are largely varied, which leads to the variation of the mechanical behaviour of the substrate material.

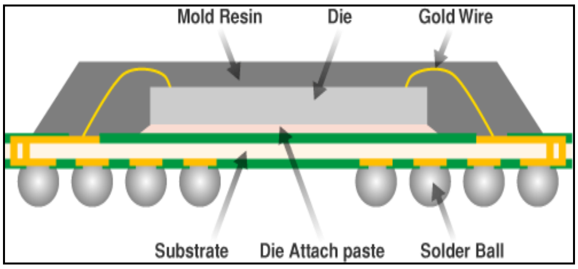


Figure 1 – Schematic Diagram of PBGA Package

Many researchers have investigated the stress, strain, and life to failure for a wide variety of microprocessors. Ping, et al., 2014, investigated the thermal stress and strain of Plastic Ball Grid Array (PBGA) for reliability evaluation and failure analysis. A one-eighth model is built to estimate the thermal stress and strain of PBGA under thermal cycling temperature (0°C–100°C). The results show that the maximum equivalent stress and equivalent plastic strain occur in the second outer solder joint and close to the position of chip. Sung, et al., 2012, on their paper provided a design and material selection guideline for a plastic ball grid array (PBGA) package in order to improve its reliability and manufacturing ability after post mold cure. Their study showed that the material properties such as modulus and CTE of molding compounds play an important role in warpages and reliability of PBGA packages. SW, et al., 1997, presents a non-linear numerical study to investigate the effect of chip dimension and substrate thickness on the solder joint reliability of plastic ball grid array (PBGA) packages. Yuan and Carpenter, 2003, showed that trace cracks in the substrate of a thin PBGA package were detected after temperature cycle testing during a product qualification. Numerical simulations with the finite element method were performed to investigatethe impact of design parameters and material selection. Bongtae, et al., 1996, investigated the thermo-mechanical behavior of a Flip Chip Plastic Ball Grid Array package assembly. The results reveal that the CTE of a substrate is one of the most critical design parameters to solder ball reliability. For the assembly with a relatively small chip analyzed in the study, a significant improvement of solder joint reliability is predicted by optimizing the CTE of the substrate. However, there have been insufficient studies that deal with the characterization of the substrate properties using the specimen from the real PBGA packages and investigating the effects of substrate elastic modulus on the thermal cycling life of the PBGA components.

This study has been performed to investigate how the predicted life of a PBGA microprocessor changes when there is variation in the mechanical properties of the BT-epoxy laminate (substrate) material. Also, an experimental procedure has been established to determine the actual mechanical properties of substrate materials by extracting tensile test specimens from a real package. This gives the capability to check the vendor data for errors and to build a reliable model for the finite element analysis to accurately predict the life to failure in accelerated life testing.

EXPERIMENTAL PROCEDURES

The PBGA components under current investigation became available from an anonymous motherboard. The intel® microprocessor on one of the PCBs is shown in Figure 2. Three test vehicles of the similar kind were selected for the experiments to measure the stress-strain data of the BT laminates of these packages. Initially the packages were separated from the motherboards using a precision cutting machine. After slitting the packages into two halves, one halves was allocated for microscopic analysis and another half was allocated for making tensile test specimens. Figure 3 shows some of the processing stages of the PBGA components.

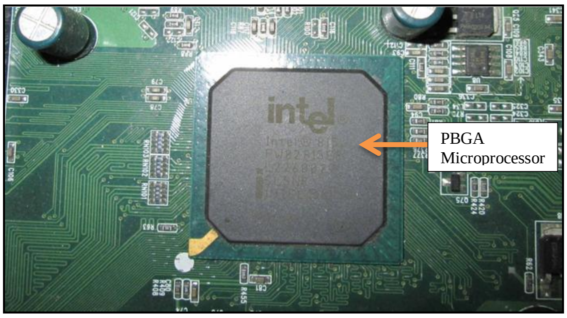


Figure 2 – The test vehicle with the PBGA component

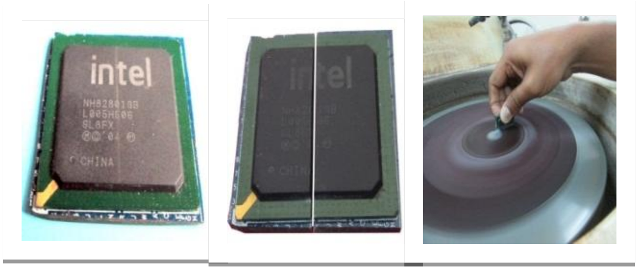


Figure 3 – Processing of the PBGA component for the tensile testing of BT and for Microscopic analysis.

The stress-strain properties of the BT substrate have been characterized using tensile specimens extracted from actual PBGA components. In this case, the PBGA components have been polished from the molding compound (top) side of the part until the die is exposed. The silicon was then removed using the dry plasma etching process, and the remaining mold compound was polished away. This left only the BT laminate with attached solder balls. A second phase of polishing was then done to remove the solder balls and leave only the BT substrate, which could then be cut up into thin 31mm × 3mm × 0.6 mm tensile specimens.

Microscopic Analysis

Identification of different layers in the PBGA package and to determine their dimensions, microscopic analyses of the package cross section is performed. The results have been used in the finite element modeling of the package. Surface polishing is done for this purpose. Emery papers and velvet cloth rotator polishing machine were used for fine finishing of the cross section of the packages. After the polishing, the arrangements of different layers of the package are observed by an optical microscope. Figure 4 shows the cross section obtained from the microscope for package no. 1.

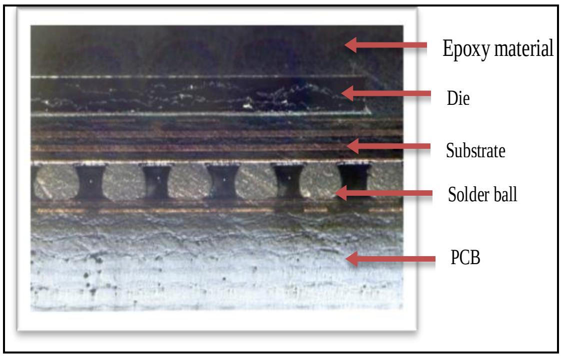


Figure 4 – Cross Section of PBGA Microprocessor under the Optical Microscope

Although the packages are identical in macroscopic observation but the substrates are different due to the differences in copper layer orientation. This can also lead to the variation of the mechanical properties of the substrate material from one package to other.

Tensile Test Results for Substrate Material

The stress-strain properties of the BT substrate have been characterized using tensile specimens extracted from actual PBGA components. Figure 5 shows the tensile test specimen. Tensile tests are done in Instron 2716-020 testing machine. Stress-strain data were measured for each sample and modulus of elasticity was calculated from the curves.

The stress-strain curve for the substrate material extracted from different packages is shown in Figure 6. The elastic modulus, ultimate tensile strength, and the ultimate elongations are recorded from the test. The variation of the stress-strain curves in the substrate materials from three different packages can be visualized in Figure 6. As mentioned earlier, the differences are mainly due to the variation in the orientation of copper layer in the substrate. The extracted values of the mechanical properties for all the specimens are listed in Figure7.

Figure 5 - Tensile Test Specimen of the BT Substrate Material Extracted from PBGA Package

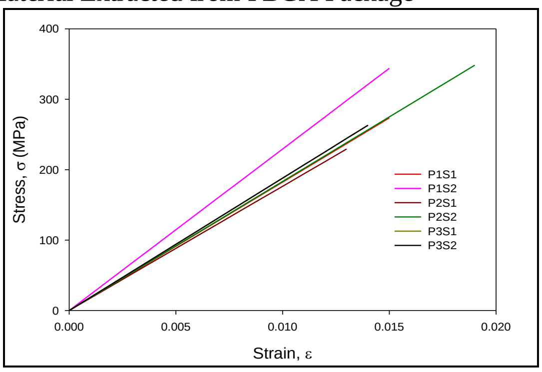


Figure 6 - Tensile Test Specimen and the Stress-Strain Curves for the BT Substrate Materials from Different Packages

Many manufacturers are now producing the BT-epoxy substrate material for PBGA packages. Wide variation of mechanical properties (i.e. elastic modulus, UTS, etc.) has been observed from the substrates made by different manufacturers. The elastic modulus has been found as low as 13 MPa and as high as 28 MPa indicating large variations as shown in Figure 8. This range of elastic modulus has been used in the finite element simulations to investigate the effects of substrate elastic modulus on the PBGA thermal cycling life. The CTE of the substrate material has been considered constant for this study and is assumed as 0.35.

Package No.	Sample No.	Load at Max. Load (kN)	Elastic Modulus (MPa)	Strain at Max.Load (mm/mm)
1	1	.296939	18240	.014606
	2	.338005	22940	.014658615
2	1	.275922	17645	.013106
	2	.321650	18334	.0185
3	1	.325215	19776	0.015653846
	2	.287606	18800	.01387

Figure 7 - Tensile Test Results of the BT Substrate Material

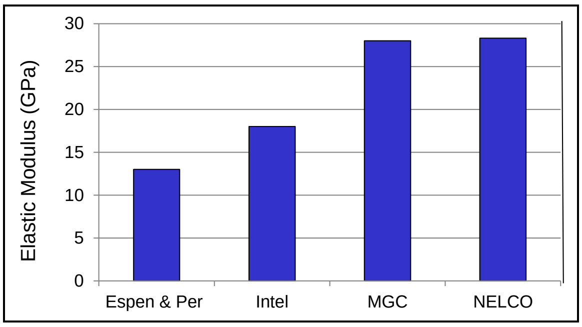
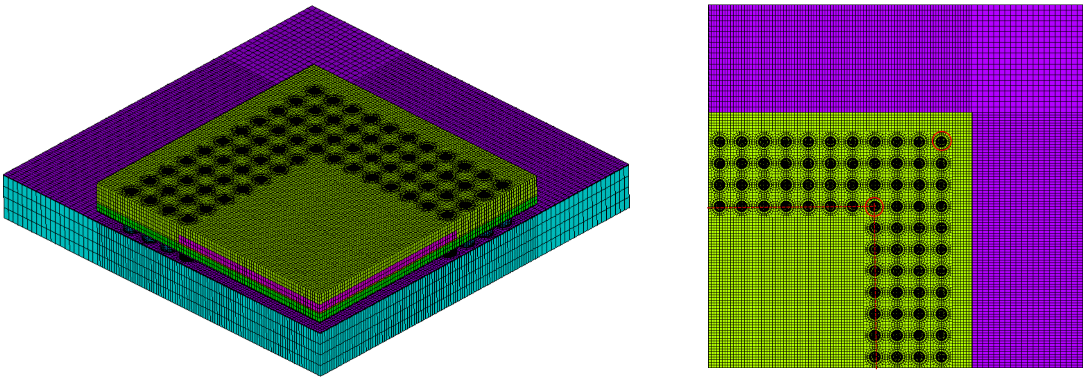


Figure 8 - Variation of the Elastic Modulus of the BT Substrate Material Found in Literature (Espen&Per – "Characterization of Material Properties (2014), Intel – "Physical Constants of IC Package" (2015, 12 July), MGC – "BT Materials" (2015, 10 July), NELCO – 'Park electrochemical" (2015, 15 July)

FINITE ELEMENT MODELING OF THE PBGA PACKAGE

Three dimensional nonlinear finite element modeling of the anonymous microprocessor component has been used to calculate the accumulated strain energy dissipation per cycle in the solder joints as a result of thermal cycling between -40 to 125 ^{o}C. Figure 9 shows the quarter symmetry model of the PBGA package that was developed and solved using ANSYS finite element software. The entire model utilized a structured finite element mesh with 650,450 elements and 703,110 nodes.

The quarter model has been appropriately constrained along the axes of symmetry, so that for a node in a symmetry plane, the displacement component perpendicular to the symmetry plane was required to be zer**o.** In addition, all three displacements were set to zero for the center node at the bottom surface of the PCB to prevent any rigid body motions. The entire assembly was subjected to a time dependent temperature distribution to reflect the -40 to +125 C thermal cycling performed in the life testing experiments. The ramp rate for this thermal cycling profile was 16.5 ^{o}C/min, and the high and low temperature dwell times were each 20 minutes. The stress-free temperature of the package has been assumed to be T = 220 ^{o}C, which is the solidification temperature of the lead free solder joints. The applied thermal loading including the cool down after solder joint reflow and the first several thermal cycles is shown in Figure 10.



(a) (b)

Figure 9 - (a) Finite Element Mesh (Quarter Symmetry) (b) Top View Showing the Die Boundary and Probable Critical Solder Ball Locations

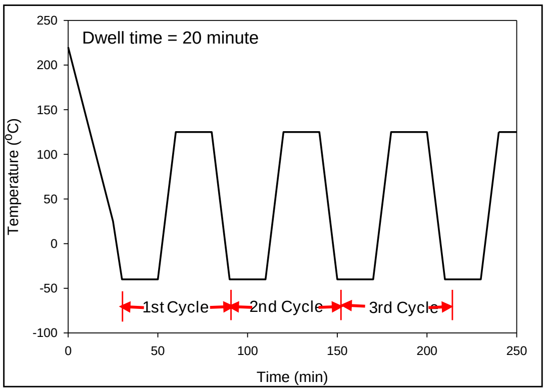


Figure 10 - Applied Thermal Loading

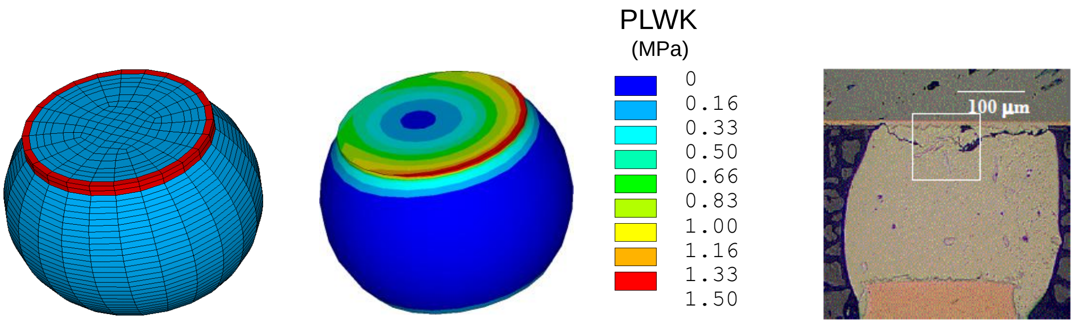
The solder balls were modeled in ANSYS with Solid185 structural elements with 8 nodes. This element is designed to solve both isochoric (volume preserving) rate-independent and rate-dependent large strain plasticity problems. For the other materials in the model, SOLID45 structural solid elements have been used, which are 8 node elements with plasticity, creep, large deflection and large strain capabilities. Iterative solution procedures have been used due to the nonlinear material and kinematic properties of the model. Typical solution run times were about 2 hours per thermal cycle using a workstation with quad core processor and 16 GB of memory. The solder balls have been modeled as viscoplastic material with the Anand model (Motalab, et al., 2013) .The properties of other materials have been used as listed in Figure11(Motalab, et al., 2013).

Material	Elastic Modulus (GPa)	Poisson's Ratio	CTE (ppm/C)
PCB	Ex = 16.90 Ey = 7.44 Ez = 16.90	PRxy = 0.39 PRyz = 0.39 PRxz = 0.11	CTEx = 14.5 CTEy = 67.2 CTEz = 14.5
Solder Mask	3.1	0.3	16.3
Copper Pad	128	0.34	17
Die Attachment Adhesive	1.5	0.35	65 ($T<T_g$) 200 ($T>T_g$) T_g = 60 °C
Die	169	0.28	2.54

Figure 11 - Room Temperature Material Properties used in the PBGA Model

FEA Simulation Results

For all analyses, the critical solder ball in this PBGA assembly was found to be the diagonal ball located near the corner of the package. The volume averaged inelastic energy dissipation ΔW = PLWK (plastic work) accumulated per cycle is often taken to be the metric for damage accumulation and failure of solder joints. Following Che, et al., 2005, the outer ring of elements in the top two rows were used to calculate ΔW for the third thermal cycle. Figure 12 shows the mesh plot of the critical solder joint with the ring elements. It has been observed that the finite element analysis predicts the maximum plastic energy dissipation near the top right side of the critical solder joint. This is in agreement with the origination of crack in a similar package that is also shown in Figure 12 according to Lamaye, et al., 2006. The effects of substrate elastic modulus on the calculated accumulated inelastic energy dissipation values are shown in Figure 13. It has been found that the inelastic energy dissipation increases by about 25% in the critical solder joint when the BT elastic modulus changes from 28 to 16 GPa.



(a) (b) (c)

Figure 12 - (a) Finite Element Mesh of a solder ball and the elements used for PLWK calculation (b) Contours of PLWK in the Critical Solder Joint (c) Crack Propagation in a PBGA Solder Ball(Limaye, et al., 2006)

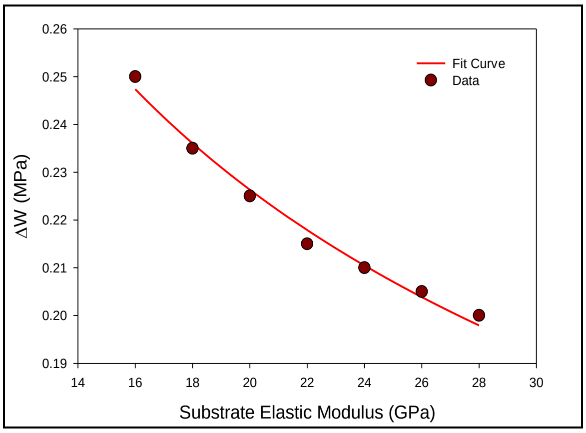


Figure 13 - Variation of Plastic Energy Dissipation per Cycle with Substrate Elastic Modulus

Darveaux, 2000, has presented energy dissipation based models for life prediction in solder joints subjected to cyclic loading.

$$N_i = K_1 (\Delta W)^{K_2}$$

$$\frac{da}{dN} = K_3 (\Delta W)^{K_4} \tag{2}$$

where N_i is the number cycles to crack initiation, da/dN is the crack growth rate (assumed constant) occurring after crack initiation, □W is the energy dissipation per cycle in the solder sample (e.g. critical solder ball), and K_1, K_2, K_3, and K_4 are fitting constants that are used from Motalab, et al.,2013, assuming non-aged configuration. Once the crack location and path are known in the solder joint, the number of cycles to failure can be estimated using:

$$N_f = N_i + \frac{a_c}{\left[\frac{da}{dN}\right]} \tag{3}$$

whereN_f is the number of cycles to failure, a_c is the length of the fully developed crack at failure/fracture, and N_i and da/dN are calculated from □W using eqs. (1-2).

The thermal cycling life of the PBGA assemblies can now be predicted for different values of substrate elastic modulus. Using the procedure described above, the thermal cycling life of the PBGA component has been calculated and the results are plotted in Figure 14. It has been found that the life of the solder joint decreases by more than 60% when the BT elastic modulus changes from 28 to 16 GPa.

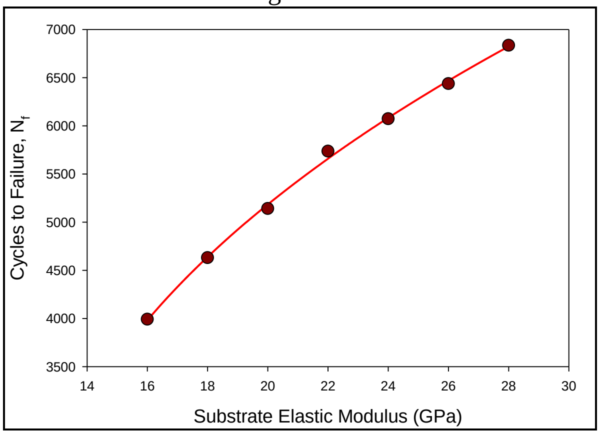


Figure 14 - Variation of Cycles to Failure with Substrate Elastic modulus

CONCLUSION

The effects of elastic modulus of the BT substrate material on the thermal cycling life (life of solder balls) of the PBGA (plastic ball grid array) microprocessor have been investigated in this research. For the accurate prediction of the life of the PBGA packages, it is important to use the correct mechanical properties of the constituent materials. The properties of the substrate material are very important in calculating solder life since the BT layer lies just above the solder balls. A wide variation of the elastic modulus (13~28 GPa) of substrate material for PBGA packages has been observed from the archival data. Also, a procedure has been established to extract the tensile test specimen of the substrate from the real processor assembly, which can help to check the vendor data for errors. Experimental results show that there is significant variation of the BT elastic modulus in the three identical PBGA packages mainly due to the differences in copper orientation in the substrate layers. Finite element simulation of the thermal cycling tests of the PBGA packages have been performed and the results show that the plastic energy dissipation (damage accumulation) in the critical solder ball increases by 25% if the elastic modulus of BT changes from 28 to 16 GPa. Also, the life of the critical solder ball decreases by 60% when the BT elastic modulus changes from 28 to 16 GPa, suggesting large degradation in solder life.

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