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RELIABILITY IMPACT OF PARTIAL PAD CRATERS

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ABSTRACT

PCB pad craters are generally associated with single overstress events that cause immediate failure. However, significant reliability concerns are raised when partial non-catastrophic cracks are present under the pads of an assembly at the beginning of service life. This investigation empirically examines the effects of partial pad craters on board reliability. Partial pad craters were created through bending over-stress events which simulate damage modes experienced during assembly, handling, test, and shipment. Crack frequency and crack area distributions were measured for a variety of board flexure magnitudes. Final long-term reliability was then characterized for specific pre-damage levels in cyclic bending environments. The results revealed a dramatic degradation in reliability which was then correlated back to the initial crack distribution from the pre-reliability characterization damage event. Furthermore, the relative effect of pre-damage on reliability was markedly greater as the fatigue stress levels were reduced.

Key words: pad crater, pb-free, BGA, defect, reliability

INTRODUCTION

Pad cratering in Pb-Free laminate systems has gained attention as a primary failure mode for electronic devices [1]. Immediate failure due to mechanical overstress is usually associated with pad cratering, as product fallout is often identified before or soon after product shipment. As a consequence, there has been a significant investment in understanding the interaction of materials, design and process variables.

As material, process and assembly design factors affect pad robustness and reliability, both pad level and assembly level characterization are necessary to understand and address the pad cratering failure mode. There has been extensive work reported on the characterization of individual pad robustness (strength) and to a more limited extent, reliability (fatigue life) [2-7]. This work has led to a much improved understanding of the influence of laminate selection, glass style, and pad design and also to the sensitivity of mechanical performance to thermal and humidity exposure. At the assembly level, pad cratering has primarily been addressed in terms of board flexure limits [8-10].

Studies of robustness and reliability have largely focused upon pad cratering as a catastrophic failure mode which results in immediate electrical failure of an assembly. However, there is increasing concern on how non-catastrophic, i.e. latent, damage may affect device reliability. Such latent damage can occur during board fabrication and storage; during assembly; while handling; in shipment; and during functional test or environmental stress testing [11]. Partial pad craters are a subset of latent damage modes where small cracks are created in the laminate layer of the board immediately under the solder pad as a result of mechanical or thermo-mechanical overstress, Figure 1. Such cracks may easily propagate in the presence of relatively mild field stresses. Device failure subsequently follows when the electrical connection to the rest of the circuit eventually ruptures. Because partial pad cratering is inherently a mechanical, non-electrical, failure, this type of damage is impossible to detect without destructive failure analysis, and therefore the risk is that a product with a defect may be put into field service and ultimately experience premature failure.

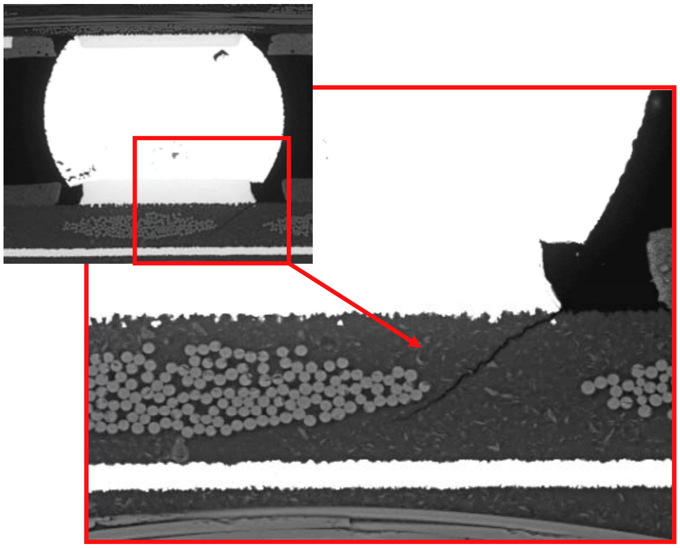

Figure 1. Partial pad crater identified in a still-functional assembly.

The following document outlines a general approach to calculate the risk factor associated with an induced latent defect on device reliability under cyclic fatigue conditions. Specifically, partial pad craters were induced through a single monotonic bending overstress and assembly reliability was characterized over a range of stress levels. By characterizing the reliability impact of latent damage over a wide range of fatigue stress conditions, such investigation can aid in the development of lifetime acceleration factors for prediction of life in service.

TEST METHODOLOGY

Test Vehicle

The test board used in this investigation is based on the JEDEC drop test board [12], but modified to a 2 layer design. The board material is a high-temperature filled phenolic commonly used in many lead-free applications.

The board measures 132 x 77 mm, and is 1 mm thick. Components were assembled only in the U4, U9, and U14 locations as shown in Figure 2. These component placements took advantage of design features on the board that allowed the electrical monitoring of each corner of each package individually. Board pads were designed to be non-solder mask defined (NSMD) with a diameter of 350 µm.

The selected test packages were Amkor CABGA100 devices, which utilized 450 µm, SAC305 solder spheres in a full 10x10 0.8mm pitch ball array. The packages were assembled to the board in a N_2 atmosphere and a peak temperature of approximately 242-245 °C.

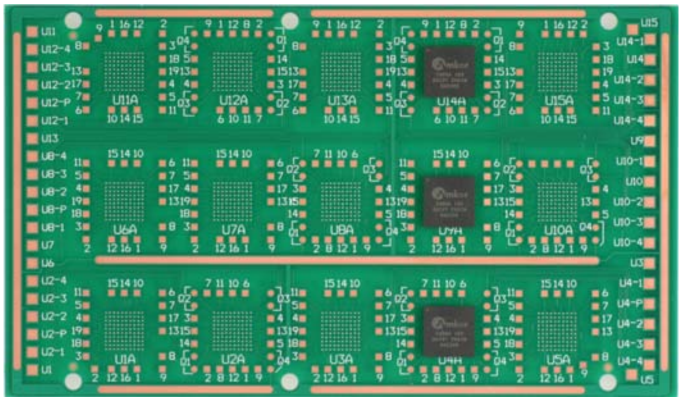

Figure 2. Assembled test board.

Test Plan

The general test plan intended to determine the reliability consequence of partial pad craters. To do so, test boards were mechanically stressed using four-point bending (Figure 3), which is addressed by industry test methods IPC/JEDEC-9702 and JEDEC JESD22-B113 [13, 14]. Monotonic 4-point bending was used to create partial pad crater defects while cyclic single sided 4-point bending was used to measure the reliability of the assemblies. Global board strain levels were calculated based on anvil spacing and board thickness and confirmed using a setup board and strain gages applied according to IPC/JEDEC-9702. Consequently, board strain levels reported within this document should be considered to be nominal.

The following outlines the general procedure:

1. Perform monotonic bending to generate partial pad craters and to develop the relationship between damage and bending strain.
2. Determine reliability of undamaged assemblies through cyclic 4-point bending. Develop the relationship between lifetime and cyclic bending strain.
3. Determine the reliability of damaged assemblies (partial pad craters) through cyclic 4-point bending. Correlate failure time to pre-damage level and cyclic strain magnitude.

All bend testing was conducted at a global PCB strain rate of 5000 µε/s to best simulate conditions where pad cratering would be most likely to occur.

Characterization

During bend testing, corner joint circuits were monitored for electrical failure. Following monotonic bending and single sided bending fatigue testing, a subset of assemblies were dyed using Dykem Steel Red Layout Fluid, dried, and the components were pried off to estimate crack area under each pad location. Oblique lighting combined with a relatively low 5X microscope objective was found to provide reasonable depth-of-field and contrast between the dye and the failure surfaces. As dye often remained largely on one surface, both the polymer failure surface under the solder pad and on the board side were imaged and analyzed.

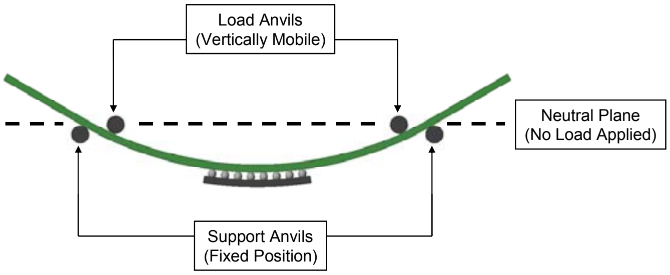

Figure 3. Illustration of 4-point bending

RESULTS AND DISCUSSION

Latent Damage Initiation by Monotonic Bend Event

To create partial pad craters under solder pads, a monotonic bend event was used and various board strain levels were investigated. The goal was to identify an appropriate strain level to damage the boards to a level such that the reliability impact would be appreciable given the relatively small number of assemblies available for test in this investigation. Both the frequency and distribution of crack areas in the outer column of joints were measured as a function of global board strain levels.

The frequency of partial pad craters resulting from a single monotonic bend event was quantified for various bending strain magnitudes at a global bending strain rate of 5000 µε/s. For this characterization, only the outer columns of pads were examined. These pads experienced equivalent stress conditions in 4-point bending and were considered the 'critical' locations for expected first failure. A total of 60 pads per strain level were analyzed through destructive dye-and-pry failure analysis to measure crack areas. Figure 4 shows the percentage of damaged pads per assembly resulting from various bending strains. For this analysis, a pad was deemed 'damaged' if any crack was observed. For the given strain rate on this specific test board and component, 2000 με represented the damage-free level while 4000 με was the strain level at which 100% of the critical pads exhibited some level of cracking. The crack frequency vs. board strain data of Figure 4 is displayed alongside a two-parameter Weibull CDF fit to the data.

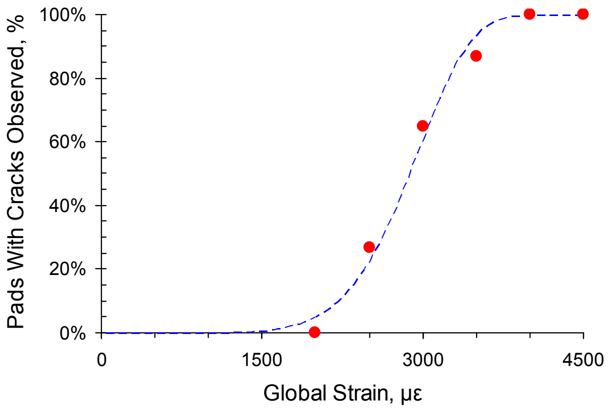

Figure 4. Percentage of pads exhibiting some amount of pad cratering damage vs. global board strain magnitude.

The crack area distributions for each strain level are shown in Figure 5. The histograms illustrate the number of pads with cracks areas ranging from 0% (no damage) to 100% (fully cratered pad) for each bending strain level. There was a wide distribution of crack areas for any given strain level, but the trends back up expectations: at the lower bending magnitudes most pads have little to no damage in terms of crack area, while higher bending magnitudes create much larger cracks (>75% by pad area).

Crack areas were measured through subjective visual inspection of red dye staining (i.e. dye and pry) with the aid of a crack area guide, as shown in Figure 6. Only the circular pad area was considered in the crack area estimate. Typically, the red dye staining was most pronounced at the crack initiation site, tapering to ever more subtle shades of the dye as the crack became ever finer. This ambiguity as to where the crack progression halted provided a significant challenge in interpretation of crack areas for each pad. As can be observed in the figure, arguments could easily be made to either advance or retract the rightmost demarcation between dye stained area and undamaged area. Both the PCB and component failure surfaces were characterized to obtain the most accurate crack area value for each pad.

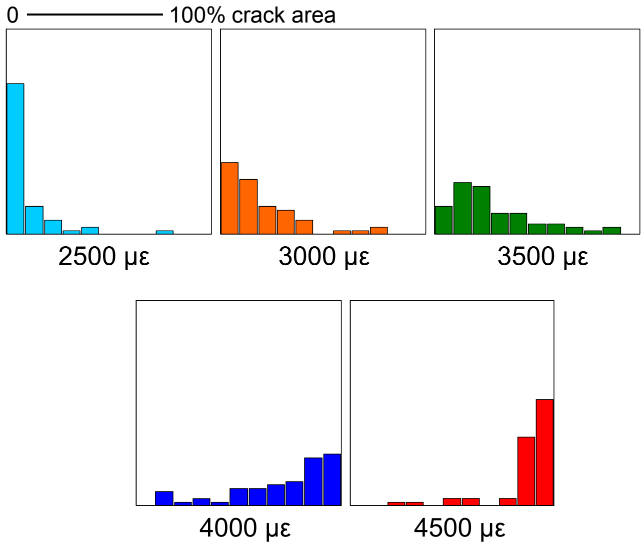

Figure 5. Crack area distributions for each strain level. Histograms illustrate partial pad crack areas ranging from 0% to 100% by pad area.

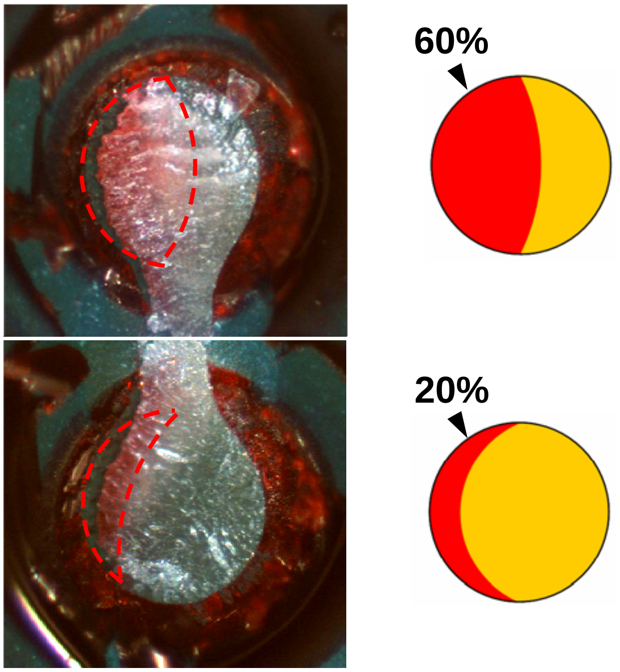

Figure 6. Examples of partial pad craters resulting from monotonic 4-point bending (contrast-enhanced images shown at left). Area coverage visual aid used to quickly quantify crack areas indicated by red dye staining.

It is important to note that while significant pad cratering was observed for these samples, all of the devices were still functional after the bending event. This particular finding represents the significant risk associated with pad cratering: this failure mode is not easily identified by electrical test and therefore damaged product may be shipped.

Bending Fatigue Characterization

Cyclic 4-point bend testing was performed to characterize the baseline reliability of undamaged assemblies. Instead of selecting high and low bending strain conditions, a trend between bending strain and cycles to first electrical failure was sought, cf. Figure 7. Predictably, the cycles to failure was observed to decrease with increasing bending strain level. Failure was attributed to cracking of the connecting trace for the majority of samples. However, at the lowest bending strain magnitude, a portion of the samples tested failed by solder fatigue; these samples are indicated by the square symbols in Figure 7. The solder failures were neglected for the development of the strain/N_f relationship that is displayed alongside the data in Figure 7. This relationship was well described by the following equation.

$$N_{f,undamaged} = 45{,}526e^{(-0.00195\mu\varepsilon)} \tag{1}$$

It can be expected that further reduction in strain levels would continue to generate more solder fatigue failures than pad cratering failures. Trace cracking correlated with pad damage for the undamaged assemblies can therefore be categorized as falling below the high-cycle regime (<10,000). A similar observation of this transition from pad cratering related failure to solder fatigue at reduced cyclic bending strain magnitudes was previously reported by Jonnalagadda in [10].

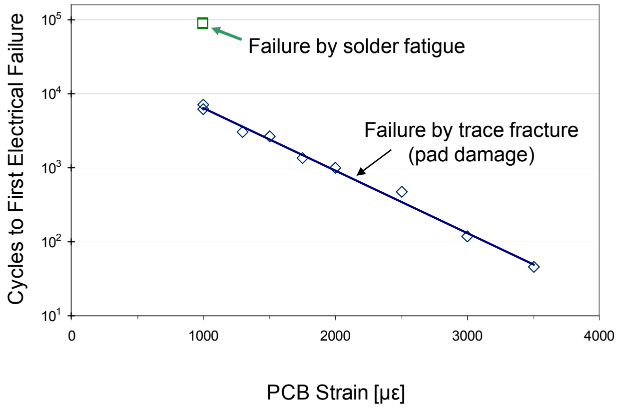

Figure 7. Cycles to first electrical failure for undamaged assemblies for various bending strain levels.

Damaged assemblies were then tested to first electrical failure using the same cyclic bending test to characterize effect of partial pad craters on reliability. Before reliability evaluation, a monotonic bend to 3500 με was used to prompt widespread damage to the board, as would be anticipated from the damage calibration results of Figure 4 and Figure 5. The results of this investigation revealed a dramatic reduction in assembly reliability following this damage event, cf. Figure 8. For the damaged assemblies, no evidence of failure by solder fatigue was evident during the failure analysis that followed test. The exponential relationship between strain and N_f displayed alongside the data of Figure 8 was described by the following equation.

$$N_{f,damaged} = 5{,}457e^{(-0.00139\mu\varepsilon)} \tag{2}$$

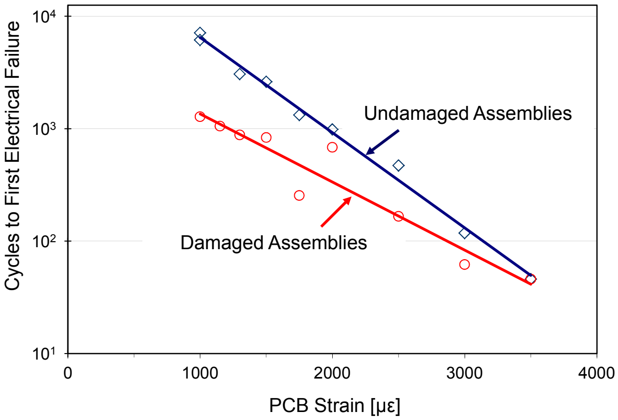

Figure 8. Cycles to first electrical failure comparing undamaged and damaged assemblies. All failures are attributed to trace cracking due to pad damage.

Of considerable concern, the reduction in reliability became especially pronounced at reduced strain levels, cf. Figure 8. At reduced cyclic strain levels, the initial damage to the assembly can be interpreted as having consumed an ever increasing portion of the assemblies' lifetime with a reduction in cyclic bending strain magnitudes. By comparing the lifetime of the damaged assembly, Eq. 2, to the undamaged assembly lifetime, Eq. 1, the pernicious effect of latent damage on device lifetime on low-stress reliability is clear in Figure 9. At 1000 με, the lifetime of the damaged assembly would be anticipated to be only 20% of the undamaged assembly lifetime. The consequence of this finding is profound.

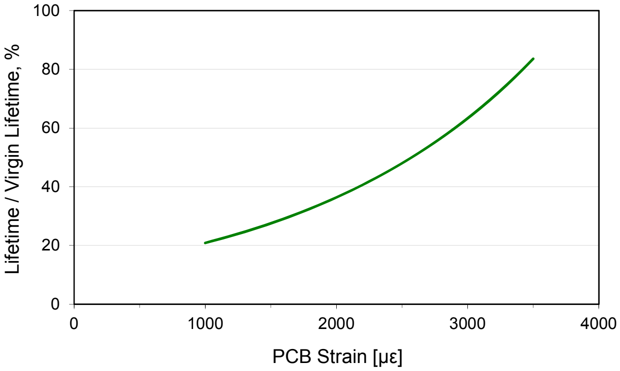

Figure 9. Normalized lifetime of damaged as a function of cyclic bending strain level.

The approach outlined in this manuscript provides a simple empirical approach to understanding the effect of latent damage on assembly reliability. By prompting latent damage and then comparing reliability in a cyclic stress test, the reduction in lifetime can be quantified and damage event stress limits may be selected. Of particular concern is the effect of environmental stress screening on long-term cycling reliability as the test conditions may induce latent damage and thus result in a dramatic over-estimation of lifetime as compared to undamaged assemblies characterized in high-cycle reliability tests. As always the case in reliability estimation, care should be taken to accelerate the correct failure mechanism so as not to fall into the trap of over-predication of reliability. Furthermore, changes to the material systems in the system and the concurrent mechanical properties drift are being found to dramatically affect assembly reliability.

CONCLUSION

Bending strain level during a single bend damage event was strongly correlated to observed partial pad craters in assemblies following dye-and-pry analysis. Even with all the pads exhibiting partial pad craters and some with 100% of the crack extending across the pad area, in this investigation, the electrical continuity of the circuit was not compromised. With increased bending strain, an increased proportion of pads exhibited cracks. The crack area distribution also exhibited a transition from no cracks at the lowest strain levels tested up through the majority of pads showing cracks extending over >80% of the pad area.

Single-sided cyclic bending fatigue testing revealed that the number of cycles to first electrical failure was well described by an exponential functional relationship to board strain magnitude for both the undamaged assemblies and damaged assemblies. The undamaged subset of assemblies was tested across a range of board strain levels (1000-3500 $\mu\varepsilon$) and the failure mode was largely attributed to trace cracking. However, at the lowest strain level (1000 $\mu\varepsilon$) a portion of the assemblies failed by solder fatigue as revealed by dye-and-pry destructive failure mode analysis. Assemblies damaged by a single 3500 $\mu\varepsilon$ bend event revealed a marked reduction in cyclic bending lifetime. The relative impact of the damage event on reliability became greater at reduced cyclic bending strain magnitudes. This finding suggests that many 'accelerated' tests may not sufficiently uncover latent damage risks.

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