

Effects of PCB Design Variations on the Reliability of Lead-Free Solder Joints

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Abstract

Sn-Ag-Cu (SAC) solder alloys, such as Sn-3.0Ag-0.5 Cu (SAC305) are the popular choices of lead-free solders replacing SnPb solders. However, SAC solders are more brittle in nature due to high stiffness and excessive intermetallic compounds growth at the solder joint to pad interface. This leads to higher risks in solder joints failures. Memory module type lead-free BGA packages are constantly under dynamic stresses during handling and thermal stresses during operations. It is important to understand the dynamic performance and long term reliability of memory module lead-free BGAs. In this study, difference pad and trace designs were introduced to evaluate the effects of PCB design variations on the bend performance of lead-free solder joints. Pad designs with NSMD (Non-solder mask defined), SMD (Solder mask defined), and a unique web design were assembled and tested. Different solder alloys including SAC305, SAC105, and SnPb solders as control, have been evaluated in this study. Different PCB materials have also been evaluated in the test. Four point monotonic bend tests were performed to characterize the bending performance variations with different PCB designs and compared with conventional Sn-Pb solder. The implications of these results for the reliability of lead-free solder joints are discussed in this paper.

Key words: Lead-free solders, Monotonic Bend test, PCB design, Aging effects, Pad Cratering,

Introduction

Lead-free solder alloys, especially SnAgCu (SAC) alloys show higher stiffness than eutectic SnPb without aging [1-2]. As a result of the stiffness, it may induce defects, particularly under dynamic loading conditions. Dynamic performance of electronics under bend and shock conditions (mechanical loading) has been an important factor on electronics quality and reliability. Monotonic bend test represents a measure of the fracture resistance to flexural loading during operation, shipping or handling of the electronics. This method has been standardized to characterize the mechanical strength of the solder assembly and can be used as a way to investigate the relative mechanical strength of the assembly. In this study, the effects of PCB design variations, such as pad design and trace width, etc. using lead-free solders are studied using monotonic bend test method.

One of the typical failure modes associated with lead-free solders is pad cratering. It is reported that PCB pad cratering failures due to the stiffness of solder joints are more severe in lead-free solder joints [3-6]. Godbole et al. believes that the pad cratering failure modes are strain rate dependent, higher strain

rate will induce higher pad cratering failure [4]. Agrawal et al. also found that pad cratering failure mode is the dominant failure mode after drop test of lead-free products, and concluded that the drop life is dependent to the input energy [5]. Ahmad et al. proposed a new method to test pad cratering failures, and found that pad size, PCB materials, pad geometry and other factors are important factors of pad cratering issues [6]. One of the potential ways to mitigate this type of failure mode is to use different pad design. Thus, it is critical to understand the level of strength among various pad designs.

In order to compare the level of improvement on lead-free assembly strength under monotonic bend test, aging treatment is one of the key factors to be applied. Recent studies also show that aging significantly degraded the tensile properties of lead-free solders [1-2]. It is also known that significant degradation of dynamic performance of lead-free solder joints after aging on large-size package assembly under shock test [3].

In this study, difference PCB design variations were proposed in understanding of the lead-free solder joints and PCB performance under monotonic bend. The pad designs with solder mask

defined (SMD) and Non-solder masked defined (NSMD), different pad sizes, trace width, solder alloys and package types were tested and analyzed in this study.

Experimental Procedure

Two types of daisy-chained packages were studied in this work. CABGA (Chip Area Ball Grid Array) with 160 I/O and FBGA (Fine Pitch Ball Grid Array) with 60 I/O were used in this study. The pitch sizes were 0.8 mm for both type of packages, and body size of 12 mm x 12 mm for CABGA and 8 mm x 12 mm for FBGA. Three types of solder alloys were used in CABGA package; they are Sn-3.0Ag-0.5Cu (SAC305), Sn-1.0Ag-0.5Cu (SAC105), and eutectic SnPb as reference. Only SAC305 solder alloy were used for FBGA package. Each package were assembled on 8 layer 93 mil thick PCB board with OSP (Organic Solderability Preservative) finishes (Figure 1). High Tg FR4 test boards compatible for lead-free applications were designed to monitor the daisy chained package connection from the resistance of the daisy-chain circuit. Two different PCB materials were used in this study. One is phenolic (PCB1) the other is non-phenolic (PCB2).

Different copper pad designs were used in this set of test vehicles, as shown in Table 1. There are four different pad designs for FBGA, they are Normal NSMD (Non-solder Mask Defined), SMD (Solder Mask Defined), NSMD with wide trace, and NSMD with Web Design. Web design pad is designed with the normal pad size with three additional copper legs with same width as the trace, which extends under the solder mask. There are three different pad designs for CABGA package; they are NSMD, SMD and NSMD with Web design. Figure 2 shows the pad design variations for both packages.

A set of assembled test boards was preconditioned (thermal aging) at 100 °C for 1000 hours before bend test. Monotonic bend test was performed based IPC 9702 spec [7], and were performed at 6000 μ strain/sec (Figure 3). All test boards were in-situ monitored its electrical continually during bend test to detect failures. An increase of 20% or more of initial resistance value during test is considered to be a failure. Figure 3 shows the bend test setup. Strain gages were attached to the test boards for in-situ recording of strain value at pre-defined locations. As shown in Figure 4, the strain value at the cross point of the resistance increase is recorded as failure strains. 15 samples of each condition were tested. Tested boards were analyzed by dye-and-pry to observe failure mode.

SEM images were also taken to observe solder joints failures and IMC growth.

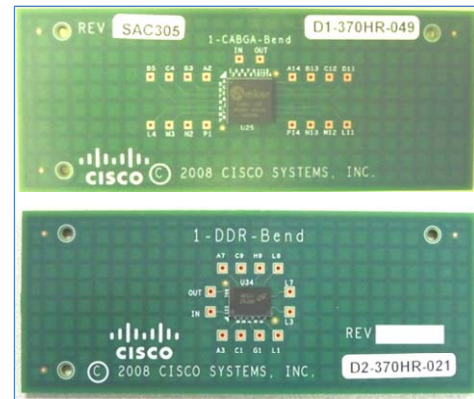


Figure 1 Bend Test Sample.

Table 1 PCB design matrix.

Package	Pad Design	Pad Size	Trace Size	Solder	Paste	Bend Sample Size
FBGA60	NSMD	0.35mm	3.5 mil	SAC305	SAC305	15
	NSMD	0.35mm	9.8 mil	SAC305	SAC305	15
	NSMD	web design	3.5 mil	SAC305	SAC305	15
	SMD	0.35mm	3.5 mil	SAC305	SAC305	15
CABGA160	NSMD	0.35mm	3.5 mil	SAC305	SAC305	15
	SMD	0.35mm	3.5 mil	SAC305	SAC305	15
	NSMD	Web design	3.5 mil	SAC305	SAC305	15
	NSMD	0.35mm	3.5 mil	SAC105	SAC305	15
	SMD	0.35mm	3.5 mil	SAC105	SAC305	15
	NSMD	Web design	3.5 mil	SAC105	SAC305	15
	NSMD	0.35mm	3.5 mil	SnPb	SnPb	15

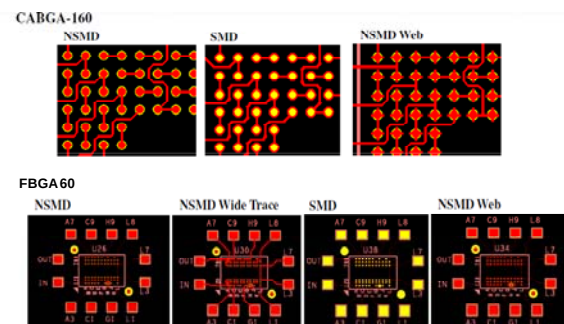


Figure 2 Different PCB designs for CABGA and FBGA.

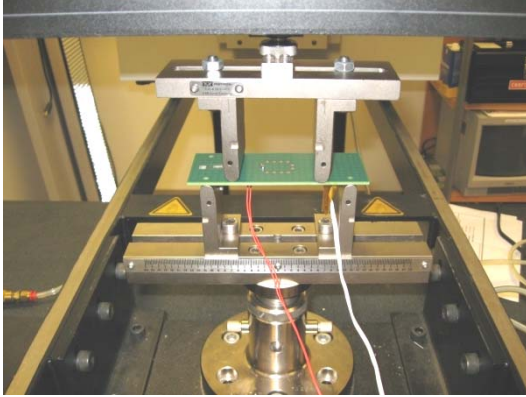


Figure 3 Monotonic bend test setup.

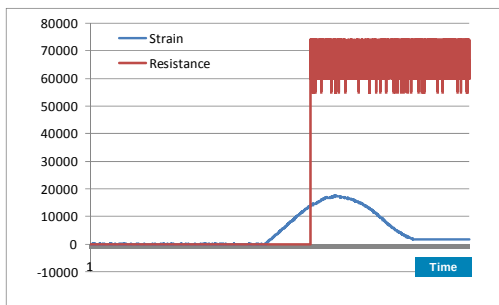


Figure 4 In-situ monitoring of resistance and measurement of strains during bend test.

Results and Discussions

Monotonic bend test results

Figure 5 shows the strain value of the monotonic bend test for CABGA 160 with SAC305 solder joints. The results indicate that SMD pad design has the highest strain-to-failure value than that of NSMD and Web Design boards. It is believed that SMD pad design with larger copper footprint and the coverage of solder mask, increases the resilience of pad to PCB adhesion strength. The results also show that the Web Design did not improve the bend performance of CABGA packages. Figure 6 summarized all bend results of CABGA with SAC305, SAC105 and SnPb. SAC105 possesses the highest bend performance with 52% higher strain value than that of SAC305, SMD design for SAC105 also has the best bend performance. SAC105 has lower strength than that of SAC305 (Figure 7), however, SAC105 is more resilience and shows improvement in bend performance than SAC305.

Figure 8 summarized the bend test failure strain results for FBGA packages, with two different PCB materials, PCB1 is phenolic and PCB2 is non-phenolic, the results indicates that PCB design with wider trace (9.8mil) has the worst bend performance

with the lowest bend strain value among all designs. The Web design moderately improves the bend strain value. It is also indicated that the bend strain value are comparable for both PCB materials indicating no significant in bend failure for both PCB materials, however, during the bend test, we observed significant delamination in testing of non-phenolic test boards, the strain results does not reflect the PCB delamination due to the daisy-chain circuits are in the surface layer. Unlike the CABGA packages, the bend results does not show significant improvement of bend performance with SMD design over normal NSMD design, which is caused the failure tend to shift to module side instead of PCB pad cratering.

Figure 9 shows that the bend test results from samples after aging treatment. The bend performance for both SAC305 and SAC105 degraded significantly by 34% and 29% respectively. The results are similar with the results on shock performance of lead-free solder joints after aging, which degraded shock performance up to 37% [3]. Unlike lead-free solders, after aging, the bend performance of eutectic SnPb solder joints is higher. It is believed that the softening of Sn/Pb solder after aging contributes to the changes. Unlike lead-free solder, eutectic SnPb solder possesses uniform two phase structure. The solder joints tend to be more resilient without losing strength after aging. However, for lead-free solder, the solder joints become brittle due to the coarsening of second phase intermetallics, and that leads to lower bend performance.

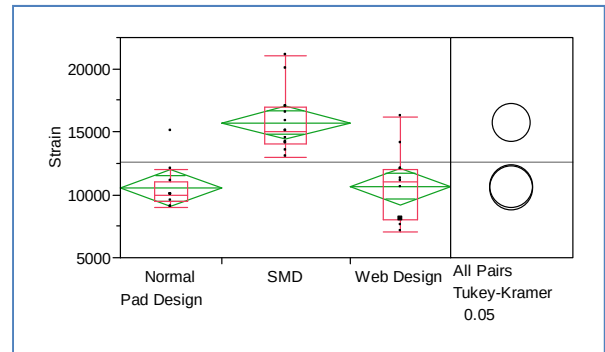


Figure 5 Bend Strain value with different pad designs for CABGA with SAC305 solder joints.

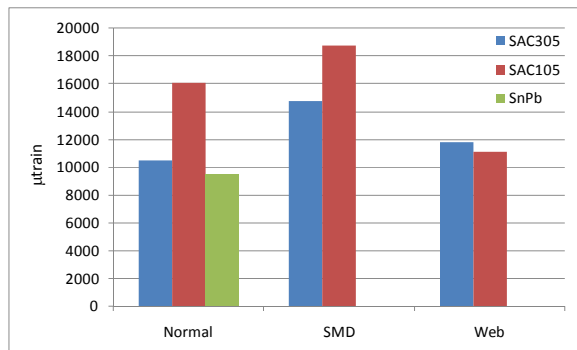


Figure 6 Bend strain performance for CABGA with different solder alloys and different pad designs.

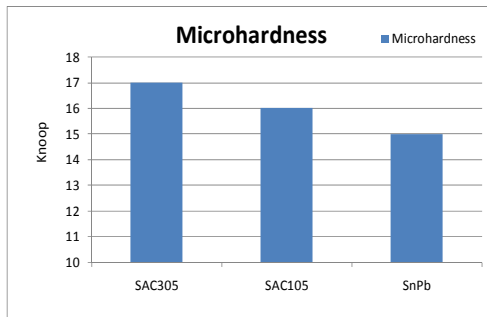


Figure 7 Microhardness of solder joints of CABGA packages.

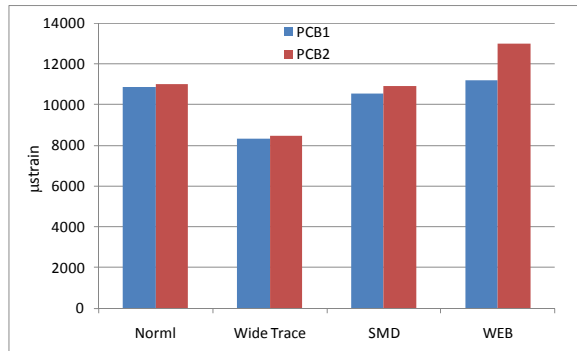


Figure 8 Bend strain performance of FBGA packages with various PCB designs.

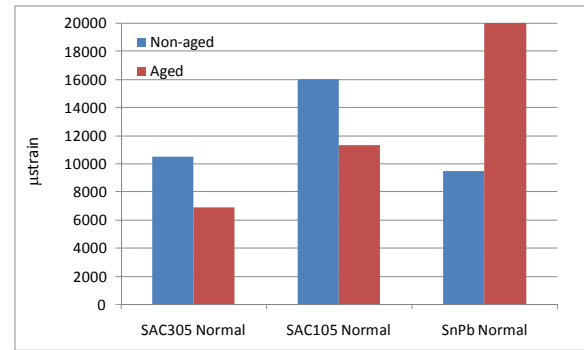


Figure 9 Aging effects of bend performance of CABGA packages.

Failure Analysis and discussion

Failure analysis including dye-and-pry and cross-section analysis were performed on the tested boards in order to investigate the failure modes and to understand the effects of PCB design variations and impact of aging on the performance of lead-free solder joints.

Figure 10 shows the typical dye-and-pry failure map of an as-assembled board of CABGA packages. The CABGA devices have massive dye penetration in the PCB laminate with pad pull out or pad cratering. This is the only failure mode that shows evidence of dye penetration for the CABGA packages. It also indicates that failures are mainly concentrated at the corner locations.

The FBGA packages also have substantial dye penetration, but in this case the dye can be found at both the PCB laminate and package laminate (Figure 11). It indicates that the cratering failure happened on both PCB side and package side. However, for the PCB with SMD design, dye penetration is only found on the package side, which indicate the failure mode for SMD design is pad pull off on package side only (Figure 12).

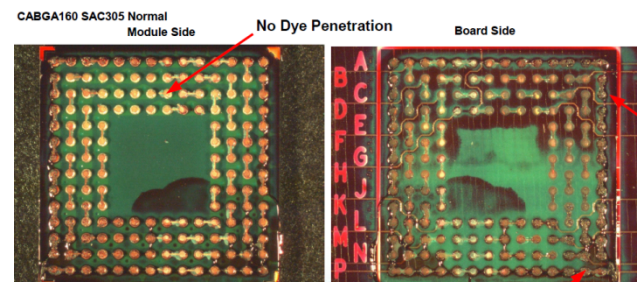


Figure 10 Typical Dye-Pry images of CABGA packages.



Figure 11 Typical dye-pry for FBGA packages.

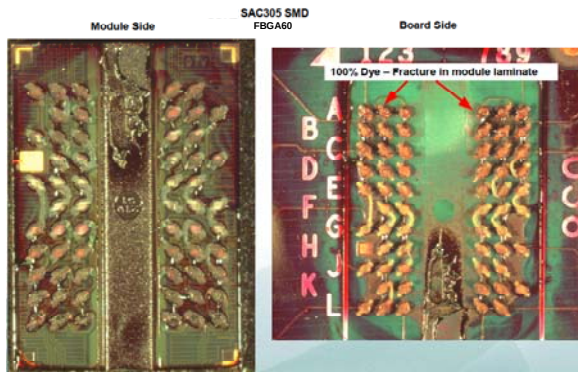


Figure 12 Dye-pry for SMD design of FBGA packages.

SEM cross-section images of the bend tested boards confirms the dye-pry results, as show in Figure 13, regardless of the pad design variations, the failure modes are pad cratering on PCB side. Although, the extent of pad cratering failures is more severe for NSMD and Web design than that of SMD design, as mentioned earlier, the SMD design shows more resilience to bend damage, and the failure happens solely at the package side.

Figure 13 shows the SEM images of the failure mode of FBGA packages, confirms with the dye-pry results, it was mixed failure modes for NSMD, Wide Trace, and Web Design with both pad cratering on PCB side and package side. For SMD design, there is no sign of pad cratering from PCB side, the dominate failure mode is package side pad pull off. It also indicates that SMD design shows improvement of mitigation PCB pad cratering. Even though the bend strain value does not show significant differences between phenolic and non-phenolic, the bend strain does not capture PCB failures due to the daisy chain circuits are on the surface layer. Non-phenolic PCB materials show much worse resilience to bend, severe delamination were observed during test, as shown in Figure 15, there is severe crack in the PCB. Apparently, phenolic PCB material seems to be better than the non-phenolic material from this set of test vehicles.

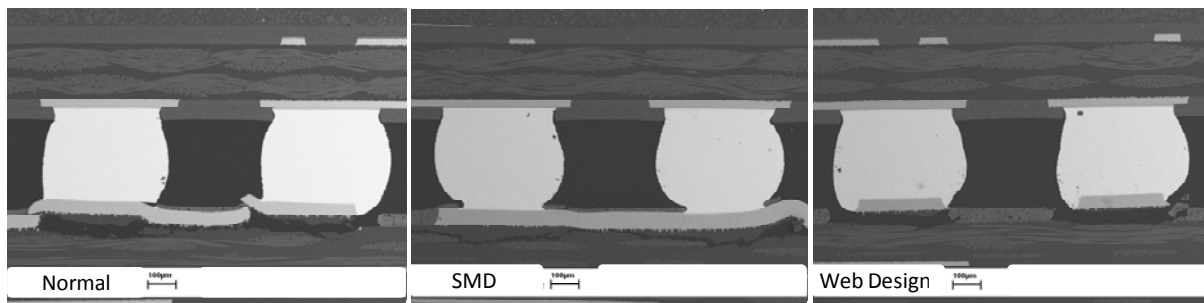


Figure 13 Failure mode of CABGA packages after bend test.

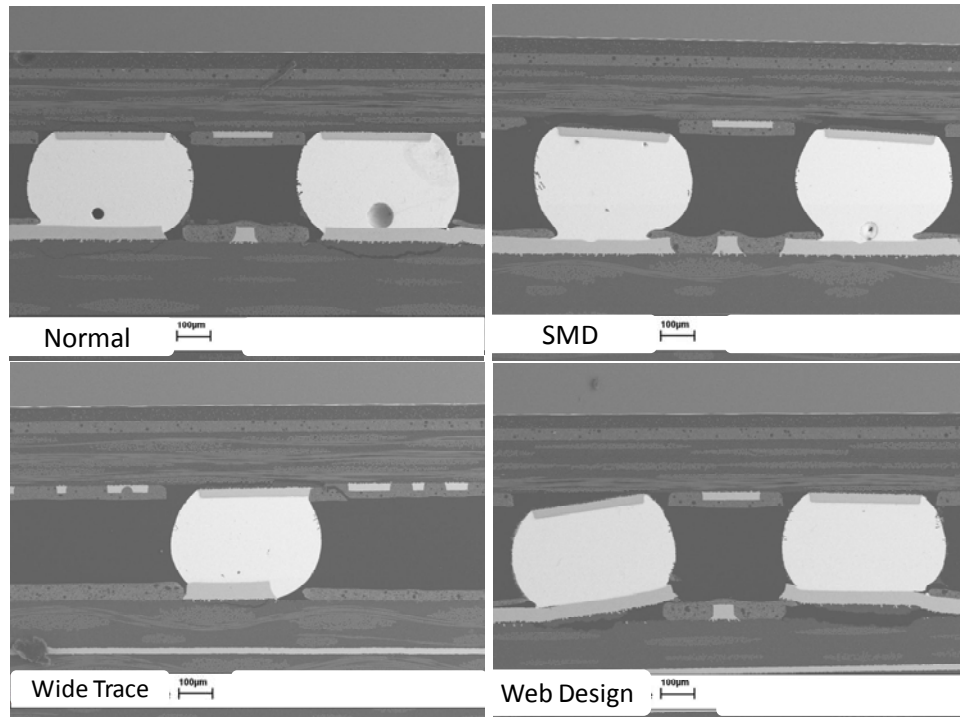


Figure 14 Failure mode of FBGA packages after bend test.

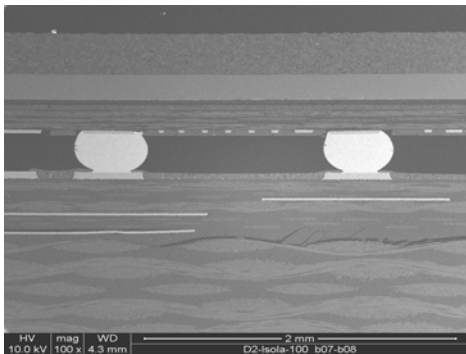


Figure 15 Failure mode of FBGA SMD design with Non-phenolic PCB.

Conclusions

The effects of the PCB design variations on the monotonic bend test are presented in this paper. SMD pad is shown to have the best bend performance among all other types of designs in this study. In addition, this design also shows improvement in mitigation of PCB pad cratering with lead-free solders. Wide trace width seems to degrade the strength and is not preferred. Same as its superior shock resistance comparing with SAC305, SAC105 solder alloy shows better bend performance. There is no significant improvement of bend performance

with Web Design. Non-phenolic PCB material shows significant delamination during bend test. It seems not a good choice of PCB material since its interlayer adhesion is not well. After aging treatment, bend performance of both SAC305 and SAC105 degraded by up to 34% and 29% respectively. However, the bend performance of eutectic SnPb was on the opposite trend.

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