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Finite Element Analysis of Mechanical Stress in Flip Chip Ball Grid Array using ABAQUS

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Abstract: The increased use of area-array technology in electronic packaging recently has given greater importance to the manufacturers of predicting the thermal distribution of area-array solder interconnection. As the interconnection technology for flip chip package is getting finer and smaller and the shape of solder join becomes complex, it is extremely difficult to obtain the accurate stress and strain by direct experimental measurements. Different type of solder balls used for interconnection would also influence the stress effect ofthe package. This paper discussses the results of the mechanical stress load using numerical method via ABAQUS software. A precise 2D finite element model with good quality mesh was constructed to perform 2D plain strain elastoplastic analysis to predict areas of high stress. The analysis was carried out using 20N, 40N, 60N, 80N and 100N respectively on the top of the model. It is found that the bending mechanical stress impact more on outer solder ball compared to the inner solder ball. Other than that, lead-free and leaded solder ball also show different results on the different types of substrate used which are FR-4 and ceramic substrate.

Key words:

INTRODUCTION

In small integrated circuit package such as flip chip, excessive heat generation with temperature gradient may lead failures in the component such as delamination and warpage, cracking, and eventually cause the device damaged. The flip chip package reliability is mainly focuses on(Texas Instrument, 2005):

- Moisture resistance
- Thermal flows
- Flip chip solder joint and interconnect
- Resistance to high temperatures
- Materials of construction
- Material adherence and delamination issues

As the interconnections getting smaller and smaller, it is extremely difficult to get the accurate values of the strains or stress via direct experimental measurements. The experimental tools for deformation measurement cannot offer good resolution for local strain (stress) distributions, which are crucial for the package reliability estimation (Sheng et al., 1998,) Therefore, numerical method such as finite element method (FEM) is used to simulate the mechanical stress in the flip chip package.

The uses of electronic products such as cellular phones, MP4 players, USB flash drive, portable personal data assistant (PDA), portable multimedia players (PMP) and so on are always affected by thermal and mechanical impact. Therefore, reliability tests need to be performed not only for thermal loading as well as mechanical loading. For example, the factors that caused cell phones damages are due to the mechanical stresses as below (Rooney, Todd Castello, Cibulsky, Abbott, & Xie, 2004).

a. Board bending caused by repetitive mechanical stresses from keypad actuation
b. Mechanical stresses induced in solder joints to components mounted adjacent to board mounting screws
c. Mechanical vibrations effects into the electronic components when drops the phone

Strain distribution of of solder joint is very complicated. Each place on the solder interconnection has different strain. It is very difficult to determine where is the representative position for accurate result for the stress applied. Research shows that in bending cycling test maximum stress occurs at the interfae between the solder and Printed Circuit Board (PCB). Bending load is external force, so that load translates outer solder to inner one (Ilho & Soon-Bok ,2007).Other research shows that when package is subjected to mechanical loads, the corner develop intense stress and start to initiate failure (Lu, Zhang, Yoon, & Suo,2012).

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Figure 1 shows an example of the three-point cyclic bend testing for mechanical cycling fatigue reliability of package assembly. The analysis was carried out with the variation of the magnitude of at the middle of assembly. The result of the bending shows that the highest stress occurs at the corners. Higher mechanical load would result in higher stress that causees a greater gap between the chip and the substrate (Rizvi, Chan, Bailey, & Lu,2005).

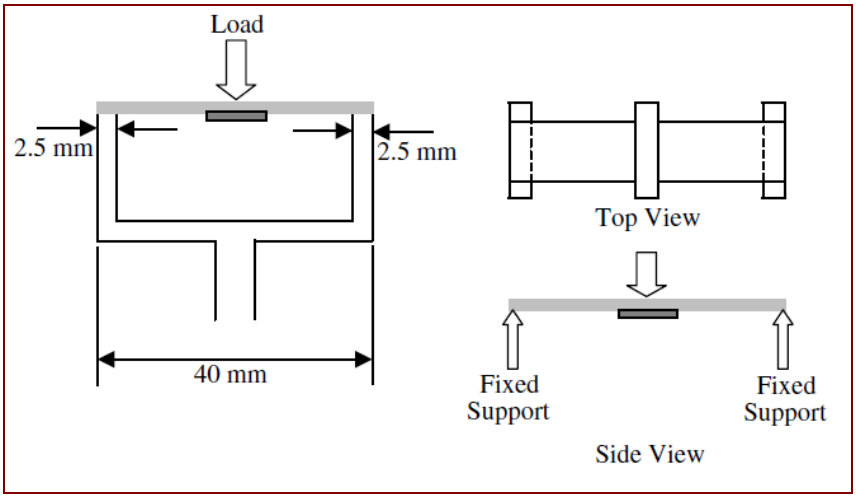

Fig. 1: A schematic model of three-point bending [6].

In the last few years, the use of the lead-free (Pb-free) solder balls to replace eutectic leaded solder balls is reflected with the increasing in the number of Pb-free applied in the manufacturing. This replacement is due to the RoHS directive on restricting the use of lead in electronic assembly. The transition from a technology using SnPb for electronic interconnections to a new Pb-free technology is a challenging and demanding task for the manufacturers. It is crucial to the new Pb-free solder ball to have a better performance whether in thermal or mechanical tests. I.Kim found that SAC has stronger fatigue resistance compared to SnPb under low loading for both thermal and bending tests. Other than that, the result also shows that the crack started at the outermost solder at the corner in the cyclic bending test (Ilho & Soon-Bok ,2007).

Other than solder balls, types of substrate used in the package plays a crucial role as well for the package reliability. It is shown that when flip chip was solder joined onto ceramic substrate, the package shows slightly better thermal reliability than the components joined onto alumina susbtrates (Lenkkeri, & Jaakola, 2001)However, for mechanical tests, ordinary stress-strain is not generally used to test ceramic substrate as they do not exhibit elastic behaviour to a great degree (Harper, 2001).

There is wide variety of customer requirements for reliability testing and there is no comprehensive industry standard for the reliability testing (Rooney et al., 2004). However, bending tests are still in interest to evaluate the performance of solder interconection under mechanical stresses in electronic assemblies (Zaal, Hochstenbach, van Driel, & Zhang, 1997)

Methodology:

Finite Element Model Design:

A flip chip package size of 33x33x1.46 mm substrate with a 15x15x0.7 mm silicon chip was used for mechanical FE model conceptual design. Figure 2 shows the cross-sectional views of the 2D flip chip FE model (not drawn to scale) for mechanical load case. The boundary conditions are also symmetry about $x = 0$ and the leftmost and rightmost of the foundation underneath the flip chip model is considered as rigid. Thus, the nodes along $x = 0$ have $y = 0$ and $z = 0$. While The parameters of the material properties used shown in Table 1(Ilho & Soon-Bok ,2007) (Hong 1997).

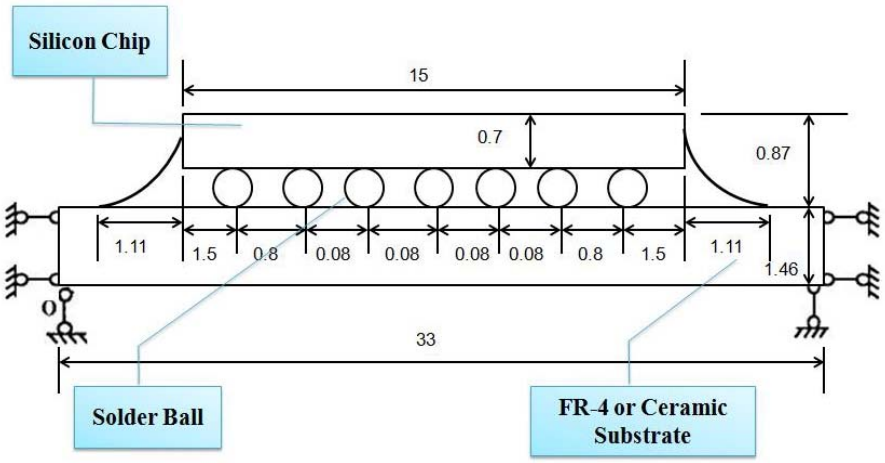

Fig. 2: Boundary conditions, dimensions and geometry of mechanical FE model (in mm).

Table 1: Material Properties.

Material	Temperature (K)	Elastic Modulus (MPa)	Poisson's Ratio	Thermal Conductivity (W/mK)	CTE (ppm/K)
Silicon	273 323 373	130194 129809 120382	0.2783 0.2781 0.278	83.7	2.8729 3.0764 3.411
63Sn 37Pb	278 323 373 398	44377 41334 36854 34586	0.36 0.365 0.3774 0.3839	51	25.2 26.1 27.3 37.9
95.5Sn 4.0Ag 0.5Cu	298 343 373	53000 47000 44000	0.4	33	21.3 22.15 23
FR-4 Substrate	-	22000	0.11	10	19
Ceramic Substrate	-	300000	0.23	21	6.7

Mechanical Loading Simulation:

For mechanical loading simulation, the largest magnitude of mechanical stress was applied between both of the leftmost and rightmost outer solder ball. The maximum stress value of the outmost solder ball was then compared with the maximum stress of solder ball which was located at the center of the FE model. The reliability of the solder ball at different locations of the package when subjected to mechanical load of 20N, 40N, 60N, 80N and 100N was investigated. The force was applied on the top direction.

Two types of solder chosen in this simulation work, that were lead-free solder (95.5Sn4.0Ag0.5Cu) and eutectic lead-contained solder (63Sn37Pb). Each of the FE simulation was developed via FR-4 and ceramic substrate respectively to investigate whether the reliability of the solder balls was affected by different types of substrate under the mechanical loading simulation. The underfill element was included in the model to avoid the 'opened section' error in the ABAQUS's part module. However, the Young's modulus and Poisson's ratio of the underfill was set to 1 and 0.01 to ensure the presence of the underfill would not affect the output results.

Load:

A static mechanical load type was created and applied on the mechanical model with different magnitude for evaluating the mechanical behaviours of the solder balls at the outermost and inner interconnetion in flip chip package. Figure 3 shows the magnitude of mechanical load applied on the model, which is from the top.

Meshing:

Mesh is one of the most important modules since accuracy of FEA will depend on the meshing of the assemblies. The finer the mesh element size. leads to better simulation results. For mechanical model, the mesh control was applied with element size of 0.4 mm . Figure 4 shows the mesh system of mechanical stress model.

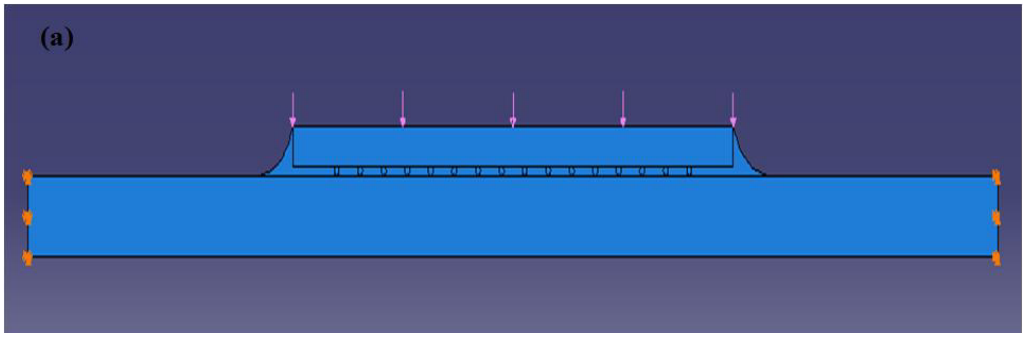

Fig. 3: Magnitude of mechanical load on 2D FE model.

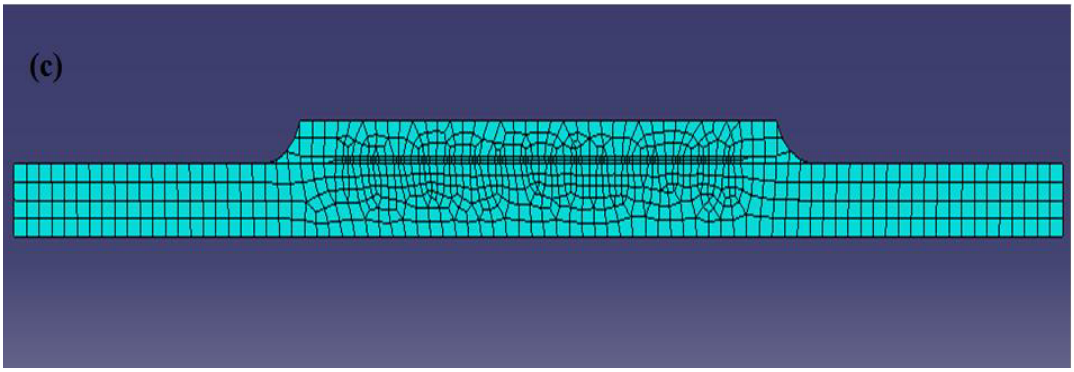

Fig. 4: The mesh system of mechanical stress model.

RESULT AND DISCUSSION

Mechanical Loading Simulation Results Analysis:

For mechanical loading bending simulation, the technique chose to investigate the behavior of solder balls was to apply the loads on the model from top direction. The main objective of this analytical method is to observe the stress level of the solder balls at different locations (outermost and center) in the package. Figure 5 (a) and (b) are the simulation profile for mechanical bending of 100N load applied on top of the package. The direction of applied load (from top) would be the same for all simulation as in Figure 4. The load applied for the three-point bending tests performed from studies is one point focus on the model, whereas in this project, the load is distributed uniformly on the whole surface of the top of the FE model respectively instead of using one point focus technique. The differences of that bending test technique constructed on the model may affect the mechanical stress level results.

Solder balls jointed onto FR-4 substrate:

The simulation was done using leaded solder ball joined onto FR-4 substrate. Table 2 shows the reading of the maximum stress values when the model subjected to 5 different loads. It is shown that the load applied on top has a big influence to the outermost solder ball. The outmost solder ball has higher stress level than center solder ball under all of the loading conditions. The data was plotted in the graph shown in Figure 6.

Table 2: Maximum Mechanical Stress Value for SnPb (FR-4) with Top Load.

Load (N)	Outmost Ball (MPa)	Center Ball (MPa)
20	4843.08	237.73
40	9668.15	475.696
60	14502.2	713.544
80	19336.3	951.392
100	24170.4	1189.24

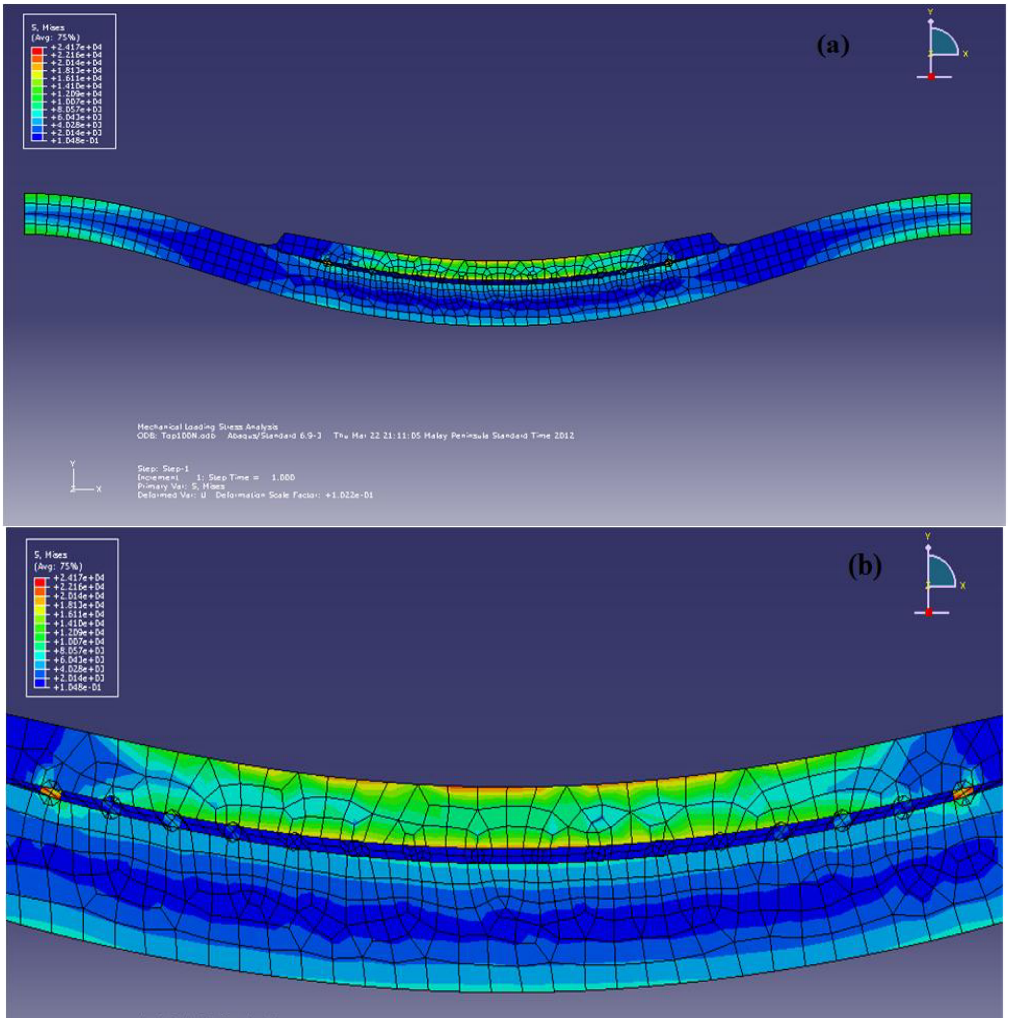

Fig. 5: (a), (b) Simulation profile for the mechanical model 100N load applied from the top.

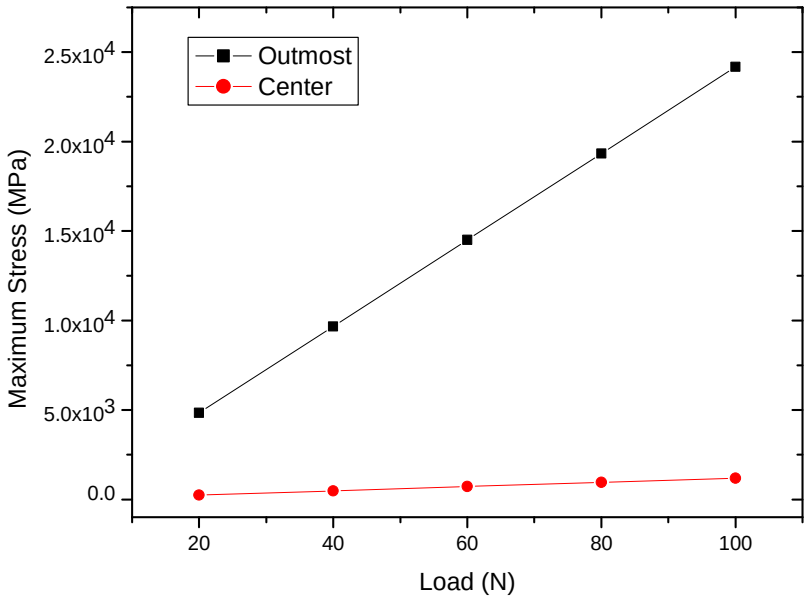

Fig. 6: Maximum Mechanical Stress Value for SnPb (FR-4) with Top Load.

From Figure 6, it could be observed that the highest stress level is distributed at the outermost solder ball and propagated towards center solder ball. The result also show that the stress distributions at the outermost solder ball is directly proportional with the applied loads whereas there is just a small increment in stress level for center ball with increasing applied top load. This indicates that the center solder ball would not affected much by the mechanical stress applied.

The simulation was proceeded with lead-free solder ball, SAC. The pattern of the result trends obtained for lead-free solder balls with FR-4 substrate is same as SnPb. The result for applied load is shown in Table 3. The reading was plotted in graph shown in Figure 7.

Table 3: Maximum Mechanical Stress Value for SAC (FR-4) with Top Load.

Load (N)	Outmost Ball (MPa)	Center Ball (MPa)
20	4952.14	240.413
40	9904.28	480.825
60	14856.4	721.238
80	19808.6	961.651
100	24760.7	1202.06

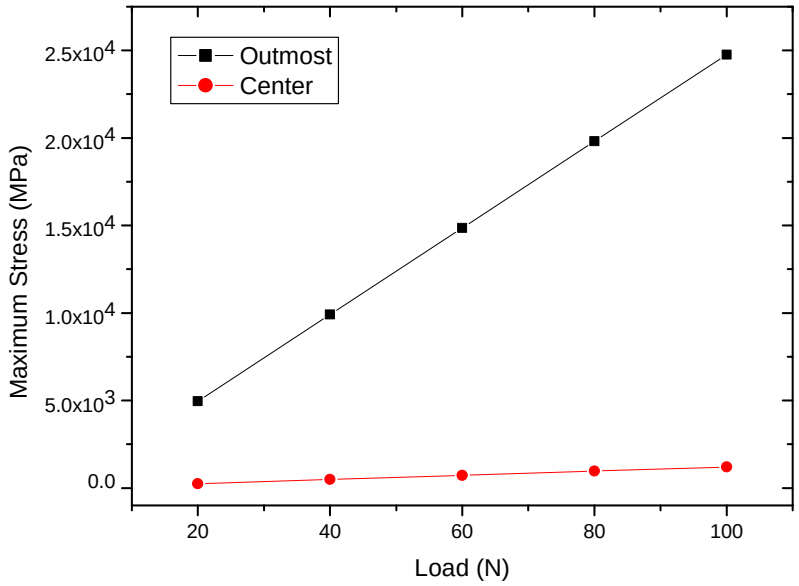

Fig. 7: Maximum Mechanical Stress Value for SAC (FR-4) with Top Load.

However, by comparing the stress level for both of the solder balls, the value of the outermost and center solder ball for SAC is slightly higher than SnPb solder balls as illustrated in Figure 8. This shows that SAC solder ball has a better performance compared to SnPb solder ball at high load. This is quite different from literature research as the research shows that at high load, SnPb would have better performance. This might due to the different bending stress applied to the model as mention earlier.

Solder Balls Jointed Onto Ceramic Substrate:

In this section, the material of the substrate for the flip chip model was changed to ceramic substrate. From the simulation profile in Figure 9, it could be observed that the highest mechanical stress was distributed at the end of the ceramic substrate instead of at the solder balls.

By comparing the stress level of the solder balls at different locations in the package, the outermost ball has higher stress value than center ball under all of the load conditions as shown in Table 4 which was plotted in Figure 10.

Table 4: Maximum Mechanical Stress Value for SnPb (Ceramic) with Top Load.

Load (N)	Outmost Ball (MPa)	Center Ball (MPa)
20	1048.57	255.517
40	2097.15	511.033
60	3145.72	766.55
80	4194.29	1022.07
100	5242.87	1277.58

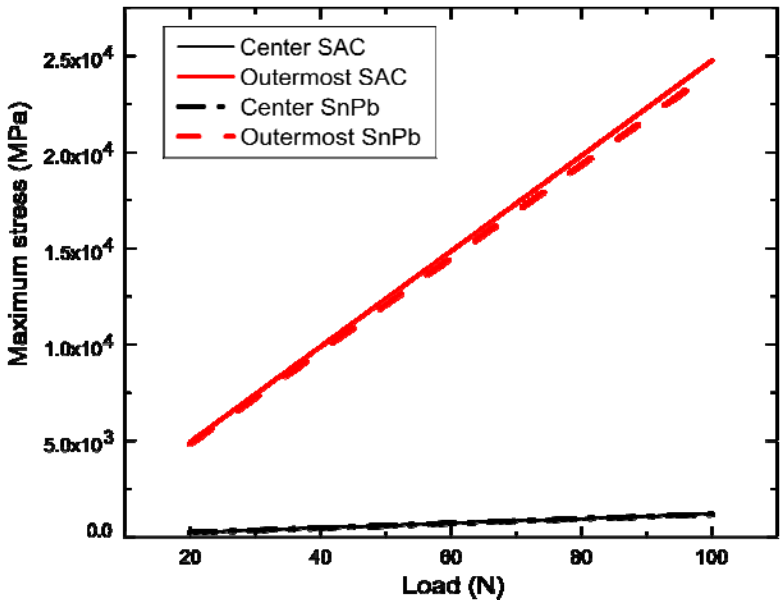

Fig. 8: Maximum Mechanical Stress Value for SAC and SnPb.

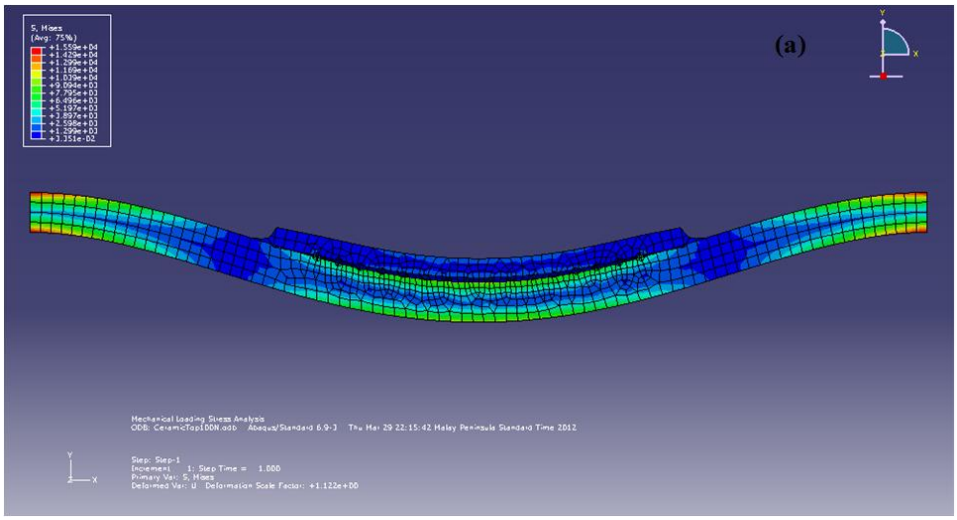

Fig. 9: The simulation profile using ceramic substrate.

The simulation was then proceeded with by changing the solder ball types to lead-free solder ball. Table 4 shows the result for the mechanical stress value of SAC with ceramic substrate. The results was then plotted in Figure 11.

Table 4: Maximum Mechanical Stress Value for SAC (Ceramic) with Top Load.

Load (N)	Outmost Ball (MPa)	Center Ball (MPa)
20	1075.93	256.692
40	2151.86	513.384
60	3227.79	770.076
80	4303.73	1026.77
100	5379.66	1283.46

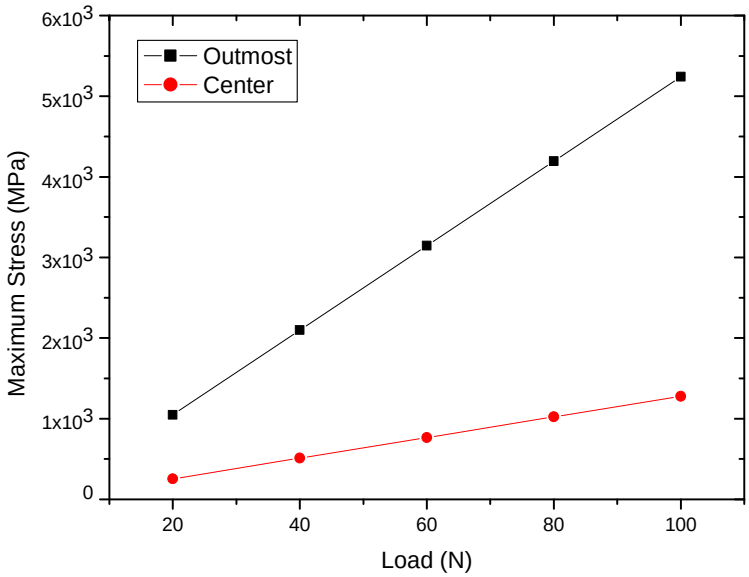

Fig. 10: Maximum Mechanical Stress Value for SnPb (Ceramic) with Top Load.

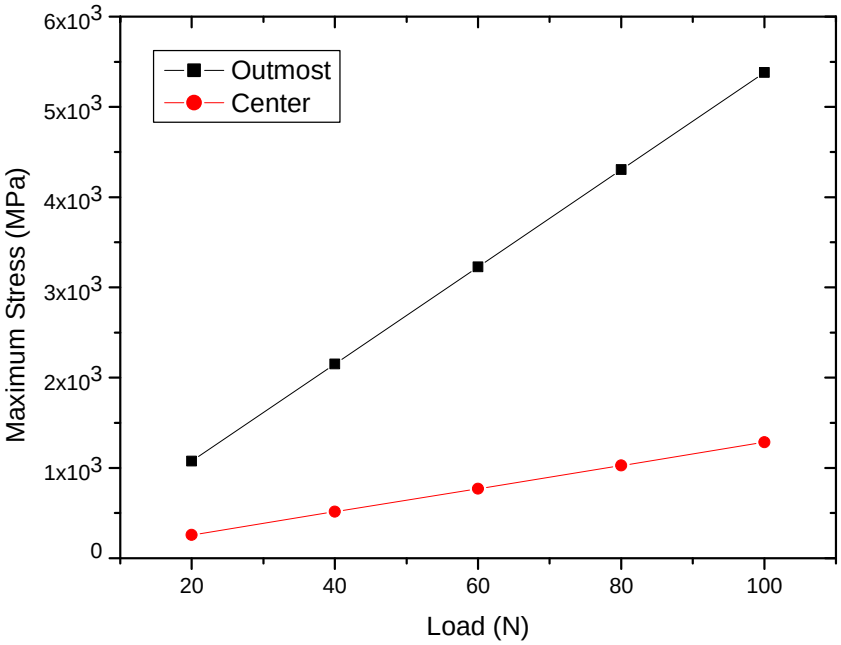

Fig. 11: Maximum Mechanical Stress Value for SAC (Ceramic) with Top Load.

The result trends obtained for SAC solder with ceramic substrate is same as SnPb joined onto ceramic substrate. Key characteristic such as maximum stress level is the main concern for the comparison work purpose.

The stress level of the SnPb and SAC outmost ball with ceramic substrate is obviously decrease compared with FR-4 substrate as illustrate in Figure 12 and Figure 13 . This may due to the stiffness of ceramic substrate is higher than FR-4, in which, when the top load is applied on the model, the ceramic substrate has the ability to resist the bending stress and caused mostly the load spread on the silicon chip and solder balls. Since the average maximum stress value obtained for the center ball is still lower than outermost ball, hence this is not the main concern.

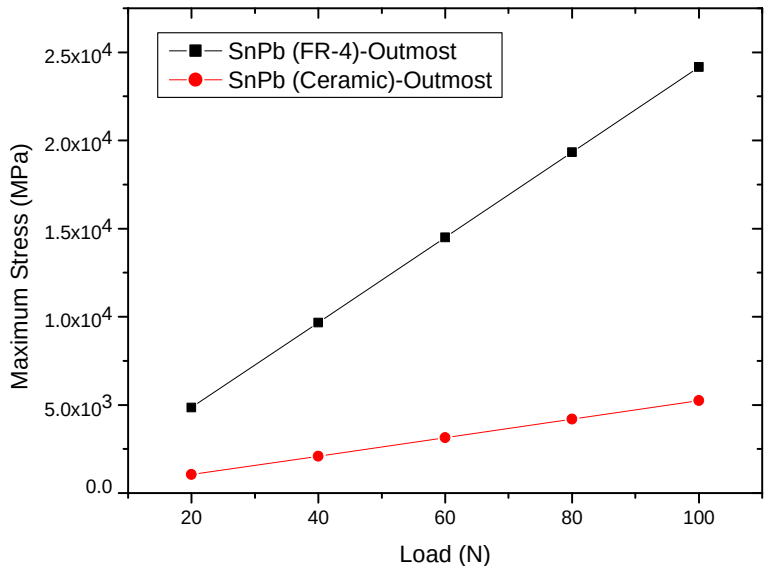

Fig. 12: SnPb (FR-4) vs SnPb (Ceramic) with Top Load at Outmost Ball.

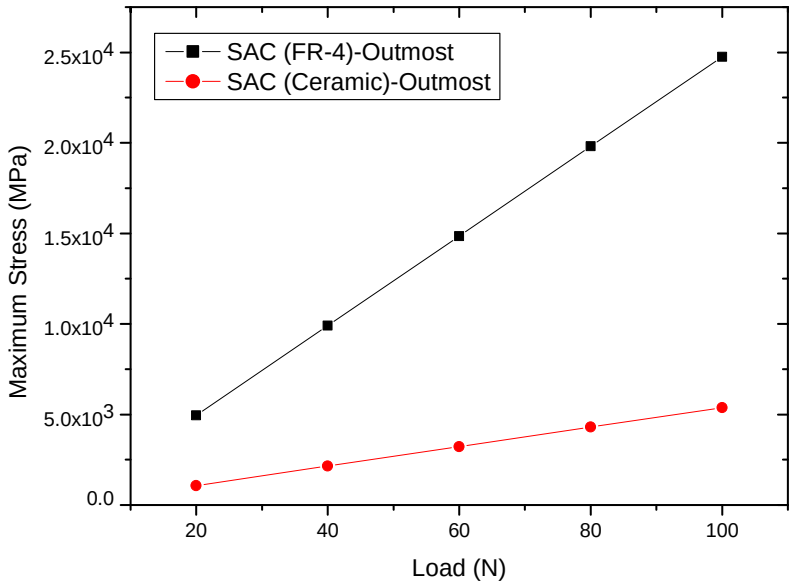

Fig. 13: SAC (FR-4) vs SAC (Ceramic) with Top Load at Outmost Ball.

Conclusion:

From the simulation done using ABAQUS, it can be conclude that:

1. The bending stress level is increasing with the increases of mechanical load
2. The maximum stress is initiated at the outer solder ball and propagated to the center. Outer solder ball has the higher stress level than center solder ball.
3. Different types of solder balls used in package may affect the stress distribution in substrate due to the different values of thermal conductivity.
4. Ceramic substrate performed better compared to FR-4 substrate when using SAC and SnPb solder balls.
5. SAC solder has higher maximum stress levels than SnPb solder when subjected to high mechanical load due to the stress direction applied.

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