

Warpage Control of Thermally Enhanced PBGA Package with Internal Heat Spreader during Reliability Test

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Abstract

Thermally enhanced PBGA (TEPBGA) package with internal heat spreader is becoming more and more popular due to the ever growing power dissipation requirement of the advanced CMOS logic devices. The additional stiffness provided by the Cu heat spreader also helps the package to remain flat during SMT reflow process. However, it has been observed that, in some cases, TEPBGA package would show large warpage in accelerated stress test such as air temperature cycling. The excessive warpage may increase yield loss during test. In this work, room temperature package warpage of TEPBGA package after temperature cycling were examined with three types of Cu alloys together with factors like stress condition and bill of material. In-situ monitoring with strain gages attached on the heat spreader was performed to understand the deformation behavior of package during temperature cycling. Hardness test on Cu heat spreaders was done at different stages of the stress. The correlation between the warpage and Cu material properties is discussed. A finite element model was also created to assess the impact of cycling condition on the thermal stress and driving force for package warpage. The results of these analyses will be used to provide a robust solution to ensure the flatness of TEPBGA package in temperature cycling. Finally, the packages were assembled to PCB board and solder joint reliability tests were performed to understand the impact of package warpage on solder joint reliability.

Key words: Warpage, Cu Alloy, Softening, Ball Grid Array, Reliability

Introduction

A thermally enhanced plastic ball grid array package (TEPBGA, Fig. 1(a)) constructed with a Copper (Cu) metal spreader over the die embedded in the thermoset mold compound is extensively used in electronic packaging. The primary function of the Cu spreader is to lower the plastic ball grid array (PBGA) package thermal resistance. Due to the mismatch of coefficient of thermal expansion (CTE) between different materials, package warpage is expected at temperatures other than the “zero” stress point where no thermal-mechanical stress exists. For a molded wire-bond PBGA package, the post-mold cure temperature ($\sim 175^{\circ}\text{C}$) is normally considered as the “zero” stress temperature. The warpage variation under solder reflow stressing, with temperature from 25°C to $220\sim 260^{\circ}\text{C}$, has been studied extensively [1~4] because excessive warpage in this temperature range will induce yield loss as a result of solder joint open or short during PCB board mounting. However, less attention has been paid to the warpage of package

under other package reliability stresses (temperature cycling, autoclave, etc), even though some industrial standards, such as JEDEC, consider warpage as one of the failure criteria to pass the test [5].

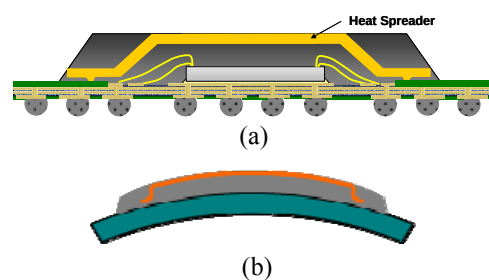


Figure 1. (a) Structure of TEPBGA package with heat spreader (b) Warpage of TEPBGA package

In the TEPBGA package, the Cu heat spreader constrains the package curvature resulting in

a flat package ($<60\mu\text{m}$) from room temperature (25°C) up to Pb-free solder reflow peak temperature (245°C). On the other hand, our recently study shows that the room temperature package warpage can accumulate on every cycle in the temperature cycle (TC) test for TEPBGA packages with certain Cu heat spreaders. The build up room temperature warpage can be as high as over $300\mu\text{m}$ after 1500 cycles at $-55\sim 125^\circ\text{C}$. The coplanarity of the BGA spheres is significantly increased due to the high warpage and causes false electrical test failure due to the misalignment of BGA to test socket. Therefore, it is important understand the mechanism driving this unusual behavior and estimate its impact on package reliability.

During TC test, the package warps toward the substrate side at low temperature (-55°C) since the substrate ($\text{CTE}\sim 14\text{ppm}/^\circ\text{C}$) is contracting more than the molding compound ($\text{CTE}\sim 9\text{ppm}/^\circ\text{C}$), as shown in Fig. 1(b). At same time, the heat spreader is “pulling” the package back toward the molding compound side. As a result, the heat spreader is stretched and under tensile stress. The stress level depends on factors such as the temperature excursion and the material properties. At the same time, the mechanical strength of the heat spreader also varies with assembly and stress condition. If the tensile stress is higher than the strength of Cu, plastic deformation should occur that is cumulative over temperature cycles.

This paper proves the above hypothesis, evaluates various factors that affect the TEPBGA package warpage under temperature cycle and examines the impact on board level reliability. Based on the understanding of the mechanism, a resolution is provided that minimizes the cumulative warpage issue without causing other degradation in package system or negative effect in the customer board application.

Experimental

$31\times 31\text{mm}$ and $29\times 29\text{mm}$ thermally enhanced PBGA (TEPBGA) package with Cu heat spreader were selected as the test vehicles. The details of the test plan for $31\times 31\text{mm}$ test vehicles are listed in Table 1. Two rounds of tests were performed. In the first test, three Cu heat spreader materials (C1100, C1220 and C194) were included in the evaluation. C1100, which is also called electrolytic tough-pitch copper (ETP), is the most common material for Cu heat spreader. It is basically pure Cu with a trace level of oxygen. C1220 is called phosphorus deoxidized copper. 150~400ppm phosphorus exists in the alloy to minimize the oxygen content. C194 is widely used for lead frames in leaded packages. It is an alloy of Cu, Fe, P and Zn. The properties of the materials are listed in Table 2. Only one molding compound A was used

for this experiment. All the samples experienced moisture sensitivity level (MSL) 3 preconditioning followed by 3 times reflow at 260°C and then were temperature cycled at $-55\sim 125^\circ\text{C}$ according to JESD22-A104C, condition B.

Table 1. Test Plan for $31\times 31\text{mm}$ TEPBGA

Test No.	Alloy Name	Alloy Lot	Molding Compound	MSL level 3 Reflow@ 260°C	Temperature Cycle
1	C1100	1	A	Yes	$-55/125^\circ\text{C}$
	C1220	1	A	Yes	
	C194	1	A	Yes	
2	C1100	1	A	Yes	$-55/125^\circ\text{C}$
			A	No	
		2	A	Yes	
			A	No	

In the second test, C1100 from two raw material lots were used. Half of the samples went through MSL3 preconditioning with 3 times reflow at 260°C and the other half did not. The samples were then temperature cycled at $-55\sim 125^\circ\text{C}$.

Table 2. Properties of Cu Alloys

Alloy Name	C1100	C1220	C194
Chemical Composition (wt%)	Cu : 99.9 O2 0.02-0.045	Cu : ≥ 99.90 P: 0.015-0.040	Cu : Balance Fe : 2.1~2.6 P 0.015~0.15 Zn : 0.005~0.20
Softening Temperature ($^\circ\text{C}$)	150~300	300	430
Thermal Conductivity ($\text{W}/\text{m}\cdot\text{K}$)	391	339	260
Tensile Strength (N/mm^2)	255-315	300~360	415~485
Modulus in Tension (kN/mm^2)	118	118	121
Elongation (%)	15	9~10	7

For $29\times 29\text{mm}$ packages, all the samples were assembled with C1100 (Lot 1) with two molding compounds, B and C. The parts were then split to go through two temperature cycling condition, $0\sim 125^\circ\text{C}$ and $-55\sim 125^\circ\text{C}$, according to JESD22-A104C, condition B and K, to evaluate the effect of temperature excursion, as shown in Table 3.

Table 3. Test Plan for $29\times 29\text{mm}$ TEPBGA

Alloy Name	Molding Compound	MSL level 3 Reflow@ 260°C	Temperature Cycle
C1100	B	Yes	$-55/125^\circ\text{C}$
		Yes	$0/125^\circ\text{C}$
	C	Yes	$-55/125^\circ\text{C}$
		Yes	$0/125^\circ\text{C}$

At each read point (post assembly, post MSL reflow and post temperature cycles), a laser profilometer from ICOS Vision Systems was used to measure the room temperature warpage of the package from the BGA side. In this paper, the warpage referred to means room temperature warpage of the package unless otherwise described.

A strain gage was attached at the center of the Cu heat spreader surface to enable in-situ observation of the package deformation during temperature cycling, as shown in Fig. 2(a). When the package warps convexly, the strain is tensile and vice versa (Fig. 2(b)). A single strain gage measures the total strain of the subject it attaches to, including the thermal strain that is induced by thermal expansion and the mechanical strain that is caused by stress. We are only interested in the mechanical strain to understand the stress level in the heat spreader. For that reason, a compensating strain gage attached to a heat spreader without package was used to form a Wheatstone Bridge circuit, as illustrated in Fig. 2(c). With this configuration, pure mechanical strain can be obtained from the active gage since the thermal strain from both strain gages will cancel each other.

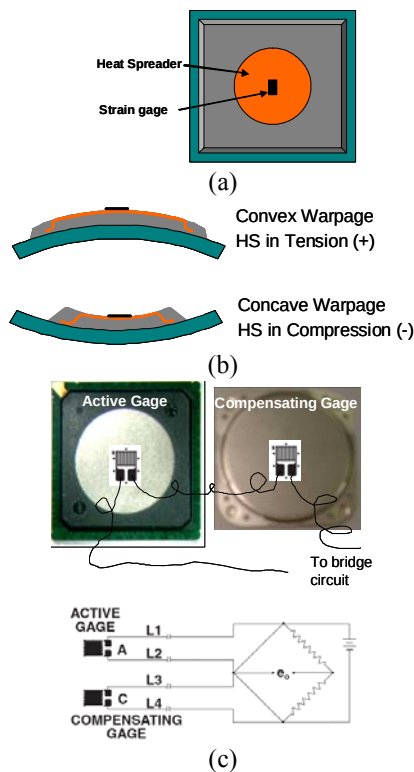


Figure 2. (a) Strain gage attached to heat spreader (HS) (b) Correlation between HS strain and package warpage (c) Wheatstone Bridge circuit connection with compensating strain gage

Hardness testing using Rockwell method with a 1/16 inch steel ball was performed to measure the heat spreader mechanical strength evolution at different steps of the reliability stressing. Meanwhile, a three dimensional finite element model (FEM) was constructed to analyze the stress distribution inside the TEPBGA package during temperature cycling. One fourth of the package was modeled due to symmetry as depicted in Fig. 3(a). The shape of the heat spreader is shown in Fig. 3(b). All the materials in the model are considered to have elastic behavior within the temperature range of interest.

To examine the effect of component level package warpage on solder joint reliability, 31x31mm packages with C1100 heat spreader and mold compound A were assembled to printed circuit boards (PCB) and went through -40~125°C and 0~100°C temperature cycling. The package warpage on PCB board and heat spreader hardness were measured at various read points and compared with solder joint reliability performance.

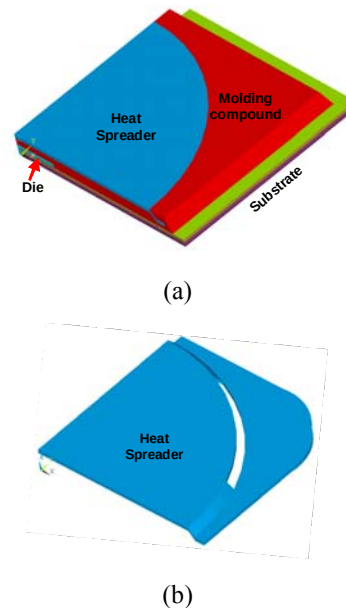


Figure 3. Finite element model of (a) TEPBGA package (b) Heat spreader

Results and Discussion

Package Warpage after Temperature Cycling

Package warpage of the 31x31mm TEPBGA with molding compound A from Test 1 is shown in Fig. 4. One can see that samples with different Cu materials had comparable warpage levels (40~70µm) at Time 0 (post assembly) and post

MSL reflow. However, the warpage increased over 100% after 200 cycles for C1100 (Lot 1) samples and the warpage continued to grow with more cycles, while C1220 and C194 samples remained almost unchanged. The direction of the warpage is convex which means that the package is warping toward the substrate side.

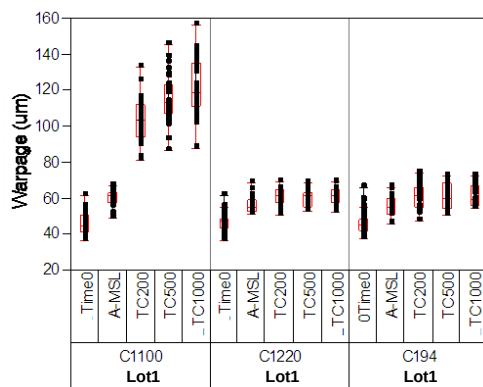


Figure 4. Warpage of 31x31mm TEPBGA package in Test 1

In the second test of the 31x31 TEPBGA, the large warpage increase (>200um) occurred again after 500 cycles from samples with C1100 (Lot 1) that went through MSL reflow, as shown in Fig. 5. However, for the same stress condition, the warpage only increased slightly (<50um) for samples with C1100 (Lot 2) post MSL reflow. A multi-lot study with C1220 and C194 did not show this level of variation; the data for which is not shown in this paper. This suggests that lot-to-lot variation exists for the warpage response of C1100 material. What is more, little warpage change was observed for both lots of C1100 samples even after 1000 cycles when the packages did not go through MSL reflow. This indicates that the package thermal history has considerable impact on the warpage after temperature cycle.

For the 29x29mm package, the warpage increased appreciably (>100um) after 500 cycles at -55~125°C with MSL reflow (Fig. 6), which is similar to the 31x31mm package with C1100 (Lot 1). When the temperature range was reduced to 0~125°C, the warpage increase was much smaller (~30um). This demonstrates that the temperature range, especially the low temperature end of the temperature cycling stress can affect the package warpage. Warpage difference can also be seen between the two molding compounds after 500 cycles.

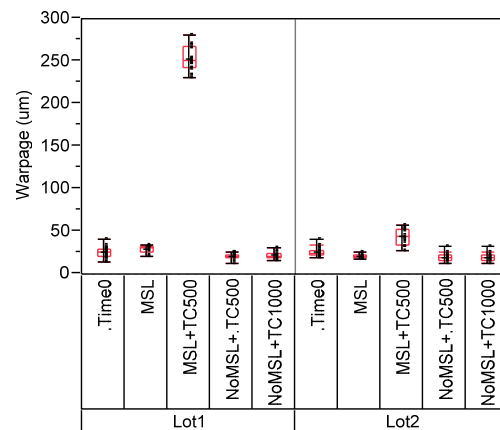


Figure 5. Warpage of 31x31mm TEPBGA package in Test 2

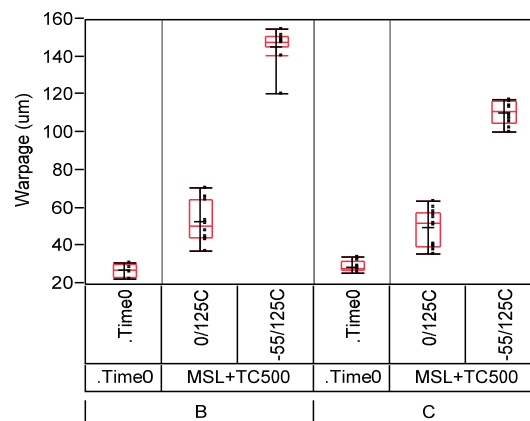


Figure 6. Warpage of 29x29mm TEPBGA package with molding compound B and C

Strain Measurement during Temperature Cycling

To understand the details of the package deformation during temperature cycling, the strain gage tests described in the experimental section were performed on the 31x31mm TEPBGA packages with C1100 material (Lot 1 and Lot 2). Due to the working temperature limitation of the strain gage, the samples were cycled between -45~85°C. The mechanical strain versus time (or number of cycles) curve for the sample with C1100 (Lot 1) is plotted in Fig. 7(a). It can be seen that ~0.1% tensile strain was generated in the Cu heat spreader in the first cooling cycle. Only ~50% of it was recovered in the first heating cycle, resulting in a plastic tensile strain of 0.05% after the first full cycle. As mentioned previously, a tensile strain in the spreader correlates to the convex shape of the package. In the following cycles, the difference in strain generated during the

cooling and heating cycle narrowed and finally reached a stable value that pushed the total strain of the spreader to be more and more tensile, indicating an ever growing convex warpage. In contrast, the strain generated in the cooling cycle in a C1100 (Lot 2) heat spreader equaled that generated in the heating cycle. The net effect was that the strain in the heat spreader, and hence the package warpage, remained unchanged over cycles (Fig. 7(b)).

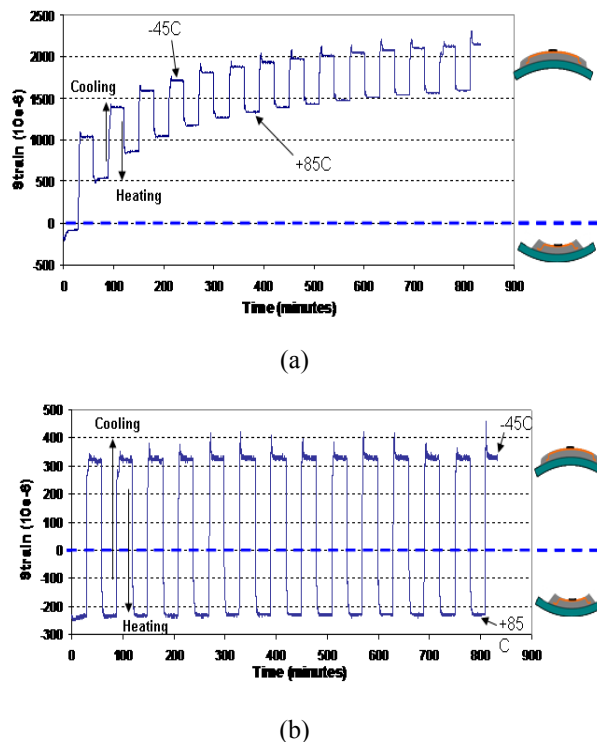


Figure 7. Strain gage measurement of (a) C1100 (Lot 1) and (b) C1100 (Lot 2) Cu heat spreader during temperature cycling

Hardness Measurement of the Heat Spreader

The warpage and strain measurement from previous sections demonstrate that the root cause of high package warpage is the plastic deformation (or yielding) of Cu heat spreader. It is clear that thermal treatment is the trigger of Cu plastic deformation by comparing the behavior of C1100 (Lot 1) material with and without MSL reflow. One parameter that describes a material's resistance to thermal annealing is softening temperature. Softening temperature is the temperature above which recovery, re-crystallization and grain growth occurs in the metal that will lead to reduced tensile strength of the material. The three Cu materials in this study have distinctly different softening temperatures which can be found in Table

2. The relatively low softening temperature of C1100, 150~300°C, makes it more susceptible to losing its strength during the reflow process where it sees 260°C peak temperature.

Hardness has close relationship to the mechanical strength. Therefore it was used to examine the strength change of the Cu heat spreader material. The hardness of different Cu materials from 31x31mm TEPBGA Test 1 is shown in Fig. 8. It can be seen that the hardness of C1100 (Lot 1) dropped significantly compared to C1220 and C194.

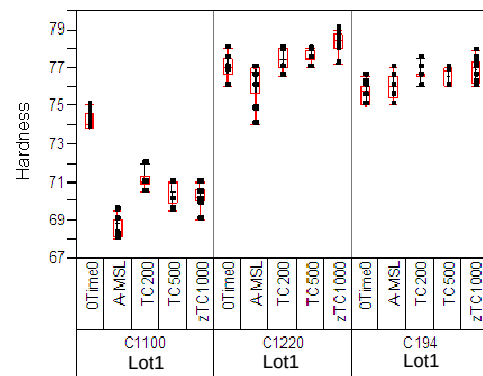


Figure 8. Hardness measurement of Cu heat spreader in 31x31mm TEPBGA package

The hardness of the C1100 (Lot 1 and Lot 2) material from 31x31mm TEPBGA Test 2 is shown in Fig. 9. Compared with Lot 1 material, C1100 (Lot 2) had much less hardness drop which could account for its low warpage change during temperature cycling. The reason for the drastic difference between the two lots of C1100 is unclear. Many factors can affect the softening temperature including the alloy composition, cold machine process, crystal defect density, etc.

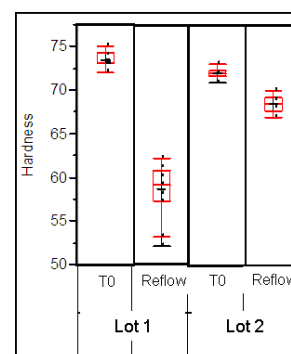


Figure 9. Hardness measurement of Cu heat spreader in 31x31mm TEPBGA package

Fig. 10 shows the correlation between heat spreader hardness and warpage after 500 cycles at -55~125°C. Based on this graph, the heat spreader hardness needs to be controlled over 60 in order to achieve a warpage level below 125µm.

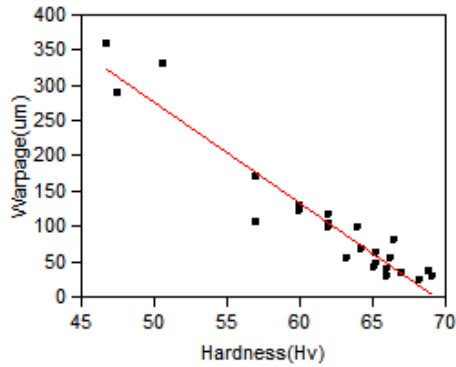


Figure 10. Correlation between warpage after temperature cycle and hardness of Cu heat spreader in 31x31mm TEPBGA package

Finite Element Analysis

The driving force of the package warpage during temperature cycling was estimated through finite element modeling. The stress in the heat spreader in 31x31mm TEPBGA package was calculated from -55~125°C. Fig. 11 shows the stress evolution in heat spreader with temperature. At -55°C, the heat spreader is under tensile stress. The maximum first principle stress, 84MPa, occurs at the center according to Fig. 12(a). High tensile stress could cause plastic yield of the Cu heat spreader. At 125°C, the heat spreader is mainly under compressive stress (Fig. 12(b)) which will not cause yielding of Cu material. Therefore, the low temperature end of the cycling profile is the most dangerous place where high warpage could occur. This explains why the warpage reduced significantly when temperature range changed from -55~125°C to 0~125°C.

The results from the strain gage measurement can be used to verify the finite element modeling. For example, sample with C1100 (Lot 2) showed a maximum 0.04% elastic strain at -45°C. The stress can be calculated using

$$\sigma = \frac{E}{1-\nu} \varepsilon \quad (1)$$

where σ is the stress, E is Young's modulus, ν is Poisson's ratio and ε is the strain. For Cu material, $E \approx 120\text{GPa}$, $\nu \approx 0.33$. Therefore, 0.04% strain corresponds to 72MPa tensile stress. This matches very well with the FEA results at this temperature.

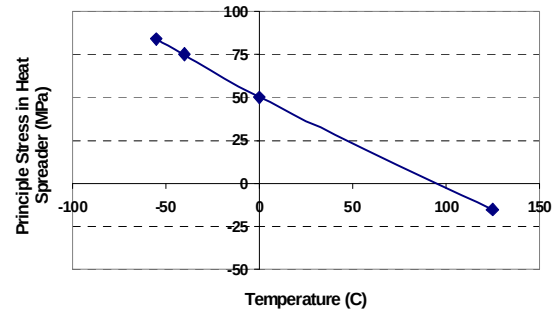


Figure 11. Thermal mechanical stress in Cu heat spreader changing with temperature

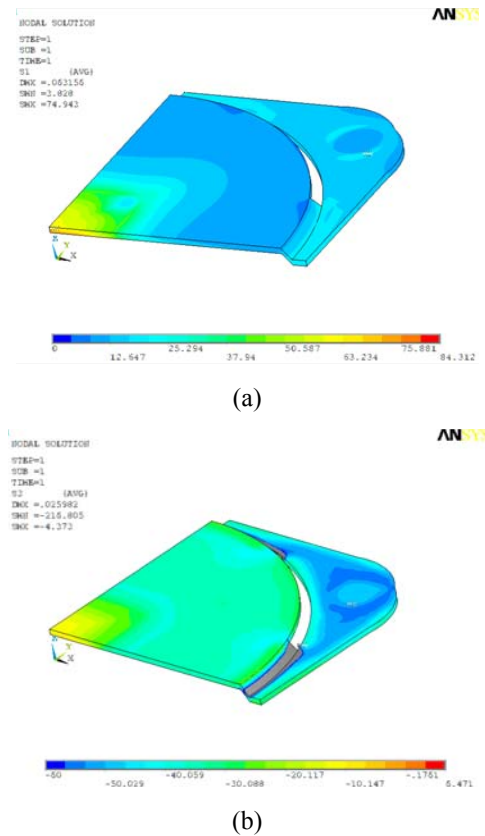


Figure 12. First principle stress in Cu heat spreader at (a) -55°C and (b) 125°C

Board Level Solder Joint Reliability Study

31x31mm package samples with C1100 (Lot 1 and Lot 2) were assembled to PCB boards for solder joint reliability (SJR) study with 0~100°C and -40~125°C condition. The hardness of the heat spreader monitored for each read point is illustrated

in Fig. 13. C1100 Lot 2 showed ~35% higher hardness than Lot 1 material at all read points for both testing conditions.

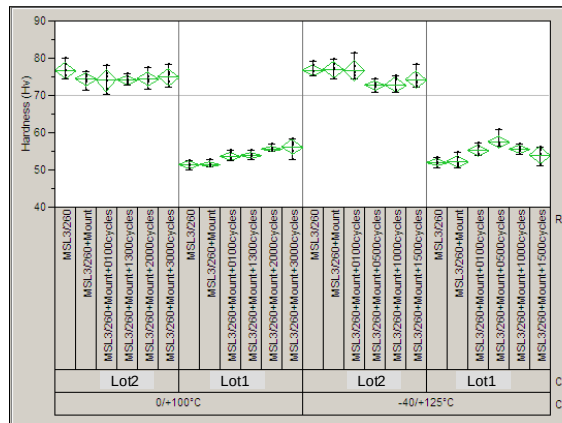


Figure 13. Hardness of heat spreader material in SJR test

For on-board package warpage, C1100 Lot 1 (concave) showed opposite warpage direction than C1100 Lot 2 (convex) in Fig. 14. However, both materials had low warpage level (20~30 μ m) which is much lower than component level warpage. Unlike component level temperature cycling, neither of the material lots in SJR study showed an increase in warpage over cycles. The stable and small warpage suggests that the plastic deformation of Cu heat spreader is not occurring and therefore will not affect SJR lifetime.

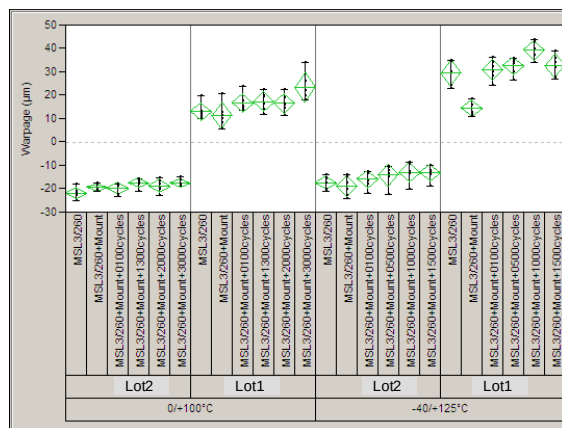


Figure 14. Warpage of TEPBGA package on PCB board in SJR test

Heat Spreader Material for Low Package Warpage

From the above evaluations, C1100 Cu is susceptible to high warpage after temperature cycling under normal reliability test flow. It is important to select materials with softening temperature higher

than the maximum temperature that the parts will see in the assembly process in order to control the warpage. C1220 and C194 meet this requirement. However, from Table 2, the thermal conductivity of C194 is only 66% of that of C1100 due to the high loading of Zn and Fe doping. Therefore, package thermal performance will be reduced with C194. Additionally, C194 has much lower elongation than C1100 which implies a higher risk of cracking during machine and forming process of the heat spreader. In contrast, the thermal conductivity and elongation of C1220 is much closer to C1100. Therefore, it could be a good candidate for heat spreader application.

Conclusions

The room temperature warpage of 31x31mm and 29x29mm TEPBGA packages with internal Cu heat spreader were studied. Three Cu alloys, C1100, C1220 and C194, together with other factors such as raw material lots, stress condition and molding compound, were included to evaluate their impact. High warpage was observed in samples with C1100 Cu alloy reflowed at 260°C at the first read point (200 cycles) after temperature cycling. The warpage continued to increase with additional cycles. The other two alloys showed no significant warpage increase after temperature cycling.

In-situ strain measurement of the Cu heat spreader found that the plastic deformation of the C1100 heat spreader is the root cause of the ever increasing warpage under temperature cycling. Hardness tests demonstrated that the mechanical strength (or hardness) of C1100 material dropped considerably after MSL reflow process as the maximum reflow temperature (260°C) is close or higher than the softening temperature of C1100 (150~300°C). Strong correlation between post-reflow hardness and warpage after temperature cycling was established. Finite element simulation showed that tensile stress necessary to drive the yielding of the Cu heat spreader exists at the cold end of the temperature profile during temperature cycling. Increasing the lowest temperature during the cycling will effectively reduce the tensile stress and thus reduce the warpage of the package. The result was confirmed by the warpage study with 0~125°C and -55~125°C temperature range. Board level warpage and hardness study with C1100 samples showed that hardness drop does not cause excessive warpage in the TEPBGA package and probably will not affect the solder joint reliability.

In order to have robust control of the component warpage after temperature cycling, C1220 Cu is suggested as the candidate material for the heat spreader due to its high softening

temperature and similar thermal conductivity and elongation to C1100 Cu.

Acknowledgments

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References

1. R.L. Shook, *et al*, "Impact of Ingressed Moisture and High Temperature Warpage Behavior on the Robust Assembly Capability for Large Body PBGAs," *Proceedings of Electronic Components and Technology Conference*, (2003), pp.1823–1828.
2. W-L. Yang and D.M.S. Yin, "The Effects of EpoxyMolding Compound Composition on the Warpage and Popcorn Resistance of PBGA", *Elec. Comp. and Tech. Conf.*, (1999), pp.721-726.
3. D. Bhogesware Roa and M. Prakash, "Effect of Substrate Warpage on the Second Level Assembly of Advanced Plastic Ball Grid Array (PBGA) Packages", *CPMT*, (1997), pp.439-446.
4. E. Haung, T. Thompson, and S. Chen, "Thin Mold ArrayPackage Warpage Control Study", *IEEE/CPMT Int'l Elec. Manuf. Tech. Symp.*, (1999), pp.223-229.
5. JEDEC Test Method, JESD22-A104C, "Temperature Cycling", (2005).