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Effect of glue on reliability of flip chip BGA packages under thermal cycling

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ABSTRACT

Glue is widely used to improve the reliability of ball grid array (BGA) under mechanical shock and vibration. Although it has been demonstrated to have a positive effect on the reliability of BGA under mechanical impact, it can have adverse effects on BGA under thermal cycling. This paper investigates the effect of glue on the reliability of BGA under thermal cycling using both experimental and numerical methods. The digital image correlation (DIC) technique was used to obtain the thermal mechanical behavior of the package. The experimental results explain in detail how the glue negatively affects the reliability of the BGA. Furthermore, a finite element analysis was performed and its results were verified with experimental results. A numerical parametric study was carried out on various mechanical properties, configurations of the glue, and introduction of a stiffener using the validated FEM model. The results show that the reliability of BGA strongly depends on geometries and material properties of the glue. Based on the results, a guideline of glue selection for BGA reliability under thermal cycling is formulated.

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1. Introduction

In a flip chip package, the CTE mismatch between the silicon chip and substrate induces significant strain on flip chip solder interconnects during thermal cycling, which may lead to the failure of package. In order to protect and prolong the life of flip chip interconnects, the underfill was introduced and became an essential component especially for organic substrates (or chip carriers). Later, underfill was also used in BGA packages at the board level in order to improve the reliability of the packages under mechanical shock and vibration. In some cases, underfill was also used on PCBs that were subjected to bending during assembly and shipment, such as on circuit boards used in PCs and gaming consoles. In many BGA applications, however, underfilling the full BGA region provides far more strength and reliability than needed at the expense of high cost in manufacturing especially for large-sized packages (30 × 30 mm and larger), due to the slow rate of capillary flow of underfill. A less costly alternative solution is to use the corner glues with or without edge glues. The glue pattern of “L” shape is usually applied at package corners to form mechanical bridges between the substrate and the PCB. Edge bonding is gaining popularity as an alternative to both underfill and corner bonding. The edge and corner bonding provide many advantages over the traditional underfill, such as the low cost, fast processing, and reworkability [1].

The use of glue to improve reliability of BGA is growing in practice. Studies have shown that glues help improve the reliability of packages significantly [1–4]. However, these studies focused on the reliability of electronic packages solely under mechanical impacts. Toleno and Schneider [5] have experimentally investigated the reliability of electronic packages in both the drop and thermal cycling tests. Their results showed that generally, the corner glues increased the reliability of electronic packages in both the drop and thermal cycling tests. However, the use of glue was also found to decrease the reliability of larger packages under thermal cycling. An explanation for this phenomenon as well as an interpretation for the results was not found in the paper.

In this paper, DIC, a deformation measurement technique [6], was successfully used to capture the behavior of a flip chip BGA package with glues under thermal cycling. The results from the DIC measurements clearly illustrated the failure mechanisms of BGA under thermal cycling. Moreover, a FEM model was developed and was validated using the experimental results. The results stemming from the experimental and numerical inquires provided novel insights into how the glues affect the reliability of electronic packages under thermal cycling. With these insights in mind, a parametric study was performed on various design parameters and material properties of glues, using the validated FEM model. Finally, a guideline of glue design and selection for BGA reliability under thermal cycling is recommended.

2. Test vehicle description

The test vehicle used for this study is a flip chip BGA as shown in Fig. 1. It is comprised of a 12 × 12 × 0.67 mm silicon chip, flip chip solder interconnects, underfill, and 35 × 35 × 1.2 mm bismaleimide triazine (BT) substrate, interconnected to a printed circuit

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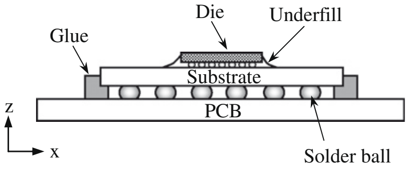
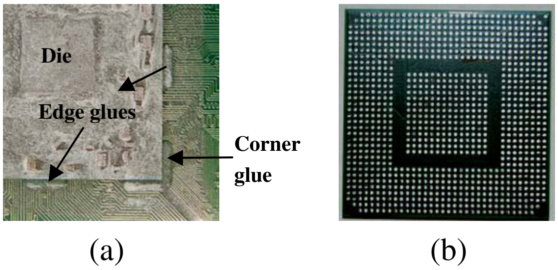


Fig. 1. Schematic drawing of the package.



(a) (b)

Fig. 2. (a) Top view of FCBGA package with edge and corner bonds and (b) BGA pattern.

board (PCB) with a full square array BGA. The corner and edge bond is dispensed using the pre-reflow process (see Fig. 2).

3. Experimental procedure

DIC, a full field optical deformation measurement technique, was used to assess in-plane and out-of-plane deformations. This is accomplished by correlating the digital images of a target object captured at a reference and subsequent deformed stages [6–8]. It recognizes distinct features on the test surface based on the gray scale variation in an image and assigns coordinates to these features. The integer values of gray scale in these facets are recorded and the facet centers are tracked, in each successive pair of images, with accuracy of up to one hundredth of a pixel. Local displacements and strains are determined from the movement of the features relative to their initial coordinates. The prepared samples were subjected to a thermal loading in a convection thermal chamber. During the thermal cycling the samples were observed through an optical window and their images were taken for DIC process. A picture of the experimental setup is shown in Fig. 3.

The 3-D DIC setup was calibrated for a 15 × 15 mm field of view by using standard calibration panels. The measurement sensitivity is approximately 0.5 μm. The samples were sprayed with a white paint to generate a variation of gray scale on the sample surface. The samples were then placed on a fixture, without imposing any additional constraints on it, inside a thermal chamber with an optical window for monitoring the deformation. A thermocouple was mounted to a dummy sample placed near the test sample and used as a means of monitoring the temperature of the sample during the thermal loading. Images of the top surface of the substrate were taken and recorded by the DIC system at 25 °C, 45 °C, 65 °C, 85 °C, and 105 °C. These images were then processed by a DIC program to obtain the displacement and strain fields on the top surface of the substrate. The experiment was first performed on a package containing corner glues. The corner glues were then removed and the same experimental procedure was repeated on the unglued package.

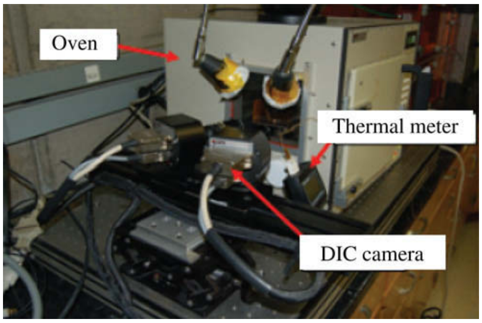


Fig. 3. Experimental setup.

4. Experimental results

Fig. 4 shows the contour plots of the out-of-plane displacement (*Z* displacement) generated along the top surface of the package with the corner glue at the temperatures ranging from 25 °C to 105 °C. Similarly, Fig. 5 shows the corresponding plots for the unglued package.

On the other hand, negligible difference in displacement and strain fields between the package with and without edge glues (contour plot not shown for the sake of brevity) is observed in the experimental results. For instance, at 105 °C, the difference in displacement at location 2 in Fig. 6 between with and without edge glues is approximately 0.6 μm, while that of location 1 in Fig. 5 between with and without corner glues is approximately 3 um. As seen in Fig. 6, the *z* displacement of the substrate near the edge is almost uniform as temperature increases. It is due to the relatively high strength of solder ball array at the edge portion of the substrate compared to that of fewer balls under the triangular portion at the corner. Therefore, the remainder of this paper will focus only on the effect of the corner glues under thermal cycling.

5. Failure mechanism

As the temperature increases, the corner glue expands significantly due to its high CTE. This produces strains in the substrate, which, in turn, induce axial strains along the vertical axis of the solder balls located in the package corners. A depiction of the thermally induced displacement is illustrated in Fig. 7. The high probability of failures due to repeated occurrences of this process makes the corner solder ball a high risk site for the packages that are exposed to thermal cycling. In the following section, a numerical treatment of these phenomena is discussed in details.

6. Finite element model

A FEM model was built in ANSYS 11.0 [9] to study the effect of corner glues quantitatively. In the FEM model the solder balls of interest including the die corner and package corner solder balls were modeled in fine mesh. Flip chip solder bumps were lumped using volume equivalence. The 3-D quarter symmetry finite element model contains approximately 23,400 hexahedral elements and 23,900 nodes. A depiction of the model is presented in Fig. 8. It is noted that the corner solder ball is the one corresponding to location 1 in Fig. 4.

All the materials were modeled as linear elastic materials except for the PbSn solder which was modeled as a temperature dependent elasto-plastic material. Anand's viscoplastic constitutive model was used for the solder [10,11]. Mechanical properties of the constitutive materials are shown in Table 1.

For this study, the thermo-mechanical properties of glue are relatively critical. Therefore, instead of using the properties provided by the supplier, the temperature dependent coefficient of thermal expansion (CTE) and Young's modulus of the glue were measured using TMA and DMA techniques, respectively. The measurement

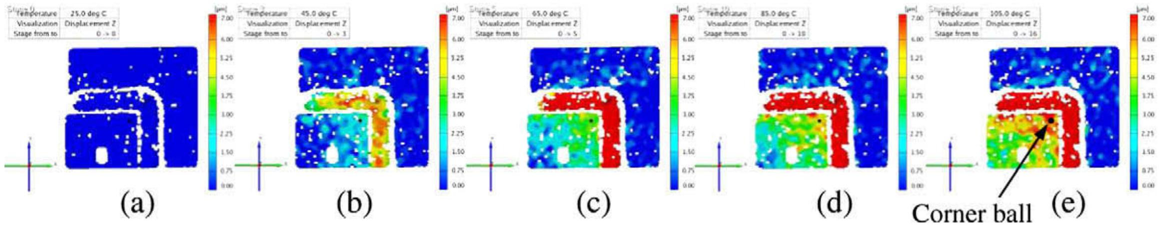


Fig. 4. Contour plot of Z displacement with corner glue at (a) 25 °C, (b) 45 °C, (c) 65 °C, (d) 85 °C, (e) 105 °C.

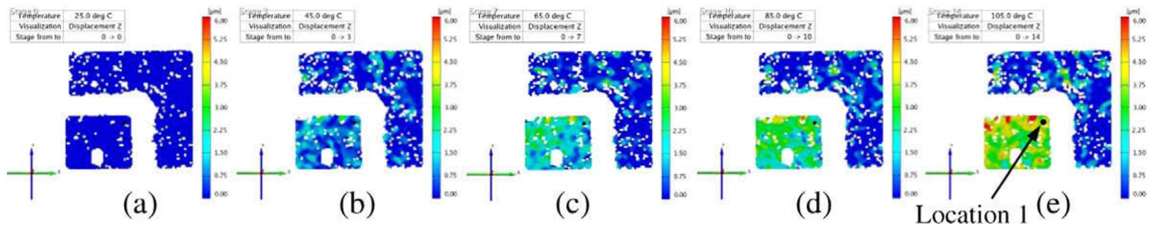


Fig. 5. Contour plot of Z displacement without corner glue at (a) 25 °C, (b) 45 °C, (c) 65 °C, (d) 85 °C, (e) 105 °C.

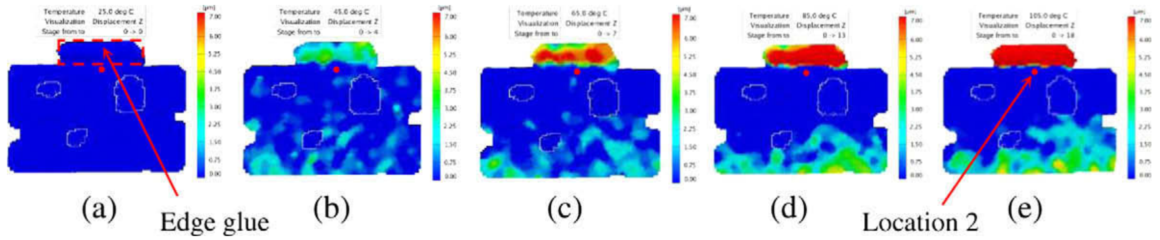


Fig. 6. Contour plot of Z displacement with edge glue at (a) 25 °C, (b) 45 °C, (c) 65 °C, (d) 85 °C, (e) 105 °C.

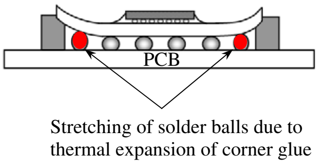


Fig. 7. Illustration of failure mechanism of corner solder balls.

results are shown in Fig. 9. It can be seen that the glue has a typical behavior of a polymer material, with a T_g of approximately 50 °C. These measured properties were applied in the FEM model.

Thermal loading from room temperature 25 °C to 105 °C was uniformly applied to the model. The displacement and strain fields were obtained from the simulation results and compared with the experimental results. The black dot seen in Figs. 4e and 5e represents the location of the corner solder ball. A comparison of the z displacement obtained at this location, for the packages without and with corner glue, is presented in Fig. 10. The results show that the use of corner glue results in approximately 3 μm more displacement than that observed in package not containing glue. A contour plot of Z displacement of the package at 105 °C was also obtained from the simulation results and is shown in Fig. 11. It is found that the experimental and numerical results agree well with each other. The contour plots in Fig. 11a and b match well with their corresponding ones obtained from DIC measurements shown in Figs. 4e and 5e, respectively. The difference in the results is less than 5%. This validates the developed FEM model.

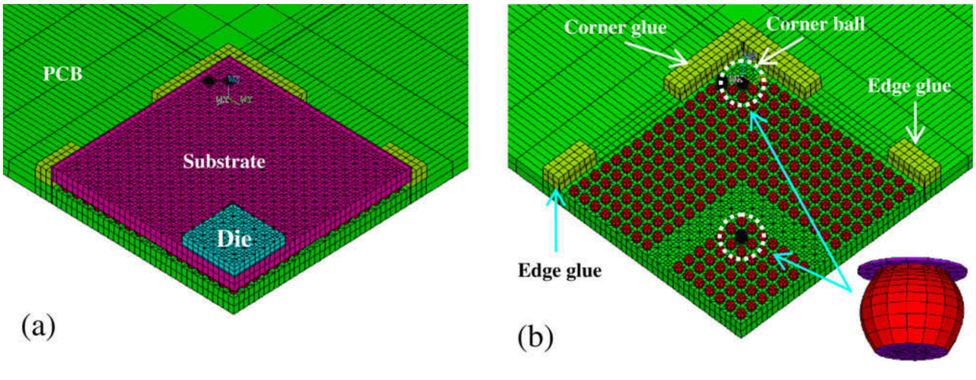


Fig. 8. (a) FEM model and (b) glue and BGA pattern with enlarged view of interested solder balls.

Table 1
Mechanical properties of the materials.

	E_x (GPa)	E_y (GPa)	E_z (GPa)	CTE$_x$ (ppm/C)	CTE$_y$ (ppm/C)	CTE$_z$ (ppm/C)	v
Si	131			2.8		0.28	0.28
Cu	129			17		0.35	0.34
Substrate	16.77	16.77	7.34	18	18	44	0.3; 0.11
Glue	See Fig. 9						0.3
Underfill T_g = 120 °C	Below T_g: 8			30			0.33
	Above T_g: 0.1			120			0.48
Solder	30.34 (25 °C), 12.4 (105 °C)			24.5			0.35
PCB	26.2	26.2	11	16	16	35	0.28

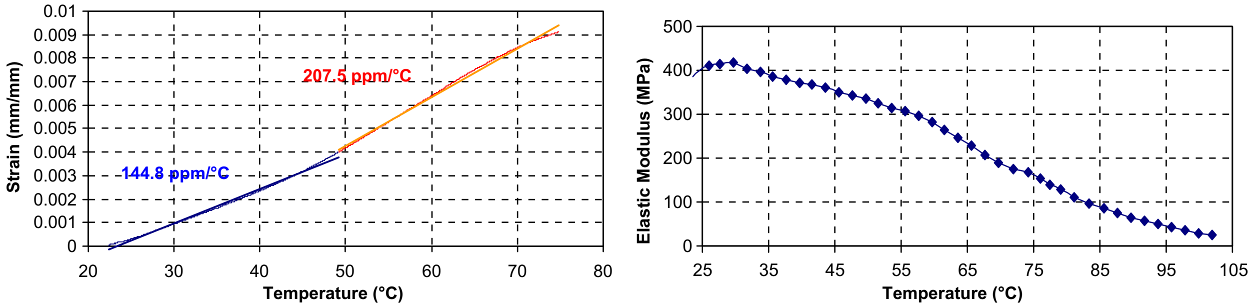


Fig. 9. Temperature dependent (a) CTE and (b) Young's modulus of the glue.

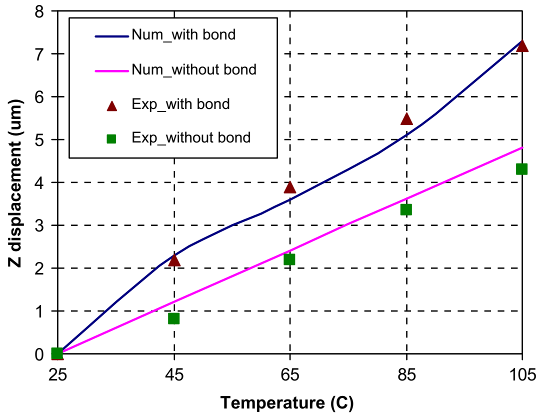


Fig. 10. Comparison of Z displacement at location 1.

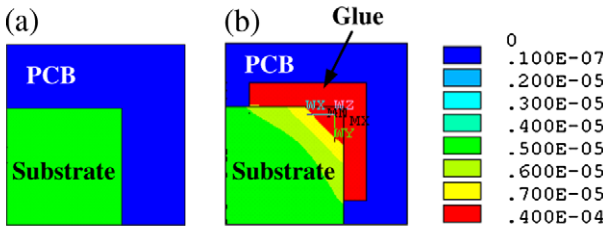


Fig. 11. Contour plot of Z displacement of the package at 105 °C (a) without corner glue and (b) with corner glue.

7. Component reliability prediction

Darveaux's model [9] was used to predict the characteristic fatigue life of solder balls. The accumulated plastic work per cycle is averaged across the top two layers of elements along the solder joint interface where the crack propagates. The equation for stabilized change in average plastic work (ΔW_{ave}) is given the following equation:

$$\Delta W_{\text{ave}} = \frac{\sum(\Delta W \cdot V)}{\sum V} \tag{1}$$

where ΔW is the plastic work accumulated per cycle of each element, and V is the volume of each element.

Calculation of thermal cycles to crack initiation N_0 and crack propagation rate $\frac{da}{dN}$ are given by:

$$N_0 = K1(\Delta W_{\text{ave}})^{K2} \tag{2}$$

$$\frac{da}{dN} = K3(\Delta W_{\text{ave}})^{K4} \tag{3}$$

The characteristic solder joint fatigue life can then be calculated by summing the cycles to crack initiation with the number of cycles taken by crack to propagate across the entire solder joint diameter shown in the following equation:

$$\alpha = N_0 + \frac{a}{da/dN} \tag{4}$$

where a is the diameter of the solder ball. ($K1$–$K4$) are constants of the prediction model. These constants for PBGA packages are listed in Table 2 [9].

8. Parametric study

A parametric study investigating the effects of the CTE and Young's modulus of a glue on the reliability of a thermally cycled BGA package was performed. In this study, the CTE and Young's modulus shown in Table 1 were chosen as the baseline values, and each parameter was varied by a factor of 0.5–1.5. Based on the insights gained during the initial investigations, the scope of

Table 2
Crack growth constants.

Constant	Value
K1	56,300 cycles/psi^{K2}
K2	−1.62
K3	3.34×10^{-7} in./cycle/psi^{K4}
K4	1.04

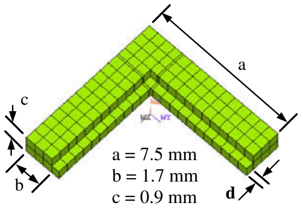


Fig. 12. Studied parameter *d* of the corner glue.

the parametric study was expanded to include the depth of the glue located underneath the substrate, shown as dimension "*d*" in Fig. 12. During the initial investigations, this parameter was found among the geometry parameters to have the strongest effect on stretching of the corner solder balls. In the parametric study, the value of *d* was varied from 0 mm to 0.5 mm. It is noted that the value of *d* in the test vehicle is approximately 0.1 mm. This is also the baseline value of *d* used in the parametric study. In addition, the effect of stiffener, which is expected to reduce the warpage of the substrate, was also studied. A FEM model of the package with stiffener is depicted in Fig. 13. A 1.2 mm thick copper stiffener was attached to the substrate using epoxy. Young's modulus of the epoxy, called Eep, was varied from 0.01 to 0.3 GPa in the study. The study was performed by varying those parameters one at a time.

Three cycles of thermal cycling with the temperature range from 25 °C to 105 °C were run for each simulation. The ramp up, ramp down, dwell at the high temperature, and dwell at the low temperature periods were all 15 min. The volumetrically averaged plastic work per cycle was calculated over the two bottom layers of elements (approximately 1 mil thick) of the critical solder balls which are the die corner and package corner solder balls for the third cycle. The fatigue life for the solder balls was predicted using the methodology described in the above section. The results and discussion of the parametric study are presented in the following section.

9. Results and discussion

Fig. 14 graphically shows the effect of the dimension *d* on the *z*-plastic strain and the characteristic life of the package corner and the die corner solder balls. It is observed from Fig. 14a that the corner glue induces significant *z*-plastic strain in the package corner solder ball. Fig. 14b shows that with the introduction of the glue the characteristic life of the package corner ball decreases. Also, the characteristic life of the package corner solder ball decreases as the depth *d* increases, while the characteristic life of the die corner solder ball is almost constant. Typically, the critical solder ball, defined as the one with the lowest characteristic life among the BGA, of a flip chip PBGA package without corner glue is the die corner (die shadow) solder ball. However, the critical solder ball was found to switch from the die corner one to the package corner one in the package with the corner glue as "*d*" increases from 0 mm to 0.5 mm (see Fig. 15).

Fig. 16 shows the effect of the CTE on the *z*-plastic strain of the package corner solder ball and the characteristic life of the critical solder balls, respectively. As expected the strain increases significantly as the CTE increases. This is due to the higher expansion of the glue as a result of its higher CTE. The characteristic life of the package corner solder ball decreases, while that of the die corner ball remains constant with the CTE. The critical solder ball was found to switch from the die corner solder ball to the package

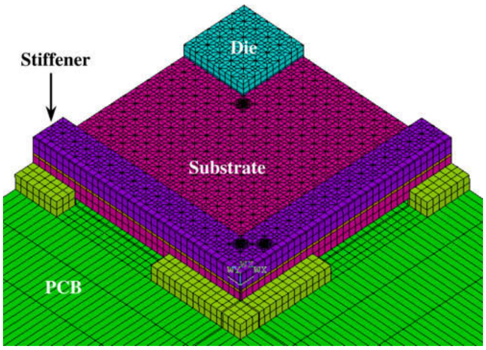


Fig. 13. FEM model with an introduction of stiffener.

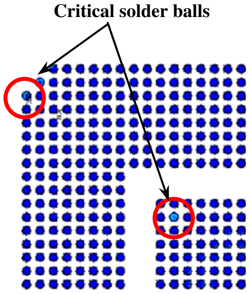


Fig. 15. Critical solder balls: (a) die corner solder ball when $d = 0$ and (b) package corner solder ball when $d = 0.5$ mm.

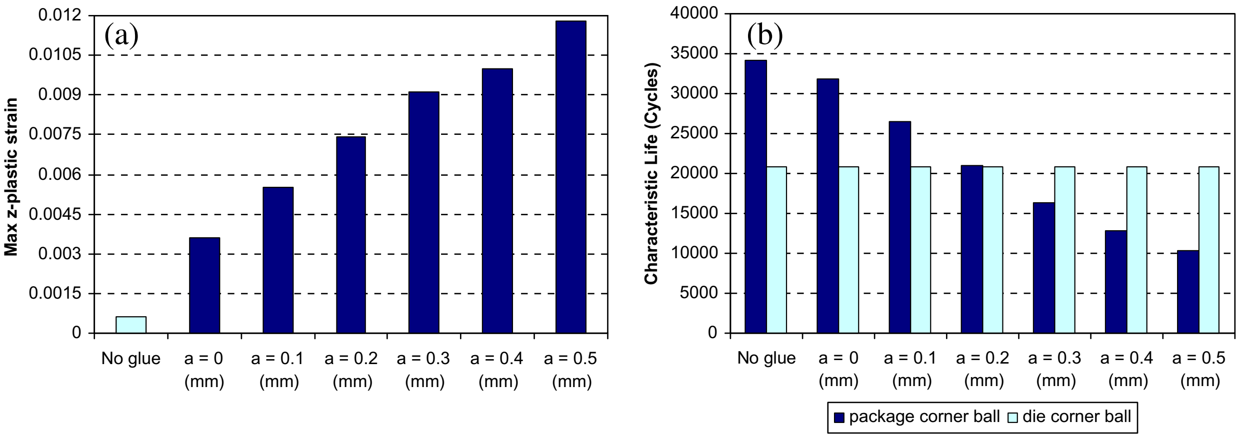


Fig. 14. Effect of *d* on (a) maximum *z*-plastic strain and (b) characteristic life of the package corner and die corner solder balls.

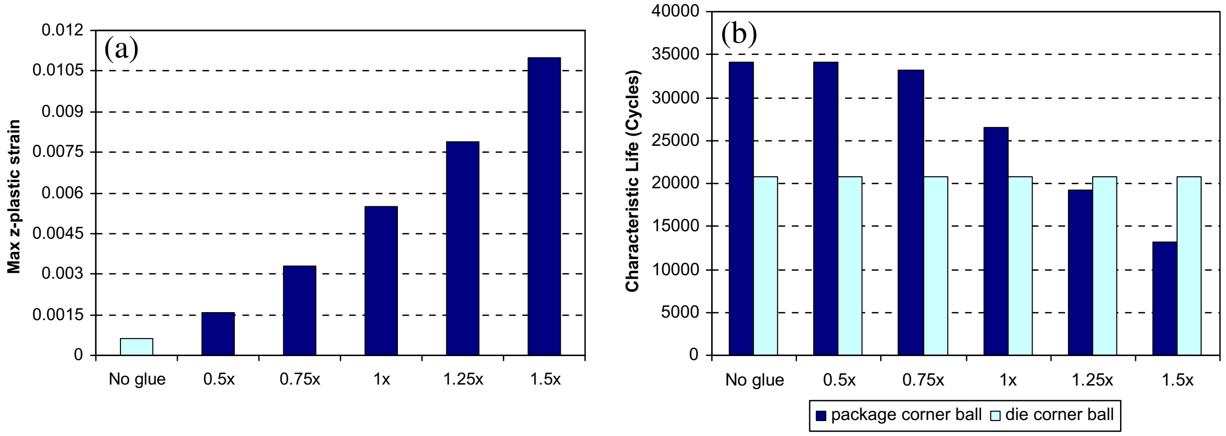


Fig. 16. Effect of the CTE of the glue on (a) maximum z-plastic strain and (b) characteristic life of the package corner and die corner solder balls.

corner one as the CTE increases above approximately 1.25 times its baseline value.

The effect of Young's modulus of the glue on the plastic strain and the characteristic life is somewhat similar to that of CTE. The strain increases and the characteristic life decreases with Young's modulus as shown in Fig. 17.

Fig. 18a and b shows the effect of stiffener. It is obvious that with the introduction of the stiffener the strain is reduced significantly and the characteristic life is improved. Young's modulus of the epoxy in this case has a strong impact. A higher modulus helps reduce the strain and improve the characteristic life. When the modulus is equal or higher than 0.1 GPa the characteristic life is very close to that of the case without the glue.

Based on the above results, the recommended methods for improving the fatigue life of the package are as follows. First, a low CTE glue is highly recommended. Ideally, CTE of the glue should be matched with that of the solder material, which is around 25 ppm/°C. This is similar to the recommendation for flip chip underfill. However, the results in this study show that even when the CTE is relatively high, 0.75 times the baseline value,

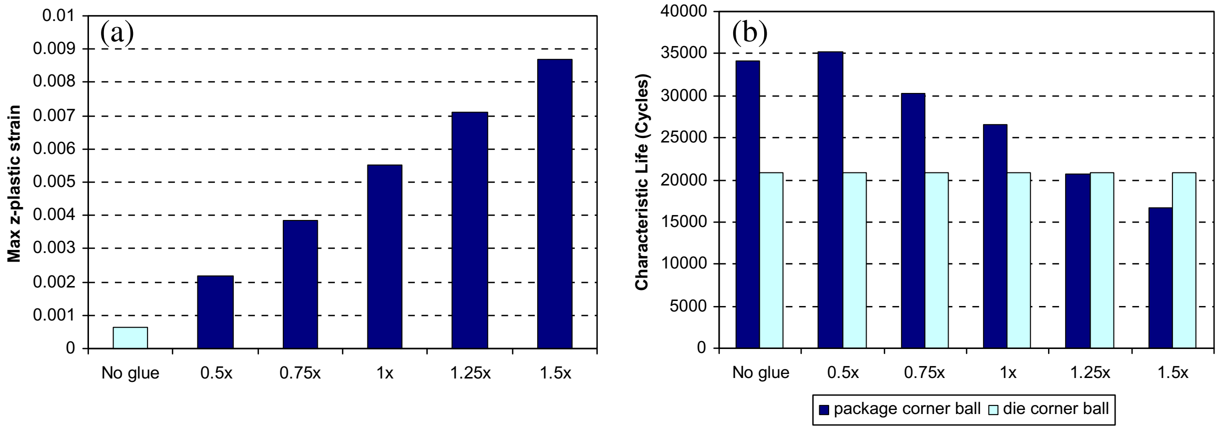


Fig. 17. Effect of the Young's modulus of the glue on (a) maximum z-plastic strain and (b) characteristic life of the package corner and die corner solder balls.

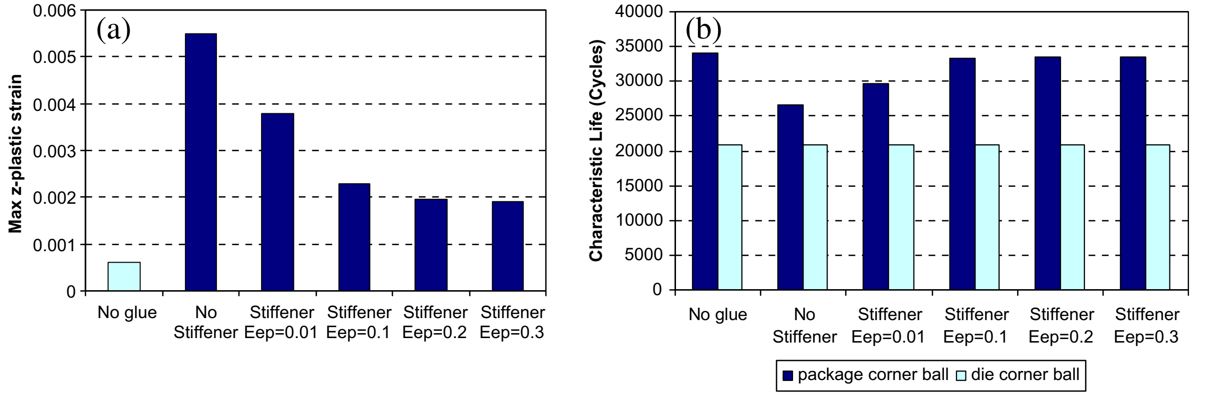


Fig. 18. Effect of the stiffener and Young's modulus of the epoxy on (a) maximum z-plastic strain and (b) characteristic life of the package corner and die corner solder balls.

the fatigue life is very close to the case without glue. This is due to the relatively low Young's modulus of the glue. A low Young's modulus glue is preferable. However, low Young's modulus may degrade performance of the package under mechanical impacts. Therefore, mechanical impacts should also be taken into account. Second, regarding the configuration of the glue, the dispensing process should be designed appropriately in order to reduce the depth of the glue located underneath the substrate. Third, an implementation of a stiffener may be considered to help reduce the warpage of the substrate and increase the characteristic life of the package corner solder ball. Such a technique may be a good solution when further reliability for the package corner solder ball is needed.

Generally, the die corner solder balls fail before the package corner ones for flip chip packages [12]. However, according to the results of this work, with the introduction of corner glues, the corner package solder balls may fail before the die corner ones, meaning that corner glue may reduce the overall reliability of BGA. Therefore, the authors recommend that users apply the above design guidelines appropriately so that the package corner solder balls would not fail before die corner solder ones. In that case, the corner glue does not degrade the overall reliability of the package. Finally, it is mentioned that, in this study, the effect of edge glues on the reliability of the BGA under thermal cycling has been also investigated through the numerical model. Details of the results are not shown here, for the sake of brevity, but the edge glue was found not to have any adverse effect under thermal cycling. Therefore, it is a good solution for the reliability of BGA packages. Edge glues could be used along with corner glues. However, they should be used alone without corner glues if they alone can achieve the desired reliability for BGA packages under mechanical impacts.

10. Conclusion

In this paper, experiments and FEM were used to study the effect glue has on the reliability of BGA packages under thermal cycling. The results show that edge glue has very little effect on the reliability of the BGA, while corner glue can degrades the reliability of the BGA under thermal cycling significantly by stretching the package corner solder as temperature changes. This makes the package corner solder ball a high risk site in a BGA. A parametric study using FEM was performed on the CTE, Young's modulus of the glue, the depth *d* of the glue located underneath the substrate, and the introduction of a stiffener. The reliability of the corner solder ball under thermal cycle decreases as the CTE, Young's modulus of the glue, and the glue depth increase. Based on the results low values of CTE and *d* are highly recommended. Performance of the package under mechanical impacts should be considered when choosing Young's modulus of the glue. A stiffener can also be used to reduce the warpage of the substrate and to improve the reliability of the BGA package. Moreover, whenever possible, the use of edge glue without corner glue is highly recommended.

Acknowledgments

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