QUALITATIVE MODEL DESCRIBING HOT TEAR ABOVE VIPPO AND NUMEROUS OTHER DESIGN ELEMENTS

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ABSTRACT

Over the last couples of years there have been numerous reports of a unique soldering failure resulting in a separation of BGA solder joints from the intermetallic compound at the interposer during reflow. In most cases, the failures were correlated with the use of Via-In-Pad-Plated-Over-Technology (VIPPO). Since the separation could be proven to occur during the Phase transition from solid to liquid [1] it was called Hot Tear. Since the Hot Tear results in a very thin separation it is usually not inspectable neither by means of X-Ray inspection nor by electrical testing, but results in very early field failures.

In this paper, the general mechanism for the formation of Hot Tears will be discussed and applied to numerous other design elements that can be found on Printed Circuit Board Assemblies (PCBA). We will show that due to several industry trends e.g. VIPPO, heavy copper PCBs, buried vias, non-eutectic alloys, thinner components, thicker boards, via in pad, etc. the probability of Hot Tears is steadily increasing.

Key words: VIPPO, Hot Tear, Solder, Separation, Reflow Soldering, BGA, Fillet Lifting. ePad

INTRODUCTION

Today's electronic devices mainly consist of PCBAs, where solder joints are by far the most common way to connect the electronic components with the Printed Circuit Board (PCB). In order to avoid early field failures due to shorts and opens the PCBAs are typically inspected for misplaced components, insufficient solder, wetting failures, etc.

Failure modes, which cannot be inspected after production, have to be thoroughly understood and avoided by design. Since Hot Tear results in a separation between solder and IMC, which is so thin that it can't be inspected by Optical Inspection (AOI), X-Ray Inspection (AXI) nor Electrical Testing (ICT) it has to be avoided by design. (See Fig 1)

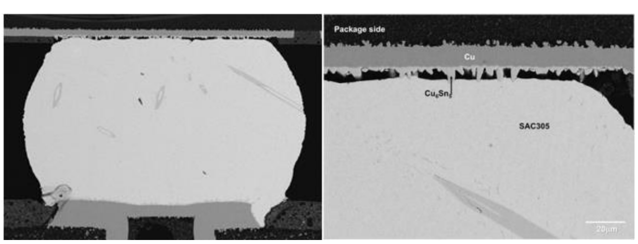

Figure 1. Very thin separation between Solder and IMC due to Hot Tear Defect (taken from [2] with permission)

Cohesive Hot Tear in Bulk

The most common form of Hot Tear is the shrinkage crack – a cohesive tearing in the bulk of the material during solidification. It is one of the main casting defects, but is also know to occur in solder joints. According to IPC-A-610 "There is no defect associated with this anomaly provided the connection meets all other acceptance criteria." [3] Even though shrinkage cracks are most common in Though Hole Technology (THT) solder joints they can also be observed in almost any other design situation.

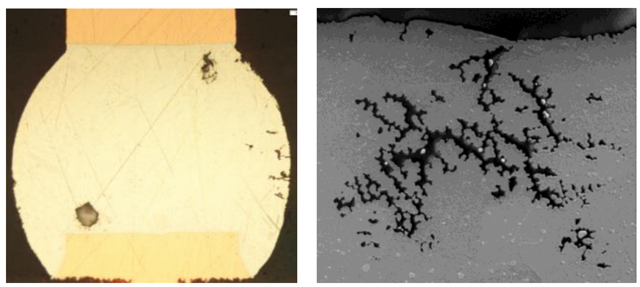

Figure 2. Hot Tear in the bulk solder of a BGA solder joint and a exposed Pad solder joint.

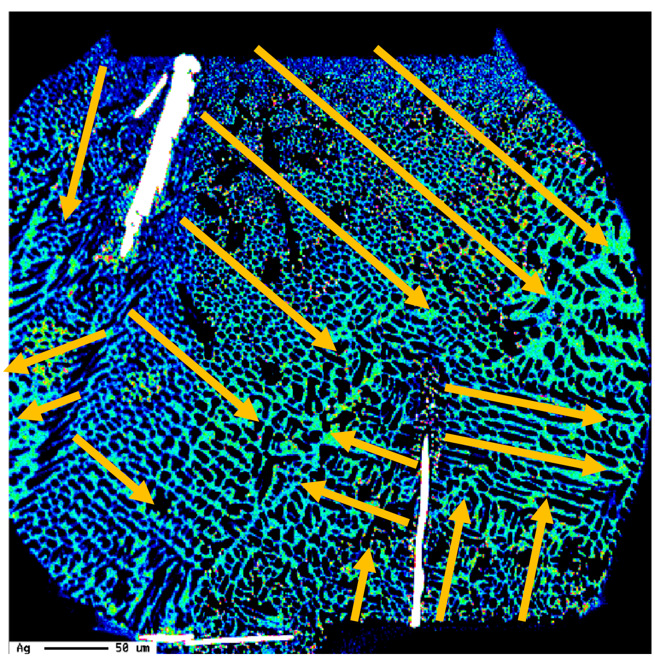

Figure 3. Electron Probe Micro Analysis (EPMA) of a SnAg3.5Cu0.7 - BGA Ball. Coloring represents Ag content. Yellow arrows represent derived directions of solidification.

Looking at the Micro Structure of a solder joint it is possible to understand why Hot Tear form in bulk solder. The direction of solidification is always along the lines of the laminar Ag_3Sn structures from fine to coarse. In Fig.3 the BGA ball starts to solidify both from top and bottom. Since the last parts to solidify are at the edge of the ball there is no liquid solder left to feed the solidification shrinkage. A Hot Tear like in Fig.2 can occur.

Adhesive Hot Tear at Interfaces

Though the cohesive Hot Tear of the bulk solder is most common it usually does not have any influence on the reliability of the solder joints, because crack paths due to environmental stress are typically close to one of the terminations of the solder joint. The most commonly known Hot Tear at an interface of the Solder Joint is the Fillet Lifting of a THT solder joint (see Fig.4). According to IPC-A-610 "There is no defect associated with this anomaly." provided the connection meets all other acceptance criteria. [2]

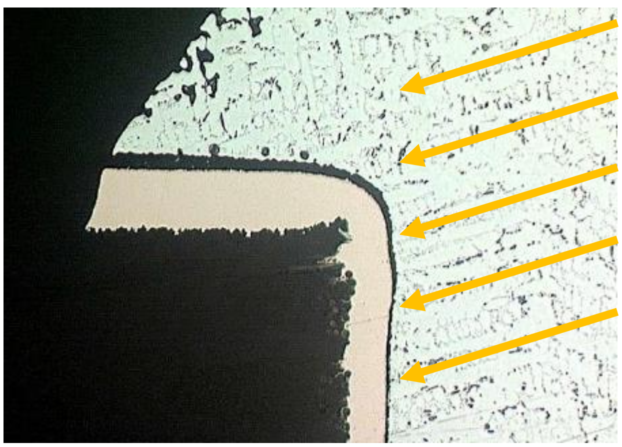

Figure 4. Fillet Lifting observed at a SnAgCu THT solder joint. Yellow arrows represent derived directions of solidification.

Since the solidification is directional, the last point of solidification is at the termination of the PCB. If no liquid solder is available to feed the gaps a Hot Tear can occur.

MODEL FOR HOT TEAR AT INTERFACES

Theoretical Model

As already observed for shrinkage cracks and fillet liftings Hot Tears occur during the phase transition while the solder is "Hot". As the word "Tear" implies, some kind of tensile stress has to be applied during this phase transition. Looking at the material properties of solid and liquid solder it is possible to understand the mechanism.

Due to the high Young's modulus E the deformation ε of the solid solder is always well below the elongation at fracture ε_f. Hot Tear is therefore not possible. (See Fig.5)

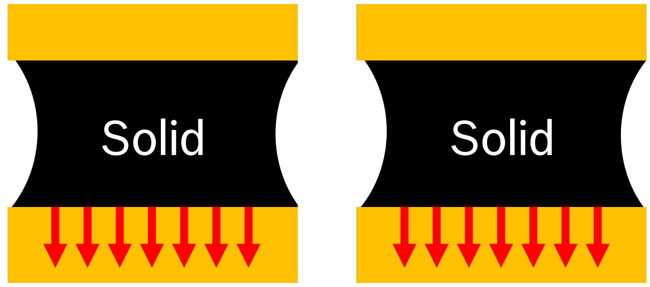

Figure 5. Tensile stress on the solid solder joint does not result in a significant deformation

The stress necessary to deform the liquid solder can be described using the Young-Laplace-equation [5]

$$\sigma = \gamma\left(\frac{1}{R_1} + \frac{1}{R_2} + u\right) \approx \gamma\frac{2\,Cos(\theta)}{h(1+\varepsilon)}$$

,where γ is the surface tension of the solder, u is the circumference of the solder joint and R_1 and R_2 are the local radii of curvature of the solder joint surface. Using the wetting angle θ for a small standoff height h it is possible to describe this stress as a function of the elongation ε. Even though this stress is much lower than for the solid solder it is usually not possible to achieve a Hot Tear, because the very large elongation at fracture ε_f. (See Fig.6)

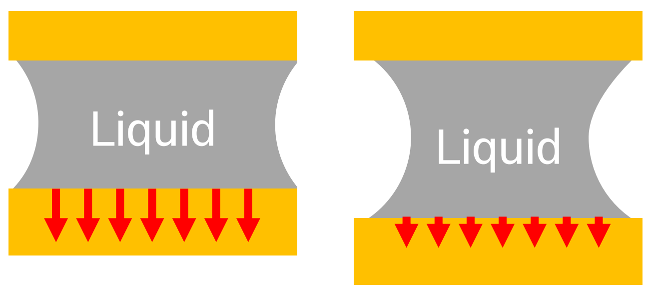

Figure 6. Tensile stress on the liquid solder joint results in a significant deformation, but is usually not able to break the liquid bridge

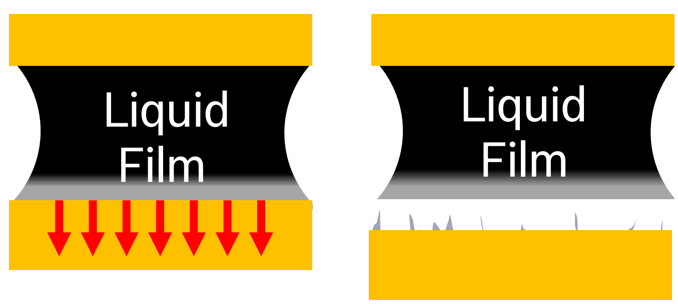

Figure 7. Tensile stress on the liquid film results in a significant deformation. The film will break from the adjacent termination.

In case the solder joint solidifies directionally, the thickness of the liquid film becomes gradually thinner during this process. This will slightly increase the Young-Laplace pressure necessary to deform the surface, but leaving it still orders of magnitude below that of the solid solder. If the liquid film is very thin right before the complete solidification, the amount of liquid solder is insufficient to feed the gaps resulting in a very low elongation at fracture ε_f. (See Fig.7)

All three situations can be visualized as load capability graphs in a common stress-strain diagram. (See Fig.8) For a given load, the physical state is represented by the intersection between load and load capability graphs. Since in case of the liquid film there is no intersection, the Hot Tear Failure occurs.

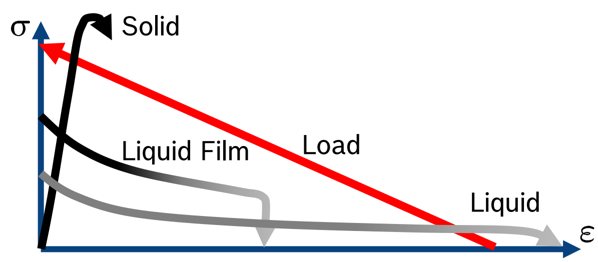

Figure 8. Stress-strain diagram for solid solder, liquid solder and a liquid solder film.

DIRECTIONAL PHASE TRANSITIONS

Liquid Films

In order to a achieve a the thin liquid films mandatory for the occurrence of adhesive Hot Tear either a directional solidification or a directional melting is required. Both are driven by a temperature gradient ∇T that can in one dimension be transformed to $\nabla T \xrightarrow{1d} \frac{\Delta T}{d}$, where ΔT is the temperature difference and d is the distance between the solder joint terminations. A sufficient temperature gradient for the directional phase transition will be achieved if either the temperature difference ΔT is very big or the distance d is very small. Examples will be discussed in the following sections.

THT solder joints

Large differences in temperature ΔT can typically be observed if heat is inserted at one specific point. The most prominent example is THT soldering. While the electronic components at the top side of the PCB stay relatively cool, heat is inserted through the wave of liquid solder at the bottom of the PCB. Additionally the heat capacity of the PCB is larger than the heat capacity of the pin. This results in a solidification path from top to bottom and from inside to outside. Inner layers can act as local heat capacities changing the path of solidification. (see Fig.9)

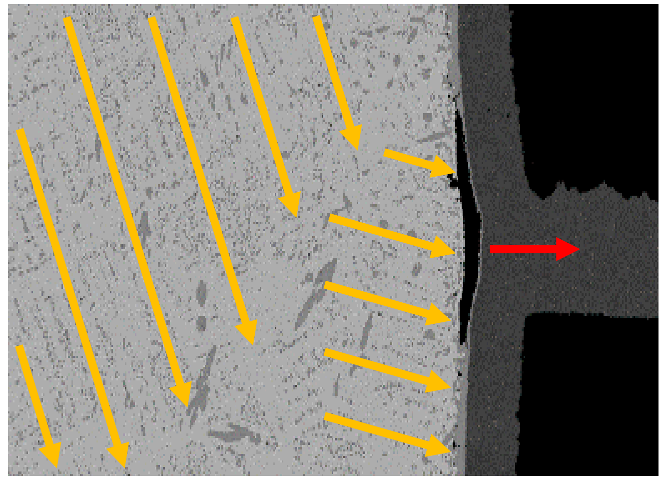

Figure 9. Directional solidification of a THT solder joint (represented by yellow arrows). Tensile stress due to PCB shrink (represented by red arrows).

SMT solder joints after THT soldering

A rather ununsual exaple for a directional phase transition is the melting of an SMT solder joint due to heat from the THT soldering process. The heat is conducted through the PCB and, if a sufficient temperature is reached, the solder joint will melt from the bottom. The thin liquid film in combination with the tensile stress due to component warpage results in the formation of a Hot Tear failure.

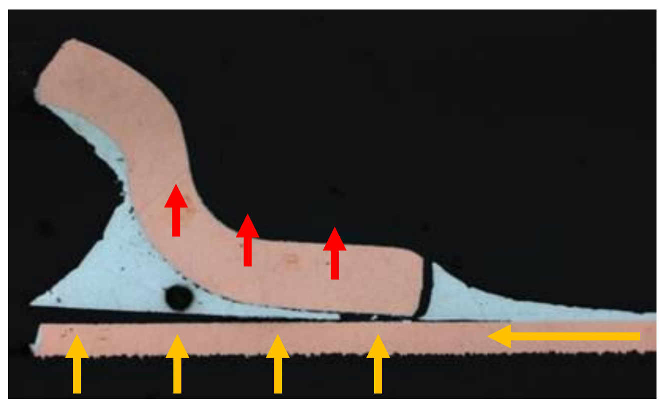

Figure 10. Directional melding of a SMT solder joint due to heat from the THT soldering (represented by yellow arrows). Tensile stress due to component warpage (represented by red arrows).

SMT solder joints

Typically, during the SMT process the heat is transferred via convection of hot gas - air or nitrogen. In some cases due to geometrical restrictions, it is not possible to guarantee sufficient flow of hot gas between the PCB and the component. Especially in case of area array components and exposed pads, the heat is mainly transferred by means of conduction through the PCB and the electronic component. Since the heat is inserted through the termination of the solder joint that is also where the melting of the solder joint starts. If the surface area of the termination is very small, it is very likely that a complete thin liquid film forms. (See Fig.11)

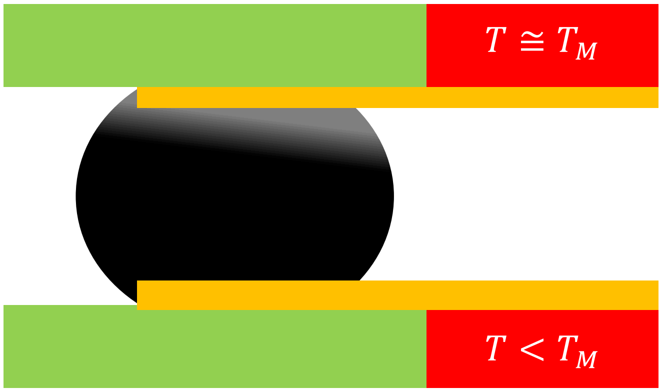

Figure 11. Schematic picture of the directional melting of a BGA solder joint

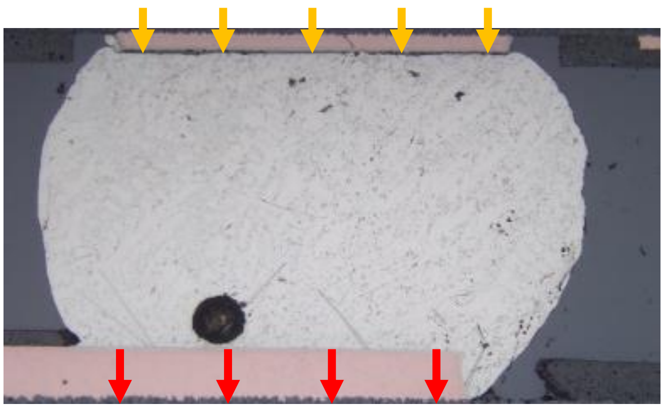

Figure 12. BGA ball with Hot Tear. Yellow arrows represent directional melting. Red arrows represent tensile stress.

Small Standoff

Even if the temperature difference ΔT is rather small, the small standoff d in exposed pad solder joints can still create a sufficiently large temperature gradient ∇T for directional solidification. Since this process is highly sensitive to small changes in temperature, heat capacity and cooling it is possible to observe both directions of solidification. (See Fig. 13 & 14)

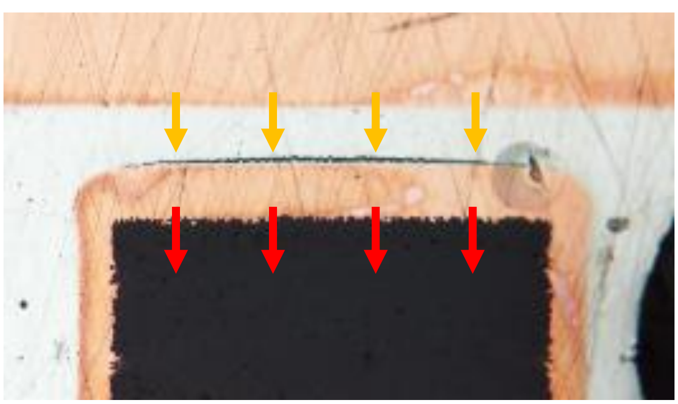

Figure 13. Exposed Pad solder joint with Hot Tear. Yellow arrows represent solidification from top to bottom. Red arrows represent tensile stress.

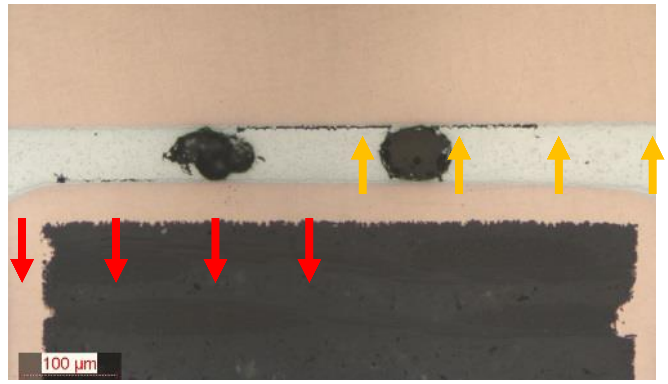

Figure 14. Exposed Pad solder joint with Hot Tear. Yellow arrows represent solidification from bottom to top. Red arrows represent tensile stress.

LOAD

Tensile Stress

Whether a liquid film actually results in a Hot Tear strongly depends on the amount of tensile stress applied. If the tensile stress is insufficient to overcome the capillary, pressure no Hot Tear forms. (See Fig 16a). Intermediate loads will result in a deformation of the liquid film and in depletion voids, but not in a full-grown Hot Tear. (See Fig. 16b) Only if the Load is sufficient to completely severe the thin liquid film a complete Hot Tear will form. (See. Fig 16c)

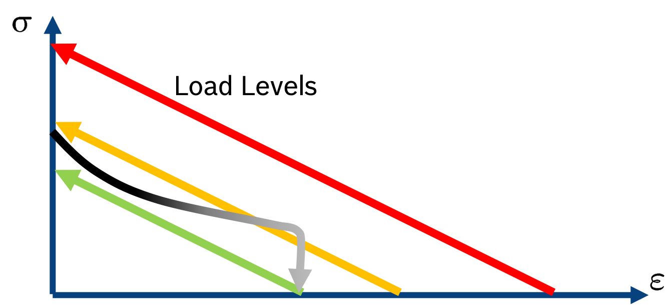

Figure 15. Stress-strain diagram for a liquid solder film and three different load levels. The green graph represents an uncritical load. The yellow graph represents a load resulting in partial Hot Tear. The red graph represents a load resulting in a full Hot Tear.

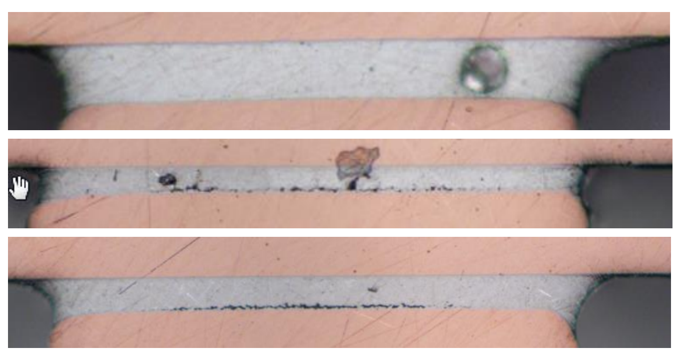

Figure 16. a) Solder joint without Hot Tear b) Solder joint with localized Hot Tear spots c) Solder joint with large area of Hot Tearing

PCB induced Stress during cooling

Tensile stress on solder joints is almost unavoidable. This stress can originate from the solidification shrinkage of the solder alloy itself or from the warpage of electronic components on the board. Next to those two well-known sources, there is also the possibility that tensile stress is induced by the local deformation of the PCB. This can be the case if there are big variations of copper content below a solder joint. While the coefficient of thermal expansion (CTE) of copper is 16 ppm/K, the CTE perpendicular to the surface of the PCB above the glass transition temperature T_G can amount to up to $200ppm/K$. During the solidification of the solder joint this results in a bigger shrink of the parts above the base material compared to the areas above the copper. If the solder solidifies directionally, a Hot Tear is can occur. (See Fig. 17)

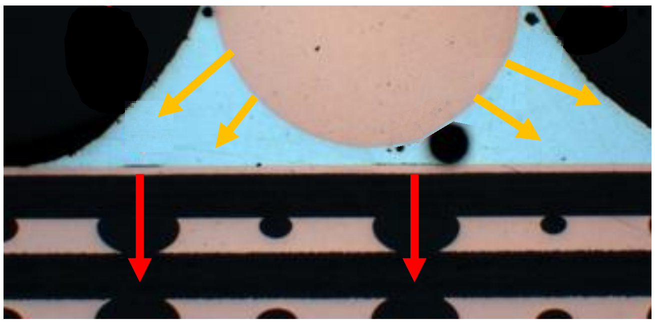

Figure 17. Hot Tear above areas with lower copper content in the PCB inner layers. Yellow arrows represent directional solidification. Red arrows represent tensile stress.

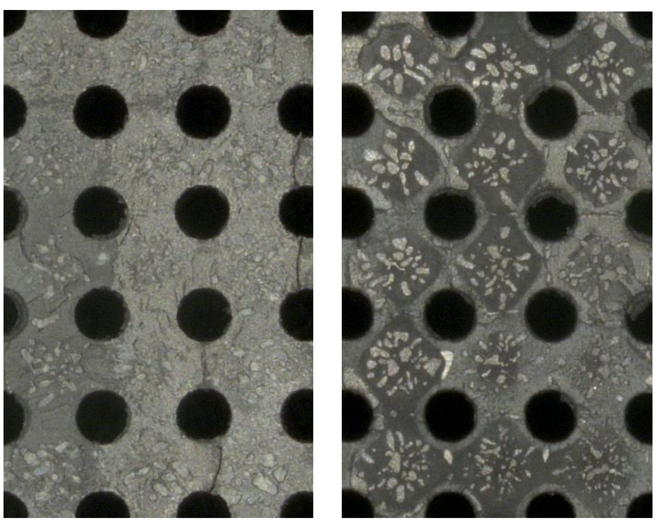

Figure 18. Exposed Pad solder joints with via in pad design that had the component pulled from the PCB. Black areas are Plated Through holes. Light gray areas are soldered areas. Dark gray areas are Hot Tear. The left solder joint was soldered with SAC305 and the right with Innolot.

Luckily, this effect usually does not occur with eutectic and nearly eutectic solder alloys such as SAC or SnPb. The reason is the temperature range in which the thin liquid film exists. For nearly eutectic alloys, the Temperature difference between Solidus temperature T_S and Liquidus temperature T_L is very small. Even with the huge CTE mismatch between PCB base material and copper the displacement ε that can be reached is very small. The load is not sufficient to create a Hot Tear. Advanced alloys (e.g. Innolot, SnCuIn, etc.) are usually not a eutectic composition. Typically the difference between Solidus and Liquidus can be $10K$ and more. During the phase transition, the first dendritic structures start to solidify after passing the Liquidus. Those phase hinder a further sinking in of the electronic component. Tensile stress can build up until the Solidus is reached. (See Fig. 19) Due to the larger temperature difference, the tensile stress can be more than 10 times higher for non-eutectic alloys than for nearly eutectic alloys.

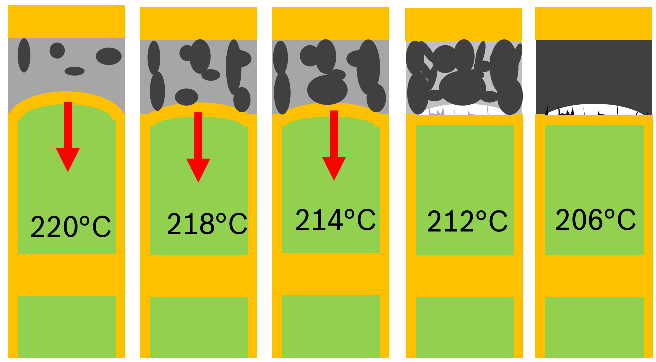

Figure 19. During cooling, the tensile stress can build up between Liquidus and Solidus. For non-eutectic alloys, the stress is much higher due to the larger melting range.

PCB induced Stress during cooling

Analog to the tensile stress during cooling tensile stress can also be invoked during heating. Whereas the tensile stress and thus the Hot Tear always occurs above regions with less copper content in case of cooling, in case of heating it is the other way around. Areas with low copper content expand much more during the reflow process. (See Fig. 20)

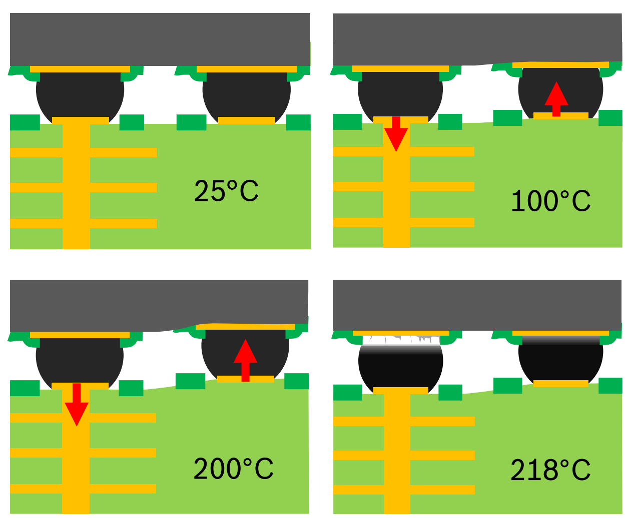

Figure 20. During the heating, the tensile stress can build up between room temperature and Solidus. After passing Solidus, a Hot Tear will form if a thin liquid film is present.

Since in case of heating the solder joints are solid over the complete range from room temperature until solidus the tensile stress can build up over this complete range. Accordingly, the stresses due to this expansion of the PCB are much higher than during cooling. Even deformation of the interposer have been observed. [REF 4]

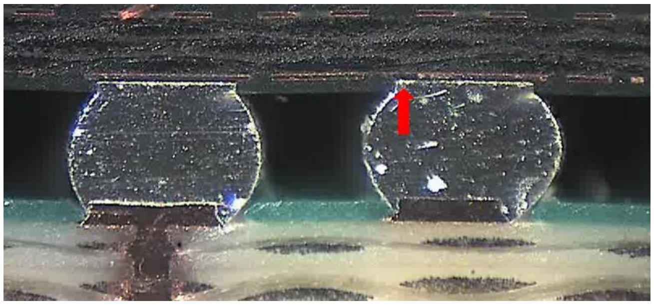

Figure 21. Cross Section of BGA with mixed VIPPO/non-VIPPO technology heated up just below Solidus. The red arrow marks the visible deformation of the BGA Interposer due to the stress induced by the PCB expansion. (taken from [2] with permission)

It is often observed that Hot Tear failures at BGA balls only occur during the second [1] reflow process. This can be understood, if we keep in mind that only during the melting of the second reflow we have both a directional melting and a tensile stress. During the melting of the first reflow, the solder paste is not able to transfer the tensile stress and directional solidification is very unlikely due to the large height of the BGA solder joint.

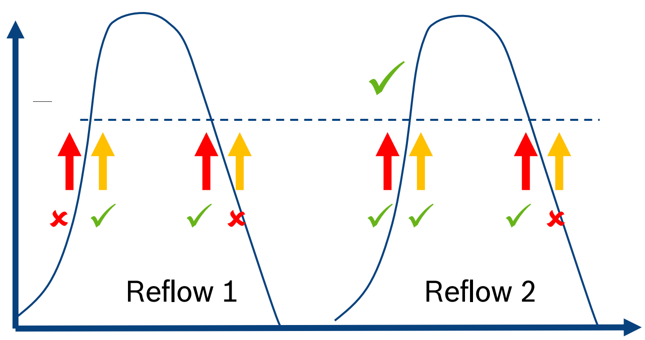

Figure 22. Schematic of two reflow profiles.

CONCLUSION

The understanding of the failure mode Hot Tear has been extended from cohesive tearing during the solidification of liquid material to all possible forms of tearing - cohesive and adhesive – during the phase transition both from solid to liquid and from liquid to solid. It could be shown that for the Hot Tears a thin liquid film needs to be present. Adhesive Hot Tears occur if the liquid film forms near one of the interfaces by means of directional melting or solidification. The temperature difference ΔT and the thickness of the solder joint d could be identified as the main influencing factors on the directional phase transition. The tensile stress necessary for the formation of Hot Tears can be originated either by the Component, the solder material itself or by the PCB. With respect to PCB induced stress, it could be shown that local variations of the copper content have a strong impact on the thermal expansion perpendicular to the PCB surface. With this qualitative model, it is possible to completely understand the formation of Hot Tears of BGA balls on mixed VIPPO/non-VIPPO designs during the second Reflow.

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