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Finite Element Analysis of Flip Chip Ball Grid Array Packages for BGA Life Prediction: 2D, 3D or Axisymmetric?

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Abstract
A variety of mechanical and thermal stress related problems related to Flip Chip Ball Grid Array Packages (FCBGAs) are often solved by the Finite Element Method. Often, the question for the stress analyst is how to simplify the problem at hand and come up with a sufficiently accurate model in a reasonable amount of time. The aim of this paper is to examine several different modeling strategies and compare the performance of various models so as to provide a guideline for selection of a modeling strategy. For the comparison of various models, the problem of thermal cycling is addressed here. The comparison of various models is based on strains in the critical solder ball. A common geometric layout is assumed. Properties of the laminate are varied so as to cover the range of properties of various laminates available. Pros and cons of various methodologies are pointed out and are expected to provide useful guidelines for the stress analysts in the electronic packaging area. The paper shows that making meaningful comparisons and predictions using modeling requires in-depth knowledge experience in the field of modeling as well as the physical phenomena being modeled.

Introduction
With an ever increasing pressure for TTM (Time to Market), semi-conductor, semiconductor packaging and EMS (Electronic Manufacturing Services) companies are increasing their efforts in using modeling and simulation. Modeling and simulation is finding use in the design as well as manufacturing ramp-up phases to rapidly optimize designs and accomplish problem resolution, respectively.[1]

The complexity of the problems solved and the pressure of reaching the market quickly mean that mistakes can be costly. Indeed, it was shown[1] that catching a mistake further down in the product cycle exponentially increases the cost of the mistake. As a consequence, sophisticated simulations must be carried out by experts that have an in-depth knowledge of not only the subject matter - heat transfer, physics, mechanics etc. but also the computational methods tailored for each subject.

Case studies of how thermal and mechanical analyses were used to optimize the design characteristics – thermal performance and reliability – were demonstrated recently for flip-chip packages.[2, 3] Extension of component models to the system is useful in many cases. This enables the system designer to choose components based on system level performance as opposed to performance lab-level or other industry standard environments. This was demonstrated through a system-level thermal design and simulation for game boxes.[4]

Several papers related to FEM simulations in FCBGA have been published. The study by Cheng et al.[5] explores a new approach for 3-D simulations to come up with an effective local-global approach. In this approach, coarse grids are used in an overall module simulation to obtain constraint for a more local region of interest. A ten-fold decrease in computational time is reported. Rassaian et al[6] consider a similar study, but 2D, that uses a multi-domain analysis of PBGA solder joints. A four-fold decrease in computational time was reported. 2D non-linear FEM was used in[7] to study the long-term reliability of solder joints for BGAs of various configurations. None of these studies compare different dimensionalities of the FEM methods. Variam and Sitaraman address the design optimization aspects of a flip-chip BGA package through 2-D simulations. Effects of under-fill properties, die and substrate thicknesses on the stresses in assembly and in thermal cycling conditions are studied in[8] using a 2D methodology. The study[9] investigates the effect of different criteria such as strain or strain energy density and the effects of constitutive models on BGA cracking propensity, using a 2D modeling approach[10] reports a comparison of 2D plane strain vs plane stress vs. 3D FEM method for flip-chip packages with no thermal lid or lid adhesive. The results are studies on terms of stress only for assembly cool-down conditions. In the present study we study the FEM methods for a realistic high-end package that includes the thermal spreader. Both assembly cool-down and thermal fatigue conditions are considered. The results are reviewed in terms of stress, strain and strain density as appropriate for the region of the package under consideration.

A full fledged three dimensional analysis with a converged solution is the best solution that finite element analysis can provide. A typical converged solution-even with the 1/8th geometry- can take a large number of degrees of freedom and unreasonably large amount of time due to the dissimilarities and nonlinearities of various materials involved in the model. It is often necessary to understand the impact of geometric variables such as die size, body size, thicknesses of various adhesives, impact of materials selection for a given chip carrier substrate technology and even the impact of selection of chip carrier substrate technology. Further, there are manufacturing tolerances associated with geometry of the component as well as tolerances on mechanical properties of the materials involved. A thorough analysis would involve consideration of all these aspects. This can lead to a large number of finite element models to come up with an optimum solution for a particular problem. It is due to such demands that it is necessary to compromise on accuracy of a particular solution and still being able to predict the correct trends with reasonable accuracy. The models can then be verified with experimental data. The trends predicted by the models then can be used to come up with optimum design.

Methodology

Prediction of solder life in FCBGA package involves two basic steps. The first step consists of determining the critical measure of strain in the solder in the solder ball most likely to fail, typically using a finite element model. The second step then consists of substituting this measure of strain in a Coffin-Manson type failure model to obtain the number of cycles to failure. A variety of critical strain measures and specific forms of the Coffin-Manson type model have been proposed by researchers (11 for example). Each of the strain measures and specific model has been shown to be applicable to a certain set of problems. For the purpose of this paper, the solder is assumed to be elastic-perfectly plastic and the critical strain measure chosen is the maximum shear strain in the solder. The aim of this paper is to compare various modeling strategies and as long as a consistent measure of failure is used, the results are expected to be applicable over a wide range of measures. Initial stress free condition for the model is assumed to be at 180 °C, where solder solidifies after attaching the component to the card. The assembly consisting of the component, the solder balls and the card is then stressed through one temperature cycle from 0 °C to 100 °C.

BGA Life Prediction

A typical Coffin-Manson type relation used for prediction of fatigue life of solder can be written as:

$$N = \frac{F}{e^{a}} \qquad (1)$$

Where,

N = No. of cycles to failure

e = Critical measure of strain, involving elastic, plastic and creep strains

a = Fatigue exponent

F = Constant, involving activation energy, frequency effects etc.

For the purpose of this paper, the value of a is taken as 2.

The relative life of BGA joints is then predicted using:

$$\frac{N_2}{N_1} = \left(\frac{e_1}{e_2} \right)^{a} \qquad (2)$$

Where,

N_2 =No. of temperature cycles to fail for the reference strain level

N_2 =No. of temperature cycles to fail for the second strain level, to be predicted.

e_1 =Change in maximum shear strain for the reference case.

e_2 =Change in maximum shear strain for the case to be predicted.

Modeling Strategy

When the fatigue life of a solder ball is to be determined as an absolute value, use of the correct form of equation (1) is required. It is critical to get a converged finite element solution for the critical measure of strain. As discussed before, this ideal condition may not be realized in many cases due to restrictions on required resources such as time and computational power and vast possibilities of tolerances in the actual product. The more practical alternative is to use a coarse mesh along with equation (2) and get an estimate of relative solder life. Then, by using experimental data on a reference case, predictions can be made for a variety of cases.

Typically various approximations done during a simulation have a range of applicability. This range consists of material properties in case of stress analysis of BGA assembly. In this paper, we investigate the behavior of three dimensional, two dimensional plane stress and axisymmetric models over a span of material properties and geometric properties of chip carriers. A typical geometric layout of FCBGA package is assumed, see Figure 1.

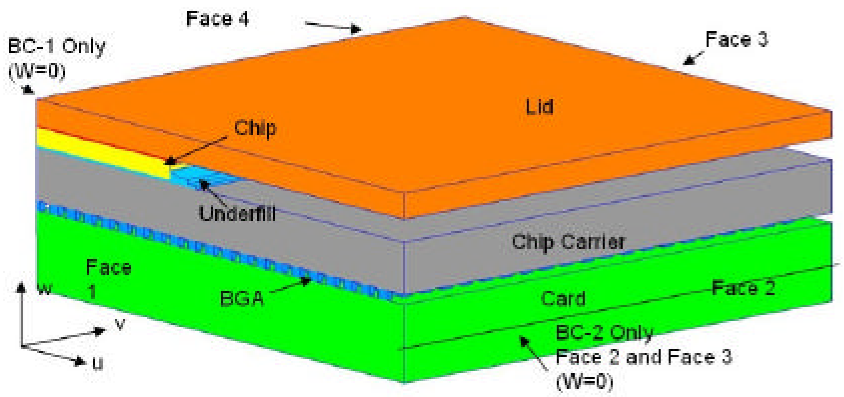

Figure 1 - Three Dimensional Model of Typical Geometry Studied

Material Properties

The material properties are selected so as to cover a broad range of chip carrier technologies available today. It is critical to know the correct stiffness properties (moduli, poisson's ratio) as well as the coefficient of thermal expansion, including the dependency on temperature as well as strain rate. In this study, the strain rate effects are not included for sake of simplicity. Material properties and key geometric parameters are listed in Table 1.

Table 1 - Geometric and Material Input for Simulations

	Dimension (mm)	Modulus (GPa)			CTE ($x10^{-6}$/C)		
Temp.(°C)		0	100	180	0	100	180
Card	32.5x32.5x3.048	16.547	16.547	16.547	18.0	18.0	18.0
Chip	10.5x10.5x0.71	186.158	186.158	186.158	3.0	3.0	3.0
Lid	32.5x32.5x1	117.211	117.211	117.211	17.0	17.0	17.0
Underfill	0.1 thick	10.480	4.964	0.552	32.0	32.0	47.0
Lid Adhesive	0.08 thick	0.008	0.008	0.008	150.0	150.0	150.0
Lam 1	32.5x32.5	344.738	344.738	344.738	5.0	5.0	5.0
Lam 2	32.5x32.5	5.171	3.516	2.206	9.0	10.0	11.0
Lam 3	32.5x32.5	17.237	14.479	12.273	15.0	17.5	19.7
Solder	Height 0.36, Pad dia 0.58	34.474	22.753	13.790	25.0	25.0	25.0
	Yield Stress (GPa)	0.057	0.036	0.020			

Three Dimensional Models

A three dimensional model of the BGA assembly can be simplified using 1/8th symmetry. In a study involving a relative life analysis, it is important to have a consistent modeling strategy. The user interaction required to ensure a consistent mesh between various models is typically greater in case of 1/8th symmetry than 1/4th symmetry models. Further, the quarter symmetry model provides opportunity to study additional loading and boundary conditions that are not necessarily possible in a 1/8th symmetry model. For this reason, the three dimensional models used in this paper consist of quarter symmetry models.

A convergence study was done using one 8 noded brick element per BGA (total 10687elements), one 20 noded brick element per BGA and two 20 noded brick elements per BGA. Two different laminate body sizes 32.5mm and 42.5mm were tested using all three meshes. The typical run times for the 20 noded brick element per BGA mesh was approximately 10 to 30 times (depending on body size) more than the 8 noded brick element per BGA mesh. For each case, relative BGA life of the 42.5mm body was predicted using the BGA life of the 32.5mm body as reference. It was found that the difference between the 8 noded brick element per BGA mesh and two 20 noded brick elements per BGA mesh was less that 5%. It was therefore decided that the mesh using just one 8 noded brick element per BGA was sufficiently accurate.

A three dimensional discretization provides the greatest flexibility to impose a variety of boundary conditions. Two different boundary conditions -BC1 and BC2- were studied here. The symmetry boundary conditions u=0 along face 4 (see Figure 1) and v=0 along face 1 are common to both cases. For the first case (BC1), the free edge of the card was not restricted from bending. Thus the third boundary condition was w=0 at the center of the model. For the second case (BC2), the center line of the card was held fixed in the w- direction (w=0) throughout the loading history. In a real application, the boundary condition is somewhere in-between, depending on surrounding components and supports.

Plane Stress and Axisymmetric Models

Typically, the solder balls along the diagonal of the BGA assembly undergo worst case strains. The two dimensional and axisymmetric discretizations therefore model a slice through the diagonal of the package. Figure 2 shows the typical geometry modeled.

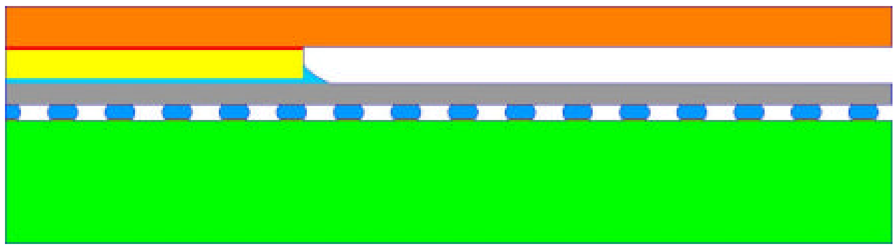

Figure 2 - Plane Stress and Axisymmetric Model of Typical Geometry Studied

Unlike three dimensional models, 2D and axisymmetric models can be refined to a large extent. The models used in this paper used 16 elements per BGA. Typical model used 10687 elements.

Plane stress or axisymmetric models can not account for relative deflection of the corner of the assembly with respect to the symmetry line. Thus the boundary conditions in plane stress and axisymmetric models are analogous to case BC2 of the three dimensional models.

Results

Figures 3, 4 and 7 show the relative life predictions of the three models for each of the three laminate technologies considered here. All life predictions are normalized with respect to the case using 80mils thick chip carrier.

It can be seen from Figure 3 that for laminate type Lam1, the axisymmetric models predict BGA life similar to the 3D models with boundary conditions BC1. The plane stress models follow the 3D models with boundary conditions BC2. In reality, the actual boundary conditions are expected to be somewhere between BC1 and BC2.

For Lam 2 (see Figure 4), the axisymmetric models and plane stress models do not fall within the bounds predicted by three dimensional models.

Three dimensional models with both boundary conditions show a shift of the critical BGA from corner of the laminate to corner of the die (See Figure 5). For BC1, this shift occurs as the thickness of the laminate changes from 40mils to 20mils. For BC2, this shift occurs when the thickness of the laminate changes from 60mils to 40mils. In either case, for a 20mils thick laminate made from Lam1 material, the critical BGA is the one under the die corner. Since the DNP of the die corner is typically much smaller than the DNP of the laminate itself, the amount of strain seen by the critical BGA is also much smaller. This accounts for a significant increase in the BGA life for the 20mils thick Lam1 chip carrier.

For the plane stress models, the critical BGA is located under the die corner. For the 20mils and 40mils thick laminates, the critical BGA is just within the shadow of the die (see Figure 6) and for 60mils and 80 mils thick laminates the critical BGA is just outside the shadow of the die.

For the axisymmetric models, the critical BGA is located under the die corner or well within die shadow. For the 20mils, 40mils and 60mils thick laminates, the critical BGA is well within the shadow of the die and for 80 mils thick laminates the critical BGA is just outside the shadow of the die.

For Lam3 material, the bounds predicted by the two 3D models are very tight. Axisymmetric models are able to mimic the 3D models fairly well; however plane stress elements are not. The jump in BGA life prediction in the plane stress curve is attributed to change in the stiffness of the laminate alone. The position of the critical BGA is near the die corner for all thicknesses (Figure 7.)

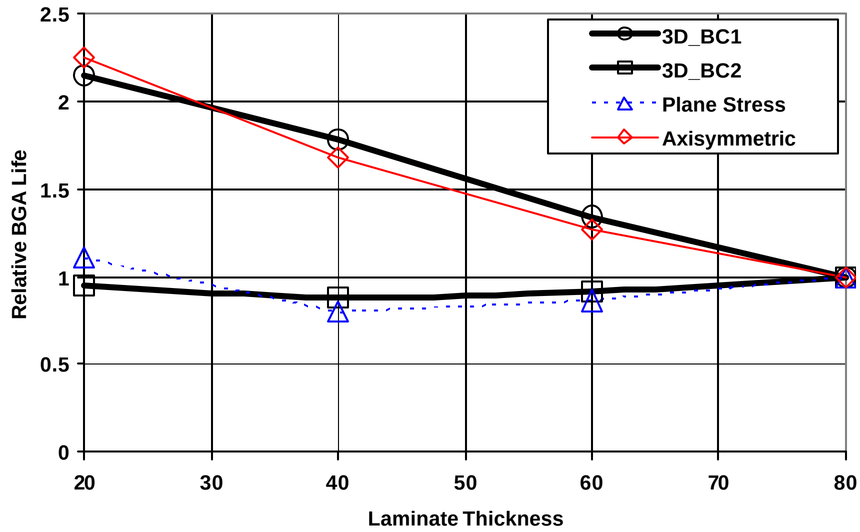

Figure 3 - Comparisons of Models for BGA Life Using Lam1

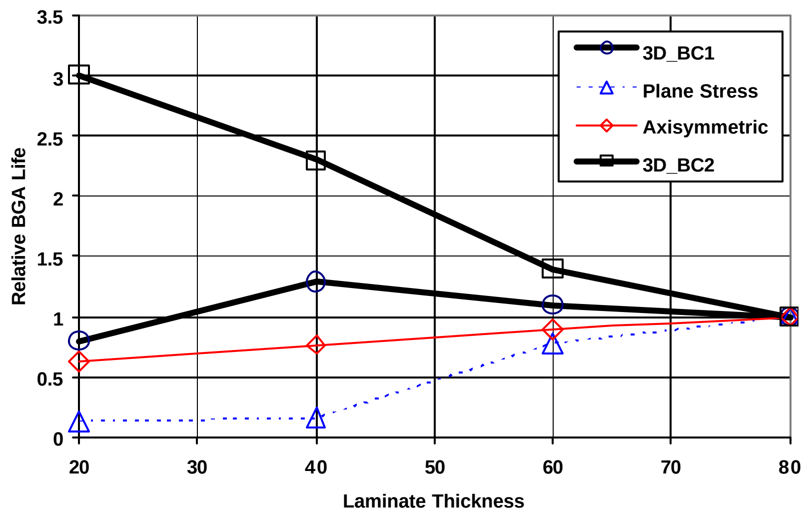

Figure 4 - Comparisons of Models for BGA Life Using Lam2

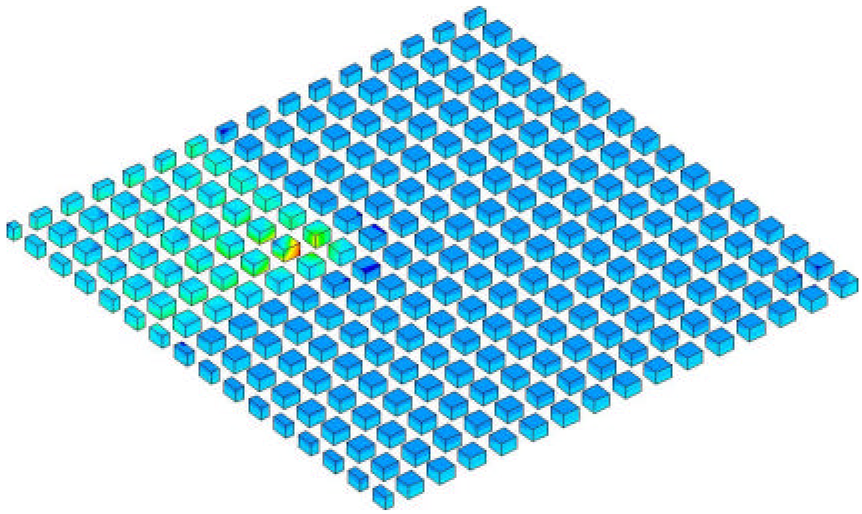

Figure 5 - Location of Critical BGAs for Lam2 as per the 3D Models

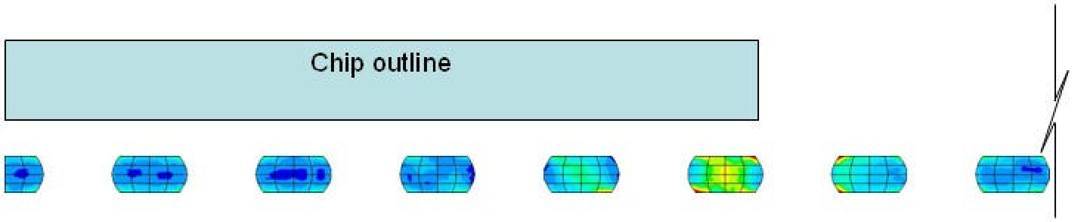

Figure 6 - Location of Critical BGAs for Lam2 as per the Plane Stress Models

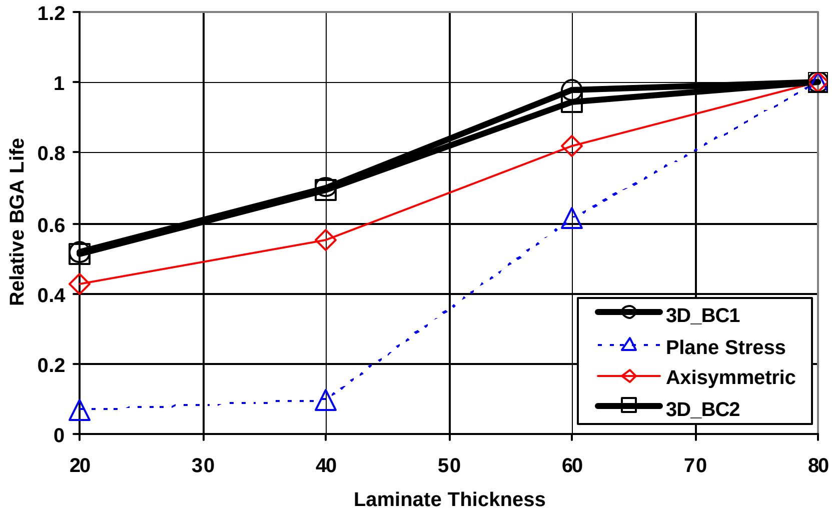

Figure 7 - Comparisons of Models for BGA Life Using Lam3

It is often necessary to compare relative advantages of various technologies to find the optimum solution for chip packaging. Figures 8 through 11 show comparisons of the three chip carrier technologies as predicted by the four models used. When the thickness of the chip carrier is 20mils, the bounds predicted by the 3D models are close. Axisymmetric models are able to mimic the general behavior. The plane stress models fail to do so, especially for chip carrier Lam1. As seen from Figures 8 through 11, as the thickness of the chip carrier increases, plane stress models provide predictions closer and closer to the axisymmetric predictions.

While making the choice of a particular chip carrier technology, it may not always be possible to optimize the thickness of the chip carrier. Thus, a real technology comparison would involve unique thicknesses associated with each technology. A sample comparison is shown in Figure 12. It shows comparison between Lam1 chip carrier with 80 mils thickness, Lam2 chip carrier with 20mils thickness and Lam3 chip carrier with 40mils thickness. It can be seen that 3D models predict Lam2 with 20mils thickness to be the best option. Axisymmetric models predict Lam3 with 40mils thickness to be the best option and plane stress models predict Lam1 with 80 mils thickness to be the best option. It is believed that the reality lies somewhere between the two 3D cases. Knowing the general behavior of plane stress models from previous cases it can be said that the use of plane stress models would lead to incorrect conclusions for technology comparisons. Axisymmetric models although able to mimic 3D models better that plane stress models can also give misleading results.

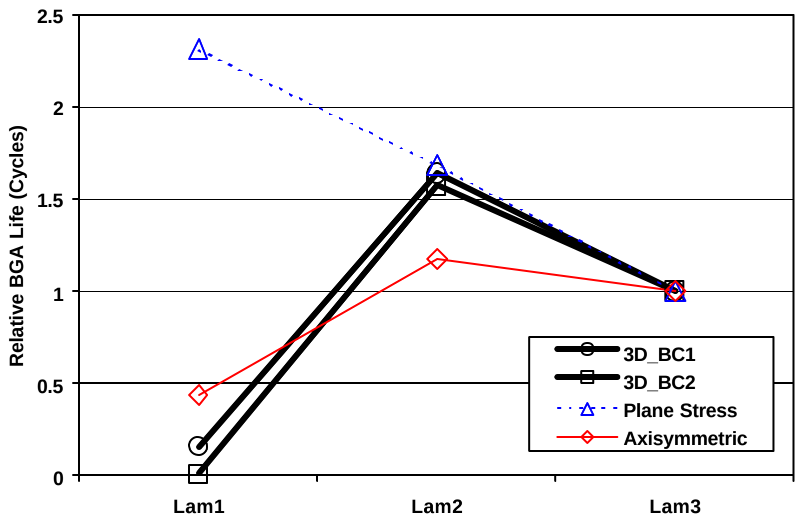

Figure 8 - Comparisons of Models for BGA Life Using 20 mils Thick Chip Carriers

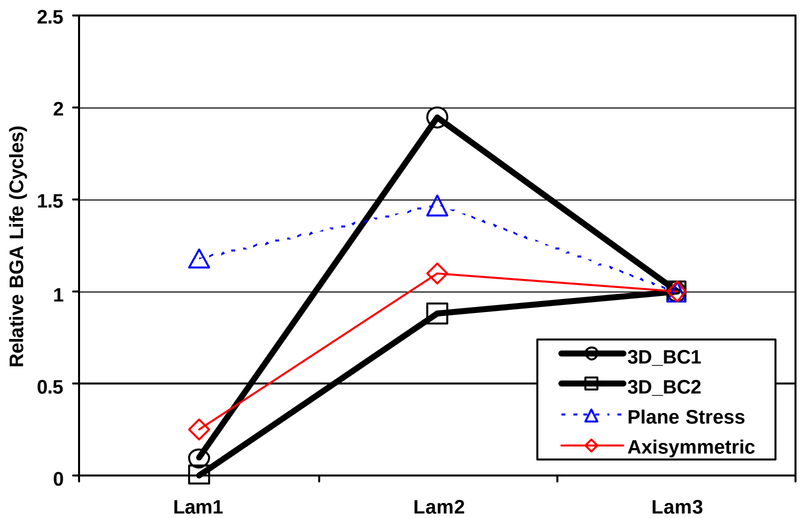

Figure 9 - Comparisons of Models for BGA Life Using 40 mils Thick Chip Carriers

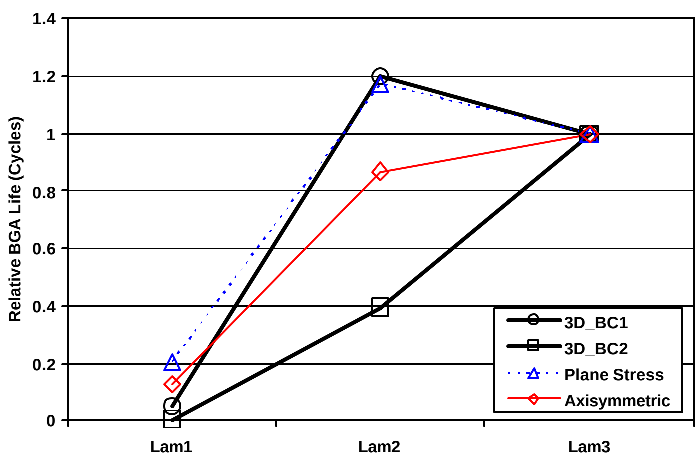

Figure 10 - Comparisons of Models for BGA Life Using 60 mils Thick Chip Carriers

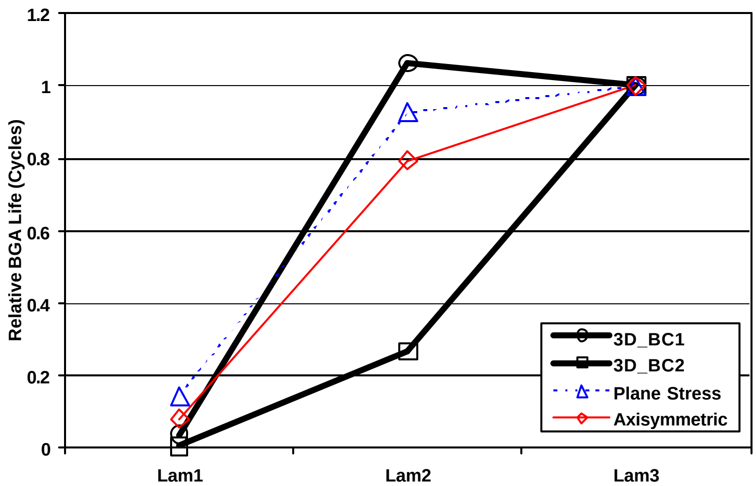

Figure 11 - Comparisons of Models for BGA Life Using 80 mils Thick Chip Carriers

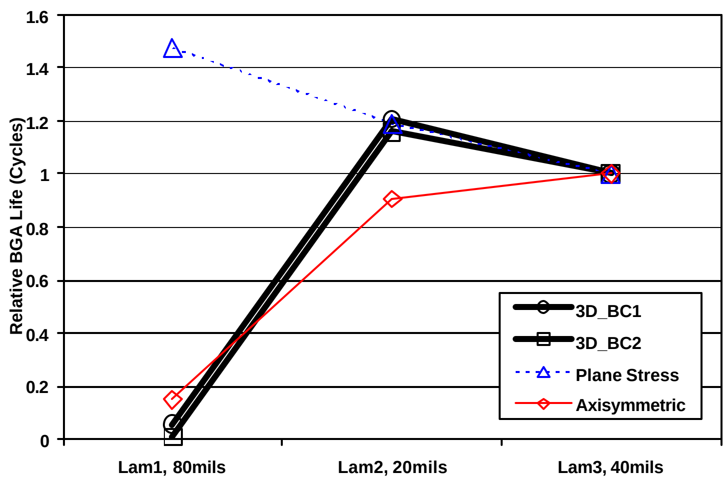

Figure 12 - Comparisons of Models for BGA Life across Technologies

Conclusions

The relative predictions for solder ball life of three different types of chip carrier materials and four different chip carrier thicknesses under 0/100 temperature cycling was investigated. For each case, the critical strains in solder were obtained using three dimensional models with two different boundary conditions, axisymmetric elements and plane stress elements.

The boundary conditions in three dimensional cases have significant influence on solder strains and hence solder life, especially for materials Lam1 and Lam2. For Lam1 and Lam2, the CTE of the chip carrier is different than the card to which it is attached. This leads to shear strains in solder due to differential thermal expansion of the card and the chip carrier. The boundary conditions influence the shear strain significantly. For chip carrier made with material Lam3, since the difference in CTE is not significant, the change in boundary conditions does not have significant impact on the solder shear strains or life. It is believed that the true boundary conditions on a chip carrier assembly lie between BC-1 and BC-2 in most practical cases. The three dimensional models with different boundary conditions thus provide bounds around the true boundary conditions.

Axisymmetric models do not always fall within the boundaries of the three dimensional models. However, they do predict the general trend that is similar to the three dimensional models. When a comparison is to be made between different technologies, axisymmetric models can be useful when the thickness of the chip carrier is 40 mils or more.

For many chip carriers, fatigue within the solder may not be the only failure mode of concern during temperature cycling. The failure may occur at the interface of solder ball and a pad on the card side or the chip carrier side or within the laminate itself. In such a situation, axisymmetric models can provide additional data related to other failure modes and may be more appropriate than three dimensional models for the same amount of computational resources.

In all the cases considered here, plane stress models did not fare well. The predictions of plane stress models were significantly different than either the three dimensional models or axisymmetric models. Considering that the same mesh can be used for axisymmetric and plane stress elements by simply changing the type of elements and boundary conditions it is far more desirable to use the axisymmetric elements instead of plane stress elements. There may be situations where plane stress models may still be desirable. However, for correct interpretation of data, the analyst should take into account the discrepancies of the plane stress and three dimensional models presented in this paper.

It was shown that the relative behavior of various modeling strategies is influenced significantly by the material properties of the chip carrier and in general every material constituting the assembly.

When evaluating a particular technology of chip carriers, it is essential to take into account the impact of the modeling strategies on the solution. In order to ensure the right modeling strategy, experimental verifications should be done at more than one data point. The work presented in this paper is being continued to examine the correlation with experiments, based on data available in literature.

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