Design-for-reliability methodology for lead-free solder joints

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DESIGN-FOR-RELIABILITY METHODOLOGY FOR LEAD-FREE SOLDER JOINTS

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Abstract

In this project, a Design-For-Reliability (DFR) methodology was developed for solder joints. This methodology consists of three parts, (1) experimental methods for reliability test, (2) Finite Element Analysis (FEA): Modeling and Simulation and (3) Fatigue Life Prediction Analysis. This methodology aims to reduce the time taken to understand and improve the reliability and performance of electronic assemblies with lead-free solder joints.

The DFR methodology is applied to two case studies, a micro-BGA package with lead-free Sn-3.8Ag-0.7Cu solder and Flip-Chip-On-Board (FCOB) package with Sn-3.5Ag lead-free and Sn-37Pb lead-based solder. These packages were subjected to temperature shock test according to JEDEC standard A106-A. The failure data from the experiments were fitted to the Weibull failure distribution and the Weibull parameters were extracted together with the mean-time-to-failure (MTTF). Failure analysis was conducted on the failed specimens and indicated fatigue crack propagation behavior in the bulk solders. Finite Element Analysis (FEA) was employed to study the thermal-mechanical behavior of the assemblies. Different constitutive models, namely the viscoplastic flow and evolution equations and the phenomenal Elastic-Plastic-Creep (EPC) equations were used to model the deformation behavior of the solder joints. The effect of the different temperature cycling frequency and different stress-free states were also studied. Different fatigue life prediction models were employed for solder joint fatigue life prediction subject to temperature cycling loading and found to have satisfactory correlation to the experiment MTTF life.

Abstract

Solder fatigue life prediction database software has been developed using Visual Basic as a post-processing DFR tool. Computed failure parameters such as strain or energy density from the FEA study were input to the software for solder joint fatigue life prediction calculation. This DFR fatigue database include new Pb-free solder fatigue models and establish Sn-based solder fatigue database compiled from published reports. The software provides engineers with a comprehensive solder joint fatigue database and analysis program.

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CHAPTER 1 INTRODUCTION

1.1 Background

Electronic products such as hand-phones, digital cameras and notebooks face increasing demands for higher quality and reliability. Electronic packaging manufacturers are constantly seeking ways to miniaturize the electronic packaging assemblies without compromising on reliability particularly on solder joint reliability. Because of the shorter product life cycle of electronic equipment, there's a need for a more comprehensive design approach to improve the solder joint reliability. Meeting these challenges requires developing a Design-For-Reliability (DFR) methodology. The approach for the DFR methodology is shown in figure 1.1. This methodology can be applied to both lead-free and eutectic lead-based solder joints.

Figure 1.1: DFR Methodology

For a long time both high Pb-Sn and eutectic Sn-37Pb have been suitable materials for the interconnection of electronic components due to their low cost and physical properties. Due to environmental concerns, legislation to ban lead (Pb) in electronic products requires lead-free solder applications in electronic assemblies and products. Increasing attention within the semiconductor and electronic industry is focused on getting ready for lead-free solder manufacturing. Currently, lead is found in electronic components, printed circuit boards (PCBs) of electronic products.

The EU Parliament and the EU Council of Ministers reached an agreement to ban lead (Pb) from 1st July 2006. The impending ban on lead (Pb) has generated much interest and research work on lead-free solders. The National Electronic Manufacturing Initiative (NEMI) recommended Sn-3.9Ag-0.6Cu for reflow soldering and 99.3Sn-0.7Cu for wave soldering. Schubert et al [1] has also pointed out that the Sn-3.5Ag alloy is expected to be one of the best candidate as lead-free solder. Ye et al paper [2] compared the solder joint of several solder pastes, 96.5Sn-3.5Ag, 93.5Sn-3.2Ag-0.5Cu, and 63Sn-37Pb and found that the Sn-Ag-Cu has the highest shear strength for the as-assembled and aged condition after 1000 thermal cycles of aging. Some examples of lead-free research programs in Multi-National Companies (MNC) are as follows:

- (1) Intel is working with its suppliers, its customers, and several industry consortia to develop lead-free manufacturing standards and processes. [3]
  - (2) National Semiconductor is currently considering approaches that would help to discontinue the use of lead in their products as well as in the manufacturing processes of their customers. [4]
-

- (3) Fairchild has recently launched the Lead-Free Implementation to provide their customers with lead-free finishes. Lead-free finishes utilizing pure tin (Sn), nickel palladium (NiPd) and nickel palladium with a gold flash (NiPdAu) have already been qualified at Fairchild. [5]

The DFR methodology shown in figure 1.1 consist of three parts mainly experimental methods for reliability test, Finite Element Analysis (FEA) and fatigue life prediction analysis which would be expained in greater detail in the following sections.

1.2 Role of Reliability Testing

Solder joints are needed as electrical interconnections and mechanical attachments for IC components to printed circuit boards (PCB). The technology trend for IC components is a decrease in solder joint size and pitch, and increase in the number of input/output (I/O) connections. This will pose increasing challenges to reliability problems. The role of reliability testing is to characterize the reliability performance of soldered assemblies quantifying the cumulative distribution function (CDF) given by a Weibull plot.

Table 1.1: PCB Reliability Test

Tests	Description
Thermal Cycling (TC)	Finds fatigue-related defects. Test use slow temperature transition often to allow for creep-related problems and temperature transition analysis.
Thermal Shock (TS)	Finds fatigue-related defects. Test uses fast temperature transition for expansion/contraction-related defects.
Vibration	Test mechanical integrity of mounted components

A major concern with solder joint reliability is to quantify solder joint failure resulting from reliability tests shown in table 1.1. Electronic components soldered onto a PCB are subjected to mismatch in thermal expansion coefficients during temperature cycling test. The components are cycled between the minimum and maximum temperature limits. Devices cycled in this way experience expansion and contraction effects, which induce cyclic fatigue related failures in the solder joints. Exposure to temperature cycles contributes to the thermally activated deformation by creep and intermetallic growth at the solder-intermetallic interface.

1.2.1 Role of Accelerated Testing

The electronic packaging industry is motivated to shorten product development cycle time while maintaining desirable levels of quality and reliability. Two of the most commonly used accelerated tests are the Accelerated Thermal Cycling (ATC) test and the Accelerated Stress Testing (AST). Other accelerated solder joint reliability test methods [6-9] have also been used to obtain fatigue performance data for solder joint reliability analysis.

1.2.2 Accelerated Thermal Cycling (ATC) test

Most electronic products are often subjected to changes in temperature for example a computer turning on/off or starting/stopping a car engine. The change in temperature causes the different types of material in the electronic assembly to expand or contract differently thus generating thermal mismatch deformation. However, it is impractical to test the components under actual temperature conditions as the service life is anticipated to take years. Therefore, ATC test aims to compress time and accelerate the failure mechanisms in a reasonable test period by accelerating the environment in which the test is performed. It is also important to ensure that the failure mechanisms and modes of the ATC test and the normal operating conditions are similar. Two test methods used in the ATC test as described in table 1.1 are thermal cycling (TC) test and the thermal shock (TS) test illustrated in figure 1.2.

Figure 1.2: TC and TS Profiles

In order to extrapolate from the MTTF obtained from the ATC test to the MTTF obtained from the field, an acceleration factor (AF) is used. This AF is defined mathematically by equation 1.1 where t_{field} is the life under normal or field condition and

t_{test} is the life under accelerated test conditions. Figure 1.3 illustrates the AF between the Time to failure from the TS and the test under operating condition.

$$AF = \frac{t_{\text{field}}}{t_{\text{test}}} \quad \text{--- (1.1)}$$

The most well-accepted and frequently used empirical acceleration factors for solder joint thermal fatigue is given as follow [9]:

$$AF = \left[\frac{\Delta T_t}{\Delta T_f} \right]^{1.9} \left[\frac{f_f}{f_t} \right]^{\frac{1}{3}} e^{\left[1414 \left(\frac{1}{T_{MAX}^f} - \frac{1}{T_{MAX}^t} \right) \right]}$$

where

$\Delta T_t, \Delta T_f$ = temperature ranges at test field condition.

f_t, f_f = cyclic frequencies at test and field condition.

$T_{\text{max}}^t, T_{\text{min}}^f$ = highest on-off temperature at test and field condition in Kelvin.

Figure 1.3: Illustration of accelerating factor

1.2.3 Accelerated Stress Test (AST)

AST is stress stimulation testing that combines different testing techniques to stimulate package failure. AST is used as a qualitative assessment of the product. It induces fatigue, which in turn causes failures that can be analyzed to determine the appropriate corrective action. Product robustness is a result of following the AST process. In this way, AST will reduce development time and cost; eliminate design deficiencies before release to manufacturing [10]. AST is also a good tool to assess changes made to products during sustaining activity. [11]

1.3 Role of Finite Element Analysis in Modeling and Simulation

As stated in the previous sectioning, to understand the thermo-mechanical reliability of a package, actual reliability testing is usually required. However, such physical testing tend to be very time consuming and not cost effective. Another way to assess the reliability is through Finite Element Analysis (FEA). FEA is a numerical modeling technique for structural analysis of engineering structures and used to calculate force-deflection, stress-strain and energy density in a material. For solder joint reliability assessments, viscoplastic analysis resulting from temperature cycling loading is analyzed for an electronic assembly. A high performance computer is required because of the computational resource needed to analyze a 3D non-linear FEA problem.

FEA consists of a computer model of a structure that is stressed and analyzed for specific results. It may be used in the design for reliability methodology before any new product design is built, and also for improving product refinement. It is often used to verify a proposed design, which will be able to perform to the client's specifications prior to manufacturing or construction. Modifying an existing product or structure is utilized to qualify the product or structure for a new service condition. In case of structural failure, FEA may be used to help determine the design modifications to meet the new condition.

In finite element analysis, a structure is modeled into a geometric model consisting of elements forming the finite element mesh in 2D or 3D. While 2-D modeling conserves simplicity and allows the analysis to be run on a low-end computer, it tends to yield less accurate results. 3-D modeling, however, produces more accurate results on a high-end workstation and much higher computer resources. Within each of these modeling schemes, the user can insert numerous algorithms (functions), which may make the system behave linearly or non-linearly. Linear systems are far less complex and generally do not take into account plastic deformation. Non-linear systems do account for plastic deformation in non-linear materials for example solder subject to thermal cycling loading.

The FEA process involves solving a matrix of stiffness equations describing the force-displacement behavior of the nodes and elements in a structure. The force-displacement result at the nodes of each element is used to calculate the element stresses and strains. In electronic packaging design, FEA modeling helps to reduce physical design problem of solder joints subject to thermo-mechanical loading[12-15]. Stoyanov et al [16] demonstrated a strategy where computational mechanics is coupled with optimization tools to predict suitable design parameters for improved electronic package reliability. Tee et al [17] used moisture-hygro-thermo-mechanical modeling as a tool to analyze and enhance

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the reliability of FCBGA against moisture-induced failures. Wong et al [18] performed three finite element analysis to understand the physics of failure in board-level drop impact. Syed [19] uses advanced finite element modeling and analysis techniques such as constraint equations and sub-structuring and documented the ability to predict life within 25% of the Mean Time to Failure (MTTF). Finite element analysis of soldered assemblies subject to thermal cycling loading will be investigated in this study.

FEA uses a complex system of points called nodes, which make a grid called a mesh. This mesh is programmed to contain the material and structural properties, which define how the structure will react to certain loading conditions. Nodes are assigned at a certain density throughout the material depending on the anticipated stress levels of a particular area. Regions, which will receive large amounts of stress usually, have a higher node density than those that experience little or no stress. In the case of the electronic package, the points of interest will be the interface between the solder joint that is furthest away from the Distance from the Neutral Point (DNP).

In general, a finite element solution may be broken into the following three stages.

1. **Preprocessing: defining the problem;** the major steps in preprocessing are given below:

- Define keypoints/lines/areas/volumes
- Define element type and material/geometric properties
- Mesh lines/areas/volumes as required

The amount of detail required will depend on the dimensionality of the analysis (i.e. 1D, 2D, axi-symmetric, 3D).

2. **Solution: assigning loads, constraints and solving;** here we specify the loads

(point or pressure), constraints (translational and rotational) and finally solve the resulting set of equations.

3. **Postprocessing: further processing and viewing of the results;** in this stage, the following is obtained:

- Plastic and elastic strain values
- Stress contour diagrams
- Deflection plots

Figure 1.4 shows the methodology of the Finite Element Analysis (FEA).

Figure 1.4: Overview of FEA procedure

1.4 Role of Fatigue Life Prediction Analysis

After FEA modeling and simulation, fatigue life prediction analysis is needed to predict the fatigue life cycles of the solder joint interconnect. This post-processing of the FEA data, aims to correlate the solder joint fatigue life to certain failure parameters such as, stress range, strain range or energy density obtained from the FEA results. With the increasing number of fatigue life prediction models and constants being published for specific solder alloys and failure parameter, it is often a challenging task to search for suitable fatigue life prediction models for individual applications. In this project, a post-FEA fatigue life prediction software was developed to perform the fatigue life prediction calculations and include a database of solder fatigue life prediction models. There is a potential to integrate this software into the FEA output system.

1.5 Objective

The overall objective of this project is to develop a DFR test and analysis for lead-free and lead-based soldered assemblies. The specific objectives are as follows:

- i) To conduct temperature shock test on lead-free Sn-3.8Ag-0.7Cu solder as second level interconnect in micro-BGA assemblies and lead-free Sn-3.5Ag and lead-based Sn-37Pb solder bumps in FCOB assemblies.

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- ii) To develop 2D plane strain and 3D strip models of micro-BGA and 2D plane strain FCOB assemblies, and to study the influences of these models on the solder joint fatigue life prediction results.
  - iii) To study the effect of different FEA parameters on the FEA results:
    - (a) The ramp rate effect comparing temperature shock vs temperature cycling test,
    - (b) The influence of different stress free states (T_{SFS}) of the thermal cycling load and
    - (c) The use of visco-elastic properties instead of elastic properties of underfill material.
  - iv) Develop a Fatigue Life Prediction Software for solder that will allow the user to perform fatigue life calculations and compare different models with relative ease

1.6 Scope

The purpose of this work is to develop case studies for DFR test and analysis for lead-free (Sn-3.8Ag-0.7Cu and Sn-3.5Ag) and lead based (Sn-37Pb) solder. A comprehensive summary of the scope is found in figure 1.5.

Figure 1.5: Scope of Project

The scope of this project consists of 4 major parts:

(a) **Board Level Reliability testing** will be performed on 2 different types of packages, the *micro-BGA* and the *FCOB* assemblies. The accelerated thermal cycling test or thermal shock test is a commonly used technique for evaluating the reliability of electronic package assemblies [20] and will be used in this study. From the ATC test, the Weibull distribution is plotted and the MTTF obtained. Solder joint failures were

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determined with in-situ datalogging system and verified by resistance measurements. Failure analysis was conducted and the failure mechanism determined.

The micro-BGA assemblies were supplied by Motorola in collaboration with NTU. The lead-free solder joints, Sn-3.8Ag-0.7Cu on micro-BGA assemblies was chosen as test vehicles for application of the DFR methodology. The micro-BGA package represents the state-of-the-art electronic package with 179 I/Os, 0.5mm Pb-free solder joints with 0.8mm pitch. This package features the HDI (High Density Interconnect) layers and micro vias-in-pad design on a BT board.

The other package evaluated is the 500 I/Os FCOB assembly. This study provides a comparison of the thermal shock reliability of lead-free Sn-3.5Ag FCOB assemblies with eutectic Sn-37Pb assemblies. The FCOB assemblies are supplied by Infineon Technologies as part of the collaboration work with NTU. At the time of this study, lead-free Sn-3.8Ag-0.7Cu solder bumping was not available, and lead-free Sn-3.5Ag solder bumps was chosen instead.

(b) Finite element modeling methodology for both the micro-BGA and FCOB assemblies were developed. Micro-BGA For the micro-BGA case study, 2D plane strain and 3D strip models were investigated. For the FCOB assembly, 2D plane strain model were used. The temperature profile was simulated to represent the actual reliability temperature shock test. Failure parameters such as the accumulated inelastic plastic or creep strain and accumulated inelastic energy density were obtained and used in solder joint fatigue life prediction models to predict the fatigue life cycles of the solder joints. This predicted solder joint fatigue life will then be compared to the experimental MTTF.

(c) Both temperature shock (TS) and temperature cycling (TC) reliability test has been used to characterize the reliability of electronic packages. The advantage of temperature

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shock test is the ability to shorten the temperature test time by up to 5X. Agarwal et al [21] has provided experimental results for both the TS and TC test. In this study, the FCOB assembly reported by Agarwal will be modeled and the fatigue life prediction analysis will be employed and validated by the MTTF from both the TS and TC test. Conclusions will be drawn as to the accuracy of FEA for simulation of different temperature profiles. In temperature loading simulations, many different starting temperatures can be modeled with room temperature 25°C being the most common starting point. The different stress free states are expected to affect the deformation behavior of the FCOB assembly. The scope of this study will extend to the study of the effect of different stress-free states on the energy density and the fatigue life predicted.

(d) Another scope of this work is to develop a Lead-free and Lead-based solder fatigue database and analysis software. There are many fatigue life prediction models for different conditions and different solder alloys. There's a need for a development of software which will seek to create a platform for previously time-consuming and cumbersome fatigue life calculations on a simplified user interface platform, consisting of the most commonly used fatigue life prediction models. This will be a One-Stop post processing software for the FEA fatigue life prediction analysis.

1.7 Structure of the Report

Chapter One of the report gives an introduction of the DFR methodology and the scope of the project. Chapter Two presents the literature review on the accelerated test, FEA modeling and simulation, fatigue life prediction analysis and reliability analysis. Chapter Three will present temperature shock experimental procedure for the reliability testing conducted for both the micro-BGA and the FCOB assemblies. Chapter Four and Five provides the FEA study and the fatigue life prediction analysis for both the micro-

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BGA and the FCOB assemblies respectively. Chapter Six will document the post-processing software developed for the post-processing fatigue life prediction analysis. Chapter Seven will present the FEA results in varying modeling parameters such as temperature cycling profile and different stress-free states. Conclusions and recommendations are made in Chapter Eight.

Chapter Two: Literature Review on Design for Reliability Methodology

2.0 Overview of the Chapter

This chapter will provide a review on the DFR methodology (figure 2.1) applied to this project. *Section 2.1* provides a description of the ATC profiles developed for board-level solder joint reliability evaluation. *Section 2.2* reviews applications of 2D and 3D FEA modeling and simulation for solder joint reliability analysis. A detailed review of solder fatigue life prediction models is documented in *section 2.3*. *Section 2.4* documents the reliability analysis concepts, the MTTF and the Weibull Distribution.

Figure 2.1: Literature Review

2.1 Accelerated Tests for Solder Joints Reliability

Accelerated thermal cycling tests (ATC) are usually carried out to evaluate the reliability of solder joints. These accelerated tests, as the name of the test implies causes the failure process to occur at a shorter time. Two commonly used reliability tests are Thermal Cycling (JESD22-A104-A) and Thermal Shock (JESD22-A106-A). Thermal cycling (TC) has a ramp rate varying from 8°C /min to 33°C /min, whereas thermal shock (TS) condition has a ramp rate between 33°C /min and 50°C /min. Dwell time is included at the cycle extremes to allow for creep and stress relaxation process to take place. The thermal environment for solder joints in electronic packages can be seen in table 2.1.

Table 2.1: Thermal environment for solder joints

Use Conditions	Thermal Excursion (°C)
Consumer Electronics	0 to 60
Telecommunications	-40 to 85
Commercial Aircraft	-55 to 95
Military Aircraft	-55 to 125
Space	-40 to 85
Automotive – Passenger	-55 to 65
Automotive – Under the Hood	-55 to 150

A typical TC and TS profile is shown in figure 2.2.

Figure 2.2: TC and TS Typical Profiles

2.2 FEA modeling and Simulation

FEA has been used very extensively in the electronic packaging industry for thermo-mechanical reliability design. It is used as a tool to model the package and simulate the temperature cycling profiles. The FEA stress strain results are used with the appropriate fatigue life prediction models to estimate the solder joint fatigue life cycles. There are however different ways of modeling the assemblies; the electronic package could be modeled as two-dimensional (2-D) plane strain or 2-D plane stress, three-dimensional (3-D) Strip, 3-D $1/8^{\text{th}}$ model, 3-D $1/4^{\text{th}}$ model and full 3-D model. Figure 2.3a, 2.3b and 2.3c shows the FEA models of 2-D, 3-D Strip and 3-D $1/8^{\text{th}}$ model respectively.

Figure 2.3: FEA Models

Pang et al [22] investigated the effects of employing different 2-D plane strain and plane stress, 3-D strip and 3-D $1/8^{\text{th}}$ model. It was found that the 2-D plane stress and 2-D plane strain usually bound the 3-D FEA model results. The 2-D plane strain results usually predict higher strain values resulting in a more conservative fatigue life. It was also found that computational time and hard disk space were saved using the 2-D plane strain model without sacrificing much of the accuracy. Therefore in this study, a two-dimensional (2-D) plane strain model of a micro-BGA and flip chip package were used. The plane strain condition is used because the thickness of the assembly is large compared to its cross section.

2.3 Fatigue Life Prediction Models

Many solder fatigue models have been used for fatigue life prediction of solder joints subjected to accelerated test.

2.3.1 Methods of predicting fatigue life

Solder joint fatigue life prediction models are widely used for predicting solder joint time to failure. There are four classifications of the solder fatigue models: stress-based, plastic strain-based, creep strain-based and energy-based. The stress-based model is based on the application of a force or stress to a component, causing a resultant strain. Typically, stress-based fatigue applies to vibrational or physically shocked or stressed components. In the strain-based models, a strain is applied, resulting in stresses within a component. Thermal fatigue-induced strains from CTE mismatch fall under this category.

2.3.1.1 Strain range approach

For the strain range approach, the total number of cycles to failure, N_f , is dependent on the strain range amplitude, $\Delta\epsilon$. As the solder joint deforms, the accumulated strains will

weaken the structure of the solder joints and eventually lead to solder fatigue failure. Figure 2.4 will show an idealized total strain range and hysteresis loop.

Figure 2.4: Elastic-Perfectly Plastic Hysteresis Loop

2.3.1.2 Energy-based approach

For the energy-based approach, the total number of cycles to failure, N_f , is dependant on the inelastic strain energy density. When a material is loaded, there are 2 parts of energy being dissipated; they are the recoverable (elastic) part and an irrecoverable part which causes inelastic deformation. This is the energy that causes permanent inelastic deformation and damage in the material. The plastic work (ΔW) is the area under the hysteresis loop as shown in Figure 2.4.

2.3.2 Coffin Manson's Model

For strain-based analysis, Coffin-Manson fatigue model [23-24] is widely used for low cycle fatigue analysis. The total number of cycles to failure, N_f , is dependent on the plastic strain range, $\Delta\epsilon_p$, the fatigue ductility coefficient, C , and the fatigue exponent, m , given in the expression below:

$$N_f^m \Delta\epsilon_p = C \quad \text{--- (2.0)}$$

Solomon [25] reported low cycle fatigue experimental results for 60Sn/40Pb solder joints tested in simple shear. The test was conducted under strain control with plastic strain control limits (i.e. plastic strain applied was constant).

The total number of cycles to failure, N_f is dependent on the plastic strain range, $\Delta\epsilon_p$, the fatigue ductility coefficient, C , and the fatigue exponent, m , given in the expression below:

$$N_f^m \Delta\epsilon_p = C \quad \text{--- (2.1)}$$

Solomon has tested solder joints in simple shear for 60Sn – 40Pb and presented the plastic strain strain range versus fatigue life data for temperatures at -50°C , 35°C , 125°C and 150°C . The frequency of the tests was at 0.3 Hz. The fatigue life was defined as the number of cycles to a 50% load drop condition. Table 2.2 shows the c and m parameters with respect to test temperature.

Table 2.2: Parameters (θ, α) versus test temperature

Temp	-50°C	35°C	125°C	150°C
c	1.36	1.32	0.74	0.30
m	0.50	0.52	0.51	0.37

It was concluded that between -50°C and 125°C , the fatigue life can be approximated by an average Coffin-Manson expression given by

$$N_f = \left(\frac{1.14}{\Delta\gamma_p} \right)^2 \quad \text{--- (2.2)}$$

Pang et al [26] reported low cycle fatigue experimental results for 95.5Sn-3.8Ag-0.7Cu bulk solder specimens. The solder were investigated over a range of test temperatures (25°C , 75°C and 125°C) and frequencies (1Hz and 0.01Hz). Figure 8 shows the hysteresis loop at two test conditions at strain range of 3.5% which shown to give

different cyclic stress strain response. Table 2.3 shows the constants m and c for each test condition.

Figure 2.5: Hysteresis loop at two test conditions

Table 2.3: Curve-fitted Coffin Manson Model for Sn-3.8Ag-0.7Cu

	m			C		
	25°C	75°C	125°C	25°C	75°C	125°C
1Hz	0.913	0.896	0.889	26.3	19.8	16.0
0.01Hz	0.904	0.889	0.871	20.7	16.0	12.1

The life prediction model of 96.5Sn-3.5Ag solder was taken from Kanchanomai et al [27]. Their low cycle fatigue test on Sn-Ag solders were at 20°C, with a constant frequency of 0.1Hz. The failure condition reported in their solder fatigue test is at 25% reduction of maximum tensile load, instead of 50%, which is recommended by ASTM [28].

Equation (2.3) shows the Coffin-Manson type of fatigue model for the 96.5Sn-3.5Ag solder alloy.

$$N_f = 27.63 \Delta \epsilon_{\text{inelastic}}^{-1.08}$$

----- (2.3)

2.3.3 Morrow’s Model

Morrow’s model was used to predict the low cycle fatigue life based on the energy density analysis. The model predicts fatigue life N_f in terms of inelastic strain energy density W_p , as shown below:

$$N_f^n W_p = A$$

--- (2.4)

where n is fatigue exponent, and A is material ductility coefficient. The inelastic strain energy density was determined from the area within the stable hysteresis loop. Table 2.4 shows the constants n and A for each of the conditions tested.

Table 2.4: Morrow’s Constants at Different Conditions [26]

	n			A		
	25°C	75°C	125°C	25°C	75°C	125°C
1Hz	1.103	1.079	0.953	14865	6208.3	1492.8
0.01Hz	0.973	0.944	0.926	1426.2	1144.3	578.9

The constants in the Coffin-Manson and Morrow’s model are dependent on test temperature and cyclic frequency. The creep-fatigue damage effects are more pronounced at higher test temperatures and slower test frequencies for solder alloys, causing shorted fatigue lives.

2.3.4 Engelmaier's Model

The low cycle fatigue life equation for eutectic solder (60Sn/40Pb) provided by Engelmaier [29,30] is given as:

$$N_f = (0.5) \left[\Delta\gamma_T / 2\varepsilon_f \right]^{1/c} \quad \text{--- (2.5)}$$

where c = fatigue ductility exponent

$$= -0.442 - (6 \times 10^{-4}) T_m + (1.74 \times 10^{-2}) \ln(1 + f)$$

with N_f = mean cycle to failure

$\Delta\gamma_T$ = total shear strain range

ε_f = fatigue ductility constant

T_m = mean temperature of the lower limit and upper limit

f = cyclic frequency (operation cycles per day)

Engelmaier curved fitted it using the experimental data of Wild [31]. His data was collected by performing lap shear test (isothermal) with three different conditions, a) 25°C, 300 cycles/hr, b) 100°C, 300 cycles/hr, c) 25°C, 4 cycles/hr.

From Fig. 2.6, the number of mean cycles to failure for a given imposed strain range decreases with decreasing cyclic frequency and increasing temperature.

Fig 2.6: Plots of Wild's data [31]

2.3.5 Shi et al Model (Strain Range Method)

Shi et al [32] developed a temperature and frequency-dependent solder fatigue life prediction model (using the total strain range) from the frequency-modified Coffin-Manson relationship:

$$N_f v^{(k-1)} = \left[\frac{C}{\Delta \varepsilon_T} \right]^{1/m} \quad \text{--- (2.6)}$$

C = ductility coefficient

m = fatigue exponent

v = applied frequency

k = temperature and frequency-dependent exponent.

$\Delta \varepsilon_T$ = Equivalent total strain range

The constants were determined from experiments and are given by,

$$k_1 = 0.919 - 1.765 \times 10^{-4} (T) - 8.634 \times 10^{-7} T^2$$

$$k_2 = 0.437 - 3.753 \times 10^{-4} (T) - 8.04 \times 10^{-7} T^2$$

$$m = 0.731 - 1.63 \times 10^{-4} T + 1.392 \times 10^{-6} T^2 - 1.151 \times 10^{-8} T^3$$

$$C = 2.122 - 3.57 \times 10^{-3} T + 1.329 \times 10^{-5} T^2 - 2.502 \times 10^{-7} T^3$$

Shi et al's experimental data was collected over a wide range of frequencies (10^{-4} to 1 Hz) and temperatures (-40°C to 150°C). From Figure 2.7, the fatigue life was found to decrease linearly with increasing temperature (for a frequency of 1 Hz).

Fig 2.7: Fatigue Life Vs Temperature at 1 Hz [32]

Figure 2.8 shows that the fatigue life cycles of solder decrease with decreasing frequency. As the frequency decreases, the time to failure increases. And this will allow more time for creep to develop and thus lead to lower fatigue life cycles.

Figure 2.8: Relationship Between Fatigue Life and Frequency at 25°C [32]

Figure 2.8 also shows a different trend when frequency change over at 10⁻³ Hz. Hence, the frequency-modified relation, (v^{k-1}), for the two different frequency range are given by:

$$v^{k-1} = v^{k_1-1} \quad \text{---} 10^{-3} \leq v \leq 1\text{Hz} \quad \text{--- (2.7)}$$

$$v^{k-1} = \left[\frac{v}{10^{-3}} \right]^{k_2-1} (10^{-3})^{k_1-1} \quad \text{---} 10^{-4} \leq v \leq 10^{-3}$$

2.3.6 Shi et al Energy Density Fatigue Model

Shi et al [33], also proposed a temperature and frequency dependent energy based, low cycle fatigue life prediction model for eutectic solder given by:

$$\left[N_f v^{(h-1)} \right]^m \frac{W_p}{\sigma_f} = C \quad \text{--- (2.8)}$$

$$v^{h-1} = v^{h_1-1} \quad \text{--- } 10^{-3} \leq v \leq 1 \text{ Hz}$$

$$v^{h-1} = \left[\frac{v}{10^{-3}} \right]^{h_2-1} (10^{-3})^{h_1-1} \quad \text{--- } 10^{-4} \leq v \leq 10^{-3} \text{ Hz}$$

where σ_f is the stress range and W_p is the inelastic energy density in MJ/m^3 , is output from Ansys. The constants are $C = 1.69$ and $m = 0.70$, $(1 - h_1) = 0.1$ for $v \geq 10^{-3} \text{ Hz}$ or $(1 - h_2) = 0.59$ for $< 10^{-3} \text{ Hz}$.

2.3.7 Darveaux's Model (Energy Density Method)

Darveaux [34,35] used a model to correlate the complete failure of a solder joint to the strain energy density. This model utilizes finite element analysis to calculate the viscoplastic work accumulated per cycle during thermal cycling using the Anand viscoplastic constitutive model. The plastic work is employed with crack growth data to calculate the number of cycles to crack initiation and the number of cycles to propagate cracks through a joint. The relationship is given in equation (2.9) and equation (2.10) respectively.

$$N_0 = 22400 \Delta W^{-1.52} \quad \text{--- (2.9)}$$

$$\frac{da}{dN} = 5.86E - 7 (\Delta W^{0.98}) \quad \text{--- (2.10)}$$

ΔW = Strain energy density in Psi

The fatigue life to MTTF is given as [35]:

$$N_f = N_o + \frac{\phi}{da/dN} \quad \text{--- (2.11)}$$

ϕ = Diameter of the solder ball at the Cu-pad interface in inch.

2.3.8 Knecht & Fox Model

Knecht & Fox [36] have developed a life prediction technique based upon the amount of matrix creep accumulated in temperature cycling. A relation between the matrix creep failure parameter with the mean fatigue life to failure is describes in Equation (2.12). This Model is based on the matrix creep strain range per cycle, which assumes the creep shear strain is dominant in the solder joint during thermal cycling.

$$N_c = 8.9/\Delta\gamma_c \quad \text{---- (2.12)}$$

It is noted that the approach is applicable for high strain rates where matrix creep rather than grain boundary deformation predominates, and frequency dependence is not observed.

2.3.9 Creep-Fatigue Interaction Model

This model combines Solomon's low cycle fatigue model with Knecht/Fox's model using Miner's superposition principle. Pang et al [37] have reported the used of this model on predicting the 1st level and 2nd level solder joint fatigue life. This model account for both the plastic and creep strain of the solder joint during temperature cycling.

$$1/N_f = 1/N_p + 1/N_c \quad \text{---- (2.13)}$$

2.4 Reliability Analysis

This section will present some of the fundamental definitions and mathematical theory for reliability. The terms such as reliability function, the probability distribution, the hazard rate and the mean time to failure will be defined.

Reliability is defined as the probability that a system will perform properly for a specified period of time under a given set of operating conditions[38,39]. For a constant sample size, n_0 , of identical products, which are tested or monitored, it may be observed at time t that n_f have failed and that the remaining n_s , are still operating satisfactory. Thus

$$n_s(t) + n_f(t) = n_0 \quad \text{--- (2.14)}$$

The reliability $R(t)$ of a product at time t is estimated by the ratio of operating products per sample size,

$$R(t) = n_s(t)/n_0 \quad \text{--- (2.15)}$$

Similarly, the unreliability or probability of failure $F(t)$ of the product at time t is estimated by the equation

$$F(t) = n_f(t)/n_0 = 1 - R(t) \quad \text{--- (2.16)}$$

A plot of the ratio of the number of product failures $n_f(t)$ per total number of products, as a function of operating life, is called the failure probability density function (PDF) $f(t)$ curve. The PDF is expressed by

$$f(t) = \frac{1}{n_0} \frac{d[n_f(t)]}{dt} \quad \text{--- (2.17)}$$

The unreliability, $F(t)$, is the cumulative distribution function (CDF) of t indicating the probability that the system will fail before the specified time t .

$$F(t) = \int_0^t f(x)dx \quad \text{--- (2.18)}$$

The reliability, $R(t)$, is the complementary cumulative distribution function (CCDF) of t indicating the percentage of products that have not failed up to time t .

$$R(t) = 1 - \int_0^t f(x) dx \quad \text{--- (2.19)}$$

The hazard rate $\lambda(t)$, is defined as the number of failures per unit time per number of operational parts left. It is thus a relative rate of failures. It is also known as failure rate and is the most important reliability metric [40].

$$\lambda(t) = \frac{f(t)}{R(t)} = \frac{-dR(t)/Dt}{R(t)} \quad \text{--- (2.20)}$$

The Mean time to failure (MTTF) is the mean (average) value of the failure time. It is computed with the probability (of failure) density function

$$MTTF = \int_0^{\infty} t f(t) dt \quad \text{--- (2.21)}$$

This integral can be shown to be equivalent to

$$MTTF = \int_0^{\infty} R(t) dt \quad \text{--- (2.22)}$$

2.4.1 Bathtub Curve

Most products exhibit failure characteristics as shown in the bathtub curve of figure 2.9.

Figure 2.9: Bathtub Curve

The life can be in minutes, hours, years, actuations or any other quantifiable unit of time or use. The failure rate is given as failures amount surviving units per time.

The infant mortality stage occurs at the short period of time on the left hand-side with a high but decreasing failure rate. Many products will begin their lives with a higher failure rate which may be due to substandard material, violating tolerances in manufacture, missing parts and damage in shipping. In the case of electronic packaging, failures may potentially be due to non-optimized materials, tolerances violation in the bonding design or the lack of qualification or reliability testing.

The middle section of the bathtub curve contains the smallest and most nearly constant failure rates and is often referred to as useful life. Since this flat behavior is characteristic of failures caused by random events, it is also referred to as random failures.

Aging failure takes place in the wear-out region on the right of the bathtub with increasing failure rate. It is dominated by cumulative effects such as corrosion, fatigue and so on. Failures in the electronic packaging are most likely fatigue failures. As will be described in the later chapters, the solder joint is potentially the weakest material in the electronic package that serves a crucial role for first level interconnection (flip chip bumping or wire-bonding) or Second level interconnection (Solder Joints).

2.4.2 Weibull Distribution Applied in Solder Joint Assemblies

The failure rate is historically modeled using the traditional bathtub curve as shown in the previous section in figure 2.9. Each region can be modeled with a different reliability function. The Weibull distribution [41,42], through the appropriate choice of parameters, can be used to model the early failure, the random failure, as well as the aging failure. This distribution is therefore a general-purpose reliability distribution used to model material

strength, times-to-failure of electronic and mechanical components, equipment, or systems. It is often used as an essential part of Surface mount (SM) assembly reliability assessment programs for statistical analysis of solder joint failure data.

This distribution is widely used in the electronic industry for providing information needed for troubleshooting, classifying failure types, scheduling preventive maintenance, and scheduling inspections.

The Weibull probability density function is defined as follows:

$$f(t) = \frac{\beta}{\eta} \left(\frac{t-\gamma}{\eta} \right)^{\beta-1} \exp \left[- \left(\frac{t-\gamma}{\eta} \right)^{\beta} \right] \quad \text{--- (2.23)}$$

where β = shape parameter, η = scale parameter and γ = location parameter

The mean time to failure (MTTF) is one of the measures of the system's reliability. It defines the time or number of cycles for 50% of the population (that has failed) to fail. The Mean Time to Failure (MTTF) of the Weibull pdf is given by,

$$MTTF = \gamma + \eta \Gamma \left(\frac{1}{\beta} + 1 \right) \quad \text{---(2.24)}$$

For the two-parameter case, the MTTF is reduced to

$$MTTF = \eta \Gamma \left(\frac{1}{\beta} + 1 \right) \quad \text{---(2.25)}$$

Chapter Three: Experimental Methods for Reliability Test

3.0 Overview of Chapter

This chapter documents the experimental procedures for ATC test strategy to experimental set-up, test procedures and program. The test methodology for the ATC test for solder joint reliability in electronic packages for the Micro-BGA and FCOB assemblies will be presented. Section 3.2 will report on the layout of the test system, the equipment used, the experimental procedure describing the test vehicle used, temperature loading profile, monitoring of solder joint failure and the failure criteria chosen.

3.1 Methodology for ATC Test

Thermo-mechanical failures are the most common cause of failure in the electronic package. It is caused during temperature loading from ATC test or service environment. Due to the thermal expansion between the different materials of the package, the package will deform and results in stresses and strains generated and ultimately cause failure. Since solder is the weakest material in the package, the most likely cause of failure is either within the solder or at the interface between the solder and the copper pad. Temperature loading test has become the most widely used strategy for understanding the reliability of the solder joint.

The test strategy is shown in Figure 3.1. The test matrix for the micro-BGA and the FCOB assemblies is shown in table 3.1. During the setting up of the temperature loading profile, thermocouples were placed at different corners of the chamber to ensure that the temperature and airflow are relatively equal. The test vehicles were connected by high-temperature Teflon wires to an Agilent data logger for continuity resistance measurement and placed in a fabricated test fixture. During the test, the resistances are measured at equal interval of 15 mins to monitor the rise in resistance. The failed samples were then cold mounted with room-temperature curing resin for failure analysis and microstructure study.

Table 3.1: Test Matrix for Temperature Shock Test

Package Type	Solder Alloy	Temperature Shock Test
FCOB	Sn-Pb37	9 units
	Sn-3.5Ag	12 units
Micro-BGA	Sn-3.8Ag-0.7Cu	8 units

Figure 3.1: Test Strategy

3.2 Experimental Setup

Figure 3.2 shows the temperature cycling test facilities which consist of the followings:

- a) Temperature Cycling Chamber
- b) Test Fixture
- c) Data Logger
- d) Personal Computer
- e) High Temperature Wires

The temperature cycling test is carried out in a three-zone temperature cycling chamber.

The temperature limit of the system is from -80°C and 220°C with ramp rates of up to $70^{\circ}\text{C}/\text{min}$. The daisy chains connecting the units under test is connected to the data logger via high temperature wires.

Figure 3.2: Temperature 3-Chamber System

3.3 Experimental Procedure

3.3.1 Micro-BGA board-level assembly

The test vehicle is a Micro-ball grid array (micro-BGA) assembly that consists of Polyimide, HDI, Silicon(Si), Cu Pads, Sn-3.8Ag-0.7Cu solder joint and a BT board with 9 mounting sites. The micro-BGA package [43] has been successfully applied in many advanced electronic products, due to its capacity of high density, high performance and low power dissipation. As the electronic industry continues to push the envelope of extreme miniaturization, product development teams are being forced further into the realm of high density interconnect and micro via technology. Among the benefits of HDI technology is:

- Size reduction (lower substrate size, weight and volume)
- Increased wiring density including closer component spacing and smaller component footprint
- Higher densities, which translates to lower cost per connection
- Greater design efficiency (micro vias allow for easier part placement on both sides of the board, and "via in pad" allows for easier escape routing and higher densities).

The high density interconnect (HDI) and micro-via in Pad design Studies have also shown that micro-BGA packages show improvement of reliability compared to other types of package [44-46]. A SEM picture of the lead-free solder interconnect for the micro-BGA is taken to measure the details at the solder joint and is found in figure 3.3.

Figure 3.3: Cross Sectioned Picture of Micro-BGA

The details of the test specimen can be found in table 3.2.

Table 3.2 Test Board Details for Micro-BGA specimen

Description	14 by 14 rows, depopulated
Number of solders	179
Die size	3.49 by 3.49

Die height	0.25 mm
Solder Bump Height	0.4 mm
Solder Diameter	0.54 mm
Solder pitch	0.8 mm

Before the start of temperature cycling test, a fluke multimeter was used to measure the resistance at time zero. This is to ensure that all the solder interconnects have not failed. The interconnections are connected via daisy chains for resistance monitoring.

Figure 3.4 (a): Test Vehicle for Thermal Fatigue Studies

Figure 3.4 (b) : Test Vehicle (with die removed) for Thermal Fatigue Studies

3.3.2 FCOB board-level assembly

The test vehicles used in this test evaluation are 2 sets of FCOB assembly that consists of electroplated Sn-37Pb and Sn-3.5Ag solder bump. Figure 3.5 shows the SEM cross sectioned picture of a FCOB assembly test vehicle. For both solder bump composition, the same test board was used and the properties documented in table 6.

Figure 3.5: Cross Section Picture of FCOB Assembly Test Vehicle

Table 3.3: Test Board Details for FCOB Assembly

Test Board Characteristics	
Material	BT Core
Cu Pad Finishing	Electroless Ni Au
Board Dimension	50mm x 50 mm
Board Thickness	0.5mm
Pad Diameter	100 µm
Pad Pitch	200 µm
Solder Mask Design	NSMD

Figure 3.6 shows the test vehicle that was used in the temperature cycling test. The solder bumps were connected via daisy chain for continuous monitoring. The test die characteristics are shown in table 3.4.

Figure 3.6. FCOB Assembly Test Vehicle

Table 3.4 Test Die Details

Test Die Characteristics		
UBM	Cr / Cu	Cr / Cu
UBM Diameter	100μm	100μm
Bump Type	Sn63/Pb37	Sn96.5/Ag3.5
Passivation	BCB	BCB
Die Dimension	5mm x 5mm	5mm x 5mm
Die thickness	0.725mm	0.725mm
Bump Pitch	200μm	200μm
No. of Bumps	572, Full Array	572, Full Array
Bump Height / Diameter	100μm / 120μm	70μm / 100μm

3.4 Loading Profile

The period of the thermal shock was 18 min, with the temperature varying from -55 to 125°C according to JEDEC A106-A Thermal Shock Standard Test, Condition C [47]. Table 3.5 shows the several test conditions that were recommended for temperature shock limits. The temperature was ramped up from -55 to 125°C at the rate of 40°C/min and then remained for 5 min at the maximum temperature of 125°C. Next, it was ramped down at a similar rate to -55°C and held for another 5 min at the minimum temperature, before the

repetition of the next cycle. Temperature cycling at temperatures greater than or equal to half the melting temperature of solder causes cyclic creep and plastic deformation which leads to low cycle thermal fatigue of solder joints. Figure 3.7 shows the temperature loading profile.

Table 3.5: Recommended Thermal Shock Test Conditions

Test Conditions	A	B	*C	D
T _{max}	85	100	125	150
T _{min}	-40	-0	-55	-65

* Condition selected for ATC test

Figure 3.7: Temperature Loading Profile

3.5 In-situ resistance monitoring of Solder Joints

The most common methods of determining joint failure during a temperature cycling test is by continuous resistance monitoring. In this project, electrical resistance measurement or continuity monitoring [48] was used to detect for failure of solder joint. Failure of the solder joint (ie: an open joint or resistance) values exceeding 300Ω was

---

defined in this study [45]. The MTTF was calculated based on a two-parameter Weibull analysis using the experimentally obtained solder fatigue failure cycles as an input.

3.6 Cross Sectioning

Cross-sectioning of the failed units were carried out to analyze the physics of failure and to identify the failure location and the mode of failure. The failed sample is cut to appropriate size and near the location of failure site, by using a diamond cutter saw. The sample was then placed in a plastic cup holder. A dry film lubricant was sprayed in the mounting cup for easy removal of the sample after solidification. A mixture of 16.1g of epotic resin and 1.9g of hardener epofix is poured into the plastic cup. Since the mixture of resin to hardener is crucial, a SB24001 Delta Range weighing machine is used. The sample was then left to cure for 24 hours. After curing, the sample was taken out from the plastic cup holder. The sample (Figure 3.3) was then polished and grinded for failure analysis and microstructure studies.

Chapter Four: Case Study I – DFR Methodology for Micro-BGA Assemblies

4.0 Overview of Chapter

In this chapter, the results from the experimental work and the finite element analysis of the micro-BGA will be documented. *Section 4.1* documents the number of temperature cycles to failure for individual samples. It presents the Weibull distribution plotted and the Mean Time to Failure calculated from the Weibull plot. *Section 4.2* presents the failure analysis of the samples after temperature cycling test. It will document the failure sites and modes. *Section 4.3* employs the use of finite element modeling for solder joint fatigue life prediction modeling and compares it to the MTTF.

4.1 Experimental Results

Table 4.1 shows the test results for the micro-BGA that undergone temperature shock test. The number of cycles to the first and the last failure detected by the datalogger is 1269 and 3412 cycles respectively. The failure criterion is 300 ohms.

Table 4.1: Failure Cycles of micro-BGA Specimens

Chip Number	Cycles to Failure
105	1269
108	2866
106	2991
102	3011
103	3047
101	3167
107	3218
104	3412

4.1.1 Weibull Distribution of results

The Weibull distribution was introduced in section 2.5 and would be plotted to determine the Mean-Time-To-Failure (MTTF) and the Characteristic life. Based on equation (2.19), if the location parameter, γ , is assumed to be zero, the distribution then becomes the two-parameter Weibull or,

$$f(t) = \frac{\beta}{\eta} \left(\frac{t}{\eta} \right)^{\beta-1} \exp - \left(\frac{t}{\eta} \right)^{\beta} \quad \text{---(4.1)}$$

The Mean Time to Failure (MTTF) of the Weibull pdf is given by,

$$MTTF = \gamma + \eta \Gamma \left(\frac{1}{\beta} + 1 \right) \quad \text{---(4.2)}$$

For the two-parameter case, the MTTF is reduced to

$$MTTF = \eta \Gamma \left(\frac{1}{\beta} + 1 \right) \quad \text{---(4.3)}$$

The 2-parameter Weibull chart was plotted using the ReliaSoft's Weibull++ 6.0 software and shown in figure 4.1. The 1st failure, MTTF and the Beta or slope is given in table 4.2.

Table 4.2: MicroBGA Temperature Shock Test Results

	1 st Failure	Beta/Slope	MTTF
MicroBGA	1269	4.2	2846

Figure 4.1: Weibull Plot of Micro-BGA Test Units

4.2 Failure Analysis

The purpose of the analysis is to look at the failure site, mode and mechanism in the solder joint that was subjected to the temperature shock loading profile. Scanning Electron Microscopy (SEM) and optical microscope were used in this study. Figure 4.2 shows corner solder joint after the thermal shock test. The figure shows that the failure initiation point to be at the corner of the joint. This phenomenon is due to the concentration of stress at this point. The fractures all occur inside the solder, near and approximately parallel to the copper pad. This is because the cracks propagate along the interface region between the IMC layer and the bulk solder, similar to the behavior seen by Tu et al [43].

It was also observed in the figure that most of the solder joints has voids in them signifying a manufacturing defects. In the process report on lead-free solder joint, National Electronics Manufacturing Initiative (NEMI) [49] had observed the trend that lead-free sphere component assembled with lead-free paste has higher number of voids then in the Tin-lead sphere component assembled with tin-lead paste. John H. Lau [50] has also documented large voiding appearing in microvia-in-pad solder joint. Figure 4.2 also shows that the initiation sites could also be in the voids.

Figure 4.2: Possible Crack Initiation and propagation Sites

4.3 Fatigue Life Prediction Modeling

The section employs FEA modeling and simulation to predict the number of cycles to failure for this micro-BGA package. The use of 2-D plane strain model and 3-D slice model is very often used by many researches in the industry studying the thermo-mechanical behavior of electronic packages.

Although using 2D plane strain model and 3D slice model does not capture the full thermo-mechanical deformation behavior perfectly compared to a full 3D model, extensive literature reviewed have provided calibrated FEA results of 2D plane strain model, 3D slice model and full 3D model results and their expected differences within engineering expectations. FEA simulations of flip chip solder joint reliability studies often employ 2-D-

plane strain models [51]–[54]. In recent years, there were also similar studies employing the use of 3-D slice models to investigate the solder joint stress and strain behavior [55]–[58]. In those cited references, different packages such as Low profile Fine-Pitch Ball Grid Array (LFBGA), Flip Chip On Board (FCOB) and Ball Grid Array (BGA) were studied.

Zhu et al. [59] conducted a study comparing the results from 3D Slice model and 3D 1/8th model. He noted that while 3D 1/8th model may give a better approximate to the real package compared to other models, the obvious disadvantage is of the calculation time and harddisk space needed to perform a simulation run. In his study comparing the simulation and the experimental results, he noted that the fatigue life predicted using 3D slice model and 1/8th model is within 8% while the deviation from the experimental results is within 20% and 10% respectively. Yeo et al [60] also conducted a study comparing the results from 3D Slice model and 3D 1/8th model. He noted that the difference in the fatigue life predicted is less than 6% comparing both models. Yeo et al concluded that the 3D-Slice model was preferred to 3D-octant model due to better computational efficiency.

4.3.1 Finite Element Modeling of Micro-BGA

From the extensive literature reviewed, the micro-BGA was chosen to be modeled as a 2-D plane strain and 3-D slice model using the ANSYS software. In this work, a commercial FEA program, ANSYS 6.1 was used to solve this thermal-mechanical problem. The temperature profile loading is based on the temperature profile used in the experimental work. Figure 4.3 and 4.4 shows the 2-Dimension micro-BGA plane strain FEA model with the materials defined respectively.

For the 2-Dimension model, 2 boundary conditions were set as shown in figure 4.3(b). Nodes along the plane of symmetry was restricted to prevent movement

perpendicular to its plane. A node was restricted in the y-direction to prevent free body translation and rotation in the space during simulation.

Figure 4.3: 2-D micro-BGA Finite Element Model

For the 3-Dimension Slice model, 5 boundary conditions were set as shown in figure 4.4. Boundary conditions were set along a plane of symmetry and at a node to prevent free body translation and rotation in the space during simulation. For the 3-D slice model, 2 other boundary conditions, BC4 and BC5, coupling needs to be defined. The purpose of this boundary condition is to couple the nodes at the edge and constraint to only out of plane movement during thermal loading condition.

Figure 4.4: 3-D Slice micro-BGA Finite Element Model

The constitutive models used for various materials in the micro-BGA assembly are summarized in Table 4.3.

Table 4.3: Thermo-Mechanical Constitutive Models of Micro-BGA Assembly Materials

Material	Constitutive model	Source
Silicon Die	Elastic-isotropic	[20]
Polyimide	Elastic-isotropic	Vendors data
Mould	Temp-dependent elastic, isotropic	[20]
Copper Pad	Elastic-isotropic	[20]
HDI	Elastic-isotropic	Vendors data
PCB	Temp-dependent elastic, isotropic	[20]
Die Adhesive	Temp-dependent elastic, isotropic	[20]
Sn-3.8Ag-0.7Cu Solder	Viscoplastic	Curve-fitted

The temperature profile used has a dwell time of approximately 5 minutes and a ramp time of approximately 3 minutes. Table 4.4 and figure 4.5 shows the profile for the temperature cycling. This temperature profile was obtained from the Jedec Standard (JESD22-A106-A).

Table 4.4: Thermal Cycling Profile

T _L (°C)	T _H (°C)	Ramp Rates	Dwell time (mins)
-55	125	50°C	5

Figure 4.5: Thermal Cycling Profile

4.3.2 Constitutive Models and Mechanical Property for Solder Material

The high homologous temperatures (e.g., $0.5T_m$ for eutectic SnAgCu at room temperature) experienced by the solder and the thermally activated strains imposed on it due to the thermal expansion mismatch between the materials in a packaging assembly give rise to a complex deformation behavior. This deformation behavior is associated with the irreversible, temperature and rate (or time) dependent inelastic characteristics. This deformation behavior is known to be viscoplasticity with general relations such as creep and stress relaxation phenomena in materials working in the high homologous temperature regime. Two approaches of simulating the behavior of solder are often used. Firstly, a phenomenological approach using an elastic-plastic-creep analysis model simulates time independent plasticity and time dependent creep deformations in the solder joints. Secondly, a state-variable approach using a viscoplastic analysis based on the Anand model simulates the strain rate dependent inelastic deformations in the solder joints.

4.3.2.1 Anand Viscoplastic Model

ANSYS has an option for viscoplastic analysis using the Anand's viscoplastic model [61] to describe the rate-dependent material behavior with the large strain solid, VISCO107 element, for 3-dimensional large strain solid. The basic features of the Anand model is that there is no explicit yield surface, rather the instantaneous response of the material is dependent on its current state. Secondly, a single scalar internal variable "s", called the deformation resistance, is used to represent the resistance to inelastic flow of the material. Anand's model is expressed by a flow and three evolution equations:

$$\frac{d\varepsilon_p}{dt} = A \left[\sinh \left(\frac{\xi \sigma}{s} \right) \right]^{\frac{1}{m}} e^{\left(\frac{-Q}{kT} \right)} \quad \text{----- (4.4)}$$

$$\frac{ds}{dt} = \left\{ h_o (|B|)^a \frac{B}{|B|} \right\} \frac{d\varepsilon_p}{dt} \quad \text{----- (4.5)}$$

$$B = 1 - \frac{s}{s^*} \quad \text{---- (4.6)}$$

$$s^* = s^{\wedge} \left(\frac{1}{A} \frac{d\varepsilon_p}{dt} e^{\frac{Q}{kT}} \right)^n \quad \text{---- (4.7)}$$

Some of the Anand's constants published were documented in table 4.5. In this study, the constants for the lead-free solder Sn-3.8Ag-0.7Cu were implemented in ANSYS.

Table 4.5 Anand model constants for different solder alloys [62,63,64 and 65]

Parameters	62Sn36Pb2Ag	92.5Pb5Sn2.5Ag	60Sn40Pb	96.5Sn3.5Ag	97.5Pb2.5Sn	63Sn37Pb	Sn3.8Ag0.7Cu*
S0 (MPa)	12.41	33.07	56.33	39.09	15.09	38	S01
Q/k (°K)	9400	11010	10830	8900	15583	5797	k1
A	4.00E6	1.05E5	1.49E7	2.23E4	3.25E12	26	A1
ξ	1.5	7	11	6	7	10	ξ1
m	0.303	0.241	0.303	0.182	0.143	0.256	m1
ho (MPa)	1379	1432	2640.75	3321.15	1787.02	92148	ho1
s^ (MPa)	13.79	41.63	80.42	73.81	72.73	83.1	s^1
n	0.07	0.002	0.0231	0.018	0.00437	0.043	n1
a	1.3	1.3	1.34	1.82	3.73	1.24	a1

* Proprietary Data

ANSYS has an option for viscoplastic analysis using the Anand's viscoplastic model to describe the rate-dependent material behavior with the large strain solid, VISCO108 element, for 2-dimensional large strain solid and VISCO107 element, for 3-dimension large strain solid. Many solders were curve fitted to the viscoplastic anand's model for use in ANSYS software because it is more convenient to implement and faster to solve compared to the elastic-plastic-creep constitutive model.

4.3.2.2 Elastic-Plastic-Creep (EPC) Analysis

Alternatively, the solder can be modeled as a separate constitutive model taking into account the time-independent plasticity and the time-dependent creep. This EPC analysis method breaks down the non-linear deformation process of the solder into time independent plastic strain and time dependent creep strain in a phenomenological manner. This approach enables the user to analyze the deformation behavior of the solder due to creep and plastic behavior.

The elastic modulus and yield stress [66] of the lead-free solder Sn-3.8Ag-0.7Cu solder is given in equation (4.8) and (4.9) respectively which was taken to be temperature and strain rate dependent. The solder is assumed to exhibit elastic and then perfectly plastic behavior after exceeding the yield stress.

Figure 4.6: Effect of strain rate and temperature on Elastic Modulus

Figure 4.7: Effect of strain rate and temperature on Yield Stress

The Young's modulus of 95.5Sn-3.8Ag-0.7Cu is as follows:

$$E(T, \dot{\epsilon})_{SnAgCu} = (-0.0005T + 6.4625) \log(\dot{\epsilon}) + (-0.2512T + 71.123) \quad \text{----- (4.8)}$$

The yield stress were established and expressed individually as follows:

$$\sigma_y(T, \dot{\epsilon})_{SnAgCu} = (-0.2314T + 68.37)(\dot{\epsilon})^{(2.29 \times 10^{-4}T + 0.074)} \quad \text{----- (4.9)}$$

Creep is a rate dependent material non-linearity in which the material continues to deform under a constant load. Conversely, if a displacement is imposed, the reaction force (and stresses) will diminish over time due to stress relaxation as shown in figure 4.8a. The three stages of creep are shown in figure 4.8b.

Figure 4.8: Creep Illustration

ANSYS analyzes creep using two time integration methods, implicit and explicit creep method. The *implicit* creep method is used as it is robust, fast, accurate, and recommended for general use. It can handle temperature dependent creep constants, as well as simultaneous coupling with isotropic hardening plasticity models.

The hyperbolic-sine steady state creep model for 95.5Sn-3.7Ag-0.8Cu solder alloy [26] is given in equation (4.10).

$$\dot{\epsilon} = 3.2 \times 10^4 [\sinh(0.037\sigma)]^{5.1} \exp\left(-\frac{6524.7}{T}\right) \quad \text{--- (4.10)}$$

4.3.3 Mesh Refinement Study

In finite element modeling, a finer mesh typically results in a more accurate solution. However, as a mesh is made finer, the computation time increases and the recourses increases. Therefore an optimization of computing accuracy, computing time and storage space is necessary to determine the mesh size density. One way is to perform a mesh convergence study. The steps are as follows:

1. Create a mesh using the fewest, reasonable number of elements and analyze the model.
2. Recreate the mesh with a denser element distribution, re-analyze it and compare the results to those of the previous mesh.

3. Keep increasing the mesh density and re-analyzing the model until the results converge satisfactorily.

Figure 4.9: Mesh Refinement Study

4.3.4 Fatigue Failure Parameters Extraction

For viscoplastic simulations, the average accumulated plastic work in the solder at the interface of the joint is acquired for fatigue life prediction. It was shown that the calculated strain energy density increases as element size decreases. Hence a volume averaging technique [34-35] was used to reduce this sensitivity to meshing.

In the post-processing stage, the averaged accumulated plastic work, ΔW , is obtained by subtracting the plastic work after 2nd cycle from the plastic work after the 3rd cycle. The average accumulated plastic work, ΔW , is defined as

$$\Delta W_{ave} = \frac{\sum \Delta W \cdot V}{\sum V} \quad \text{---- (4.11)}$$

Where

- ΔW_{ave} : Average viscoplastic strain energy density accumulated per cycle for the interface elements
- V : Volume of each element
- ΔW : viscoplastic strain energy density accumulated per cycle of each element

For E-P-C analysis of the solder joint, the accumulated equivalent inelastic strain and accumulated inelastic energy per cycle is obtained as failure parameters for fatigue life prediction. Volume average method is similarly used. The failure parameters are documented in equations (4.12) and (4.13).

Accumulated equivalent plastic strain $\Delta \varepsilon_{pl} = [\sum \Delta \varepsilon_{pl} \times V] / \sum V$

Accumulated equivalent creep strain $\Delta \varepsilon_{cp} = [\sum \Delta \varepsilon_{cp} \times V] / \sum V$

Accumulated inelastic strain $\Delta \varepsilon_{inelastic} = \Delta \varepsilon_{pl} + \Delta \varepsilon_{cp}$ --- (4.12)

Accumulated equivalent plastic strain energy density $\Delta W_{cp} = [\sum \Delta W_{pl} \times V] / \sum V$

Accumulated equivalent creep strain energy density $\Delta W_{cp} = [\sum \Delta W_{cp} \times V] / \sum V$

Accumulated inelastic strain energy density $\Delta W_{inelastic} = \Delta W_{pl} + \Delta W_{cp}$ --- (4.13)

The energy density of the solder joints was extracted to determine the location of the solder joint most likely to fail first. Figure 4.10 shows the plastic work of the solder joint at different location of the package after the 2nd cycle. The solder joint that has the highest plastic work is located next to the die. This solder joint is predicted to fail first and the failure parameters would be extracted based on this solder joint.

Figure 4.10: Contour plot of plastic work after 2nd temperature cycle

From the experimental results observed in the previous section 4.2, crack initiation and failure sites can occur at both the interface of the solder and copper pad and the solder and the micro-via. Both interfaces are shown in figure 4.11. The inelastic plastic work obtained from both interfaces was documented in table 4.6. For both viscoplastic and E-P-C analysis, the bottom surface, at the interface of the via, indicates a higher inelastic plastic work which would lead to an early failure. In this analysis, this interface would be used to obtain a conservative predicted number of cycles to failure.

Table 4.6: Inelastic Plastic Work obtained from 3-D slice model

Inelastic Plastic Work	3-D Slice Model	
	Copper Pad and Solder Interface (Top)	Micro-via and Solder Interface (bottom)
Visco-plastic	0.16	0.23
E-P-C	0.118	0.172

Figure 4.11: Extraction of Parameters for Fatigue Life Prediction

4.3.5 Solder Fatigue Life Prediction Results

Table 4.7 summarizes the fatigue life prediction analysis using the viscoplastic and the elastic plastic creep constitutive models for the solder joint alloy.

Table 4.7: Summary of Fatigue Life Prediction Results

Experimental Results (MTTF)	2846	
Visco-plastic Analysis		
	2-D Plane Strain Model	3-D Slice Model
Energy Density	0.337	0.23
<i>N_f</i>	3,120	4,714
Elastic-Plastic-Creep Analysis		
	2-D Plane Strain Model	3-D Slice Model
Accumulated Equivalent Plastic Strain	0.92E-3	0.9E-3
Accumulated Equivalent Creep Strain	0.11E-1	0.8E-2
Total Accumulated Equivalent Strain	0.012	0.0089
<i>N_f</i>	2,796	3,939
Plastic Strain Energy Density	0.2E-1	0.12E-1
Creep Strain Energy Density	0.265	0.16
Total Energy Density	0.285	0.172
<i>N_f</i>	3739	6,452
Elastic-Creep Analysis		
Accumulated Equivalent Creep Strain	0.1E-1	0.08
<i>N_f</i>	3,446	4,452
Creep Strain Energy Density	0.256	0.15
<i>N_f</i>	4,199	7,480

4.4 Discussion

In this section, the DFR methodology was implemented on the lead-free solder joints micro-BGA electronic package. The board level micro-BGA electronic package was

subjected to temperature cycling loading utilizing the temperature shock profile as specified from the JEDEC standard. All the packages failed before 3412 cycles. The MTTF cycle (50% failure) calculated from the Weibull distribution is 3092 cycles. This result is favorable as the MTTF have exceeded the industry’s criteria of no failure before 1000 cycles. Finite element analysis was employed to predict the number of cycles for the solder joints to fail under cyclic temperature loading.

(a) Mesh Refinement Studies

Table 4.8 compares the time taken to run 3 temperature cycles, number of elements for the finite element model, hard disk space required for the generating the model and the energy density output using the volume averaging method. Comparing the refined 3-D model to the 3-D model, there’s a 2.1% increase in energy density but the time taken to run the simulation increased by 1hr. From the results, the element size is chosen based on its optimized processing time and results.

Table 4.8: Summary of Mesh Refinement Studies

	2-D plane Strain	3-D Slice Model (Coarse)	3-D Slice Model (Refined)
Time Taken	36 mins	5 hrs 48mins	6 hrs 42 mins
Number of Elements	2495	13316	15900
Hard Disk Space Required	305Meg	2.55Gig	3.2 Gig
<i>Energy Density</i>	<i>0.35</i>	<i>0.23</i>	<i>0.235</i>

(b) Comparison of different Constitutive models

In this analysis work, 3 constitutive models, viscoplastic, elastic-creep, and elastic-plastic-creep analysis was implemented on the solder joint.

In the elastic-creep analysis, the inelastic deformation of the solder joint is dominated by creep with no plastic deformation. This means that the dwell time and the ramp time of the temperature cycling will determine the inelastic response of the solder in this analysis. In the elastic-plastic-creep analysis, both the plastic deformation, which is the time-independent inelastic strain and the creep deformation, which is the time-dependent inelastic strain, is taken into consideration. From the analysis, the creep deformation dominates the inelastic deformation of the solder. It can be noted that the accumulated creep strain and the creep strain energy output from the FEA simulation for both the elastic-creep and the elastic-plastic-creep analysis is similar. It is also observed from the elastic-plastic-creep analysis that the creep response dominates over the plastic response with one order of magnitude for the inelastic deformation.

Viscoplasticity is characterized by the irreversible straining that occurs in a material over time. The plastic strains are assumed to develop as a function of the strain rate. For metals, it has been long been recognized that the notion of rate-independence of plastic response is only a convenient approximation at low temperature. In this study, a rate-dependent plasticity model as proposed by Anand [61], was applied to the lead-free solder joint. Comparing the results from the 2-D plane strain model, the viscoplastic energy density calculated of 0.337MPa is close to the accumulated energy density from the elastic-plastic-creep analysis of 0.285MPa.

(c) Comparison between 2D plane strain and 3D Strip Model

Both 2D plane strain and a 3D strip model were chosen to represent the micro-BGA package and the results compared and plotted in Figure 5.12. Some observations can be made from the graph. Because of the small thickness for the 3-D strip model, the CTE mismatch effect would be negligible in the out-of plane direction. On the other hand with an in-finite thickness for the 2-D plane strain model, the CTE mismatch is in three directions and therefore contributes to larger deformations of the FCOB assembly. Since the energy density is dependent on the strain and stress responses, the energy density decreases from the plane strain to the 3-D strip model. As a result, the 2-D plane strain results give lower and more conservative fatigue life compared to the 3-D strip model. Similar observations were noted by Pang et al [22]. In his study, he compared results produced by 2D plane strain and 3D strip model and documented similar trends.

Figure 4.12: Comparison of Failure Parameters on the Predicted Fatigue Life Cycle

Chapter Five: Case Study II – DFR Methodology for FCOB Assemblies

5.0 Overview of Chapter

In this chapter, the results from the experimental work and the finite element analysis of the FCOB assemblies will be documented. *Section 5.1* documents the number of temperature cycles to failure for individual samples. It presents the Weibull distribution plotted and the Mean Time to Failure calculated from the Weibull plot. *Section 5.2* presents the failure analysis of the samples after temperature cycling test. *Section 5.3* employs the use of finite element modeling for solder joint fatigue life prediction modeling and compares it to the MTTF.

5.1 Experimental Results

Table 5.1 shows the board level reliability test results for the FCOB packages that undergone temperature shock test. The failure criterion is 300 ohms.

Table 5.1: Cycles to Failure of Sn-37Pb and Sn-3.5Ag FCOB Packages

Cycles to Failure (Sn-37Pb)	Cycles to Failure (SnAg)
2559	1255
2679	2062
2867	2079
2949	2093
3683	2104
3707	2109
3757	2143
4457	2151
4668	2165
2559	2259
	2317
	4000

5.1.1 Weibull Distribution of results

The 2-parameter Weibull chart was plotted using the ReliaSoft's Weibull++ 6.0 software and shown in figure 5.1.

Figure 5.1: 2 Parameter Weibull Plot

Table 5.2: Test Results for the FCOB Assemblies

	1 st Failure	Beta/Slope	MTTF
Sn-37Pb	2559	5.32	3461
Sn-3.5Ag	2195	5.71	2195

5.2 Failure Analysis

The purpose of the analysis is to look at the failure site, mode and mechanism in the solder joint that was subjected to the temperature shock loading profile. Scanning Electron Microscopy (SEM) and optical microscope were used in this study. Figure 5.2 and figure 5.3 shows the SEM picture of the solder joint in the failed unit for the Sn-37Pb and the Sn-3.5Ag respectively after the thermal shock test. The failure mode of the 2 solder compositions is fatigue failure through the bulk solder. The fatigue crack is expected to start near the outer die pad edge and to grow underneath the die pad. In the case of Sn-3.5Ag composition, the failure is accompanied by delamination at the underfill/die interface in the region of the bump vicinity. This is also demonstrated in the study conducted by Schubert et al [1].

Figure 5.2: SEM Picture of Sn-37Pb FCOB Failure Specimen

Figure 5.3: SEM Picture of Sn-3.5Ag FCOB Failure Specimen

5.3 Fatigue Life Prediction Modeling

The section employs FEA modeling and simulation to predict the number of cycles to failure for this FCOB package.

5.3.1 Finite Element Modeling of FCOB

The FCOB was modeled as a 2-D plane strain model using the ANSYS software. The temperature profile loading is based on the temperature profile used in the experimental work. Figure 5.4 shows the 2-Dimension plane strain FEA model with the materials defined respectively. Table 5.3 documents the geometry detail of the FCOB structure while table 3.3 and 3.4 in chapter 3 gives in detail the test board and die geometry.

Table 5.3: Geometry Detail

<i>Material</i>	<i>Description</i>	<i>Dimension (μm)</i>
BCB	Thickness	3
UBM	Thickness / Diameter	3 / 50
Cu pad	Thickness / Diameter	12 / 50
Solder mask	Thickness / Opening Diameter	23 / 75
Standoff Height	Sn-Pb / Sn-Ag	70 / 30

Figure 5.4: 2-D FCOB Finite Element Model

For the 2-Dimension model, 2 boundary conditions were set as shown in figure 5.5.

Nodes along the plane of symmetry was restricted to prevent movement perpendicular to its plane. A node was restricted in the y-direction to prevent free body translation and rotation in the space during simulation.

Figure 5.5: Boundary Conditions for FEA model

The constitutive models used for various materials in the FCOB assembly are summarized in Table 5.4 and the properties are documented in table 5.5.

Table 5.4: Constitutive models for FCOB Assembly materials

Material	Constitutive model
Silicon Die	Elastic-isotropic
Cr-Cu UBM	Elastic-isotropic
Cu Pad	Elastic-isotropic
BCB	Elastic-isotropic
Solder Mask	Temp-dependent elastic-isotropic
BT Substrate	Temp-dependent elastic-isotropic
Underfill	Temp-dependent elastic-isotropic
Solder	Elastic-plastic-creep / Viscoplastic

Table 5.5. Thermo-mechanical Properties of FCOB assembly materials

Material	Young Modulus (Mpa)	CTE (ppm/K)	Poisson Ratio
Silicon Die	131000	2.8	0.3
Cr-Cu UBM	100000	15	0.3
Cu Pad	76000	17	0.35
BCB	325000	2.9	0.24
Solder mask	4700 @ 298K 3914 @ 323K 2342 @ 373K 1556 @ 398K	60	0.47
BT substrate	22000	18	0.28
Underfill	6400 @ 223K 6000 @ 273K 5600 @ 298K 4500 @ 353K 2300 @ 398K	45	0.3

5.3.2 Constitutive Models and Mechanical Property for Solder Material

As was performed for the micro-BGA FEA analysis, two approaches of simulating the behavior of solder are used; the phenomenological approach using an elastic-plastic-creep analysis model and a state-variable approach using a viscoplastic analysis based on the Anand's model. The viscoplastic Anand's constants used for the Sn-37Pb solder is documented in table 5.4 of chapter 5.

The elastic modulus of 96.5Sn-3.5Ag solder is given in equation (5.1). The equation was fitted to a mean loading rate over the range reported from 0.64 MPa/sec to 51 MPa/sec [67]. The solder response is assumed to exhibit elastic and perfectly plastic behavior after yielding. The plastic deformation is characterized by non-recoverable strain and occurs when stresses exceed the yield point of solder. The temperature dependent yield stress given in equation (5.2) is fitted to the average data reported for the strain rates of $5\text{E-}5$ to $5\text{E-}3 \text{ sec}^{-1}$ [67].

$$E \text{ (MPa)} = 92295 - 149.7 \cdot T \quad \text{----- (5.1)}$$

$$\sigma_y \text{ (MPa)} = 200.45 - 0.7756T + 0.0007T^2 \quad \text{----- (5.2)}$$

The elastic modulus of Sn-37Pb solder given in equation 5.3 is taken to be temperature & strain rate dependent. Experiments were conducted [68-70] and found that the strain rate has some impact on the material behavior of solder under loading and at elevated temperatures. Shi et al [71] reported temperature and strain-rate dependent mechanical properties for eutectic solder, where the Elastic modulus and the Yield Stress, $\sigma_y(T, \dot{\epsilon})$ are given by :

$$E = [(-0.006T + 4.72) * \log(d\epsilon/dt)] + (-0.117T + 37) \quad \text{---- (5.3)}$$

$$\sigma_y(T, \dot{\epsilon}) = \begin{cases} (-0.22T + 62) * \dot{\epsilon}^{(8.27e-05T + 0.0726)} & , \text{for } \dot{\epsilon} \geq 5E - 4s^{-1} \\ (0.723T + 105.22) * \dot{\epsilon}^{(1.6224e-03T + 0.1304)} & , \text{for } \dot{\epsilon} < 5E - 4s^{-1} \end{cases} \quad \text{---- (5.4)}$$

where σ_y is in MPa, T is in $^{\circ}\text{C}$, and $\dot{\epsilon}$ is in s^{-1} .

The yield stress used for the Thermal shock condition corresponds to a strain rate of $10^{-4} s^{-1}$ and for Thermal Cycling condition to a strain rate of $10^{-5} s^{-1}$ respectively.

The steady state creep behavior of 96.5Sn-3.5Ag and Sn-37Pb flip chip solder joint tests by Wiese [72-73] were employed. The steady state creep equation of the Sn-3.5Ag solder is given in the simple power law given in equation 5.5 while the Sn-37Pb solder is given in the Sinh-formulation given in equation 5.6. Ansys has the similar implicit creep model, TBOPT = 10 for simple power law and TBOPT = 8 for Sinh equation. The constants $C1$, $C2$, $C3$ and $C4$ are given in Table 5.6.

$$d\epsilon/dt = C_1.(C_3.\sigma)^{C_2}.\exp(-C_4/kT) \quad \text{----- (5.5)}$$

$$d\epsilon/dt = C_1.[\sinh(C_3.\sigma)]^{C_2}.\exp(-C_4/kT) \quad \text{----- (5.6)}$$

Where $k = 8.3145 \text{ J/mol K}$

Table 5.6: ANSYS input for Implicit Creep Analysis

Solder Alloy	$C1$ [s^{-1}]	$C2$	$C3$ [MPa^{-1}]	$C4$ [KJ/Mol]
Sn-3.5Ag	5E-6	11	1	57.1
Sn-37Pb	10	2	0.2	44.9

5.3.3 Solder Fatigue Life Prediction Results

Table 5.7 summarizes the fatigue life prediction analysis using the viscoplastic and the elastic plastic creep constitutive models for the solder joint alloy.

Table 5.7: Summary of Fatigue Life Prediction Results

	Sn-Pb	Sn-Ag
<i>Experimental Results (MTTF)</i>	3461	2144
Energy Density	0.37	-
<i>Nf (Darveaux)</i>	232	-
<i>Nf (Shi)</i>	1581	-
Accumulated Equivalent Plastic Strain	12E-3	11.5E-3
Accumulated Equivalent Creep Strain	3.3E-3	17.04E-3
Total Accumulated Equivalent Strain	15E-3	28.6E-3
<i>Nf (Solomon) – Plastic Strain</i>	8,429	-
<i>Nf (Knech and Fox) – Creep Strain</i>	405	-
<i>Nf (Plastic-Creep Fatigue Interaction Model)</i>	2043	-
<i>Nf (Engelmaier)</i>	8,797	-
<i>Nf (Shi's Strain Range)</i>	450	-
<i>Nf (Kanchanomai)</i>	-	1286
Plastic Strain Energy Density	0.28	-
Creep Strain Energy Density	0.57e-1	-
Total Energy Density	0.344	-
<i>Nf (Shi)</i>	1755	-

5.4 Discussion

5.4.1 Board Level Reliability Test

In this study, both Eutectic Sn-Pb and Lead-free Sn-Ag were studied. Board level reliability test was conducted for both solders using FCOB assemblies and the results compared. The MTTF of the FCOB assemblies with 2 solder types, Sn-37Pb and Sn-3.5Ag

is over 2000 Cycles which is accepted in the industry. The main mechanism of failure of both the solder alloys is solder fractures which is also observed by Ashok et al [74].

From the Weibull distribution, it is shown that the Sn-Pb has a better reliability than the Lead-free Sn-Ag solder. This trend is also observed by Schubert et al [1] when he compared lead-free Sn-Ag and lead-tin Sn-Pb solder in FCOB assemblies. Some of the reasons for this phenomenon might be:

(1) The stand-off height of the Sn-37Pb solder is 70micron while that of the Sn-3.5Ag is 30micron. This will result in a higher strain level induced on the Sn-3.5Ag solder joint and may lead to a shorter fatigue life compared to the Sn-37Pb solder joint.

(2) There have been many studies now determining the best surface finish for lead-free solders but up to today, there has been no clear indication. Two of the most promising surface finishes for use on lead-free solder alloys are Electroless Nickel/Immersion Gold (ENIG) and copper OSP. Michael et al [75] has published results comparing both finishes on BGA devices with Sn-3.5Ag solder joint as the 2nd level interconnection. There is an estimated improvement in characteristic life ranged from 10% to over 100% in copper OSP compared to lead-free samples assembled onto ENIG pads.

5.4.2 Fatigue Life Prediction Analysis

The methodology for performing this solder joint fatigue life prediction analysis is similar to that performed for the micro-BGA analysis in chapter 5. However, for the case of Eutectic Pb-Sn solder alloy, extensive research has been conducted with many researches publishing different variations of fatigue life prediction models. These models are documented in the literature review.

(a) Pb-37Sn Solder Alloy

The number of cycles predicted using the various models compared to the MTTF obtained from the experimental results is tabulated in a graphical format in figure 5.6. At a first glance, the predicted fatigue life falls in the range of 232 utilizing Darveaux model to 8,797 using Engelmaiers model which is in a range factor of around 38 times apart. This is because there is currently no specific standard for the model and researchers are individually using their own failure criteria such as 25 or 50% reduction in inelastic strain range as in Coffin-Manson’s model or modifying the models to better represent the temperature and frequency dependency of the solder joint fatigue such as the frequency modified model as in Shi’s frequency modified inelastic strain range or energy density. In addition, the thermo-mechanical FEA simulation of electronic packaging has many assumptions such as the assumption that the adhesion of the different materials in the package is perfect and there are free of voids and defects. Because of all these factors, it is a readily acceptable that the fatigue life predicted is within 2X the MTTF.

Figure 5.6: Solder Joint Fatigue life prediction Results

Most of the fatigue life prediction model predicted a lower fatigue life compared to Solomon’s and Engelmaier’s model. One possible reason is because in this FEA study, a 2-

D plane strain model is used which will give a highest solder joint strains which was also observed by Pang et al[22] and will predict a conservative life.

Using the Darveaux's model produced the lowest fatigue life. These results were expected because Darveaux used a PBGA package, in which the solder ball diameter is around 5 times smaller than the solder ball used in a FCOB assembly, to obtain the crack growth correlation constants for fatigue life prediction. The plastic-creep fatigue interaction model, Shi's frequency modified energy density method and the plastic-creep fatigue model produced life cycles which are close to that of the MTTF.

From this study, it is concluded that the use of different fatigue life prediction models can result in a large difference in the life predicted. Therefore it is up to the user to make the selection of the solder fatigue life prediction model based on the good understanding of the model.

(b) *Sn-3.5Ag Solder Alloy*

At the point of submission of this thesis, only Kanchanomai et al [76] have conducted low-cycle fatigue test and curve-fitted into Coffin-Manson's inelastic strain based model. This model has predicted a conservative life of 1286 cycles compared to the MTTF of 2144 cycles. This is satisfactory to within 2X of the MTTF. There may be several reasons contributing to the conservative results. Firstly, the failure criterion used by Kanchanomai for their solder fatigue test is at 25% reduction of maximum tensile load, instead of 50%, which is recommended by ASTM [28]. This will result in the predicted conservative life compared to if the criterion is at 50% reduction of maximum tensile load. Secondly, mix-mode failures of delamination and solder fracture are found and can not be accounted in the FEA models.

Chapter Six: Solder Joint Fatigue Life Prediction Software Development

6.0 Overview of Chapter

The Solder Fatigue Life Prediction software, has been developed for solder joint fatigue life calculation for a wide range of Pb-free and Sn/Pb solder fatigue life prediction models. The fatigue life predictions models include new Pb-free solder fatigue models, Sn/Pb solder fatigue database compiled from published reports. This software will provide researchers and engineers with a comprehensive solder joint fatigue database and analysis program.

Various solder fatigue life prediction models have been used in the electronic packaging industry. The solder fatigue models can be classified into five categories namely; stress-based, plastic strain-based, creep strain-based and energy-based fatigue models. The stress-based method employs stress-life or S-N curve fatigue data and is typically used for High Cycle Fatigue (HCF) applications. The plastic strain or creep strain-

based methods employ strain-life or ϵ -N curve fatigue data and is used for Low Cycle Fatigue (LCF) applications. The energy-based method is an extension of the LCF method by employing the stress-strain hysteresis loop energy dissipated per cycle or plastic work done per cycle.

The application of the solder fatigue life prediction models requires input of the critical stress, strain or energy accumulated per cycle of loading. Finite Element Analysis (FEA) modeling of the electronic assembly geometry, material properties and simulation of the thermal cycling loading is often employed to compute the required stress, strain or energy accumulated per cycle.

6.1 Software Development

Microsoft's Visual Basic 6.0 (V.B) was used to develop the fatigue analysis program. The program was selected based on its relative ease of programming and the ability to create user interface and perform simple calculations. The entire process of solder joint fatigue life prediction can be represented in the flow chart in Figure 6.1.

The first step to solder joint fatigue life prediction modeling is to obtain the failure parameter from the stress-strain data of the solder joint under thermal loading. Since it is not easy to measure the solder joint strain due to the small size of the solder joint, Finite Element Analysis (FEA) is employed to calculate the strain. Failure parameters such as the shear strain, plastic strain, creep strain, or the energy density can then be obtained.

The failure parameter derived from FEA will be used in the solder fatigue program. The user could select either the lead-tin solder or leadfree solder options. Based on the failure parameter obtained from the FEA, the required fatigue life prediction model can then be selected. The fatigue life prediction calculations can then be performed using the

solder fatigue model constants provided in the program. This program provides the user with a simple and fast post-processing solder fatigue life prediction analysis.

Figure 6.1: Software Flow Chart

6.2 Brief Overview of V.B Software

V.B. is a high level programming language evolved from the earlier DOS version called BASIC. BASIC means **B**eginners' **A**ll-purpose **S**ymbolic **I**nstruction **C**ode. It is a fairly easy programming language to learn. The codes look a bit like English Language.

V.B however is a VISUAL and events driven Programming Language. Programming is done in a graphical environment. Each object is to be programmed independently in order to be able to response to actions (events). Therefore, a V.B. program is made up of many subprograms, each has its own program codes, and each can be executed independently and at the same time each is to be linked together in one way or another. As such, V.B. is the most appropriate language to use for this application because of the many fatigue life prediction models available for different compositions of solders.

6.3 Software User Interface and Demo

The user will enter the menu as seen in Figure 6.2 when the software is executed. The user would then be given a choice to choose the type of solder. By clicking the lead/tin button, the menu containing the most commonly use fatigue life prediction models will appear as seen in the figure.

Figure 6.2: Main Menu of Solder Fatigue Software

6.3.1 Micro-BGA Solder Joint Fatigue Life Prediction

In this section, the solder joint fatigue software was used to illustrate the calculation of the micro-BGA’s number of cycles to failure from section 4.3.5. For illustration purposes, only the model with constants at frequency at 0.01 Hz and temperature at 75°C will be shown. In the opening menu of the software, the leadfree solder was chosen and shown in figure 6.3a. The micro-BGA solder joint leadfree solder of composition Sn-3.8Ag-0.7Cu was chosen and the menu shown in figure 6.3b. Figure 6.4 and 6.5 shows the screen capture of the software using Coffin Manson’s plastic strain model and Morrow’s Energy Density Model respectively for fatigue life prediction.

Figure 6.3a: Lead-Free Solder Menu

Figure 6.3b: Lead-Free Solder Menu

Figure 6.4: Coffin Manson’s Strain Range Model

Figure 6.5: Morrow’s Energy Density Model

6.3.2 FCOB Solder Joint Fatigue Life Prediction

In this section, the solder joint fatigue software was illustrated to calculate the FCOB Solder Joint number of cycles to failure In using Shi’s Energy Density method, the button was pressed and a menu as shown in figure 6.6 was shown on the screen. Figure 6.7

and 6.8 shows the Darveaux’s energy density and the Shi’s Total strain range method respectively.

Figure 6.6: Shi’s Energy Density Fatigue Model

Figure 6.7: Darveaux’s Energy Density Fatigue Model

Figure 6.8: Shi's Total Strain Range Fatigue Model

Figure 6.7 shows Darveaux's energy density model which was used as an example to illustrate the software calculations. In the 2-D FCOB FEA model, the default constants of slice, non-linear FEM with Anand's constitutive model was chosen. The joint diameter and the energy density from the FEA results were then manually entered. Next, the "Calculate" button was selected and the predicted number of cycles to failure will appear as shown in the figure.

6.4 Sample of programming code

In this section, a sample of programming code for the above calculation using Darveaux's energy density model will be documented.

(a) Setting of constants :

Variables k1 to k4 are constants either input by the user or chosen from a table of values from Darveaux's paper for the purpose of calculating the crack initiation cycle and crack propagation rate. The constants diameter and energy density will be determined by the user.

Dim k1 As Double

Dim k2 As Double

Dim k3 As Double

Dim k4 As Double

Dim diameter As Double

Dim energydensity As Double

Dim initiation As Double

Dim growth As Double

Each text box on the screen (figure 6.7) is identified. The follow codes will be assigned to the constants once the test box is filled.

k1 = Frm_DarvEnergy.Txt_k1.Text

k2 = Frm_DarvEnergy.Txt_k2.Text

k3 = Frm_DarvEnergy.Txt_k3.Text

k4 = Frm_DarvEnergy.Txt_K4.Text

diameter = Frm_DarvEnergy.txt_diameter.Text

energydensity = Frm_DarvEnergy.Txt_energydensity.Text

(b) Solder Fatigue Life Calculation

initiation = k1 * (energydensity ^ k2)

growth = k3 * (energydensity ^ k4)

Txt_FatigueLife = FormatNumber((initiation + (diameter / growth)), 0) & " cycles"

6.5 Summary

This design of this program is to accommodate for addition leadfree solder fatigue life prediction models and composition since there are so much on-going research to evaluate new leadfree solders. Some of the advantages of this program are listed below:

- (a) Simple and user-friendly program.
- (b) Efficient as the end-users do not require the extensive use of calculators in their studies with the program providing a list of recommended or specific constants.
- (c) Comprehensive as the program provides abstracts to the references used in this program.
- (d) It is designed in such a way for new equations to be easily input into the program and
- (e) It is easily installed and configured to any window-based personal computers.

Chapter Seven: Case Study III – FEA studies in modeling parameters

7.0 Overview of Chapter

Reliability tests are often conducted to quantify the integrity of solder joints for board level reliability test. Temperature cycling (TC) and temperature Shock (TS) tests are commonly used for such reliability tests. There are differences between these two test conditions. First the TS test condition will have a higher ramp rate of $>20^{\circ}\text{C}$ based on IPC-9701 standard compared to TC test profile of $< 20^{\circ}\text{C}/\text{min}$. The TS test profile will have a shorter cycle time and thus preferable to industries. The TS test will have a faster strain rate compared to the TC test. Because of these differences, the fatigue life of the solder joints will be expected to be different for different test profiles. It will be interesting to determine if using the FEA method is able to correctly predict the fatigue life and the trend of both the TS vs TC. Extensive literature research is conducted and Agarwal et al [21] has conducted both experiments of the TC and TS test on FCOB assemblies. This will present a good case study for FEA to be conducted and validated by Agarwal's MTTF. In section 7.1, the FCOB assembly based on the geometry presented by Agarwal was modeled as a 2-D plane strain model. Section 7.2 will present the fatigue life prediction results comparing both TC and TS test.

In thermal loading simulations, many different starting temperatures can be modeled. In the past, researchers have used different kind of stress-free temperatures as the starting point of simulation. G. Gustafsson [77], Yeo et al [78], Pang et al [79] and Seetoh [80] used a stress free temperature of 25°C in their simulation. Others begin their thermal loading at the minimum temperature of -55°C [81-82] and some others at 125°C [83-84]. It will be interesting to understand how the different stress free states are expected to affect the deformation behavior of the FCOB assemblies when it undergoes different sequences

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of temperature changes. In this study, four different stress free state temperature, 183°C, 140°C, 125°C, 25°C and –55°C were investigated and presented in section .

Pang et al's [22] presented stress free state studies at 140°C. However, elastic properties were defined for the underfill. In Liu Chen et al's paper [85], the effects of elastic properties and viscoelastic properties of underfill in temperature cycling simulation and found that the viscoelastic properties give comparatively large plastic strain range and large displacements. In this next section of work, viscoelastic properties will be used to represent the underfill instead of linear-elastic properties and the results will be compared.

7.1 Finite Element Modeling of the FCOB Assembly

The FCOB assembly modeled is similar to the dimensions given in Agarwal's [21] publication. In this study, a two-dimensional (2-D) plane strain model of a flip chip package was used. Due to symmetry, only half of the 2-D model was meshed with 2-D eight-node elements as shown in Fig. 7.1. The elements of the solder ball with the furthest distance from the neutral point (DNP) were refined, as it will experience the largest deformation. For nodes along a plane of symmetry, movement perpendicular to its plane must be restricted. A node was restricted in the y-direction to prevent free body translation and rotation in the space during simulation. The assembly has a silicon die size of 6.35 mm x 6.35 mm, a die thickness of 0.635, and a flip chip joint diameter of 0.15 mm.

Figure 7.1: 2-D Finite Element Model of the FCOB model

7.1.1 Material Properties of FCOB

The material properties of the flip chip assembly can be found in Table 7.1. For simplicity the PCB and the silicon die are considered as isotropic elastic materials with constant properties. The solder joint is represented by the state-variable approach using a viscoplastic analysis explained in detail in section 4.3.2.1. The viscoplastic Anand's constants is documented in table 4.5.

Table 7.1. Material Properties used to represent the FCOB Assembly

Material	Young Modulus (GPa)	CTE (ppm/°C)	Poisson's Ratio
Die	131	2.8	0.3
Underfil	6.9	29	0.3
Solder Joint	75.970-0.152T(K)	21	0.35
PCB	22	18	0.28

Underfill material used in FCOB assemblies is polymer-based material, which is sensitive to both time and temperature [86-88] in their glass transition temperature range. Flip chip packages are usually faced with temperatures ranging from -55°C to 155°C, which covers the glass transition temperature range. In a separate study in section 7.5, the effect on the implementation of viscoelastic mechanical properties of the underfill is considered. A linear viscoelastic model based on the generalized Maxwell elements in an ANSYS finite element code was used. The parameters of the viscoelastic underfill model [89,90] are shown in table 7.2.

$$E(t) = \sum_{i=1}^n E_i e^{(-t/\tau_i)} + E(\infty)$$
$$\tau_i = \tau_{io} \times e^{H/R_o T}$$

--- (7.4)

Table 7.2. Parameters of the Viscoelastic Underfill Model

H/R ₀ (K)	E ₀ (Mpa)	E _∞	C ₁	τ ₁ (s)	C ₂	τ ₂	C ₃	τ ₃
15644	5630	1300	0.264	0.198	0.200	451	0.536	30435

7.2 Thermal Loading Profiles for Thermal Shock Vs Thermal Cycling studies

Table 7.3 shows the loading conditions for the comparison of thermal shock and thermal cycling. These profiles were performed by Argawal et. al.[21] in his experimental work, and presented the results on the 2-parameter Weibull plot and the MTTF for both the thermal shock and thermal cycling.

Table 7.3: Thermal Loading Profiles for TS and TC Test Conditions

	Tmax (°C)	Tmin (°C)	Ramp Rate (°C/Min)	Dwell Time (Mins)	Ramp Time (Mins)	Cycle Time (Mins)	MTTF
TS	150	-50	100	3	2	10	5220
TC	150	-50	10	5	20	50	2945

7.3 Solder Joint Fatigue Life Prediction Results

The procedure for the extraction of the failure criteria, energy density, is documented in section 4.3.4. Table 7.6 presents the energy density outputted from running the thermal cycling and thermal shock loading profile. From the results, it was observed that the energy density of the thermal shock is higher than the thermal cycling. This may be attributed to two reasons. Firstly, the solder material is weaker at a lower strain rate because the smaller yield stress at a lower strain rate. Secondly, with a slower ramp rate it allows more creep to take place and hence stress relaxes to a greater extent. The energy density for TS test is larger because of a faster strain rate (shorter ramp periods), creep deformation in the solder is less prominent. Solder joints under TS test are thus stronger and able to withstand higher stress levels and sustain longer fatigue life. Both Darveaux’s (section 2.3.6) and Shi’s frequency modified energy density (section 2.3.5) solder joint fatigue life prediction model were used. The results of the fatigue life prediction are shown in the following table 7.6.

Table 7.6: Results from the Thermal Loading Studies

	Thermal Shock (TS)	Thermal Cycling (TC)	Scale Factor (TS/TC)
<i>MTTF [21]</i>	5220	2945	1.6
Energy Density (MPa)	0.218	0.17	
Shi's Frequency Modified Energy Density Model	3611	1951	1.85
Darveaux's Energy Density Model	637	780	0.817

The energy density for the TS test is larger (0.218) than that of TC test (0.17) because with a faster strain rate (shorter ramp periods), creep deformation in the solder is less prominent. Solder joints under TS test are thus stronger and able to withstand higher stress levels and sustain longer fatigue life cycles. This is verified in the experimental data and the fatigue life predicted by Shi et al.

Shi et al's fatigue life prediction model using Anand's constants by Darveaux is capable of both capturing the trend and to predict the life cycles accurately comparing to the experimental results. Darveaux's model gave a trend which is opposite to that of the experimental data and predicts a conservative life. This is because Shi's life prediction model takes into account the frequency as one of its parameters while Darveaux's model doesn't.

Despite the discrepancies between the FEM and experimental results in using the Darveaux's energy density method, the scale factor trends and fatigue life predicted by using Shi's energy density model and Agarwal's [21] experiment results were similar. This indicates the ability of the constitutive equations implemented to capture the key deformation modes, i.e., plasticity and creep, as functions of temperature. The discrepancies between the FEM and experimental results may be attributed to the

difference between the parameters in the constitutive equation and the material used in the experiment, since those parameters were determined from separate tests.

7.4 Thermal Loading for Different Stress-Free Temperatures

The different stress free states are expected to affect the deformation behavior of the FCOB assembly when it undergoes different sequences of temperature changes. In this study, 5 different starting temperatures were modeled. Figure 7.2 shows the temperature loading profile. Room temperature of 25°C (starting at position C) is the most common starting conditions. The stress free temperatures of 183°C, 140°C and 125°C were being modeled (starting at position A). This case studies the effect of underfill epoxy curing on the thermal load profile history as it includes the cooling effect from the underfill cure temperature, and continues with thermal cycles based on MIL-STD-883E specification standard, method 1011.9, condition B. The ramp rate for this condition is 50°C/min with a dwell period of 5 minutes.

Figure 7.2: Temperature Profile

7.4.1 Deformation Behavior of Package at different Stress-Free States Temperature

(a) Stress-free Temperature at 183°C

Figure 7.3 shows deformation of the FCOB package after curing from 183°C to 25°C. This case studies the underfill epoxy curing effect before simulating the temperature shock profile. It can be seen that when the temperature is decreased from 183°C to 25°C, the FCOB deflects downwards due to the CTE in the Silicon being lower than that of the FR4. The stress free temperature at 140°C and 125°C follows the same deformation behavior.

Figure 7.3 Deformation Behavior of FCOB Assembly at $T_{SFS} = 183^{\circ}\text{C}$

(b) Stress-free Temperature at -55°C

Figure 7.4 shows the deformation behavior of the FCOB solder joint with a stress-free temperature of -55°C . In some engineering applications, the temperature cycling begins at -55°C . In this case, when temperature begins at -55°C to 125°C , the PCB

expands more than the Silicon and deforms upwards instead of downwards in the previous case.

Figure 7.4 Deformation Behavior of FCOB solder Joint at $T_{SFS} = -55^{\circ}\text{C}$

(c) Stress-free Temperature at 25°C

Figure 7.5 shows the deformation behavior of the FCOB solder joint deformation with the stress-free temperature starting at 25°C . Figure 7.5b and 7.5c shows the deformation behavior after ramping up from 25°C and ramping down from 125°C respectively.

Figure 7.5 Deformation Behavior of FCOB Solder Joint at $T_{SFS} = 25^{\circ}\text{C}$

In the case when the stress-free temperature is 25°C , the FCOB deflects upwards and downwards depending on whether the temperature is ramping down or up. However in the case when the stressfree temperature is 183°C , 140°C or 125°C , the FCOB assembly will remain in the hogging position (bend downwards) throughout the thermal cycles. In

the case when the stressfree temperatures is -55°C , the FCOB will remain in the sagging position (bend upwards) throughout the thermal cycles. In the last case of temperature cycling at stressfree temperature of 25°C , the FCOB will bend alternatively upwards and downwards during the temperature cycling.

7.4.2 Stress and strain response in Solder Joint

The shear stress vs shear strain loops for the thermal shock test at the 3rd circle is shown in figure 7.6.

Figure 7.6: Hysteresis Plots for Different Stress Free States

In Figure 7.6, similar trends in the hysteresis loops were observed for all the different stress free states. It was also observed that the hysteresis loops shift from the right to the left as the stressfree temperature decreases. The different positions of the hysteresis plots are due to the deformation behavior of the solder joint upwards (figure 7.7a) and downwards (figure 7.7b) when the stress free state is at -55°C and 125°C respectively. For

the stressfree states of 25°C, the hysteresis loop appear to be at the origin with the shear strain falling on both sides of the stress-axis.

Figure 7.7: Displacement of Solder Joint During Deformation

7.4.3 Solder Joint Fatigue Life Prediction Analysis for Different Stress Free States

Similar solder joint fatigue life prediction strategy as in section 7.3 is used in this section. The energy density was documented in table 7.4 for different stress free states.

Table 7.4: Energy Densities at different stress free states

Stress Free States	Energy Density (Mpa)
183°C	0.214
140°C	0.211
125°C	0.209
25°C	0.203
-55°C	0.200

Figure 7.8 shows the plot of the energy density vs the different stress free state temperatures. The plot shows the trend where the energy density increases with the stress free states.

Figure 7.8: Energy Density for Different Stress Free States

At a stress free state of -55°C , the FCOB package will bend upwards as shown in Figure 7.3. During the ramp up period, the PCB expands more than the Silicon and will bend upwards. The Silicon however will be restricting the bending of the PCB as it has a lower CTE. This results in a lower energy density.

At a stress free state of 125°C , 140°C and 183°C , the temperature ramps down from the stress free temperature to 25°C and drops to -55°C . Due to the CTE mismatch, the PCB will contract faster than the Die and cause the package to bend downwards. There will be no material to restrict the PCB from bending downwards, thus producing a larger energy density.

The energy density in table 7.5 were applied to fatigue life prediction models for solder to predict the number of cycles to failure for the FCOB solder joints under different stress free state temperatures.

Table 7.5: Solder Joint Fatigue Prediction Results

Stress Free States	183°C	140°C	125°C	25°C	-55°C
<i>Energy Density (Mpa)</i>	0.214	0.211	0.20988	0.203	0.2
Shi et al Energy Density Model	3,724	3,800	3,829	4,016	4,102
Darveaux’s Energy Density Model	585	596	600	625	637

Table 7.5 shows the predicted number of cycles to failure using the Shi et al’s energy density method. Many experimental works [91,92] found that the flip-chip joints usually fail in the vicinity of a few thousand cycles. The predicted number of cycles to failure increases with the decrease in the stress free state temperature. This trend of results was also realized in Pang et al’s [22] paper on his study of stress free states. Their FEA simulation, which uses MARC, also predicts a lower fatigue life for the stress free temperature of 140°C then 25°C. The low fatigue life is expected because the curing process of the underfill epoxy has induced residual stress and strain in the solder joints before the start of the thermal cycle. It is also caused by the deformation behavior that permits the larger deformation of the solder joint as discussed in the previous section.

With the above observations, the stress free state of a temperature cycling test has influences on the deformation behavior of the FCOB assembly. It is shown that the simulation of a curing profile of the FCOB underfill epoxy causes the lowest and most conservative fatigue life for the solder joints. In the following section, viscoelastic properties, which accurately described the relaxation modulus of underfill, are assigned to the underfill rather than using the elastic properties.

7.5 Implementation of viscoelastic properties in the Underfill

In the following section, viscoelastic properties, which accurately described the relaxation modulus of underfill, are assigned to the underfill rather than using the elastic properties. In this section, the effect of viscoelastic vs elastic properties of underfill on the behavior of the FCOB and solder joints was studied. Table 7.6 and figure 7.9 shows the energy density obtained from the finite element model with elastic and viscoelastic underfill. It can be seen that the model with elastic properties has a lower energy density compared to the viscoelastic properties.

Table 7.6: Results from the FEA Stress-free Studies

Stress Free States	183°C	140°C	125°C	25°C	-55°C
<i>Elastic Underfill</i>	0.214	0.211	0.20988	0.203	0.2
Shi et al Energy Density Model	3,708	3784	3813	3999	4085
<i>Viscoelastic Underfill</i>	0.294	0.289	0.287	0.275	0.271
Shi et al Energy Density Model	2356	2414	2438	2591	2646

Figure 7.9: Energy Density Vs Stress Free Temperatures

The model with the Viscoelastic model gave a wider range of results for the different starting temperatures with the energy density of -55°C and 183°C to be 0.271 and 0.294 while the elastic model gave the energy density of -55°C and 183°C to be 0.2 and 0.214.

7.5.1 Stress Distribution Analysis

In this section, the Von Mises stress contour plots in the solder obtained at 125°C and those in the underfill fillet obtained at -55°C were compared between the elastic and viscoelastic underfill in Figures 7.10a and 7.10b respectively. The reasons for choosing different temperatures for the solder and underfill fillet were because the accelerated creep rate of the solder was the highest at a high temperature which makes the solder the softest at that time, whereas the stress in the underfill fillet was the highest at a low temperature [39].

Figure 7.10: Von Mises Stress Distributions in the Solder at 125°C

Comparing the elastic and viscoelastic underfill, the solder joints in the viscoelastic underfill predicts a higher stress level then the elastic underfill. This suggests that an earlier failure will occur as predicted from the earlier section. One reason is because the relaxation of underfill with time was considered in the Visco-elastic model, where the solder will gradually lose the mechanical support. In Figure 7.11, the Von Mises stress contour plots were plotted for the underfill. In the viscoelastic underfill model contour plots, the stress distribution in the fillet is more uniform because the underfill in the elastic model was highly constrained and the stresses were concentrated near the silicon die. It can also be observed that at the die interface, the stress level with the elastic underfill is around 6 times higher then the Visco-elastic model.

(a) Elastic Underfill

(b) Viscoelastic Underfill

Figure 7.11: Von Mises Stress Distributions in underfill fillet at -55°C

From the implementation of the Viscoelastic properties to the underfill, the following observations can be made:

- (1) The energy density obtained is higher than that of the elastic underfill.
- (2) The fatigue life predicted is closer to the MTTF of the FCOB package.
- (3) The elastic model underestimates the stress level at the solder
- (4) It predicts more than five times lower stress than the Elastic model around the die corner at the underfill fillet

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Chapter Eight: Conclusions

8.1 Conclusions

In this project, a DFR methodology for lead-free solder joints was developed and extended to lead-based solder joints in a limited study. This methodology includes experimental reliability test, finite element analysis and fatigue life prediction modeling of lead-free solder joints. Case studies applying this DFR methodology to 2 test package type, micro-BGA and FCOB with Sn-3.8-0.7Cu and Sn-3.5Ag eutectic lead-free alloys respectively were conducted. Case studies on the numerical analysis of the effect of different temperature profiles and the comparison of representing applying both visco-elastic or elastic properties in the underfill of FCOB assemblies were conducted concurrently. Thermo-mechanical analysis on the micro-BGA was also conducted and the predicted life cycle compared to the MTTF from the reliability test. The following conclusions can be made:

(a) Experimental Reliability Test

Accelerated temperature cycling (ATC) methodology was developed and applied to the micro-BGA and FCOB test assemblies. In both cases, the Weibull plot was plotted and the MTTF calculated. The failure mechanism was identified as solder joint fracture. The micro-BGA MTTF is 2846. The FCOB package with Sn-37Pb and Sn-3.5Ag solder composition is 4361 and 2195 respectively. The assemblies were cross-sectioned and viewed under SEM to identify the failure sites and mechanism.

(b) Finite Element Analysis: Modeling and Simulation

b.1 Micro-BGA Analysis

In this study, different material models, which are widely used by different researches, were used to represent the viscoplasticity of Sn-Ag-Cu solder. Two modeling

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approaches were evaluated: State-variable approach using Anand's model and phenomena approach using elastic-plastic-creep analysis. It was observed that different model approaches lead to different FEA results.

The 2-D plane strain and 3-D strip model for the packages was modeled and subjected to similar temperature cycling profile in the experiment. The results have been compared based on the different fatigue life prediction models used. The 2-D plane strain results gives lower and more conservative fatigue life compared to the 3-D strip model. Failure parameter, accumulated inelastic strain and energy density, was outputted for fatigue life prediction modeling. The number of cycles to failure was predicted and found to be within 2X the MTTF which is in an acceptable range. However, the author acknowledged that the use of 2D plane strain model and 3D slice model does not capture the full thermo-mechanical deformation behavior perfectly compared to a full 3D model but listed down extensive literature review providing the use of 2D, 3D slice and full 3D model results and their expected differences within engineering expectations.

In this project, the effect of mesh refinement study was conducted. A finer mesh typically results in a more accurate solution, however, as a mesh is made finer, the computational time and the recourses increases. Therefore it is recommended that mesh refinement studies is conducted before embarking in further work to optimize accuracy, time and resources.

b.2 FCOB Analysis

In the FCOB analysis, a 2-D plane strain FCOB package was selected and modeled for this study.

An in-depth study of the effect of different starting temperature on the deformation behaviors of the FCOB package was studied. It was recommended that the stress free state

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temperature be modeled before the temperature cycling to have a better representation of the curing of the underfill and to have a more conservative result.

In the fatigue life prediction study of 2 different ramp rates, thermal shock and thermal cycling, it is recommended that Shi's energy density model is used as it takes into account the frequency. It was also concluded that Darveaux's energy density model is conservative due to the author using a PBGA package, in which the solder ball diameter is around 5 times smaller than the solder ball used in Flip Chip package, to obtain the crack growth correlation constants for fatigue life prediction.

In the study of implementing Viscoelastic model instead of elastic property, it is recommended that Viscoelastic model be used as it gives a better representation of the polymer material and predicts the solder joint to have a more conservative number of cycles compared to using an elastic model. The Viscoelastic model is also to better capture the effect of different stress free temperature.

With this methodology, parametric studies, such as the study of die size effect, substrate thickness or the solder pitch can be performed without the arduous task of building the package to undergo reliability test.

(C) Development of Fatigue Life Prediction Calculation Software

In this project, the fatigue life prediction software was developed. The software included the most frequently used fatigue life prediction models and has reduced significantly the time taken for predicting the number of cycles to failure. This software was developed for easy expandability to include additional constants or models. References were included to provide a more comprehensive package for engineers.

8.2 Recommendations and Proposal for Future Work

The following are recommended for future research and simulation work:

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- i) Use of other reliability test such as drop test, 4-point bend test or vibration test. This current work using temperature cycling test to evaluate the reliability of electronic packages is well accepted in the industry, however, the time taken usually takes up to a few months depending on the temperature profile. Because of the shortening of the life product cycles, it is necessary to evaluate other reliability test tools to shorten the time yet able to generate qualitative and quantitative results for analysis.
  - ii) In the area of electronic package, analysis methods such as moisture absorption which causes “popcorn” or delamination of materials in a package should be looked into in order to aid in the design-for-manufacturability of electronic packages.

8.3 List of Publications

- T. H. Low, John H. L. Pang, Charles W. C. Lin, Sam C. L. Chiang and T. K. Andrew Yang ,”Modeling Plated Copper Interconnections in a Bumpless Flip Chip Package,” *5th Electronics Packaging Technology Conference*, 2003
- John H.L. Pang, T.H. Low, B.S. Xiong and F.X.Che ,”Design-for-Reliability Methodology for Electronic Packaging Assemblies,” *5th Electronics Packaging Technology Conference*, 2003
- Pang H.L John., Xiong B.S. and Low T.H., “Creep and Fatigue Properties of Lead Free Sn-3.8Ag-0.7Cu Solder,” *IEEE Proceedings of 2004 Electronic Components and Technology Conference*, pp.1333-1337
- John H.L. Pang, T.H. Low, K.A. Prakash and C.C. Neo ,” Thermal Cycling Aging Effects On Sn-Ag-Cu Solder Joint Microstructure, IMC and strength,” *ICMAT 2003, International Conference on Materials for Advanced Technologies*
- J.H.L. Pang and T.H. Low ,”Thermal Fatigue Analysis of Solder Joints”, *8th International Fatigue Congress*, 2002, Sweden
- John H.L. Pang, B.S Xiong and T.H. Low,” Low Cycle Fatigue Models For Lead Free Solders,” *5th Electronics Packaging Technology Conference*, 2003
- John H.L. Pang, D.Y.R Chong and T.H. Low ,”Thermal cycling analysis of flip chip solder joints reliability analysis”, *IEEE transactions on Components and Packaging technologies*,” volume 24 number 4, Dec 2001, pp 705 - 712

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