STUDY OF THE EFFECT OF HUMIDITY ON THERMAL CYCLING OF A BALL GRID ARRAY (BGA) PACKAGE

by

SAMUEL AMBOSTA

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Abstract

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Samuel Ambosta, MS

The University of Texas at Arlington, 2018

Supervising Professor: Dereje Agonafer

Thermal Cycling (TC) Test is one of the most important reliability tests in the packaging and semiconductor industry. Humidity on the other hand is one of the significant factors for the reliability of packages, since there are several failures due to moisture absorption in packages. Humidity in packages can lead to soften them and decrease adhesive strength resulting into delamination near the solder tip and wire bond joint, which results in poor electric performance as well as reduced mechanical reliability. In addition, decrease in adhesive strength also causes corrosion in that area which leads to package failure. Absorption of humidity causes oxidization on the solder and well as the PCB board which have been studied in the paper. To analyze this effect of humidity, we followed the JEDEC standards. To induce humidity in the material, the solder and PCB samples were kept in an environmental chamber for 5 days or 120 hours. The material properties of these samples were measured and analyzed. These samples are then examined under SEM and EBSD to analyze the micro structural changes and material spectroscopy. This paper deals with the study of the effect of humidity on thermal cycling of BGA packages through simulation and experimental verification. The temperature range of the thermal cycling test on the package is -40˚C to 125˚C. For Finite Element Modelling commercial software ANSYS and ANSYS fluent are used. Also, a humidity modelling technique is proposed which is validated by experimental data. Also, a detailed comparison is made on deformation, stresses and strains in normal thermal cycling against thermal cycling with humidity. In this study, Multiphysics simulations and reliability analysis has been done to analyze failures in the package.

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Chapter 1

Introduction

1.1 Electronic Packaging

Electronic Packaging is a multi-disciplinary subject which needs knowledge of all field i.e. Mechanical, Industrial and Electrical Engineering, Chemistry, Physics and Material Science Department. All these disciplines are equally important in Packaging. Electronic packaging provides housing and interconnections of integrated circuits to form electronic system.

Electronic Packaging must provide:

- Circuit support and protection

- Heat dissipation

- Signal distribution

- Manufacturability and serviceability

- Power distribution

Level Gate-to-gate interconnections on the silicon die

Level 1 - Connections from the chip to its package

Level 2 - PCB, from component to component or to external connector

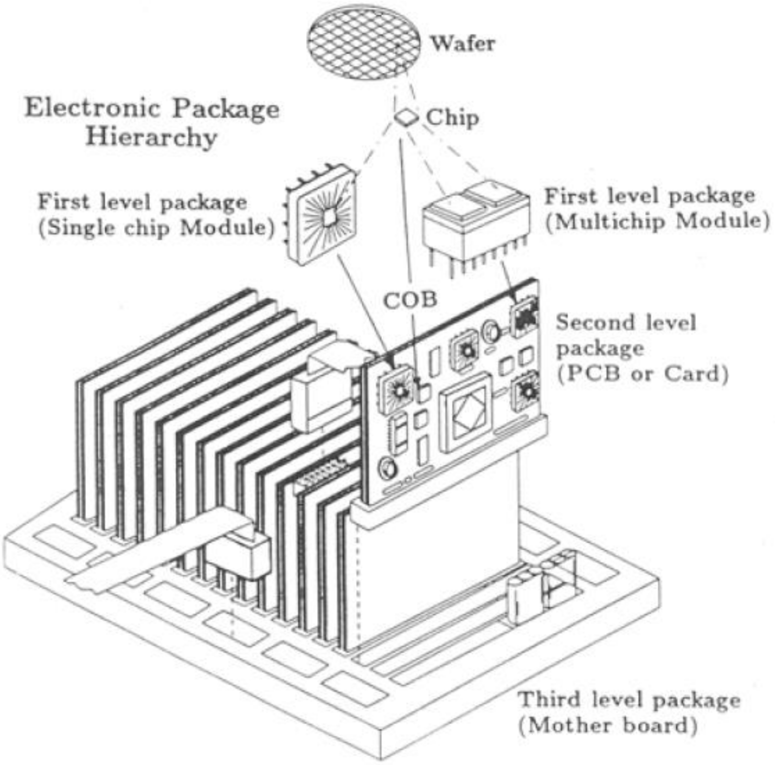

Figure 1.1 Electronic Package Hierarchy

Level 3 - Connections between PCBs, including backplanes or motherboards

Level 4 - Connections between subassemblies, for example a rack

Level 5 - Connections between physically separate systems, using for example an Ethernet LAN

1.2 Packages Classification and Assembly

Packages can be broadly classified as-

- Through Hole Mount IC Packages
  - Dual in-line Package(DIP)
  - Pin Grid
- Surface Mount IC Packages
  - Quad Flat Package(QFP)
  - Thin small outline package(TSOP)
  - Small outline J-leaded package (SOJ)
  - Ball Grid Array (BGA)
- Chip Scale IC Packages
  - Chip Scale Package (CSP)
  - Wafer Level
  - Stacked Die (2.5D & 3D Packages)

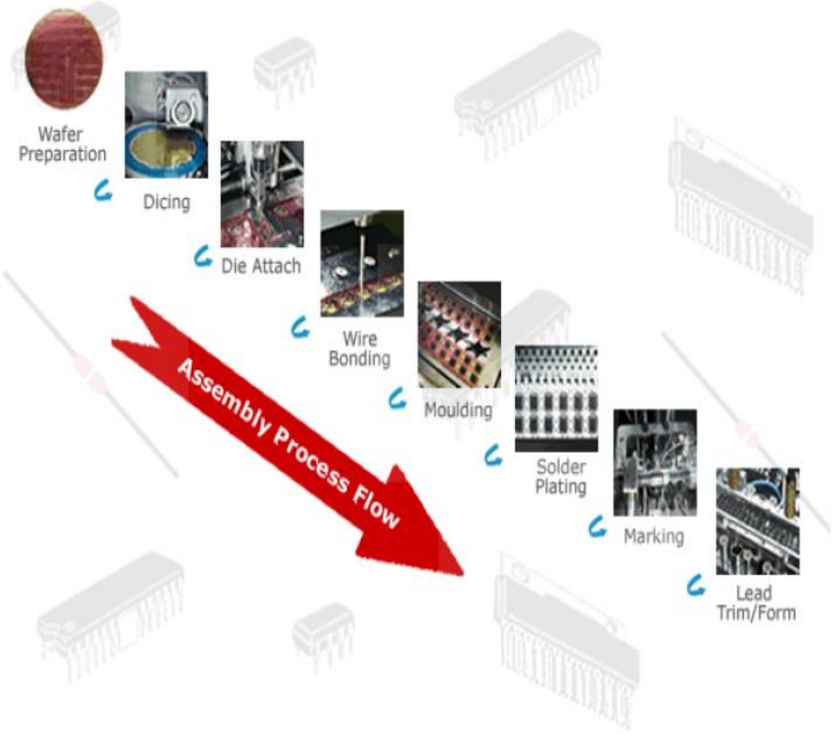

Figure 1.2 Manufacturing Process Flow of Electronic Packages.

1.3 Ball Grid Array Packages (BGA's)

Ball grid array (BGA) is a common surface mount package derived from a pin grid array (PIN) technology. It uses a grid of solder balls or leads to conduct electrical signals from the integrated circuit board. Instead of pins like the PGA, the BGA uses solder balls that are placed on the PCB. A typical BGA package is shown in the Figure 1.3. The BGA packages can provide more interconnection where the whole bottom surface of the device is used, instead of just the perimeter, thus offering high density. The lower thermal resistance offered between the package and the PCB allows the heat generated by the integrated circuit inside the package to flow more easily to the PCB, preventing the chip from overheating. The BGA package also offers the advantage of low inductance due to short distance between the package and the PCB, which prevents the unwanted distortion of signals in high-speed electronic circuits, thus enhancing the electrical performance.

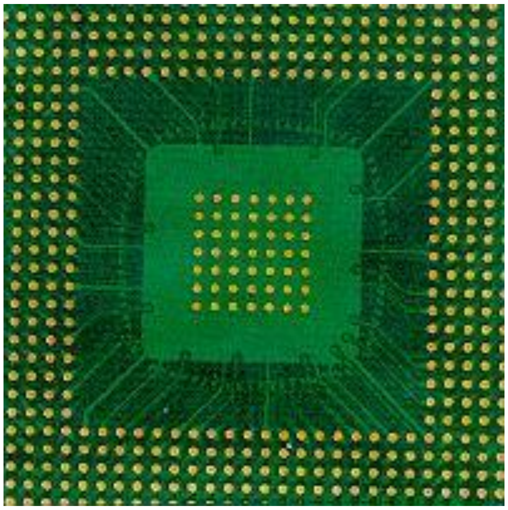

Figure 1.3 Typical BGA Package.

There are several types of BGA packages. They are:

- *CABGA*: Chip Array Ball Grid Array
- *CTBGA*: Thin Chip Array Ball Grid Array
- *CVBGA*: Very Thin Chip Array Ball Grid Array
- *DSBGA*: Die-Size Ball Grid Array
- *FBGA*: Fine Ball Grid Array based on *ball grid array*
- *FCBGA*: Flip Chip Ball Grid Array
- *LBGA*: Low-profile Ball Grid Array
- *LFBGA*: Low-profile Fine-pitch Ball Grid Array

- *MBGA*: Micro Ball Grid Array
- *MCM-PBGA*: Multi-Chip Module Plastic Ball Grid Array
- *PBGA*: Plastic Ball Grid Array
- *Super BGA (SBGA)*: Super Ball Grid Array
- *TABGA*: Tape Array BGA
- *TBGA*: Thin BGA
- *TEPBGA*: Thermally Enhanced Plastic Ball Grid Array
- *TFBGA* or Thin and Fine Ball Grid Array
- *UFBGA* and *UBGA* and Ultra Fine Ball Grid Array based on pitch ball grid array.
- *VFBGA*: Very Fine Pitch Ball Grid Array
- *WFBGA*: Very Very Thin Profile Fine Pitch Ball Grid Array

Chapter 2

Literature Review

Structural Integrity of electronic packages with consideration of moisture was studied by Fan et al. (2008). It was found that the influence of moisture on interface fracture toughness or adhesion strength is a key for package integrity and reliability despite failure mechanisms and environmental conditions. The results of the effect of hygroscopic swelling on the inter-layer dielectric reveals that the overall ILD stresses under HAST can be twice as high as those considered without the moisture effect.

Hsu et al. (2008) determined the hygroscopic swelling properties for polymeric materials used on electronic packages. The residual moisture in the interfacial accurately degrades the adhesion of the materials of the package.

Moisture absorbed in the electronic packages has adverse effects on the reliability and integrity of electronic packages by inducing corrosion, hygroscopic stress, popcorn failure, and degradation of the adhesion strength was proposed by Fan et al. (2008)

Physical changes such as swelling, and embrittlement can occur for some materials when subjected to humidity. Oxidation (corrosion) and leakage paths (between conductors) also are attributed to extreme humidity conditions.

Chapter 3

Material Characterization

Material Characterization is of utmost importance when it comes to find results in Finite Element Simulations. To get accurate results it is necessary to obtain proper material characteristics. To characterize the material for input in ANSY, following parameters were considered:

- Coefficient of Thermal Expansion (CTE)
- Young's Modulus (E)
- Poisson Ratio (ʋ)

3.1 Coefficient of Thermal Expansion (CTE)

Coefficient of Thermal Expansion (CTE) is defined as the tendency of a material which defines the amount by which it expands or contracts when heated or cooled $\alpha = \epsilon \Delta T$

Where,

α – Coefficient of Thermal Expansion (CTE) ppm/°C

ϵ - Strain (mm/mm)

ΔT – Difference in Temperature (°C)

To calculate the CTE of the material, a Thermal Mechanical Analyzer was used. Figure 3.1 shows a TMA from the lab. TMA consist of a quartz probe whose relative movement with change in temperature is used as a parameter to determine the CTE of the PCB material. The quartz probe is enclosed in a thermal chamber which can be operated in a wide range of temperatures (Rahangdale *et al (2017))*

Figure 3.1 Thermal Mechanical Analyzer to measure CTE

3.2 Youngs Modulus Measurement.

Young’s Modulus or Elastic Modulus defines the stiffness of compliance of a material when subjected to tensile or compressive loading. Materials that deform by a small amount when tensile load is applied to them are said to be stiffer as compared to the materials that deform by a considerable amount when tensile or compressive loading is applied to them. Mathematically, Young’s Modulus is defined by the stress produced in a material when some strain is applied to it.

$E=\sigma\epsilon$

Where,

E – Young’s Modulus (MPa)

σ – Stress (MPa)

ϵ - Strain (mm/mm)

Figure 3.2 Dynamic Mechanical Analyzer to measure Youngs Modulus

To measure the Youngs Modulus, Dynamic Mechanical Analyzer which has been used. A DMA machine is used for the experiment can be seen in Figure 3.2. To conduct Young’s Modulus tests, an Instron Microtester of 2kN load cell was used to apply tensile loading to the samples. An extensometer is placed on the sample to measure strain during sample extension. The extensometer is connected to a software to while the Instron is also connected and it gives in-situ force-displacement graph during the test. Stress is calculated by dividing the stress from the cross-sectional area of the sample and strain is measured using the extensometer. From the stress and strain, Young's Modulus is calculated for a sample.

Chapter 4

Modelling and Simulation

4.1 Introduction to Finite Element Analysis (FEA)

Finite element procedures are numerical method for solving a problem, now important and necessary part of engineering design and analysis. FE procedures are very extensively used in the analysis of solids and structures and of heat transfer, fluids and are virtually being employed in all the fields of engineering analysis. In the FE analysis the model body is divided into many smaller elements or units called the finite elements, are interconnected at common points of two or more elements. This common point is called a node or nodal point. This process of division of the model body into elements is called discretization. Then a set of governing algebraic equations are developed and solved under certain assumptions. There exists a governing equation for each element. All these equations are combined to obtain the solution of the model body. Since the FE analysis is a numerical procedure, there is always a necessary to check the accuracy of the obtained solution. If the required accuracy conditions are not met, the solution must be repeated with refined parameters such as using finer mesh or a different type of element until an acceptable solution is obtained. The analysis of the structural problems deals with determining the nodal displacements, stresses and strains associated with each element under the applied loading conditions. The governing equation to determine the nodal displacement using FE techniques is given by (4.1)

$[F] = [K]\{u\}$ --------- (4.1)

[F] is a column matrix which represents the force vector which depends on the boundary conditions and applied loading conditions, [K] is a symmetric matrix which is the global stiffness matrix which depends on the material properties and geometry of the object, {u} is a column matrix which represents the nodal displacement.

A typical FE analysis consists of 3 steps:

1. Preprocessing, which is divided into 3 sub steps

- Modeling the geometry.
- Assigning the material properties.
- Mesh generation.

2. Solution, which is divided into 4 sub steps

- Application of loads and boundary conditions.
- Selection of output and load step controls.
- Selection of solver.
- Obtaining the solution.

3. Post Processing

- Review the obtained results.

In this study few assumptions are made while creating the geometry (Rajmane *et al*. 2017) They are as follows:

1. The PCB is Orthotropic.

2. All the materials except the solder balls are considered as linearly elastic.

3. The solder is modeled as rate dependent viscoplastic material using Anand's Viscoelastic model.

4.2 Geometry

Schematic geometry with material properties of a BGA package is shown in Figure 4.1. The older material used for this study is SAC 305. The detailed component description with dimensions is shown in Table 4.1.

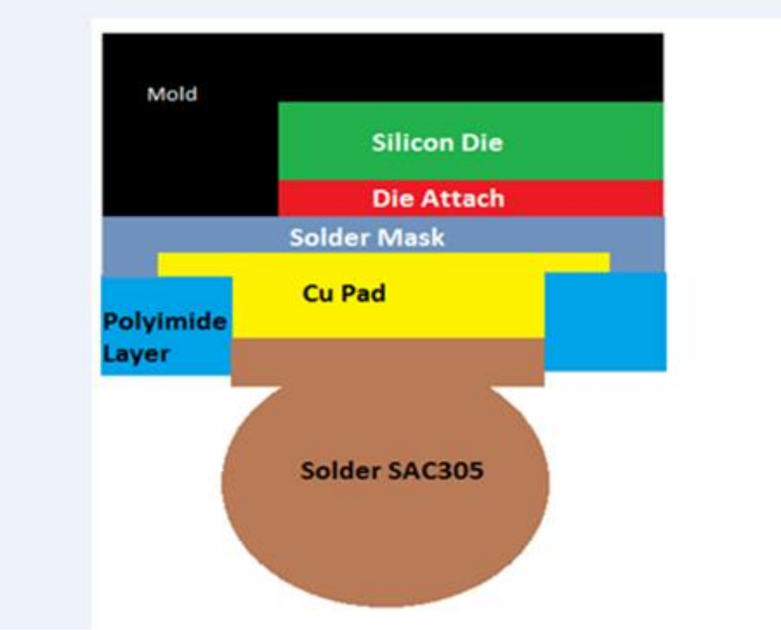

Figure 4.1 Schematic of a BGA Package

After knowing the dimensions and the material characterization of the various components of the BGA package, Design Modeler in ANSYS WORKBENCH 18 is used to model the package. As per Figure the detailed modeling is shown with respective dimension and materials. An octant model of the whole package is being used under consideration for faster simulation. The octant model created in ANSYS design modeler can be seen in Figure 4.2.

Table 4.1 Components with dimensions

Component	**Dimensions (mm)**
Package	6 x 6 x 0.74
Die	4.5 x 4.5 x 0.28
Solder ball pitch	0.5
Solder ball diameter	0.3
Solder ball height	0.2
Solder mask thickness	0.05
Substrate thickness	0.05
Copper pad thickness	0.04

The Anand viscoplastic constitutive model is often used to represent the deformation behavior of solders in electronic packages. SAC 305 is the selected solder for study in this paper. Table 4.2 represents the various constants of the Anand's model for solder SAC 305.

Table 4.2 Anand's Constants of SAC 305. (Rahangdale et al. (2017))

Anand's Constants	**Value**
Initial value of deformation resistance (MPa)	1800x(6.894757e-03)
Activation energy/universal gas constant (1/K)	9400
Pre-exponential factor (1/sec)	4.0e+06
Stress multiplier	1.5
Strain rate sensitivity of stress	0.303
Stress multiplier	2.0e+05x(6.894757e-3)
Coefficient of deformation resistance (MPa)	2.0e+05x(6.894757e-3)
Deformation resistance value	0.07
Strain rate sensitivity of hardening or softening	1.3

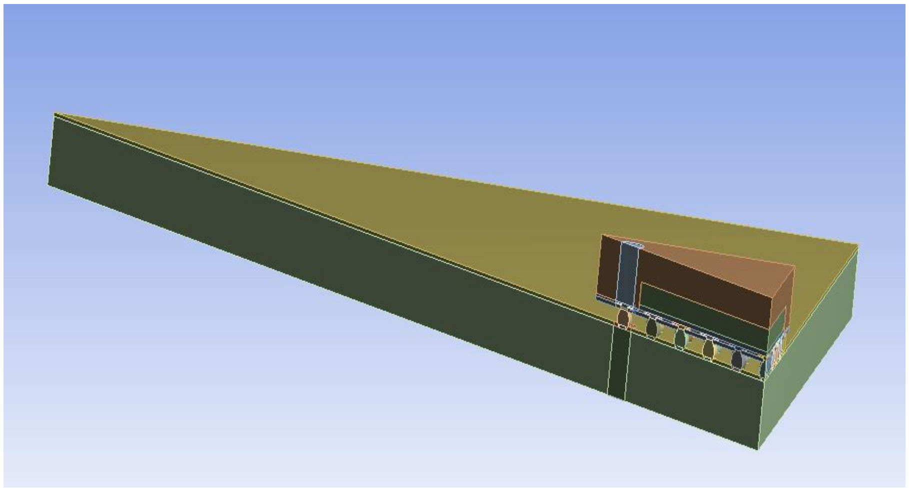

Figure 4.2 Global octant model created in ANSYS.

4.3 Meshing

Hex dominant and three node elements are used for the solder balls. The critical solder is determined to the farthest from neutral point (midpoint of the package). Different body sizing has been used for each component of the package for accurate results.

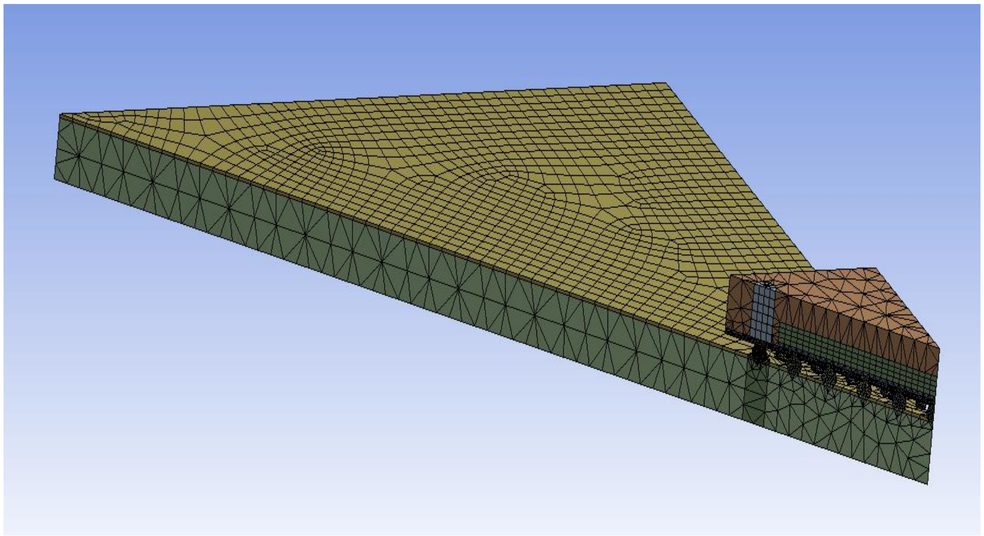

Figure 4.3 Meshed image of the octant model in ANSYS.

4.4 Boundary Conditions.

In ANSYS Static structural it is important to insert boundary conditions. For this package there are three boundary conditions which have been defined which can be seen in Figure. Frictionless support is given on two sides of the geometry while the vertex is given a fixed support.

The second boundary condition is a thermal condition. The package is being subjected to a temperature range of -125˚C TO 40˚C. This process is being done in several steps for a certain time period. The number of steps in this case is 12 and the time period for which it is being subjected to is 900s equal number of steps.

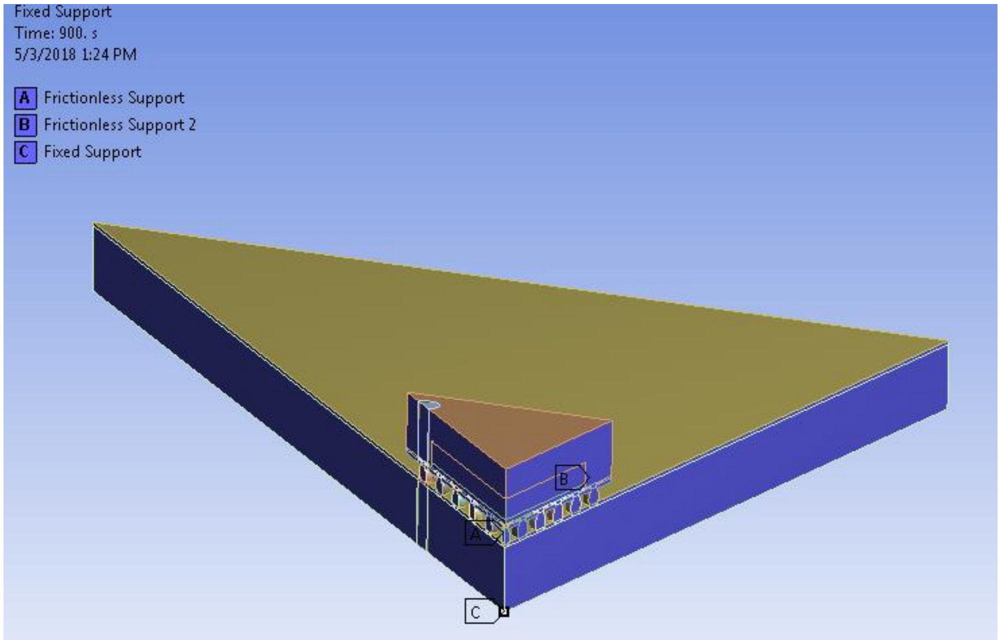

Figure 4.4 ANSYS Model showing the boundary conditions

Table 4.3 gives a representation of the time steps and temperature for which it is being held.

Table 4.3 Time steps used for Thermal Cycling

STEPS	TIME (s)	TEMPERATURE (˚C)
1	0	22
2	900	-40
3	1800	-40
4	2700	125
5	3600	125
6	4500	-40
7	5400	-40
8	6300	125
9	7200	125
10	8100	-40
11	9000	-40
12	9900	125
13	10800	125

4.5 Modeling in ANSYS Fluent

ANSYS Fluent software is the most-powerful computational fluid dynamics (CFD) tool available, empowering you to go further and faster as you optimize your product's performance. Fluent includes well-validated physical modeling capabilities to deliver fast, accurate results across the widest range of CFD and Multiphysics applications. ANSYS Fluent software contains the broad physical modeling capabilities needed to model flow, turbulence, heat transfer, and reactions for industrial applications—ranging from air flow over an aircraft wing to combustion in a furnace, from bubble columns to oil platforms, from blood flow to semiconductor manufacturing, and from clean room design to wastewater treatment plants. Fluent covers a broad reach, including special models with capabilities to model in-cylinder combustion, aero-acoustics, turbomachinery and multiphase systems. In this paper for humidity modeling ANSYS Static Structural and ANSYS Fluent has been linked.

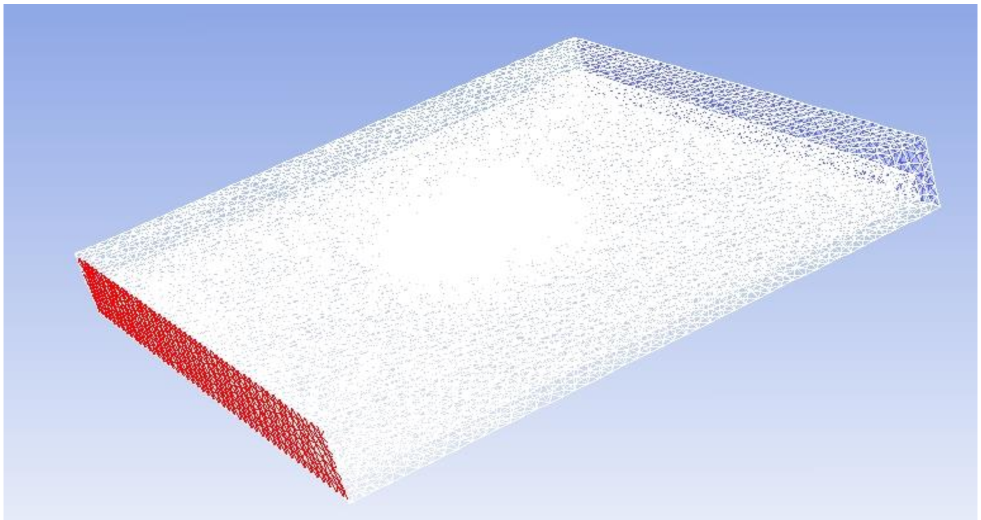

Figure 4.5 Model showing the enclosure to the package in ANSYS Fluent.

Figure 4.5 represents the geometry in ANSYS Fluent. It represents a boundary of fluid inside which the package is located.

For humidity modelling Species Model in Fluent has been used. For that purpose, mole fractions of water and oxygen must be inserted. It can be seen in Table 4.4. Calculation for mole fraction was done as follows, where, RH is Relative Humidity, P is Pressure

RH = P(H2O)/P*(H20)

P*(H20) =P(sat) (T=27˚C)

P(sat)=3.567 KPa (From Steam Table)

Mole fraction of water: Y(H20) = P(H20)/P(Total) where P(Total) = 101.3 kPa

Mole fraction of oxygen: Y(O2) = 0.21 X (1 - Y(H20))

Table 4.4 Mole fractions to the respective Relative Humidity.

RELATIVE HUMIDITY (RH) %	**Y(H20)**	**Y (02)**
90	0.03169	0.2033
50	0.0176	0.2063
20	0.00704	0.2085

Chapter 5

Experimental Setup

5.1 Environmental Chamber (THERMOTRON 7800 SE).

For the experimental part of this paper an environmental chamber was used. The Specifications of the chamber are as follows:

- Temperature Range: (-70°C to +180°C)
- Relative Humidity Range: (10% to 98% Rh)
- Workspace volume: 2.7 cubic feet (586L)

Figure 5.1 INSTRON Environmental Chamber

This chamber was suitable since it had the temperature and humidity range within the scope of this project. This Thermotron is attached with a controller where the temperature and humidity profile can be set up as per the experiment. The Mode that was selected was Humidity. The temperature was set as 80C and Relative humidity was set as 80%.

For the Experiment, the package, PCB, solder strips and solder balls were kept in the chamber as shown in Figure 5.2. The experiment duration was 5 days.

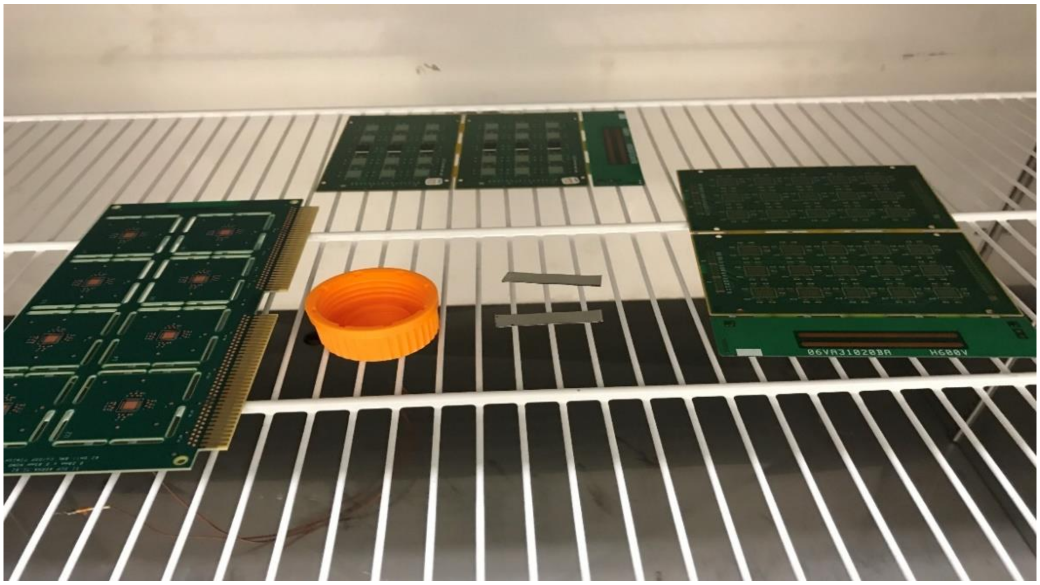

Figure 5.2 Experimental Setup in the Environmental Chamber

Chapter 6

Results and Discussion

6.1 Thermal Cycling.

Thermal Cycling is one of the most important reliability tests for electronic packages. The package is subjected to extreme temperature loads from -40˚C to 125˚C. In simulations, it consists of three equal steps. The results of thermal cycling after three cycles of equal steps leads to the corner solder ball being critical i.e. the corner solder ball experiences maximum strain. This leads to the package to fail. As shown in Figure The maximum strain can be seen on the solder balls.

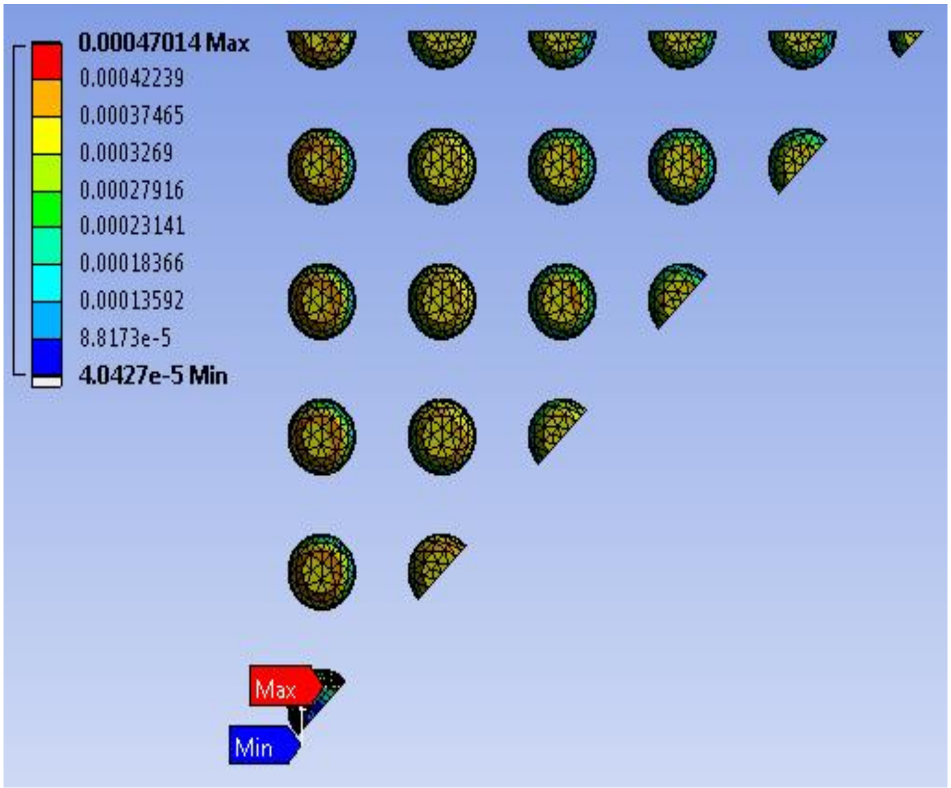

Figure 6.1 Equivalent strain on solder balls during thermal cycling

6.2 Thermal Cycling with induced Humidity.

To induce humidity in the package ANSYS Fluent has been used. It is linked to static structural model in ANSYS Workbench. In Fluent the species model is activated. The imported pressure for 90% RH is shown in Figure.

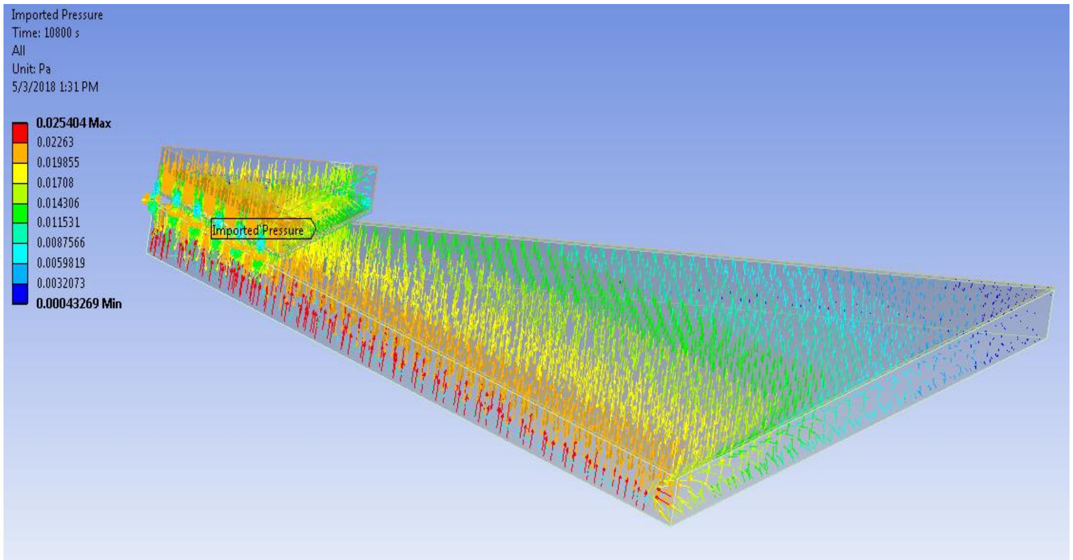

Figure 6.2 Imported Pressure from Fluent in Static Structural Model of ANSYS.

After importing the pressure from Fluent, the same procedure for thermal cycling analysis is followed as the previous section. After thermal cycling with induced humidity the maximum strain on the solder balls appears to be on the middle solder ball and not on the critical corner solder ball. It can be seen in Figure 6.3.

Simulations were performed with humidity values varying. It was subjected to 90% RH, 50% RH and 20% RH. The various values for maximum strain on the solder balls can be seen in Table 6.1.

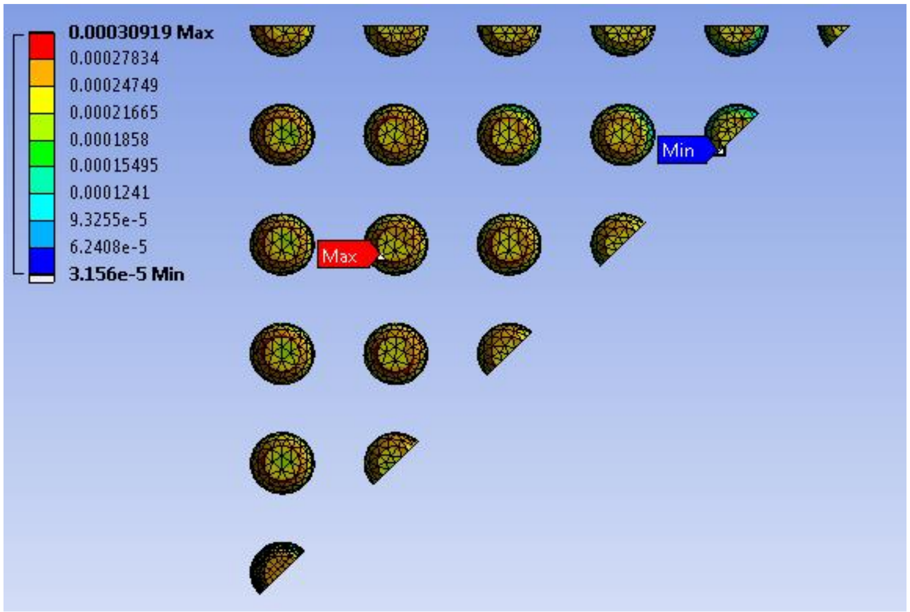

Figure 6.3 Equivalent strain on solder balls during thermal cycling and 90% Relative Humidity (RH).

Table 6.1 Strain Distribution of the various models from simulations

Conditions	**Max Strain (m/m)**	**Min Strain (m/m)**
TC	4.7014e-004	4.0427e-005
TC + 90 RH	3.0919e-004	3.156e-005
TC + 50 RH	3.0919e-004	3.1563e-005
TC + 20RH	3.0899e-004	3.13e-005

6.3 Thermal Cycling simulaion after experiment.

After experiment performed in the environmental chamber, the material properties of the PCB and Solder were measured in the Dynamic Mechanical Analyzer and Thermal Mechanical Analyzer and the new properties were given to the same model. The results for maximum strain can be seen in Figure 6.4

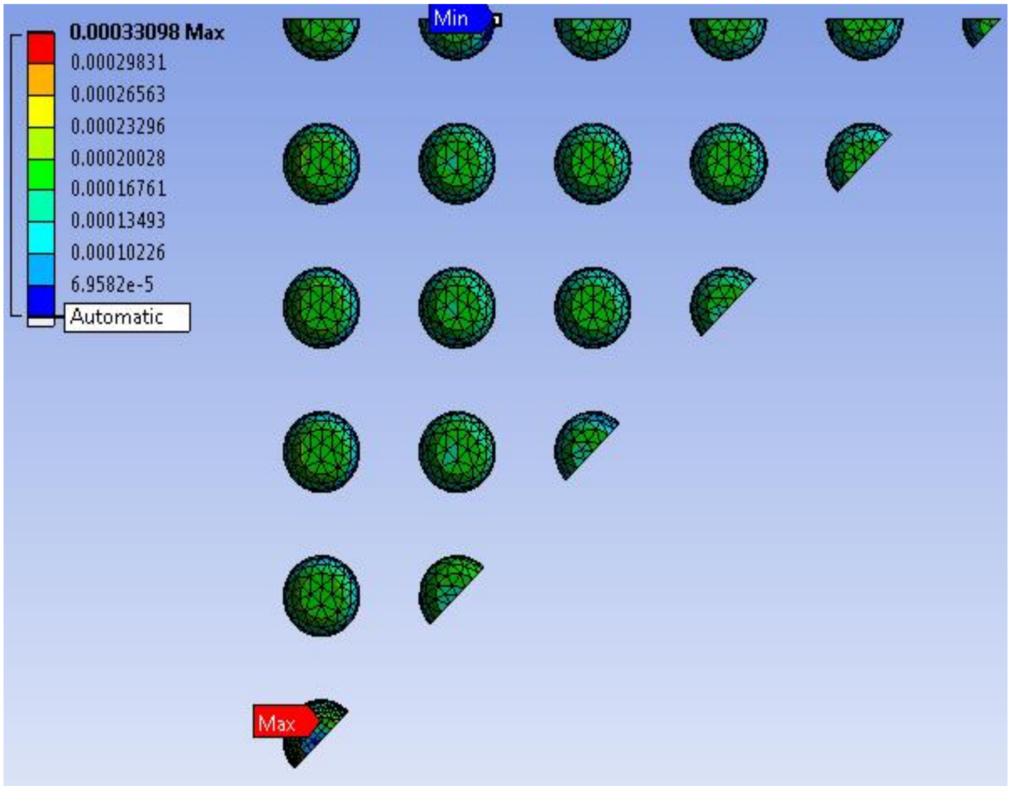

Figure 6.4 : Equivalent strain on solder balls after thermal cycling by taking material properties of PCB and Solder after experimentation

6.4 Validation of Finite Element Analysis.

Previously humidity simulations on packages were never performed. Only experimental work has been regarding humidity effect on packages. In this research work, the simulations done using Fluent and static structural has been verified and hence a new modelling method for humidity has been proposed. After comparing the results of all the simulations, it can be seen in table that the values of humidity simulations are approximately similar. Only material properties of PCB and solder were experimented and inserted in the model. The accuracy of the model would be more accurate if properties of the rest of the parts of the package were analyzed. This is the ground work that has been done in this project and can be further be carried out for better and more accurate results.

Table 6.2 Stress Distribution for validation of simulation

Conditions	**Max Strain (m/m)**
Thermal Cycling	4.7014e-004
Thermal Cycling with Fluent Modelling (90RH)	3.0919e-004
Thermal Cycling with new material properties from the experiment	3.3098e-004

6.5 Comparison of material properties.

After experiments in the environmental chamber the material properties of the PCB and solder were measured as seen in Section. As per the graphs shown in Figures it can be clearly seen that since the Young's modulus and CTE is increasing. A bigger value of Young's Modulus and CTE means that the materials are getting stiffer. This will ultimately lead the package to fail sooner than it must fail. Hence package life can be predicted to be lower when humidity is introduced compared to normal package at room temperature.

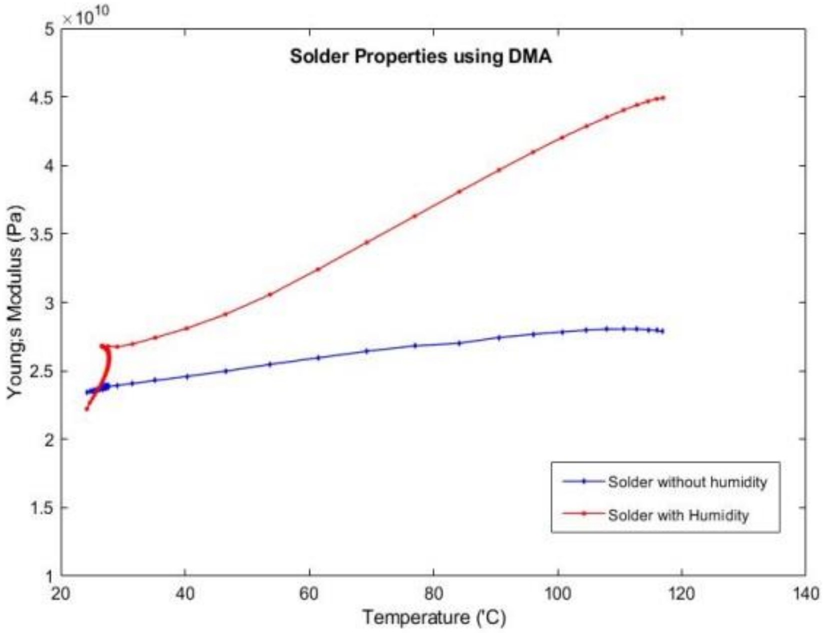

Figure 6.5 Solder properties using DMA after experiment

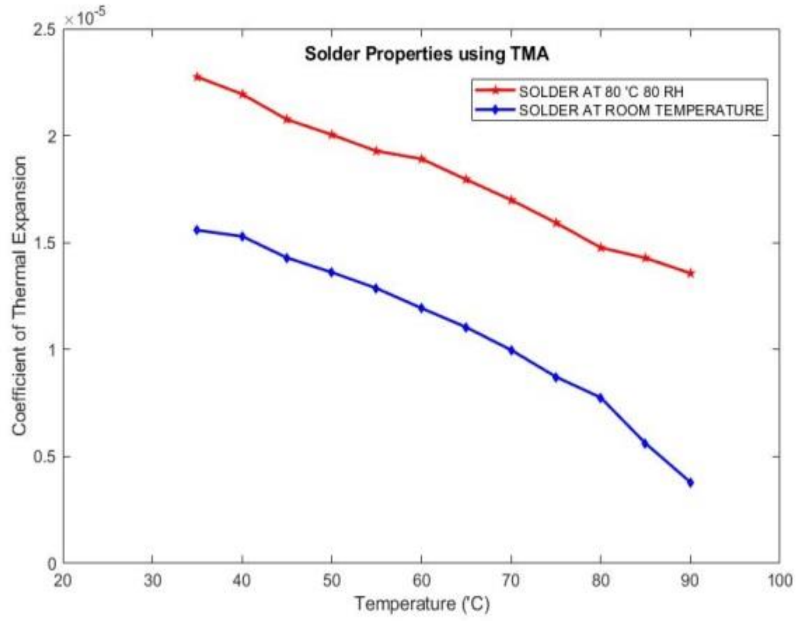

Figure 6.6 Solder Properties using TMA after experiment

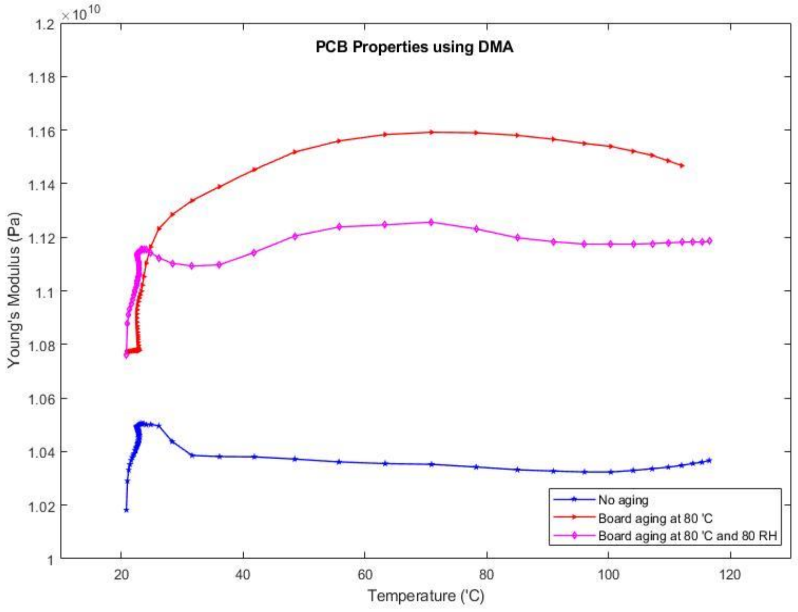

Figure 6.7 PCB Properties using DMA

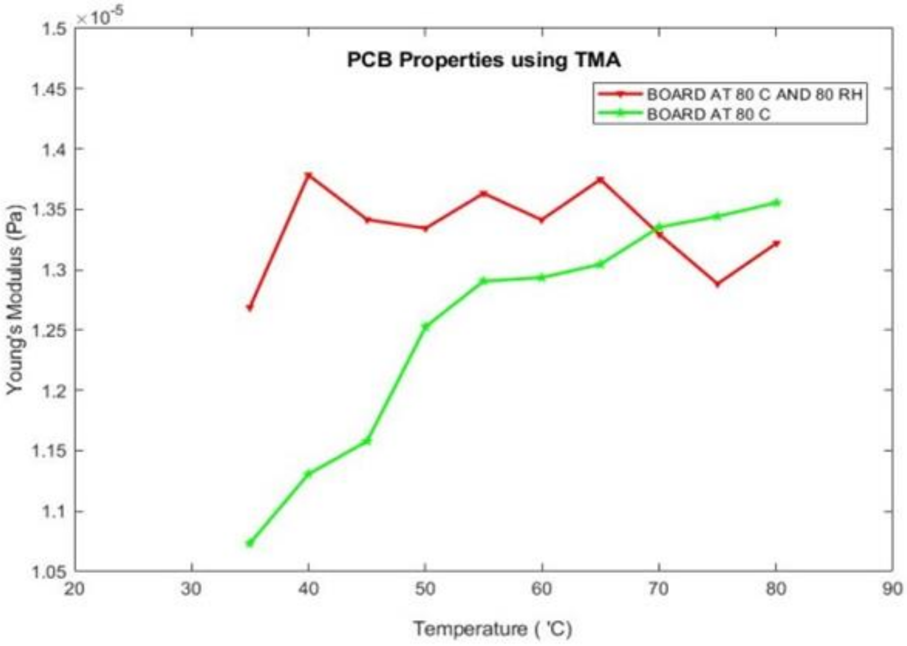

Figure 6.8 PCB Properties using TMA

6.5 Imaging using Scanning Electron Microscope (SEM) and Electron Back Scattered Diffraction (EBSD)

A scanning electron microscope is a type of electron microscope that produces images of a sample by scanning the surface with a focused beam of electrons. After keeping the samples in the environmental chamber, the Solder strips were examined using SEM. SEM was used to see the surface defects on it. These samples were not polished since it would erase the defects caused due to humidity. The images were seen at 500 um as seen Figures 6.9 and 6.10. After looking at these images, black spots appeared on the sample which was induced with humidity and high temperature.

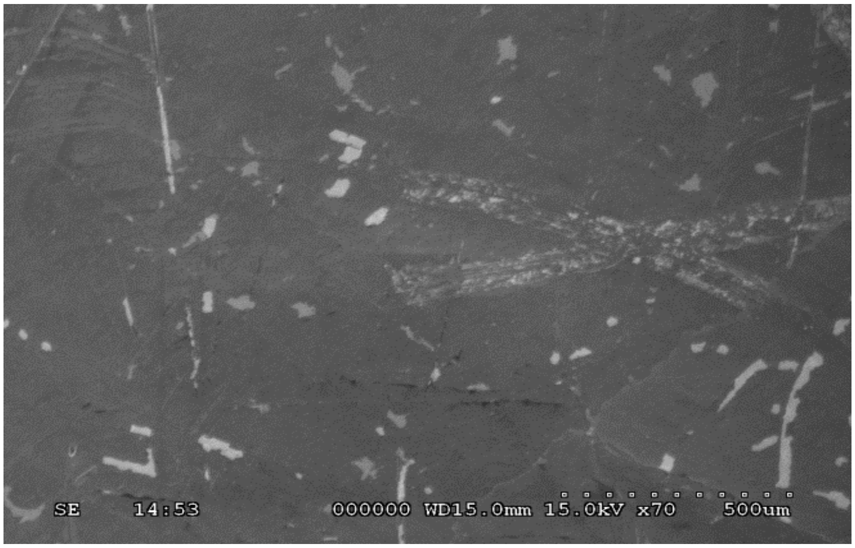

Figure 6.9 SEM image of solder sample at room temperature.

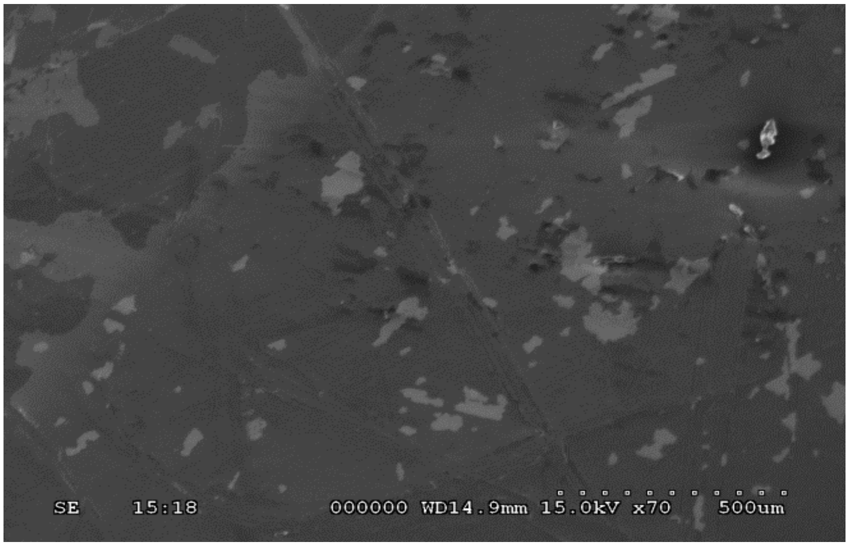

Figure 6.10 SEM image of Solder Strip at 80°C and 80RH

Figure 6.11 Zoomed SEM image of Solder Strip at 80°C and 80RH.

Electron backscatter diffraction (EBSD) imaging technique is a microstructural crystallographic characterization technique to study any crystalline or polycrystalline material. The technique involves understanding the structure, crystal orientation and phase of materials in the Scanning Electron Microscope (SEM). Typically, it is used to explore microstructures, revealing texture, defects, grain morphology and deformation. It can be combined with complementary techniques within the SEM for phase discrimination. Samples must be prepared well to be used for imaging in EBSD. The samples were cut into small pieces and then put in a mold of epoxy as seen in Figures 6.12 and 6.13.

Figure 6.12 Package sample in epoxy mold after polishing.

Figure 6.13 Solder samples in epoxy mold after polishing

The samples were then introduced to Aluminum Silicate. They were polished using 1200um, 1000 um, 900 um 600 um and 300 um grade polishing papers. Lastly for the polishing process a diamond paper was used to achieve a good sample. After polishing the samples were cleaned and then left for some time before performing testing in EBSD. After EBSD testing it was found that, the amount of Oxygen (O) in the solder that underwent humidity was way higher than the solder which was at room temperature. Thus, it can be said that the solder surface undergoes oxidization and corrosion after it is exposed to humidity. The die and silicon area were concentrated for imaging for the package as seen in Figure 6.14. After EBSD testing it was clear that there was oxidation at that region as seen in Figure 6.15. Hence, humidity also affects the Package and hence is a reliability issue for electronic packages.

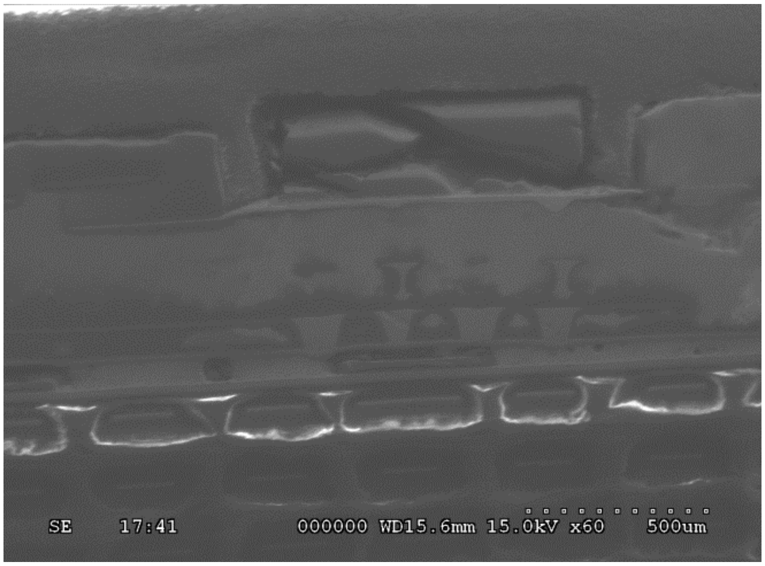

Figure 6.14 SEM image of package at 80°C and 80RH

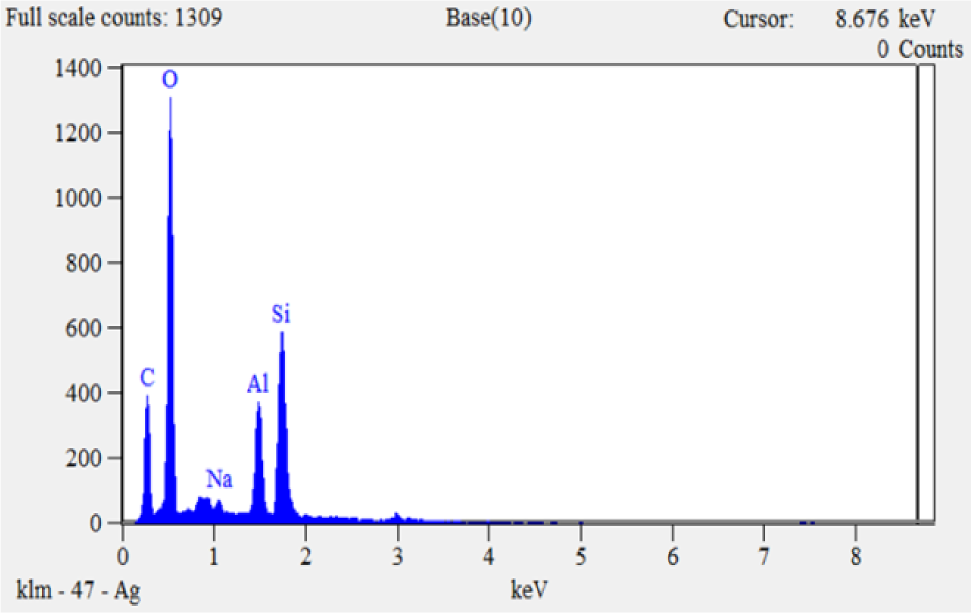

Figure 6.15 EBSD material spectroscopy of PCB at 80°C and 80RH

Chapter 7

Conclusion

1. Humidity is one of the crucial factors for the reliability of BGA packages and for that matter all electronic packages.

2. From Finite Element Modelling we can say that the stress of the whole package increases, strain on the solder balls decreases to a small extent. Also, the critical solder ball changes from corner during normal thermal cycling to the center when humidity is induced in it. Also modelling using board and solder properties after experimentation suggests the validation of the Finite Element Model. Hence, a new humidity modelling theory is proposed.

3. After experimentation the Young's modulus and CTE of the solder and PCB increases. Thus, the materials are getting stiffer and would fail faster. Hence, humidity causes the package to fail sooner.

4. When the samples were examined through SEM and EBSD it was clear that they were oxidized after undergoing through a humid environment. Hence, it can be stated that corrosion occurs when there is high amount of humidity on the packages.

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Biographical Information

Samuel Ambosta is originally Mumbai, India. He completed his undergraduate studies in mechanical engineering from Don Bosco Institute of Technology, Mumbai in June 2015. He worked as a Junior Engineer at Marconi Elevators from June 2015 to June 2016.

His passion for engineering led him to pursue graduate studies at The University of Texas at Arlington in Fall 2016. He worked at the Electronics MEMS & Nanoelectronics Systems Packaging Center (EMNSPC) with Dr. Dereje Agonafer and developed a keen interest in reliability and failure analysis of electronic packages. His research interest includes reliability, thermo-mechanical simulation, material characterization, material preparation and failure analysis of electronic packages.

He has a strong knowledge in CAD modelling and simulation software's. Samuel successfully graduated with a Master of Science degree in Mechanical Engineering from The University of Texas at Arlington in May 2018.