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Managing Thermomechanical Behaviour in Automotive Electronics

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ABSTRACT

Increasing complexity of critical components, designs, manufacturing processes and harsher test conditions continues to challenge the automotive electronics development life cycle. The drive for right first time makes it critical to pre-empt potential board level issues as early as possible to avoid costly and time-consuming repeat validations.

Historically, solder interconnection separation due to Coefficient of Thermal Expansion (CTE) Mismatch between the components and Printed Circuit Board (PCB) were the most prolific failures. With increasingly high density interconnection designs, advanced packaging, increased localised self heating, additional sources of thermomechanical stress are introducing more complex failures. It is important to consider the full design and each element's thermomechanical behaviour across relevant stress load conditions.

Key Words: Coefficient of Expansion, Thermomechanical, Thermal Stress, Interconnection, Solder Joint, Warpage, Deformation

INTRODUCTION

Temperature cycling is the most common stress load on electronics in automotive. Temperature cycling refers to changes in temperature from low to high due to environmental change, power cycling, self-heating and / or power dissipation.

Thermal cycling generates cyclic CTE mismatches that can contribute to cumulative stress load resulting in failure. Thermomechanical stress is introduced throughout the process for electronics, from the component manufacturing process right through to the final assembly.

Figure 1. Chip Scale Package Pad Deformation during Reflow Soldering

DEFECTS

Thermal cycling results in various defects in electronics such as solder interconnection fatigue failure, solder bulk separation, intermetallic separation, component package material cracks, Printed Circuit Board (PCB) track / via damage, delamination and protective coating separation and/or cracks. The most dominant and known failure type is fatigue failure of the solder interconnection upon repeated temperature cycling exposure. The mechanics of failure are understood and well documented. The scope of this paper is to review the defects arising from additional external factors influencing defects in addition to CTE mismatch. Although there are many similarities in the defects between mechanical overstress and thermomechanical induced defects, the cases studied in this paper are for the most part primarily thermomechanical.

Intermetallic Separation (Fig 2.) is a solder defect resulting in open circuit failure. Thermal excursions such as Reflow Soldering or temperature cycling can result in such failure. The defect is characterised by a fracture between the intermetallic and solder interconnection. The intermetallic is between the solder and pad is the most brittle region of the solder joint that is most susceptible to overstress [1].

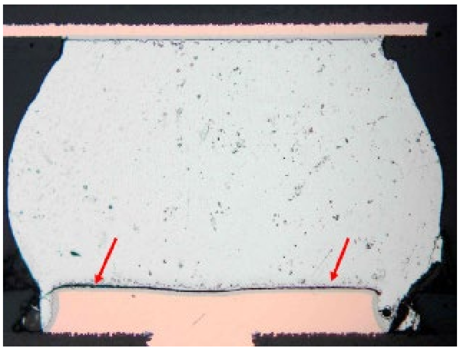

Figure 2. Solder Ball Intermetallic Separation

Bob Willis has created an informative video showing the thermomechanical stress during Reflow Soldering resulting in BGA Separation and Secondary Reflow [2] at both the PCB and Component side. The video shows the cumulative stress due to Component and PCB warpage at elevated Reflow Soldering temperatures. This video allows us to identify and acknowledge the presence of thermomechanical stress during the reflow soldering process and thereby understand this stress in various potential failures.

The separation can occur in First Reflow during cooldown of the solidified solder joints as the PCBA contracts, during Second Reflow as the bottom side components solidified solder interconnections are restrained as the PCB increasingly expands above the Glass Transition (Tg), upon a mechanical stress event and / or during temperature cycling due to external forces acting upon the package such as excessive PCB warpage.

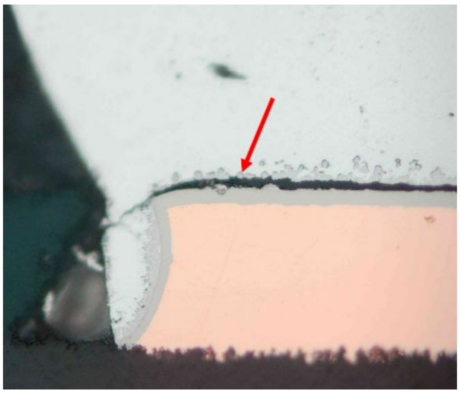

Figure 3. PCB Pad Intermetallic Separation

Another associated failure is pad cratering (Fig 4.) where the solder interconnection remains intact and the PCB pad detaches from the laminate.

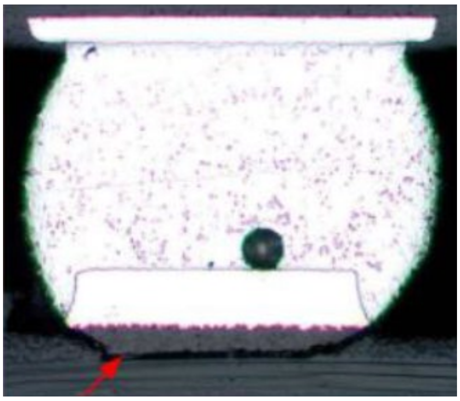

Figure 4. Pad Cratering

In some cases, both Intermetallic Separation and Pad Cratering (Fig.5) can occur on the same interconnection. Additional track damage can also be evident indicating significant levels of localised stress.

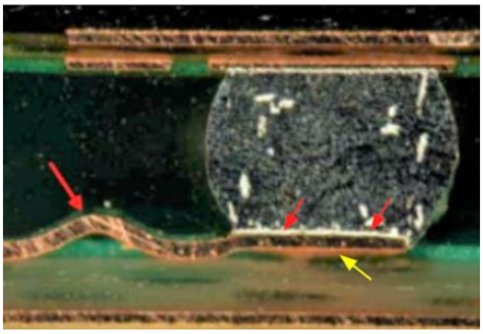

Figure 5. Intermetallic Separation and Pad Cratering

This failure is not specific to just the PCB side and defects can also occur on the component side. For example, the deformation of the component pad (Fig 1.) or full component pad separation (Fig 6.).

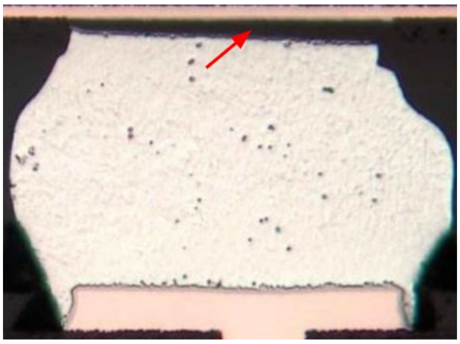

Figure 6. Component Pad Separation

The component pad separation (Fig 6.) occurred prior to Second Reflow as evident by the inconsistent solder ball formation. This indicates that the defect occurred during First Reflow and the solder shape was reformed after the solder remelted and solidified again in Second Reflow.

Intermetallic Separation is such a challenging failure that it can occur on either side of neighbouring solder balls. In this case, external stress load from a Thermal Interface Material (TIM) on the BGA package transferred onto the component body during Powered Temperature Cycling [3.]. The stress load was dependent on numerous factors including the type of thermal paste, the BGA construction and materials.

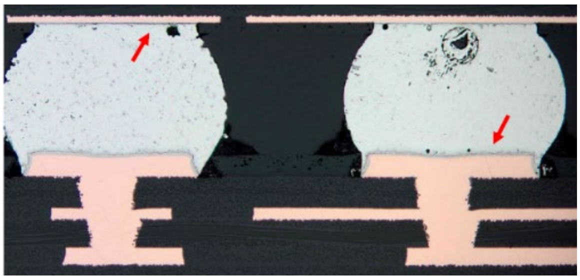

Figure 7. Intermetallic Separation evident on both sides of neighbouring solder ball interconnections

Another similar defect is Transient Solder Separation that occurs on BGA packages located on the bottom side during Second Reflow due to thermomechanical stress originating from vias beneath the BGA pad. The defect has been recorded in respect to different via configurations; Via-In-Pad Plated Over (VIPPO), Buried Vias and Stacked Microvias.

At SMTAI 2019 [4], Steven Perng and Weidong Xie Cisco Systems, Inc presented a video of VIPPO Transient solder separation demonstrating the thermomechanical stress present during a simulated reflow soldering process.

FACTORS

Thermal behaviour of materials in electronics is a complex topic with numerous failure types and mechanisms. The following is an overview of critical factors that contribute to failures in the automotive environment. Overall, the most susceptible components are Surface Mount Devices, namely Bottom Termination and Area Array packages inclusive of both Wafer Level Chip Scale Packages (WLCSP) and Ball Grid Array (BGA) although larger ceramic / ferrite / crystal chip components can also succumb to thermomechanical stress.

The first significant factor is Coefficient of Thermal Expansion (CTE) Mismatch as determined by the materials of the component and the PCB. It is important when identifying the CTE mismatch to consider all contributing materials and their properties. Solder, Copper and Silicon are for the most part consistent with component Epoxy Mold Compound and PCB Laminate introducing levels of variation. BGA packages (Fig 8.) are less susceptible to CTE mismatch due to the presence of a substrate between the Die and encapsulating Epoxy Mold Compound compared with the WLCSP (Fig 9.) with the solder balls in proximity to the Silicon Die.

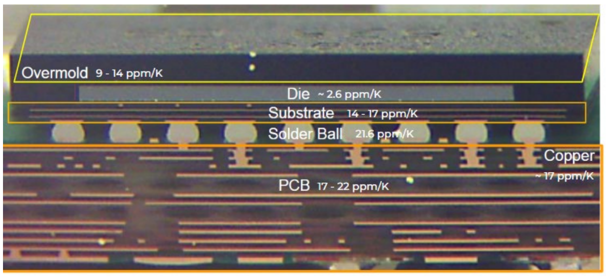

Figure 8. Cross Sectional View of BGA package

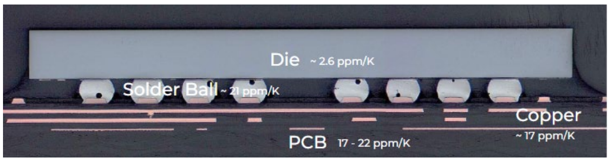

Figure 9. Cross Sectional View of WLCSP

It is important to study the materials and construction of the component. Area Array package solder ball configuration can influence the behaviour at elevated temperature as in the WLCSP pad deformation (Fig 1.). Due to depopulation of the solder ball array, the periphery isolated solder balls were not as robust to withstand the thermomechanical stress during second reflow soldering as the component was located on the bottom side. This failure is prevented with a full solder ball array or locating the WLCSP on the Second Reflow. The rigidity of the solder ball array combination increases the overall package robustness.

In general, it is recommended to not just accept the external package features but to also evaluate the internal construction of the component. Visually two BGA packages may look identical in size, construction and interconnect array but internally there may be significant differences in the die configuration. In the case of DDR BGA packages (Fig 10.), both appear identical but upon cross-sectional evaluation, it becomes clear that one has stacked die.

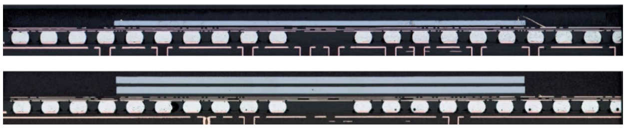

Figure 10. BGA Single vs, Stacked Die

Use X-Ray Inspection and Cross-Sectional views of packages to study different factors such as the Number of Die, Die location, Die Thickness, Die to Package Ratio etc. With increasing functionality, System on Chip (SOC) in Area Array packages format are becoming more prevalent. These packages have complex multiple die constructions (Fig 11.) that can affect the behaviour of the package at elevated temperature.

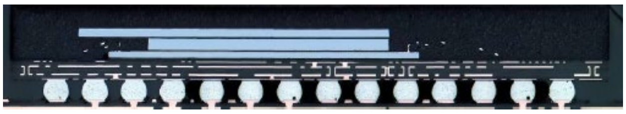

Figure 11. BGA with Multiple Stacked Die

Using Moiré Interferometry (Fig 12.), the package demonstrates a convex signature when heated compared to the conventional concave signature of a single, centred die. Similarly, the location of defects for such complex packages is at the region of the highest thermomechanical stress.

In the defects studied, components with concave warpage signatures at elevated temperature, the solder separation occurs at the corner solder ball interconnections. This correlates to the maximum Distance from Neutral Point (DNP). For the multi-stacked die package, the solder defects occur at the periphery of the die where the highest deformation occurs at elevated temperature (Fig 12.).

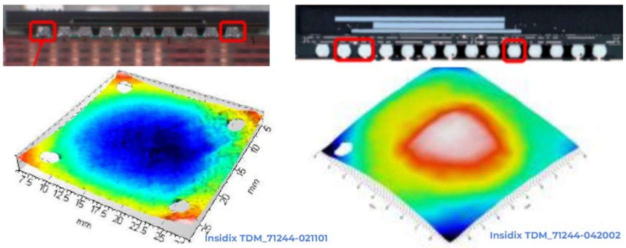

Figure 12. BGA Concave vs, Convex Deformation

Many of the cases studied involve Reflow Soldering, as there is higher risk above the Glass Transition (Tg) of the component overmold and PCB laminate. As discussed, the defects may occur either at First Reflow or Second Reflow.

previously the most prolific test for detecting weakness inherent in the designs. This aligns with increasing localised stress due to self heating and external factors.

It is important to understand the risk relative to the thermal profile. For First Reflow, as the components are not restrained when mounted on the solder paste, the risk is highest during cooldown. Once below liquidus the solder solidifies and restrains the component whereas the PCB continues to contract at a higher rate due to remaining above the Tg. This creates a thermomechanical stress that can induce intermetallic separation, pad cratering and PCB damage as shown in (Fig 5.).

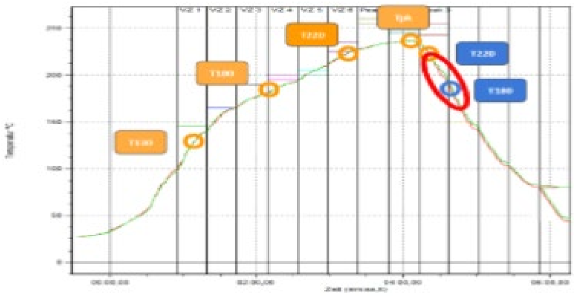

Figure 13. First Reflow Risk Region

During Second Reflow ramp up the primary concern is the solidified solder joints of the components on the bottom side experiencing excessive deformation as evident in (Fig 6.). Panel or transient solder stress due to via configuration beneath the solder interconnection may also contribute to stress load. Similar to the risk in First Reflow, again during cooldown, the same stress exists during solidification of both top and bottom side components.

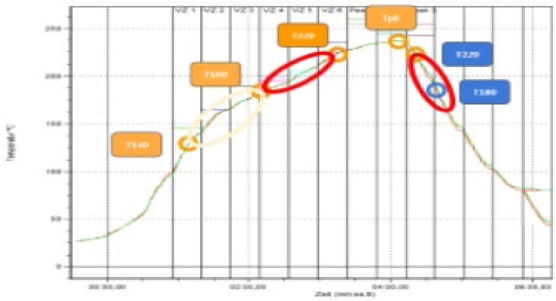

Figure 14. Second Reflow Risk Region

The Printed Circuit Board and Panel contribute to the warpage experienced during Reflow Soldering with numerous parameters. From studies, the type of surface finish has resulted in varying results indicating that even though it is a factor, product design is a much greater influence. Many of the defects are induced from exposure to validation testing during the new product lifecycle. Some defects are fatigue failures (Fig 7.) that occur from extended temperature cycling. The difference with thermomechanical stress is that Powered Temperature Cycling testing of electronic products is the test that induces the failure whereas Thermal Shock was

Design factors due to increasing design complexity to achieve the required functionality unintentionally introduce thermomechanical stress. For example, mirroring [5] opposite sensitive packages can introduce additional stress. Underfill (Fig 15.) used to mitigate solder joint failure of a WLCSP transferred an excessive Z-Axis thermomechanical stress onto the BGA package mirrored on the opposite side resulting in fatigue failures detected during Powered Temperature Cycling failures.

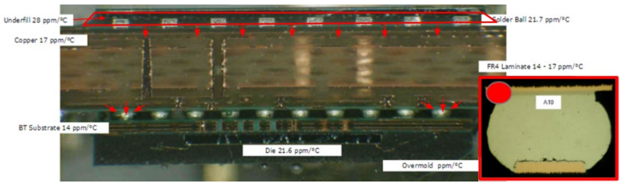

Figure 15. BGA Solder Ball Fatigue Failure due to Underfill on mirrored WLCSP

There are many similar risks of external factors such as conformal coating, potting, thermal paste, staking materials introducing thermomechanical stress onto components.

ANALYSIS

The most effective analysis is visual inspection by experienced personnel with understanding of the historical occurrence of defects, construction of components, materials, complexity of designs and stress loads the electronic parts have been subjected to. In some cases, the defect may have originated at the supplier side but not detected upon first inspection gate in the process.

For thermomechanical stress, Automated Optical Inspection (AOI) is the first inspection after Reflow Soldering. During development builds, it is important to maintain vigilance for any anomalies on the package, PCB and/or solder interconnection (Fig 16.).

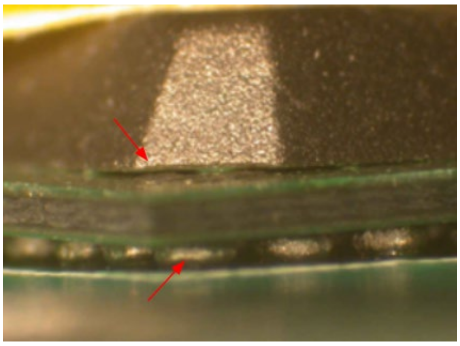

Figure 15. Component Damage

Both 2D and 3D CT X-Ray are also essential tools for determining the internal construction of components as well as verifying solder interconnections.

Microsectional analysis is the most used Destructive Physical Analysis (DPA) for evaluating component package and solder integrity. It is important to acquire a full aligned with validation testing. For example, changing the stack up of a PCB or laminate type can be performed relatively quickly rather than waiting weeks for PCB and months for actual testing to be completed. Even changing the parameters of the validation test provides guidance on the robustness of the design.

cross-sectional view of components and all the solder joints. To complement microsectional analysis use of Dye Penetrant (Fig 16.) provides more information about the failure mechanism. As a microsection only provides information relative to the centre of the solder interconnection, dye penetrant can provide additional information as to the direction of separation propagation.

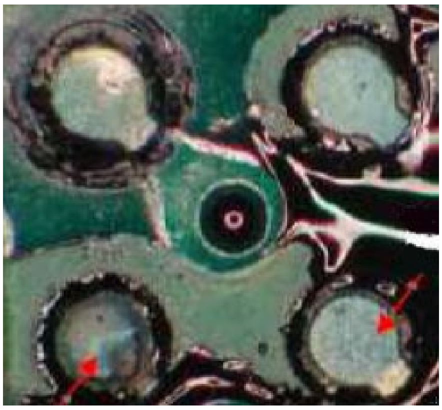

Figure 16. Dye and Pull

Defect mapping thermomechanical stress defects with microsections and dye penetrant provides a better understanding of the failure. Measuring standoff height also provides critical information that may assist with understanding of the failure, Factors such as warpage may be discernible in standoff height (Fig 17.) that aligns with other analysis to understand defects (Fig 5.).

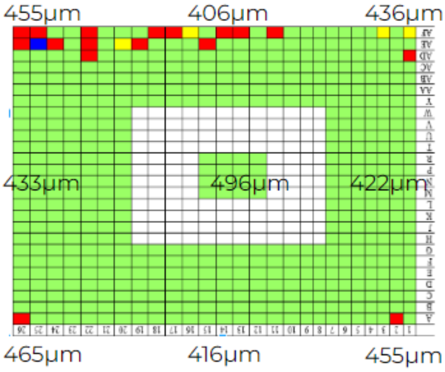

Figure 17. Defect Mapping

Dissection analysis is reactive and after the fact, as in the failure has occurred. To pre-empt failure locations, knowing where to look is critical. Use of simulation tools [6] that predict the thermomechanical strain and solder joint time to failure precise the analysis. Simulation allows quick changes in factors to study the impact on the board level reliability when subjected to thermal stresses

For the defect with a combination of intermetallic separation, pad cratering and track damage (Fig 5.), the deformation measurement shows the 2 up panel changed from a concave to a saddle, convex shape at Reflow temperature and upon cooling returned to a concave shape. The location of the critical sensitive BGA component was centred at the periphery of the maximum deformation (Fig 19.).

When evaluating the CTE Mismatch, it is important to use the component cumulative CTE value as opposed to the provided measurement of the Epoxy Mold Compound alone. To measure CTE, use of Digital Image Correlation (DIC) provides detailed information such as In Plane Deformation along with the required CTE value. This allows study of the behaviour (Fig 18.) of the component, PCB and assembly contracting upon cooling and expanding when heated. DIC measured CTE is also used in the board level simulations to further improve the accuracy of predicted time to failure.

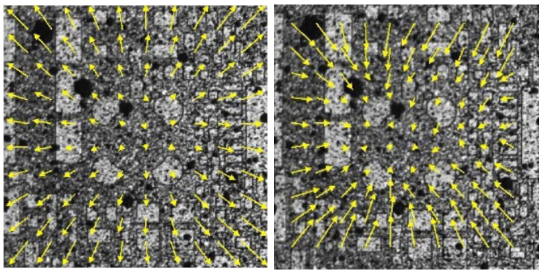

Figure 18. DIC Measurement and In Plane Deformation Cooling vs, Heating

Moiré Interferometry [7] is the primary tool for studying the behaviour of electronic components, PCBs and Assemblies at elevated temperature. There are various methods [8] with each characterising the behaviour of samples over thermal excursions. The analysis can be repeated with different materials and designs along with different thermal profiles.

The thermal profile can simulate the Reflow Soldering process, Coating Curing or even an Accelerated Temperature Cycling cycle. The region of interest may be a panel, individual circuit or component.

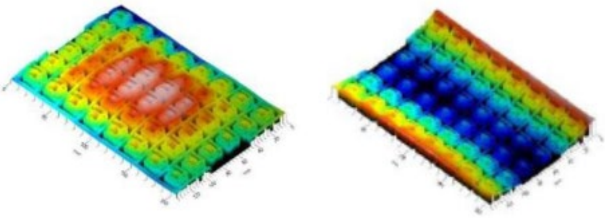

Figure 19. Convex vs, Concave Panel Deformation Measurement at Peak Reflow

PCB fabrication is a critical factor that introduces variation [9]. Performing a Design of Experiments based Moiré Interferometry study can assist with understanding the influence of each factor relative to product design.

The importance of due diligence when introducing new components, materials and designs was emphasised to ensure any potential defects are evaluated. Evaluating the construction of the component and measuring its behaviour at elevated temperature is critical to identify regions of potential weakness.

By understanding the origins of the thermomechanical stress, the required corrective and preventive actions can

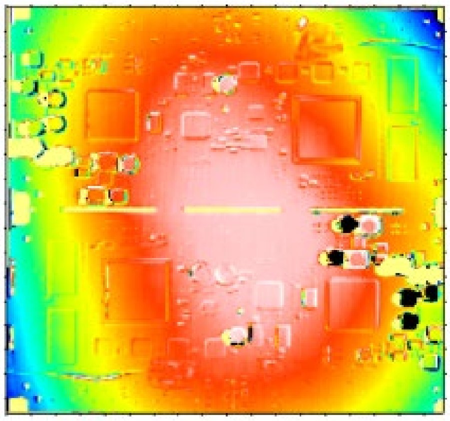

Figure 19. Deformation Measurement of Panel with BGA Defects

Upon understanding that this level of deformation was present across the panel during Second Reflow, increasing the rigidity of the panel with cross-hatching shaped copper on the technical waste edge significantly reduced the deformation (Fig 20.) from an amplitude of 1.5mm to less than 0.5mm.This eliminated any further failure recurrence of any defects.

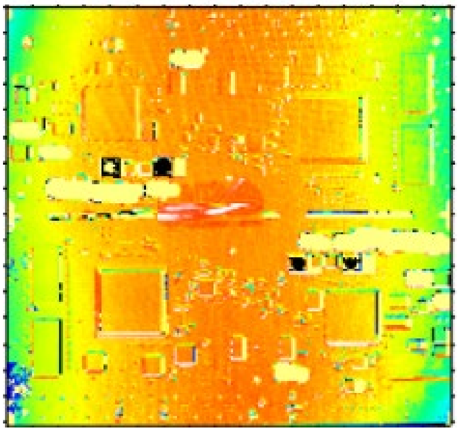

Fig 20. Deformation of Panel after Corrective Action

SUMMARY

To understand thermomechanical stress, the paper first reviewed the different defects encountered. The characteristics of the defects indicate the presence of significant stress in the solder interconnection far exceeding the level mechanical stress alone can induce. A study of primary factors that contributed to each of these failures was studied with strong indication that external factors are increasingly contributing to the failures. be implemented. This involves reviews across suppliers, manufacturing and design departments to reduce the levels of thermomechanical stress and increase the robustness of the product. Even a change of the component package Epoxy Mold Compound with reduced CTE Mismatch to the PCB may be sufficient to reduce the risk of defects,

CONCLUSIONS

Thermomechanical Stress is an ever-increasing concern with advanced packaging, complex designs and increasing functionality of automotive electronics. Many sources of thermomechanical stress are unintentionally introduced due to product designs such as mirroring, underfill, thermal interface materials and associated curing process steps. Understanding the external influence is critical to implement corrective actions.

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