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Thermo mechanical analysis of through-hole solder joint using strain partitioning method

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Thermo Mechanical Analysis of Through-Hole Solder Joint Using Strain Partitioning Method

by

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Bachelor of Engineering in Mechanical Engineering

Gulbarga University, India

A Project Presented to the Graduate School of the Ryerson University
in Partial Fulfillment of the Requirements for the Degree of Master of Engineering in the
Program of Mechanical Engineering

Toronto, Ontario, Canada, 2007

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ABSTRACT

Thermo Mechanical Analysis of Through-Hole Solder Joint Using Strain Partitioning Method

Currently in the electronics industry there is a desire to increase component reliability. Fatigue failure in solder joints is an important design consideration for electronic packaging. In through-hole components, fatigue failure of leads has been observed to antecede fatigue failure of solder joints. The main objective of the study for a solder joint in a plated-through-hole bearing the pin during the temperature cycle was to ascertain the thermo mechanical behavior and the dominant deformation mode. The Digital Speckle Correlation (DSC) technique, which is a computer vision technique, was applied for the measurement of solder joint deformation for a prescribed outlined temperature and time. The dimensions for the area of the solder joint under study were 21 by 21 μm , located at the centre of the hole. And computation of averaged shear strains at 6 data points for this area was done. R Darveaux's constitutive model was applied for the data analysis such as the solder joint yields stress with respect to the time and temperature. On achieving the stress solution, the measured total strains were partitioned into elastic, plastic and creep terms separately and hence the creep strain rate was evaluated. From the analysis, it was found that the dominant deformation mode was shear deformation due to mismatch of coefficient of thermal expansion between pin and copper plating material of through-hole under thermal loading. And the dominant deformation mechanism was creep strain while stress started to relax at the end of ramp up and continued throughout the test and creep strain rate decreased during high temperature dwell. In Addition, the elastic strain was dominating during the initial stage of thermal cycle but later it was negligible when compared to creep strain.

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NOMENCLATURE

Roman	Description
A	pre-exponential factor
T	temperature in Kelvin
E	activation energy
R	gas constant
E	young's modulus
G	temperature dependent shear modulus
Q	activation energy for the deformation process
k	Boltzmann's constant
n	stress exponent
d	grain size
m	grain size exponent
N _p	number of cycles to failure due to plastic fatigue
N _c	number of cycles to failure due to creep fatigue
N ₀	number of cycles for crack initiation
T _{sj}	mean cyclic point temperature
N _f	number of cycle to failure
e _r	plastic strain range
e _f	fatigue ductility coefficient

Greek	Description
$\dot{\epsilon}_{cr}$	steady state creep rate
ρ	cyclic stress range
ϵ'_f	fatigue strength exponent
τ	shear stress
$\Delta\gamma$	strain range
ΔT	temperature difference
σ	stress

ε	strain
α	prescribes stress level at which power law dependence breaks
ε_{in}	instantaneous Plasticity
σ'_f	fatigue strength coefficient
$\Delta\varepsilon_p$	strain amplitude
$\Delta\gamma_p$	plastic strain range
ϕ	inverse of the fatigue ductility coefficient
$\Delta\gamma_t$	total shear strain
ν	cyclic frequency
ΔW	inelastic strain energy density
$\Delta\sigma_f$	stress range
$\Delta\gamma_{mc}$	strain range due to matrix creep
$\Delta\overline{W}_{total}$	total strain energy
$\Delta\alpha$	difference between the thermal expansion
σ_f	high cycle fatigue strength constant,
ε_f	low cycle fatigue ductility constant
$\Delta\varepsilon_{eq}$	maximum equivalent strain range
ε_x	strain in x direction
ε_y	strain in y direction
γ_{xy}	shear strain
γ_{max}	shear strain maximum
γ_{il}	DSC measured total strain
γ_{el}	shear strain elastic
γ_{pl}	time independent plastic strain
γ_{cr}	time dependent creep strain.
ν	poisson's ratio
$\Delta\gamma_{s_i}$	creep strain increment

γ_{cr}	accumulated creep strain
γ_{in}	total inelastic strain
$\dot{\epsilon}$	creep rate

ACRONYMS

CTE	Coefficient of thermal expansion
CCD	Charge couple device
DIP	Dual in line Package
DSC	Digital Speckle Correlation
PWB	printed wiring board
PTH	plated through-hole
PCB	printed circuit boards
SMT	surface mount technology

Chapter 1 Introduction

1.1 Reliability of Solder Interconnects and Insertion Mounted Component

With high performance and high density of computer and other electronic circuits, it becomes very important to assure the reliability of smaller and smaller solder joints. In particular, more accurate prediction of thermal fatigue life is required for large thermal stress induced by power and temperature cycling. Sn-Pb eutectic alloy is used in electronic circuit interconnections at a maximum temperature of 100°C. Solder joints could undergo cyclic thermal strain corresponding to power on-off cycling of the equipment or environmental temperature fracture forces so that thermal fatigue fractures can occur. Therefore, in order to produce reliable electronic circuits, the thermal fatigue processes of solder joints at high temperatures must be understood for making countermeasures.

Fatigue life of leads in a through-hole package is a complex function of constitutive properties, architecture, geometry of the package, and vibrational loads applied to it. Fatigue failures occur in leads of insertion mounted components, when electronic printed circuit assemblies are subjected to severe vibrational loads, which lead to a reduction in the reliability of through-hole interconnection.

1.2 Insertion Mount Technology

A large amount of attention has been devoted to multi-layered printed wiring boards (PWBs) using surface-mounted components. However, there is a still strong and growing demand for single-sided insertion-mount boards. The primary end users tend to be the

automotive, consumer, industrial, and telecommunication sectors, who require affordable, but not the most high-end technologies [1].

Through-hole technology also known as insertion mount technology is an older process of connecting a component to the printed wiring board (PWB). In this process, the components are placed on the boards and the leads extend through the PWB, which are then conveyed over a wave of liquid solder as such allowing the solder to flow around the leads and components on the opposite side of the board. While the board leaves the solder bath, the liquid solder adheres to the metallic portion of the board where there is no solder mask (the metallic traces are covered which are not to be exposed to the mask).

The cross section of a typical insertion mounted assembly is shown in fig 1-1. The assembly consists of a leaded component on top of a PWB with the lead passing through a plated hole to the opposite side of the board. The solder joint is formed between the component lead and the plated through-hole (PTH) of the board. Though it is less space efficient than surface mount technology (SMT), insertion mount technology is often preferred when continuous performance and extended life of the solder joint is required [2]. It is utilized by products whose performance is critical, equipment down time is not tolerated and end use environment may be extremely harsh. Such operating environment includes life support and aerospace systems where an engine's electronic controls are often mounted on or near the engine [2].

Fig-1-1 Typical insertion mounted assembly [2]

Traditionally, insertion mount technology has been considered immune to solder joint wear out for electronic equipments which bear an operational life span of over 20 years. It has been recent that such systems approached life spans where fatigue wear out has begun to be observed for insertion mount device [2].

1.2.1 Dual in line Package (DIP)

Dual in line package (DIP) was designed primarily to overcome the difficulties associated with handling and inserting packages into mounting boards. DIPs are easily inserted by hand or machine and require no spreaders, spacers, insulators or lead –forming tools. Standard hand tools and soldering irons could be used to field –service the devices. Plastic DIPs are finding wide use in commercial applications, and a number of military systems are incorporating ceramic DIPs.

1.2.2 Reliability Issues

Reliability issues stated by Valentin [2] for insertion mounted components were that:

- Most insertion mount systems have failed by overstress fracture due to thermo mechanical loads or by a strain driven fatigue damage over the course of numerous cycles.
- Experiments have shown that temperature cycling, and not overstress is the dominant wear out failure mechanism.
- The fatigue damage is the result of deformation in insertion mounted component and the substrate to which they are solder attached. The solder and the materials (component, lead and substrate) to which it is bonded.

The reason for deformation would be the components internal power dissipation and or the system's internal or external temperature variations that are caused by component or system load fluctuations(on/off cycles), during cycles or by seasonal changes. An approach for rapidly assessing the life of the components is critical to enhance the business strategy for their replacement or during remaining equipment life.

1.3 Eutectic tin-lead solder as Interconnects

Lead (Pb)-containing solders have been used extensively in microelectronic applications to form electrical interconnections between packaging levels, to facilitate heat dissipation from active devices, to provide mechanical/physical support, and to serve as a solderable surface finish layer on printed circuit boards (PCBs) and lead frames.

The ever-increasing demand for improved performance and the continuous push for further miniaturization of electronic devices is focusing attention on the ability of solder

to provide structural integrity , since the consequences of joint failure may be potentially as catastrophic as with more conventional large scale structures, the comparative lack of progress in validating design is disturbing .The tension between mechanical conservatism in design and performance requirements is increasing rapidly.

In the medium term, it seems inevitable that conventional lead containing solders will be replaced by their more environmentally friendly equivalents. Even when the prime candidates have been selected and appraised in terms of processability, the problem of structural integrity would remain. It is timely for materials engineers to anticipate this situation and commence their investigations now since we are in a void of knowledge and understanding on this aspect.

1.3.1 Failure Mechanism

Solder joint failure is due to crack initiation and propagation through a joint, but the location and nature of the cracks depend on several factors. The joint configuration, intermetallic structure, strain rate, and temperature regime are some of the factors that affect the mechanism of a solder joint failure.

Cracks usually initiate at high stress concentration sides. The direction of propagation depends on the shape of the joint and the relative degree of tensile versus loading.

Higher joint stresses due to higher strain rates or creep- resistant solders results in more fractures near solder component pad interfaces. Interfacial fracture is more likely with

poor intermetallic solder adhesion, brittle intermetallics, and or depletion of a solder constituent adjacent to the intermetallic layer [3].

1.4 Project Objectives

The purpose of the reliability study for an electronic packaging is to determine the thermo mechanical behavior of a solder joint in a plated-through-hole bearing the pin during the temperature cycle. The project focuses on the data analysis after the strain measurement test that has been conducted on SnPb solder joint of an insertion mount component. The scope of the project is as follows:

1. Determine the shear stress of solder joint in plated-through-hole with the pin during the temperature cycle.
2. Calculate elastic, plastic, creep strains and creep strain rate based on DSC measured thermal strain.
3. Determine the dominant deformation mechanism in solder joint under thermal load conditions.
4. Determine the maximum shear stress of solder joint.
5. Discussion of the deformation and strain distribution in the solder joint during temperature test condition.

Chapter 2 Creep and Fatigue Behavior of Solder Joint

2.1 Creep Behavior

The reliability of solder joint often depends directly on the mechanical properties of the solder alloy. The tensile strength of the alloy determines the resistance of the joint to mechanical rupture under short term direct loading that might occur during impact testing.

The primary failure mechanism of solder joints is ductile fatigue fracture. During operation or during testing, an electronic component will be subject to changes in temperature. This causes the materials to expand and contract at different rates depending on their coefficient of thermal expansion. This cycling results in internal stresses developing which, in turn, causes the solder to creep.

2.2 Creep

Creep is a time-dependent plasticity, which occurs in metals when they are close to melting points. Over many cycles, the creep leads to ductile fatigue damage, which manifests itself as micro voids in the solder which grow and coalesce into macro-cracks that slowly propagate through the joint over the course of its lifetime, ultimately resulting in failure of the joint [4]. Creep strain is broadly defined as elastoplastic time dependent deformation under constant load at high temperatures [5]. For some electronic packaging materials such as solder, creep deformation becomes important even at room temperature.

A typical creep curve could be obtained from long time uniaxial test at constant load and constant temperature as shown in fig2-1. The slope of this curve ($\dot{\epsilon} = d\epsilon/dt$, ϵ = strain, t = time) is referred to as the creep rate ($\dot{\epsilon}$). At the first stage, the creep rate is undefined and the initial creep strain consists of either entirely elastic strain or partially elastic strain and partially plastic strain [5]. The creep then proceeds in the three stages of primary, secondary, and tertiary creep.

2.2.1 Primary creep

The second stage of creep is called primary creep. During this stage the creep rate decreases with time because the effect of strain hardening is greater than that of annealing (recovery). The primary creep is dominated by transient creep. For low temperature and stresses, as in the creep of lead at room temperature, primary creep is the predominant creep process. [5]

2.2.2 Secondary creep

The third stage of creep is called secondary creep or steady state creep. The average value of the creep rate during secondary creep is called the minimum creep rate. The strain hardening and annealing (recovery) effects are in equilibrium during this stage and the creep rate reaches essentially a steady state and changes very little with time. Log-log-plots of stress vs minimum creep rate for various temperatures are essentially straight lines for many metals. For most metals steady state creep is the dominant deformation mode at temperature above half of the melting point, T_m in degree Kelvin for eutectic SnPb, T_m is 183 C(450K) and $\frac{1}{2} T_m = 228K(-45C)$

2.2.3 Tertiary Creep

The fourth stage of creep is called tertiary creep, which is often associated with microstructure changes such as coarsening of precipitate particles, recrystallization or diffusional changes in the phases that are present.[5] The creep rate increases rapidly with time until fracture occurs at point D. This is called the reduced cross sectional area (either due to necking or to internal void formation) causes an increase in stress.

Fig 2-1 A typical creep curve [4]

2.3 Fatigue Behavior

The reliability depends on resistance to fatigue, when the solder joint is subjected to cyclic stresses and strains generated by thermal expansions during thermal cycling.

The standard mechanical reliability concern for solder joints is the measurement of resistance to failure by low cycle fatigue due to thermal cycling. If the service conditions involve any thermal cycles, strains due to thermal expansion mismatch are very difficult to avoid. Though thermal expansion coefficients are matched, there is likely to be some

strain imposed on the solder because of differential rates of heating and cooling in different regions [6]. In most designs the imposed strains exceed the elastic limit of the solder and produce plastic deformation resulting in failure by low cycle fatigue. The duration of the fatigue lifetime that is required in service typically far exceeds the time available for reliability testing. This interprets that service reliability must be estimated using some sort of extrapolation [6].

2.3.1 Fatigue

Fatigue is the result of repetitive stress on a system over a period of time. The number of repetitions of the applied stress or cycle that a system can survive before failing is generally termed the fatigue life. The stresses can be either mechanical or thermal. The most predominant failures in electronic packaging are perhaps due to fatigue [7]. Fatigue is further classified as high cycle fatigue and low cycle fatigue.

2.3.1.1 High Cycle fatigue

The number of cycle N_f to fail in a high cycle fatigue environment is given by

$$N_f = C_p \rho^m \quad (2.1)$$

Where c and m are constants and ρ is the cyclic stress range [7].

2.3.1.2 Low Cycle fatigue

Low cycle fatigue for a solder joint in plated through-hole is described by the equation

$$N_f = 0.5[e_r / 2e_f]^b \quad (2.2)$$

Where e_r , e_f , and b are plastic strain range, fatigue ductility coefficient and fatigue ductility exponent [7].

Low cycle fatigue conditions are frequently created where repeated stresses are of thermal origin since thermal stresses arise from the thermal expansion of the material; it is easy to see that fatigue results from cyclic strain rather than cyclic stress [8]. When solder materials are subjected to or operated at or above a temperature corresponding to a homologous temperature greater than 0.5, intergranular movement occurs within the joint matrix [7]. Homologous temperature is defined as the ratio of the operating temperature to the melting point of the material expressed in Kelvin respectively [7]

Fatigue damage is usually the result of stress concentrations caused by dislocation pileups due to inelastic to-and -fro slip motion of lattice defects, and due to sliding between grains at the boundaries. The dislocation slip motion is caused by mechanical stresses. Thus, mechanical stresses due to thermal expansion mismatch between connected components of dissimilar materials can result in eventual fatigue failure during thermal cycling. It is well known that eutectic Sn-Pb solder, with a melting temperature of only 183°C, could exhibit significant creep and stress relaxation at room temperature, where the homologous temperature is about 0.5 [9].

Creep fatigue is an irreversible time dependent deformation caused by intergranular movement under low cyclic loads at moderate temperature. The strain rates are about 10^{-6} /s and relatively high temperatures facilitate a significant rate of diffusion. Fracture regimes are determined by the temperature, stress rate and strain range [7].

The thermal fatigue of a solder joint could be understood when the stresses and strains experienced by solder are known. Typically the solder joint is much less stiff and more compliant than the other components. For this case a specified thermal cycle results in a specified strain cycle on the solder. The specified strain is made up of elastic and plastic strains. The stresses reached in such a cycle depend on the elastic and plastic compliance of the solder. Plastic compliance results from both very rapid plastic deformation at high stresses and much slower plastic creep at lower stresses.

During hold times, plastic creep deformation replaces elastic deformation during stress relaxation. When strain cycle history and relationship between creep rate and stress are known, then it would be possible to predict the stress cycle history.

Wilcox, Subrahmanyam and Li [10] have involved in their studies the temperature dependence of the plastic creep behavior. Creep relaxation is much faster at high temperature. The magnitude of the stresses reached upon heating is therefore lower than the magnitude reached upon cooling.

The failure of the solder eventually results from the initiation and propagation of fatigue cracks. The accumulation of creep cavitation damage would probably result in crack initiation and the rate of which is determined by the time spent at stress (the rate of damage accumulation may also depend on temperature).

After initiation, crack propagation may also depend on the time spent at stress. The stress relaxation is different in the heating and cooling parts of the cycle, which means the accumulation of damage will also be different. Though a complicated situation it could be modeled when two relationships are available:

- a) Rate of plastic deformation as a function of stress and temperature.
- b) Rate of damage accumulation as a function of stress and temperature.

In a case where these two relationships are valid, it is possible to determine the relationship from experiments at one set of conditions (frequency, temperature and strain levels) and use the relationships to predict the behavior (fatigue life time) at another set of conditions.

When the grains are small and equiaxed, intergranular creep occurs at low stresses and high temperature. Intergranular creep can lead to stable non damaging plastic deformation.

The creep deformation rate changes as a function of time at constant stress and is generally given by an equation of the form

$$\frac{dx}{dt} = A \tau^n e^{\left(-\frac{E}{RT}\right)} \quad (2.3)$$

where x is the strain, A is the pre-exponential factor, τ is the shear stress, T is the temperature in Kelvin, E is the activation energy, R is the gas constant and n is stress the exponent. The stress exponent and the activation energy depend on the particular creep mechanism that is operative. The magnitude of the pre exponential factor A, governing the stress range over which a given mechanism is operative at any given temperature depends on the microstructure [7].

2.4 Coefficient of thermal expansion (CTE)

Major failures in electronic packaging are interconnection failures such as solder joint, which are caused by thermal or mechanical stresses imposed on the solder joint.

When dissimilar metals are joined together, the difference in their thermal coefficient of expansion properties induce relative motion and displacement in the system as the system experience thermal excursion in the operating environment. The extent of such displacement motion depends on the coefficient of thermal expansion mismatch. This coefficient of thermal expansion mismatch is classified as global, local and internal.

2.4.1 Global Mismatch

It is the difference between the CTE of a package and the printed wiring board (PWB).

At a given temperature range, it gives rise to the largest displacement as it acts over a larger distance, namely the total package dimension owing to the temperature swings.

2.4.2 Local Mismatch

It is the CTE difference between the base material and the interconnection alloy. The CTE mismatch could be in the range of 7 – 20ppm/°C depending on the material set involved. The displacements are generally smaller in magnitude because they act over a smaller distance in the interconnection zone. In the case of solder joint to the board the interfaces encountered at macroscopic level are copper pad and solder interface and solder and component lead. Thus, there is a coefficient of thermal expansion difference between the copper and solder, then the solder and lead material.

2.4.3 Internal Mismatch

These mismatches are due to the difference in the thermal coefficient of expansion of phases internal to the interconnection. At a microscopic level, more interfaces are encountered such as copper to copper tin ϵ -phase and η -phase, and η -phase and the solder on the copper side. The coefficient of thermal expansion disparity of the individual interface can affect interconnection reliability.

Chapter 3 Methods of Modeling and Solder Constitutive Law

The expectation of most electronic devices to last for many years of use has made it unfeasible for companies to perform field tests due to the time and cost involved. In order to judge products reliability, accelerated tests are used, which impose very harsh conditions on joints; as such, it fails in a shorter time.

Thermal cycling is the most popular accelerated test, where a soldered assembly is placed in an oven and subjected to a cyclic temperature profile representing conditions considerably harsher than expected field use conditions. Power cycling is another accelerated test, during which heat is periodically generated from within a component. This result in isothermal temperature field that closely matches the conditions experienced in actual field.

3.1 Methods of Modelling

Modelling is a useful tool used to supplement or replace an accelerated test, particularly in the early design stage. The suitable modelling that would be applicable to induced creep ductile fracture is modelling the damage. This occurs due to typical thermal or power cycling of joints, but not the vibration or drop test or shear-strength testing.

The complexity of methods increases as it goes from top to bottom as shown in fig 3-1

- a) Analytical method
- b) Constitutive and fatigue law
- c) Damage mechanics

Fig 3-1 Modelling methods to predict cycles to fail in thermo mechanical cycling [4]

3.1.1 Analytical Method

This method is proposed by Engelmaier [4] as simple to implement but with many restrictions to use in certain situations. It is recommended in the IPC-D-279 standard for predicting the lifetime of Sn/Pb joint, for both leaded and non-leaded components and they are very simple to use when compared to finite element analysis modelling.

It assumes that the solder deforms to its maximum amount based on the coefficient of thermal expansion of the substrate and component. This strain range is calculated for non leaded joints using equation [4].

$$\Delta\gamma = c_1 \frac{L}{b} \Delta(\alpha\Delta T) \quad (3.1)$$

The calculated strain range $\Delta\gamma$ is not accurate as it does not account the stiffness and creep properties of the solder. The solder stiffness would prevent the strain range from ever reaching this value. To compensate for this, the standard Coffin-Manson fatigue law for predicting N_f (number of cycles to fail) has been modified to include temperature and frequency effects [4].

$$N_f = \frac{1}{2} \left[\frac{\Delta\gamma}{2c_1} \right]^{\frac{1}{c}} \quad (3.2)$$

$$c(T, f) = -0.442 - 6 \cdot 10^{-4} T_{sj} + 1.74 \cdot 10^2 \ln \left(1 + \frac{360}{t_D} \right) \quad (3.3)$$

Where T_{sj} is the mean cyclic point temperature and c_1 is material constant This approach has been shown to predict life time with an accuracy of $\pm 2x$ under the appropriate conditions. However, there are many conditions in which this law doesn't apply.

3.1.2 Constitutive and fatigue law

In this method, a transient simulation is done to predict the solder stress strain behavior during a thermal cycle. Upon simulation, either the accumulated effective plastic strain per cycle or the accumulated strain energy density per cycle is derived to be used in a fatigue law.

The methods of modelling the mechanical response of an assembly under thermal cycling are

- a) Finite element analysis(FEA)
- b) Alternative numerical methods

3.1.2.1 Finite element analysis

Finite element analysis is a powerful and widely used numerical method which could be used to accurately predict the mechanical response of the solder joints and surrounding assembly under thermo mechanical cycling. A detailed description of the FEA method is provided by Zienkiewicz [11]. In order to use FEA to determine the fatigue life of solder joint under thermal cycling, the following steps are required: create geometry, create mesh, specify material properties, specify boundary conditions and apply fatigue law.

3.1.2.2 Alternative numerical methods

Alternative numerical methods are more simplified that capture the creep behavior of the solder using a constitutive law and does not require much work or expertise to set up. A simulation is run where the temperature cycles between two extreme and at each time step the stress and creep strain rate of the solder are calculated. After two or three thermal cycles, the response of the solder would have stabilized and the simulation could finish. The output of the simulation is a hysteresis loop – a graph of stress versus strain and values of accumulate plastic strain per cycle and accumulate strain energy density per cycle. As it uses a constitutive law to model the solder creep behavior it would provide more accurate results over a wide range of conditions than an analytical method, although no validation against experiment has been found to back this up [4].

An example of a simple approach would be to model only the prominent shear component of strain in the solder joint. This is an approximation as in reality a ball grid array solder bump would experience significant normal and shear strains. In addition, the

strain is assumed to be uniform through out the solder joint, thus making it suitable to model global strains only [4]. Another example of approach is provided by clech [4], where the capability of modelling local as well as global thermal expansion mismatches and the effect of underfill.

R Darveaux suggested a hybrid method where two purely elastic analysis are conducted to provide:

- a) The stiffness of the assembly surrounding the joint.
- b) The displacement between the top and bottom pads assuming the solder joint is not present [12].

These were then used in a one dimension numerical model, which used a constitutive law to predict the average response of the solder joint over a thermal cycle. However, it would not predict the damage caused by the local thermal expansion mismatch between the solder and the component or substrate.

3.1.2.3 Solder Constitutive Law

A constitutive law for a material will govern its mechanical behavior when subjected to different stresses at different temperature [4].

Elasticity:-

Usually, the elastic properties of solder are determined from a strain rate controlled tensile test. Young's modulus could be determined from this test along with the ultimate tensile/shear strength of the solder. There is a large strain rate and temperature effect and the young's modulus would appear at lower stain rates or higher temperatures [13]. The elastic deformation of the solder is governed by the young's modulus and poission's

ratio. In one dimension, the relationship between the stress and strain is given by Hooke's law [28]

$$\sigma = E\varepsilon \quad (3.4)$$

In three dimensions the relationship is more complex and takes into account Poisson's ratio (the proportion by which the cross-section area shrinks for each unit strain applied) [14]. Basaran and Jiang [15] pointed out that when modelling SnPb the use of different values of Young's modulus (literature values range from 9GPa to 48GPa) could adversely affect the results of a simulation and that ideally a modulus measurement on an actual manufactured package using a nano-indentation technique.

The coefficient of thermal expansion of the solder governs the amount by which it expands under changing temperatures [4].

$$\alpha = \frac{d\varepsilon_{th}}{dT} \quad (3.5)$$

For SnPb CTE of 25 ppm / °C has been reported [4]

Creep

Creep is a time dependent plastic deformation, which occurs for metals under stress at high homologous temperature, as SnPb solder has a melting point of 183 °C and it creeps at room temperature.

During the creep test, a constant load is applied to a solder specimen at a constant temperature. The force is applied at the instant; the solder would experience a strain which is partly elastic and partly plastic. The elastic part could be predicted given the young's modulus of the solder as discussed earlier. The plastic part is the instantaneous plasticity which could be predicted by laws offered by Darveaux [12]. The strain

increases with the continuation of test, first rapidly (primary region) and gradually slows down to a steady strain rate (secondary region). Succeeding the secondary region is the tertiary region during which the strain rate increases until rupture. This occurrence is due to both necking (shrinkage of the cross section a result in increased stress) and damage (cracking) occurred in the solder.

Steady State Creep

It is very common and the only kind of creep to be modeled. The simplest steady state creep law is the Norton law [16].

$$\dot{\varepsilon}_{cr} = c_1 \sigma^{c_2} \exp\left(\frac{-Q}{kT}\right) \quad (3.6)$$

SnPb has been modeled using this law, but it does not capture the change in creep mechanism between low stresses and high stresses. An alternative and widely used method for capturing the change in creep mechanism is use a Sinh law [4]

$$\dot{\varepsilon}_s = c_1 [\sinh(c_2 \sigma)]^n \exp\left(\frac{-Q}{kT}\right) \quad (3.7)$$

Primary Creep

Three different approaches have been found to model primary creep, the use of a time variable, isotropic hardening, and kinematic hardening, of this only kinematic hardening is suitable to model the solder behavior during thermo mechanical cycling [4]

Darveaux law has made use of a time variable in the creep strain rate function as represented by [12]

$$\dot{\varepsilon}_{cr} = \dot{\varepsilon}_s (1 + c_1 c_2 \exp(-c_2 \dot{\varepsilon}_s t)) \quad (3.8)$$

Cheng et al [17] used the Anand model to model the primary and secondary regions of the creep curve using isotropic hardening

$$\dot{\varepsilon}_{cr} = c_1 \left[\sinh\left(c_2 \frac{\sigma}{s}\right) \right]^{\frac{1}{c_3}} \exp\left(\frac{-Q}{kT}\right) \quad (3.9)$$

Stolkarts et al [18] have reported that isotropic hardening does not occur in SnPb solder.

Kinematic Hardening

Mechanical fatigue test are used to understand the solder behavior under cyclic loading.

During this test a cyclic strain, either shear or tensile is imposed on a solder joint. The solder response depends on the elastic, creep and fatigue properties which makes it a useful test to validate the accuracy of constitutive laws. For SnPb kinematic hardening laws with material properties have been found and which could accurately predict the behavior shown in isothermal fatigue tests [19-21]

Instantaneous Plasticity

It occurs in creep tests and has been described by Darveaux [12] using the following equation (3.10)

$$\varepsilon_{in} = c_1 \left(\frac{\sigma}{E} \right)^{c_2} \quad (3.10)$$

But, this law cannot be applied to other loading conditions such as temperature cycling where the stress could be constantly changing [4].

3.1.2.4 Fatigue Laws

These laws are required to predict the number of cycles to fail when provided with either the accumulated effective creep strain energy from a simulation. A review of the fatigue laws for solder has been done in the following chapter.

3.1.3 Damage Mechanics

In order to overcome the geometry dependence inherent in the fatigue law approach to predicting lifetime, or to allow crack paths to be predicted, damage based constitutive

laws could be used [4]. Hence, the more advanced damage mechanics based methods avoid the geometry dependence to a large extent by explicitly modelling the crack propagation. They are in need of further development and experimental validation before they could be recommended to an industry.

3.2 Model for Project Study

In this project study, R Darveaux's Constitutive Model [12] was applied, as the study involved the determination of time independent plastic flow and creep deformations of several solder alloys. Significant features of Darveaux's creep model were that

- A set of constitutive relations have been defined which describe solder alloy deformation under a wider range of conditions.
- A power law sinh expression was used for steady –state deformation and it was described as such that at intermediate stresses, the strain rate depends on stress to the power, n . At high stresses, the strain rate is an exponential function of stress and the breakdown of power law to a single expression as

$$\frac{d\gamma_s}{dt} = C_1 \frac{G}{T} \left[\sinh \left(\alpha \frac{\tau}{G} \right) \right]^n \exp \left(\frac{-Q}{kT} \right) \quad (3.11)$$

Where G temperature dependent shear modulus

T is the temperature

τ applied shear stress

T absolute temperature (Kelvin);

C_1 is a constant

α prescribes the stress level at which power law dependence breaks down

n is the stress exponent

Q is the activation energy for deformation process

At high stresses, $\tau/G > 10^{-3}$, there is also a time-independent plastic strain component to the deformation. The following strain-hardening law can be used to describe high-stress deformation

$$\gamma_p = C_6 \left(\frac{\tau}{G} \right)^m \quad (3.12)$$

- It was applicable consistently to several solder alloys under study at a wide range of temperatures (27-132 °C).

Chapter 4 Models of Fatigue

Historically, through-hole technology has been considered a fatigue free method for soldering components to printed wiring board (PWB). With increase in component density over the board, smaller lead size and lead pitch, as well as tough quality control specification have caused problem such as solder joint failure to become important. The rate of damage accumulation in solder joint depends on the mechanical characteristics of the structure, the time/temperature profile of the system, and the properties of the solder.

The manner in which fatigue failure is defined plays a critical role in understanding the fatigue modeling and consequently the validity of the model employed ,according to classical metallurgical sense fatigue failure would occur when the component experiences cyclic stresses and strains that produce permanent damage. Fatigue failures are inherent to dynamic and fluctuating /cyclic stresses.

There are two major components of fatigue failure/fractures:

1. The initiation of fatigue cracks and the propagation of these cracks under cyclic loading.
2. The direction of crack propagation is orthogonal to the direction of the principal stress.

4.1 Fatigue Models

Based on the fundamental mechanism that induced damage are being responsible, therefore the proposed models for predicting the fatigue life of solder joints could be divided into five major categories as [39]

1. Stress-based.
2. Plastic strain-based.

3. Creep strain-based.
4. Energy- based.
5. Damage accumulation based.

4.1.1 Stress-based fatigue model

It is based on a force or stress applied to a component which causes a resulting strain.

These are typically applied to vibrational or physically shocked or stressed components.

4.1.2 Strain-based fatigue models

In this model, a strain is applied which results in stresses within a component. The strain induced fatigue could be further divided into two groups which are:

1. Plastic strain
2. Creep strain

Plastic strain focuses on the time independent plastic effects. And the creep strain takes into account the time dependent plastic effects.

4.1.2.1 Coffin-Manson's fatigue model was based on number of cycles to failure and it was dependent on plastic strain amplitude.

$$\frac{\Delta \varepsilon_p}{2} = \varepsilon'_f [(2N_f)^c] \quad (4.1)$$

Where N_f is number of cycles to failure, $\Delta \varepsilon_p$ is strain amplitude, ε'_f is fatigue ductility coefficient and c fatigue ductility exponent.

Since Coffin Manson equation (4.1) considered only plastic deformation, therefore it is commonly combined with Basquin's equation for elastic deformation to be accounted.

Thus, the equation is known as total strain equation. Plastic and elastic deformation as shown in equation (4.2)

$$\frac{\Delta \varepsilon}{2} = \frac{\sigma'_f}{E} (2N_f)^b + \varepsilon'_f [(2N_f)^c] \quad (4.2)$$

Where $\Delta \varepsilon$ is the strain range, σ'_f is the fatigue strength coefficient, E is the elastic modulus, ε'_f is the fatigue strength exponent (Basquin's exponent), and c is the fatigue ductility exponent.

4.1.2.2 Solomon's fatigue model was a low cycle fatigue model related to plastic shear strain to fatigue cycle.

$$\Delta \gamma_p N_p^\phi = \theta \quad (4.3)$$

Where $\Delta \gamma_p$ is the plastic strain range, N_p is the number of cycles to failure, ϕ is the inverse of the fatigue ductility coefficient, and is a material constant. This fatigue model is related to fatigue behavior of plastic shear strain imposed on solder joint, and experimental data of plastic strain range is required. It has been applied to leaded plastic quad flat package and under filled flip chip. It does not take into account creep.

4.1.2.3 Engelmaier's fatigue model was based on total number of cycles to failure are related to total shear strain

$$N_f = \frac{1}{2} \left[\frac{\Delta \gamma_t}{2\varepsilon'_f} \right]^{1/c} \quad (4.4)$$

$\Delta \gamma_t$ is the total shear strain, ε'_f is the fatigue ductility coefficient, and the variable c which is a function of frequency and temperature.

Where $c = -0.442 - 6 \times 10^{-4} \bar{T}_s + 1.74 \times 10^{-2} \ln(1 + f)$. $\bar{T}_s$ is the mean cyclic solder joint temperature in °C, and f is the cyclic frequency in cycles/day. For under filled flip chip $2\varepsilon'_f = 0.65$ was reported in applying Engelmaier's fatigue model. This fatigue model

improves on Solomon's and Coffin-Manson due to inclusion of cyclic frequency effects, temperature effects, and elastic-plastic strain.

4.1.3 Creep strain based fatigue models

Creep in solder joint is due to grain boundary sliding and dislocation movement.

4.1.3.1 Knecht & Fox Creep fatigue model: They proposed a dislocation movement creep fatigue model with an assumption that creep shear strain was dominant in solder joint during thermal cycling.

$$N_f = \frac{C}{\Delta\gamma_{mc}} \quad (4.5)$$

The number of cycles to failure, N_f , is related to a constant C , which is dependent on failure criteria and solder microstructure. $\Delta\gamma_{mc}$ is the strain range due to matrix creep.

4.1.3.2 Syed's Creep fatigue model included grain boundary sliding and dislocation movement

$$N_f = ([0.022D_{gbs}] + [0.063D_{mc}])^{-1} \quad (4.6)$$

Where, D_{gbs} and D_{mc} are the accumulated equivalent creep strain per cycle for grain boundary sliding and the matrix creep, respectively.

4.1.3.3 Miner's linear Superposition is a model which is combination of Solomon's fatigue model with Knecht & Fox creep model. The equation is as follows:

$$\frac{1}{N_f} = \frac{1}{N_p} + \frac{1}{N_c} \quad (4.7)$$

Where N_p is referred to the number of cycles to failure due to plastic fatigue and is obtained directly from Solomon fatigue model. N_c is referred to the number of cycles to failure due to creep fatigue and is obtained from Knecht and Fox's creep model.

4.1.4 Energy based fatigue models

These models are based on strain energy in terms of volume weighted average stress-strain hysteresis loop.

4.1.4.1 Darveaux's fatigue model was based on fracture mechanics approach for plastic work in crack initiation and crack growth to failure for ball grid array (BGA) solder joint. The calculated plastic work or inelastic strain energy density accumulated per thermal cycle was used in the model to determine the number of cycles to initiate a crack and to propagate the crack through the solder joint.

$$N_0 = C_1 \Delta W^{C_2} \quad (4.8)$$

$$\frac{da}{dN} = C_3 \Delta W^{C_4} \quad (4.9)$$

$$N_f = N_0 + \frac{da}{dN} \quad (4.10)$$

Where N_0 is the number of cycles for crack initiation, and N_f the total number of cycles for crack propagation, inclusive of crack initiation respectively, a the crack length path was taken to be the solder joint diameter near the die interface in ball grid array (BGA) package, And C_1 , C_2 , C_3 and C_4 are the constants depending on the solder element thickness used.

4.1.4.2 Shi's fatigue model included a temperature and frequency dependent energy based model to calculate the fatigue life of a solder bump. It was stress range and inelastic strain energy density that accumulated per cycle as input failure parameters. The stress range and inelastic strain energy density accumulated per cycle were used as input failure parameter, where $m = 0.7$, $C = 1.69$, frequency modified relation, $v^{k-1} = v^{-0.1}$ for $v \geq 10^{-3}$ Hz or for $v^{k-1} = [v/10^{-3}]^{-0.59} [10^{-3}]^{-0.1}$ for $v < 10^{-3}$ Hz.

$$(N_f \nu^{k-1})^m \left(\frac{\Delta \bar{W}}{\Delta \sigma_f} \right) = C \quad (4.11)$$

Where N_f is the number of cycles to failure, ν is the cyclic frequency, $\Delta \bar{W}$ is the inelastic strain energy density, $\Delta \sigma_f$ is the stress range.

4.1.4.3 Akay's fatigue model was based on the total strain energy, the equation is as follows:

$$N_f = \left(\frac{\Delta \bar{W}_{total}}{W_0} \right) \quad (4.12)$$

Where N_f is the mean cycles to failure, $\Delta \bar{W}_{total}$ is the total strain energy, W_0 and k are fatigue coefficients. This model was applied for studies on the leaded package fatigue behavior. Based on the findings the values of the coefficients were determined to be $k = -0.6342$ and $W_0 = 0.1573$ for the leaded joints tested.

4.1.5 Pan's fatigue model [22]

The model is known as 'Critical Accumulated Strain Energy 'C'. The model was based on the assumption that strain energy accumulated during thermal cycling eventually reached a critical value 'C'. The equation is as follows

$$C = N_f^* (a \dot{E}_p + b \dot{E}_c) \quad (4.13)$$

N_f is the number of cycles to failure. C is defined as the critical strain energy density and was reported to be 4.55 Mpa/mm^3 for the range of tests performed for eutectic tin-lead.

The constants a and b were essentially determined from multiple linear regression of FEA results. The creep and plastic energies denoted by E_p and E_c were also calculated from FEA. For this model, Pan used the experimental data reported by Sherry and Hall

[5], which was collected for a leadless ceramic chip carrier (LCCC) package on printed wiring board assemblies. A hyperbolic sine creep law was used to describe creep. Elastic deformation was negligible in the analysis. This fatigue model assumed that FEA accurately described both the plastic and creep energies as distinct separable parts.

4.2 Application of creep models for insertion mounted components

Pan et al [22] analyzed Pin through-hole (PTH) solder joint based on the creep strain fatigue model where total strain included elastic strain, plastic strain, creep strain by finite element analysis (ABAQUS) and validated it with experimental observations. Non-linear elastic-plastic solder properties at different temperature and a steady state creep law were used to characterize the deformation of the eutectic Pb/Sn solder joint. The creep component was characterized by hyperbolic sine equation and displacement of pin as follows

$$\dot{\epsilon} = A(\sinh B\sigma)^n (d)^m \exp\left(-\frac{Q}{RT}\right) \quad (4.14)$$

$$d = \Delta\alpha L \Delta T \quad (4.15)$$

Where $\dot{\epsilon}$ is creep strain rate, σ is the stress, d is the grain size, Q is the activation energy, R is the gas constant, T is the absolute temperature, A and B are constants, n is the stress exponent, m is the grain size exponent, $\Delta\alpha$ is difference between the thermal expansion coefficient of copper, L is the length of pin, ΔT extreme temperature difference during temperature cycle.

Thus, concluded that large geometry changes were observed experimentally in the solder and pin structure due to a combination of plastic and creep deformation that accumulated during thermal cycling.

D Barker and M Pecht [9] analyzed leaded through-hole solder joint using MARC general purpose commercial FEM code of non linear finite element method under different thermal cycles based on energy partitioning technique. Where total strain is separated into elastic, plastic and creep in generating the detailed stress-strain histories. For elastic and plastic behavior, Ramberg Osgood constitutive relationship and for steady state creep law weertman model were used. Creep fatigue damage evaluation was done on basis of Halford-Manson strain range partitioning technique. Upon analysis concluded that the failure of solder joint resulted from fatigue damage around the fillet at the interface of solder, pin, and epoxy. Since the strain concentration is highest at this site for most of the cycle duration and hence accumulation of fatigue damage. In addition, with the increase of temperature the strain concentration shifts from one corner (node) to opposite diagonal corner or node located at the interface of solder and copper PTH .They also commented that the strain is multiaxial rather than of one pure shear.

Energy partitioning method applied was:

$$\varepsilon = \varepsilon_{el} + \varepsilon_{pl} + \varepsilon_{cr} = \frac{\sigma}{E} + \left(\frac{\sigma}{K}\right)^{\frac{1}{n_p}} + \varepsilon_0 \sigma^{\left(\frac{1}{n_c}\right)} e^{\frac{-\Delta H}{T_i}} \quad (4.16)$$

Fatigue Damage model was:

$$\frac{\Delta \gamma_t}{2} = \tau_f' (2N_f)^b + \gamma_f' (2N_f)^c \quad (4.17)$$

Ling and Dasgupta [23] formulated a model based on the creep strain fatigue model. The model was based on energy principles to evaluate the fatigue life endurance of leads for two different types of through hole package under high cycle vibrational loads. The strain

energy accumulated in the leads was expressed as a function of external loads acting on the lead foot due to the deformation of PWB and geometrical constitutive parameters of the lead. Castigliano's theorem was applied to solve for lead compliance and loads. An analytical expression for distribution of elastic stress and strain in each lead caused by forces and moments at the lead foot was developed based on a modified coffin manson model as used by bhandarker et al (1992) and fatigue properties of lead material.

$$\frac{\Delta \varepsilon_{eq}}{2} = \frac{\sigma_f}{E} (2N_f)^b + \varepsilon_f (2N_f)^c \quad (4.18)$$

Where N_f is the estimated fatigue life cycle, E is the young's modulus, σ_f is the high cycle fatigue strength constant, ε_f is the low cycle fatigue ductility constant, b is the high cycle fatigue strength exponent, c is the low cycle fatigue ductility exponent, $\Delta \varepsilon_{eq}$ is

the maximum equivalent strain range($\varepsilon_{eq} = \frac{\sqrt{2}}{3} \sqrt{(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2 + (\varepsilon_3 - \varepsilon_1)^2}$)

Thus, they concluded that on using material constitutive properties, architecture and geometry of leads and package as inputs for computer program, it calculated the stiffness matrix, distribution of stress and strain, position of maximum equivalent strain and finally the estimated fatigue life. And the model was limited to small deformation, linear elasticity scheme and was valid for high cycle vibration fatigue. But a modification as such consideration of the compliance of the solder in the plated through hole would enable to generate the estimated fatigue life in a leaded through hole package in a more realistic environment. Further, by considering the in elastic deformation in the lead or solder could extend to low cycle fatigue.

Engle & Chou [24] performed an analysis based on plastic strain fatigue model using finite element ABAQUS program. As such non-linear temperature dependent stress strain curve of solder with out creep was considered for the calculation of elastic plastic foundation modulus function. In the case of thermal mismatch loading they divided the total temperature range (e.g. 0-100⁰C) into a finite number n of temperature stages and final response was superposed from the n contributions for each, which were done using an isothermal stress calculation. It was concluded that the high temperature range which required more stages of computation than the lower one yield results with a close resemblance to those of elastic foundation method, Hence inclusion of thermal and inelastic solder stress/strain dependence. The parameters used for analysis were three solders (Sn-Pb solder 68/37, 70/30 and 10/90). Solder barrel thickness and mismatch temperature range

Hardisty & Abboud [25] determined the steady state heat transfer in Dual in line package (DIP) using 3 dimensional finite element method. They carried out a systematic thermal analysis on the finite element model of 16 pin DIP which was cooled by air, first by natural and then by forced convection. Thermal analysis of DIP involved the investigation of factors affecting the shape of DIP body, die with bonding wire of the heat flow path through the DIP and thermal resistance. They concluded that finite element has confirmed the complex 3 dimensional nature of the temperature distribution with in the package. It also showed how both temperature distribution and thermal resistance changed in response to changes in external convection.

He divided the overall heat transfer process in the package into three sub process such as internal conduction, convection from outside surface, and cumulative bulk temperature in the package which are as follows

$$Q = kA (T_2 - T_1)/L \quad Q = -hA (T_c - T_A) \quad Q = \sigma \varepsilon A ((T_c^4 - T_A^4)) \quad (4.19)$$

Where Q is heat transfer rate, k is the thermal conductivity, $(T_2 - T_1)$ is temperature difference, L is the thickness of body, h is the surface heat transfer coefficient, A is the area of surface, T_c is the junction temperature, T_A is ambient temperature, σ is Stefan Boltzmann constant, ε is the emissivity

4.3 Analysis of the Pin forces and displacement

Peter A .Engle presented a set of analyses to determine the force distributions and moments of an insertion mounted component with multiple lead

Engle & K.R. Wu [26] studied the mechanical behavior of single corner pin. They performed the thermal stress analysis on a single pin (corner pin) of a pin grid array (PGA) using analytical, experimental and finite element method. Analytically, elastic-plastic foundation analysis was done to find solder joint role as an elastic foundation and on computation it was found that thermal stress on pins were greatly affected by elastic foundation action of solder filling the card hole and derived analytically that modifying effect for moments, transverse shear and solder joint displacement was in terms of function of $\gamma = \lambda L$. Plasticity of pin was also modeled and it could be significant if the

thermal mismatch displacement is in excess and pin plasticity would act as a reducer of solder stress.

Axial forces the presence and absence of pin plasticity were investigated and the overall effect of PGA was concluded that axial tension is generated on pins as they flex due to thermal mismatch on the PGA. As 'u' was increased, axial tension force (F) monotonically grew in the elastic stress range of the pin and when plasticity arised F leveled off briefly before it started increasing again. Thermal stress in solder pins were calculated under the assumption of an elastically deforming solder barrel

Engle & J.R. Webb [27] developed a secondary stress relief system for anchoring solder forces by considering flexural and in plane flexibilities of the confining module and PCB elements. They considered the primary axial force F, plate moments M_1 , M_2 and shear V acting in radial planes and the compatibility of deformation at two pin ends were stipulated to evaluate secondary pin force P. The plate equation in polar symmetry were calculated using a collection technique. A 50mm ceramic module was evaluated numerically using the contributions of transverse plate compliances and in plane compliances, then compared it with known experimental force measurements.

Valentin, Johnson, Barker et al [2] developed a method to determine the critical lead force for accuracy and rapid assessment in insertion mount components. They developed an analytical approach; based on the Vandeveld analytical approach which was used in determination of forces for surface mount interconnects. Vandeveld derived the

analytical formulae for the normal and shear stresses arising in discrete attached structure due to thermal expansion mismatch. The analysis was done on a 40 –lead DIP and a 132-Pin PGA. The analytical model was verified through extensive finite element modeling and analysis, which is as follows

$$F = \frac{Mc_1 + Mc_2}{h_c},$$

$$(\alpha_1 - \alpha_2)\Delta\theta p_i = \left(\frac{h^2}{E_1 I_1 + E_2 I_2} + \frac{1}{E_1 A_1} + \frac{1}{E_2 A_2} \right) \sum_{k=1}^i \sum_{q=k}^n F(q) p + F(i)(k_1 + k_2 + K_c) \quad (4.20)$$

They also evaluated the effects of hole size, PTH thickness and solder material and determined that these properties have little effect on the global force determination. It was also found that there was a decrease in stress with increasing stand off height and along with that a decreased cross section area of the lead. Hence, concluded that these effects lengthen the life of the lead and therefore the component. Thus these forces which were determined would be used for future determination of stresses in the critical leads and these stresses would be used to create a rapid assessment failure model for the overall assembly.

On review of fatigue models and the application of fatigue models used for analysis of fatigue life prediction of insertion mounted components. Pan's study on insertion packages for accumulated plastic deformation in the lead frame did not extend with more than three leads of the package.

Engel applied the axisymmetric disk technique to obtain a solution for the force distributions in the leads of insertion mounted components. It considered the leads as continuous entities and the analysis did not provide a function that described the effective

stress in the solder interconnects. Plastic strain based fatigue model would be appropriate for Dual in line packages where it considers elastic and plastic strain which are temperature dependent.

Chapter 5 DSC Technique and Experiment

5.1 DSC Technique

Digital Speckle Correlation (DSC) is a computer vision stress analysis technique. It involves the combination of concepts of an image processing and pattern recognition, implementation of a hybrid optoelectronic and numerical approach into a computer vision system. The applications have proved that the technique is a promising tool for the reliability of microelectronic packages. A typical schematic shown in fig 5-1.

Figure 5-1 A DSC schematic [28]

Strain measurement in the solder joint of a package using DSC technique involves two main steps which are image acquisition during the test and image processing after the test. The later is based on digital image processing and pattern recognition, the methodology of DSC is based on kinematic law of surface deformation. In a numerical process, surface deformation parameters are extracted for the correlation of images acquired under different deformation states. Thus, image processing is

comparison of a pair of digital image subsets that are recorded respectively before and after the surface is deformed.

The concept could be explained as follows:

Assume a pair, with a subset of the non-deformed image also referred to as a “reference image” and represented by $f(x, y)$ which is a light intensity distribution function. The deformed subset is given by $g^*(x^*, y^*)$, where (x, y) represents the pixel location of the charge coupled device (CCD) camera used in the image recording.

A decorrelation factor S is defined for the image pair which is as follows:

$$S(u, v, \partial u / \partial x, \partial u / \partial y, \partial v / \partial x, \partial v / \partial y) = 1 - \frac{\sum f(x, y) g^*(x^*, y^*)}{\sqrt{\sum f^2(x, y) \sum g^{*2}(x^*, y^*)}} \quad (5.1)$$

The independent variables of the S function are the displacements and displacement gradients which are defined at the center point of the image subset. These parameters are obtained in evaluation of $S = 0$ for the root.

The numerical process of image processing could be briefed as such that the image processing begins with the calculation of S with initially estimated deformation parameters. These estimates are from a earlier routine of ‘course search’ Once the S value is obtained , the estimated deformation parameters are upgraded with the application of Newton-Raphson algorithm which finds the approximate root of the S function. Thus, resulting in a progressively reduced S values, generated by subsequent iteration and the improved deformation parameters.

Usually, the S value would converge and reduce to a pre-determined minimal (very close to zero) after a few sessions of calculations. Thus, this signifies that the parameters have approached an acceptable quality at the termination of the process.

On accomplishment of image processing, the strains are calculated with the obtained displacement gradients via the following equations:

$$\varepsilon_x = \sqrt{1 + 2\frac{\partial u}{\partial x} + \left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial x}\right)^2} - 1 \quad (5.2)$$

$$\varepsilon_y = \sqrt{1 + 2\frac{\partial v}{\partial y} + \left(\frac{\partial v}{\partial y}\right)^2 + \left(\frac{\partial u}{\partial y}\right)^2} - 1 \quad (5.3)$$

$$\gamma_{xy} = \arcsin \frac{\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} + \frac{\partial u}{\partial x} \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \frac{\partial v}{\partial y}}{(1 + \varepsilon_x)(1 + \varepsilon_y)} \quad (5.4)$$

In case of small deformations the following equations could be used:

$$\varepsilon_x = \frac{\partial u}{\partial x} \quad (5.5)$$

$$\varepsilon_y = \frac{\partial v}{\partial y} \quad (5.6)$$

$$\gamma_{xy} = \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \quad (5.7)$$

Applications involving temperature changes, the measured strains would be called total strains or the sum of the mechanical strain and the thermal expansion.

In case of thermally isotropic materials which respond linearly to the temperature change ΔT with a constant coefficient of thermal expansion α , the measured total strains, mechanical strains and thermal expansion terms are related by the following equations:

$$\varepsilon_x = \sqrt{1 + 2 \frac{\partial u}{\partial x} + \left(\frac{\partial u}{\partial x} \right)^2 + \left(\frac{\partial v}{\partial x} \right)^2} - 1 + \alpha \cdot \Delta T \quad (5.8)$$

$$\varepsilon_y = \sqrt{1 + 2 \frac{\partial v}{\partial y} + \left(\frac{\partial v}{\partial y} \right)^2 + \left(\frac{\partial u}{\partial y} \right)^2} - 1 + \alpha \cdot \Delta T \quad (5.9)$$

$$\gamma_{xy} = \arcsin \frac{\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} + \frac{\partial u}{\partial x} \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \frac{\partial v}{\partial y}}{(1 + \varepsilon_x)(1 + \varepsilon_y)} \quad (5.10)$$

And in case when the deformation is small, the following equations would be:

$$\varepsilon_x = \frac{\partial u}{\partial x} + \alpha \cdot \Delta T \quad (5.11)$$

$$\varepsilon_y = \frac{\partial v}{\partial y} + \alpha \Delta T \quad (5.12)$$

$$\gamma_{xy} = \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \quad (5.13)$$

For calculating the maximum shear stress the following equations is

$$\gamma_{\max} = \sqrt{(\varepsilon_x - \varepsilon_y)^2 + (\gamma_{xy})^2} \quad (5.14)$$

5.2 Advantages of DSC Technique

The DSC technique has similar advantages of other vision techniques which are being non contact and remote sensing .The technique does not need to attach physical gauges or

sensors to test samples, though it requires a sample surface with sufficient variation of light reflectivity. This feature enables the technique to characterize materials that are highly soft, highly viscoelastic, highly fragile or super thin. In addition it is relatively insensitive to environmental instability .Hence it is applicable to unique measurements such as on bottoms of narrow notches or deep groves in an electronic assembly. It generates results almost instantly, as such yielding direct strain values. This leads to avoidance of error-prone processes of generating strain values from fringe counting. An important and attractive feature is the adjustable spatial resolution which enables it to conduct measurements at both microscopic and macroscopic levels of scale.

5.3 Test Vehicles and Sample Preparation

The sample used in this study was dual in line package to measure the solder joint strains at desired location. The sample was polished, photographed and deposited with thin layers of black and white speckles. Figure 5-2 shows the picture of the joint area with and without the speckles coverage. To locate exactly the solder layer under the coating during image processing was a key to the measurement accuracy. This is largely helped with identifying feature lines and points on the two photographs. The spray-painted random speckle pattern ensures sufficient variation of light reflectivity across the surface, which is required for the proper functioning of the image correlation calculation. The artificial speckle coating also effectively prevents the surface pattern from undesired changes during heating, since the naked surface texture may possibly experience changes due to solder micro-structural coarsening. The sample dimensions are as listed in table 5-1.

(a)

(b)

Figure 5-2 Sample without speckles (a) and with speckles (b)

Table 5-1 Approximate dimension of test samples (unit: mm)

Sample	Test (SnPb)
Package thickness	27.8mm
Board thickness	1.15mm
Length of the pin	29.3mm-32.7mm
Diameter of the pin	0.356mm-0.558mm
Solder thickness (fillet)	0.026mm

5.4 Test Parameters

Test temperature profile is plotted in Figure 5-3. The test was commenced at a room temperature (24 °C) and the solder joint temperature is increased gradually, as such the ramp up was about 18 minutes till it reach the 100°C and then dwell began. During testing, the dwell temperature was manually controlled and stabilized at 100°C. The ramp down was continued till it reached at the room temperature. To be noted that the ramp down was not controlled and it was left for cooling at the room temperature. The dwell time (10mins) is for examining the solder joint thermo mechanical behavior, especially creep behavior at an elevated temperature.

Figure 5-3 Temperature profiles of the sample

5.5 Experiment Procedure

5.5.1 Thermal Chamber

The thermal chamber used in this study is INSTRON SFL 3119-005, which has a capability from -50 to 250°C with an automatic control at the accuracy of $\pm 1^\circ\text{C}$. The ramp rate could be preset and rise up to $8^\circ\text{C}/\text{min}$. The chamber is constructed using a mild steel frame with removable painted mild steel panels. A perforated stainless steel frame surrounds the door aperture and supports a stainless steel inner chamber. The inner chamber is insulated with glass fiber and/or microtherm insulation, which are retained by painted panels and a re-circulating fan in the chamber was used to distribute the heat uniformly.

5.5.2 Sample Temperature Control

There was a temperature lag in the sample with respect to the oven air. The chamber's temperature sensor is at the intake of the ventilation with a distance from the sample.

During testing, two additional thermal couples were attached to the sample stand in the area of the sample to monitor the sample temperature. The sample temperature was also calibrated before the formal testing and was found to slightly lag behind the chamber reading. At the high temperature, the difference between the chamber and sample temperature could rise up to 10 °C, whereas no significant difference was recorded at low temperatures. Due to the high optical magnification used for resolving the solder joint, the system vibration could disturb image recording. To avoid this, the fan was turned off at the image recording time. When the chamber was set at the automatic temperature holding mode, the turn-off would cause a temperature drop of few degrees depending upon the duration of the off time and the heating rate. The automatic temperature holding facilitates well only at the sensor location and the sample temperature would experience a slight but continued rise due to delayed heat transfer. This problem was solved using manual control, which could keep the sample temperature stable at one or two degree fluctuation.

5.5.3 Image Recording and Data Processing

A series of thirty one images at different temperatures were taken from the sample. The time interval between two consecutive images was approximately two minutes. Image processing area chosen is as shown in Figure 5-4 by the solid line box, which covers a portion of the solder layer along with a pin in the hole of a printed circuit board. The processing follows a grid of 21 (horizontal) by 21 (vertical) points that cover the boxed area. A method to counteract random error in strain measurement at a single point is to calculate the average strain over a small area. In this case, the average strain was

calculated based on a sub-area covering 6 data points, as shown in Figure 5-4. This area was chosen because stress concentration exists at this location which is almost at the centre of the hole along with pin and solder attached. The contour maps of shear strain γ , normal strain in x and y direction are shown in Figure 5-5

Fig 5-4 A sketch corresponding to the image to show the processed area and the data area that the average strain is calculated

Figure 5-5 Contour maps of measured shear strain, and normal strain in x & y direction

Chapter 6 Analysis of DSC Measured Data

6.1 Solder Joint Constitutive Relation Model

The analysis of strain data with the solder constitutive relations was done for the determination of the stress, the assumptions taken into consideration are as follows:

- It is considered that there is no variation in activation energy of solder for a range of test temperatures. As stated in the literature [32], for creep, the activation energy Q is constant at relatively high temperature and therefore independent of stress and temperature.
- Solder re-crystallization has no effect on the strain measurement. An artificial speckle layer covers the surface, though the coarsening of solder joint microstructure has been observed and reported [33].
- Primary creep is negligible and thus ignored in the data analysis [34].
- Anelastic (time dependent elastic) deformation is negligible.
- Zero stress state in the solder joints exists at room temperature.

As shear is the dominant component, the analysis is focused on shear strain and stress. The total shear strain is the algebraic sum of the elastic, plastic, and creep shear strains as follows:

$$\gamma_{el} + \gamma_{pl} + \gamma_{cr} = \gamma_{tl} \quad (6.1)$$

Where γ_{tl} is the DSC measured total strain, γ_{el} is the elastic strain, γ_{pl} is the time independent plastic strain and γ_{cr} is the time dependent creep strain.

Hooke's law is applied to relate elastic shear stress and shear strain are as follows:

$$\gamma_{el} = \frac{\tau}{G} \quad (6.2)$$

Where γ_{el} , τ , and G are the elastic shear strain, shear stress and the shear modulus respectively. Shear modulus could be calculated through following relation for the constants.

$$G = E/[2(1+\nu)] \quad (6.3)$$

Where ν is Poisson's ratio and E the modulus of elasticity. The Poisson's ratios along with Young's modulus of SnPb which is temperature dependent are listed in table 6-1.

The time independent plastic deformation is expressed using Ramberg-Osgood type relation [12] which is as follows and constants are listed in table 6-2.

$$\gamma_{pl} = C \left(\frac{\tau}{G} \right)^m \quad (6.4)$$

The solder stress could be obtained from measured total strain with an appropriate selection of constitutive equation which characterizes the solder creep. In this study creep equation (3.11) applied to express creep strain behavior in the eutectic tin-lead solder joint and their constant are in table 6-3.

$$\frac{d\gamma_s}{dt} = C_1 \frac{G}{T} [\sinh(\alpha \frac{\tau}{G})]^n \exp(\frac{-Q}{kT}) \quad (6.5)$$

where C_1 is a constant characteristic of the micro-mechanism of solder creep, G is the temperature dependent shear modulus, α prescribes the stress level at which the power law dependence breaks down, n is the stress exponent, Q is the

activation energy for the deformation process, k is Boltzmann's constant and T is the temperature in absolute scale [12].

Creep strain rate could also be expressed in simplified shear or tensile form as follows [12]

$$\frac{d\gamma_s}{dt} = C_5 [\sinh(a_1 \tau)]^{C_3} \exp\left(-\frac{C_4}{T}\right) \quad (6.6)$$

$$\frac{d\varepsilon_s}{dt} = C_1 [\sinh(C_2 \sigma)]^{C_3} \exp\left(-\frac{C_4}{T}\right) \quad (6.7)$$

Where ε and σ are the effective strain and effective stress, respectively. Based on the von Mises yield criteria, the terms are related to each other as follows:

$$\sigma = \tau\sqrt{3} \quad (6.8)$$

$$\varepsilon = \frac{1}{\sqrt{3}}\gamma \quad (6.9)$$

The constants C_1 to C_4 and solders mechanical properties are listed in table 6-1.

a_1 and C_5 can be derived using Equations (6.10) and (6.11):

$$C_5 = \sqrt{3}C_1 \quad (6.10)$$

$$a_1 = \sqrt{3}C_2 \quad (6.11)$$

Table 6-1 Materials constitutive parameters [35, 36]

Material	63Sn37Pb
Young's modulus (Gpa)	75.94-0.152T
Poisson's ratio	0.35
C_1 (1/s)	462(508-T)/T

C_2 (1/Pa)	$1/(37.78 \times 10^6 - 74414T)$
C_3	3.3
C_4 (K)	6360

Note: T in K

Table 6-2 Time independent plastic flow constants [12]

Alloy	60Sn40Pb
Elastic constants:	
G_0 (Mpsi)	1.9
G_1 (Kpsi/K)	8.1
Strain-hardening:	
C	2.34×10^{13}
m	5.58

Table 6-3 Constants in equation and activation energies given by Darveaux [12]

Alloys	60Sn40Pb
C_1 (K/sec/psi)	0.198
α	1300
n	3.3
Q (eV)	0.548
K	$1.38 \text{ E-}23 \text{ Joule/K}$

6.2 Partitioning of solder joint strain & calculation of stress and creep

strain rate

6.2.1 Shear stress, strain partitioning and creep rate

Upon integration over the time interval, the creep strain increment $\Delta\gamma_{s_i}$ during a finite time interval Δt_i could be calculated by equation (6.12) as follows:

$$\Delta\gamma_{cr_i} = \int_0^{\omega_i} \dot{\gamma}_{s_i} dt = \int_0^{\omega_i} C_5 [\sinh(a_1 \tau_i)]^{C_3} \exp\left(-\frac{C_4}{T_i}\right) dt \quad (6.12)$$

In which $T_i = T_{i-1} + r_i \Delta t_i$, T_{i-1} is the initial temperature for each time interval Δt_i and r is the ramp rate. At any point of time, the accumulated creep strain γ_{cr} is the sum of all creep increments as follows:

$$\gamma_{cr_i} = \sum_0^i \Delta\gamma_{cr_i} \quad (6.13)$$

On analysis of DSC measured data, an assumption that shear stress τ_i is being kept constant during short interval Δt_i , as shown in Figure 6-1

Figure 6-1 Schematic of shear stress variation and in the short interval. Shear stress is assumed constant in the short interval

On substitution of equations (6.2), (6.4) and (6.13) into equation (6.1) of the total shear strain, an equation could be obtained as follows:

$$\frac{\tau_i}{G} + C_6 \left(\frac{\tau_i}{G} \right)^m + \sum_0^i \Delta \gamma_{cr_i} = \gamma_{il_i} \quad (\tau > 0, \text{ before } \tau_{\max}) \quad (6.14)$$

When the shear stress has reached the maximum, time independent plastic strain does not increase anymore. So, in the following analysis,

$$\frac{\tau_i}{G} + \gamma_{pl_{\max}} + \sum_{j=1}^{i-1} \Delta \gamma_{cr_j} + \int_0^{\Delta t_i} C_5 [\sinh(a_1 \tau_i)]^{C_3} \exp\left(-\frac{C_4}{T_{i-1} + r_i t}\right) dt = \gamma_{il_i} \quad (\tau > 0, \text{ after } \tau_{\max}) \quad (6.14-a)$$

Where, $\sum_{j=1}^{i-1} \Delta \gamma_{cr_j}$ sum of all creep increments before maximum shear stress

occurs. r_i is the ramp rate, in °C/s.

During, the commencement of ramp down period, the total inelastic strain γ_{in} accumulated in the ramp up and high temperature dwell is calculated by using

formulae $\gamma_{in} = \gamma_{pl} + \gamma_{cr}$. γ_{in} is the total strain at totally stress relaxation,

i.e. $\tau = 0$. The time and temperature at $\tau = 0$ by interpolation is found by using measured total strains during ramp down periods as reference. On detection of zero-stress state during ramp down period, the analysis could proceed and shear stress could be attained by solving equation (6.14-b).

$$\frac{\tau_i}{G} - C_6 \left(\frac{-\tau_i}{G} \right)^m + \gamma_{in_i} + \sum_{j=1}^{i-1} \Delta \gamma_{cr_j} = \gamma_{il_i} \quad (\tau < 0, \text{ before } \tau_{\min}) \quad (6.14-b)$$

Where $\sum_{j=1}^{i-1} \Delta \gamma_{cr_j}$ is the sum of creep increments from $\tau = 0$ to minimum shear stress occurring.

$$\frac{\tau_i}{G} - \gamma_{pl_{min}} + \gamma_{ini} + \sum_{j=1}^{i-1} \Delta\gamma_{cr_j} + \int_0^{\Delta t_i} -C_5[\sinh(-a_1\tau_i)]^{C_3} \exp\left(-\frac{C_4}{T_{i-1} + r_i t_i}\right) dt = \gamma_{ti}$$

($\tau < 0$, after τ_{min}) (6.14-c)

Where γ_{ti} , the DSC's measured total strain at time t_i . The shear stress τ_i at different point in time could be obtained by solving the above equation using a numerical method of trial and error. Since the constitutive parameters in Equation (6.14) and testing parameters t , T , and r_i are known from testing temperature profile. As the raw strain data being scattered, the total strains of Equation (6.14) at different temperatures in are from the fitting functions of the raw data at respective temperatures.

The creep strain rate could be calculated, using equations (6.2), (6.4), (6.13) and (6.5-7), respectively, when the stress is known for each point of time, the elastic, plastic, and creep strains can be separated

6.3 Assortment of total strain curve-fitting function

Total strain curve fitting of test is divided into two parts which are ramp up period and another is high dwell time period, due to the difference in the deformation mechanism of two periods. In case of ramp up, the original DSC measured strains trend is apparently curve linear and a polynomial function that is used for fitting the data. And in case of dwell time, the study test results and theory depict that the deformation mode in the solder joints is shear strain due to CTE mismatch between pin and copper plating material. The total strain in the solder joint is to be constant, when the temperature is kept constant. Hence, for

curve fitting the strain data points in the high dwell time, a linear regression function is used to curve fit the strain data point.

6.4 Trial and Error Method

It has been unfeasible to get closed-form formula for τ due to equation (6.14, a, b, c) being very complex. During this analysis to obtain τ , equation (6.13) is being solved by numerical method “trial and error”. Often trial and error method is an approach used for solving complicated equation and obtaining solution.

The basic principles of this method are explained as follows:

- i. Firstly the presumed τ is being assigned
- ii. Left side of the equation with assigned value of τ is calculated
- iii. The calculated left side and right side of equation are being compared at a point of time.

On condition that the equation is not balanced, adjust τ , and the process is done again from i to iii until the equation is balanced.

6.5 Computation of elastic strain, plastic strain, creep strain and creep rate

Using from above process the known shear stress at each calculation point, the elastic strain, and plastic strain could be calculated for test with equation (6.2) and (6.4) respectively. In case of creep strain, first of all, the equation (6.12) is used for obtaining the creep increment during the time interval; secondly, the accumulated creep is summed up with equation (6.13). Creep rate at each point could be calculated with equation (6.6). Once all calculations are done, total

strain measured by DSC could be quantitatively partitioned into three parts
elastic strain, time independent plastic strain and time dependent creep strain.

Chapter 7 Description of Results from Data Analysis

Subsequently, on analyzing the experimental data using the analytical method, results of the data analysis for the dual in line package are being represented.

The results distinguish the thermo mechanical behavior in terms of elastic, time independent plastic strain, time dependent creep strain and normal strain.

The important variables during the thermal test conditions such as shear stress, creep strain, creep strain rate, and maximum shear stress in the solder joint are as well plotted.

All over analysis equations used are; Hooke's law for elastic strain, Ramberg-Osgood plastic strain and R Darveaux for the creep strain. The constants are from R Darveaux for elastic, plastic, creep strain listed in table 6-1,2,3. Since normal strain is not linear in x and y directions and could not be negligible. Hence, the maximum shear stress is calculated to evaluate the normal strain from constitutive law.

7.1 Results

Plots for the DIP solder joint are elastic, plastic, creep strain, shear stress, creep strain rate, normal strain in x and y direction and maximum shear stress as a function of time are shown in the figs 7-1, 4, 5, 9,10. Temperature outline of ramp up till 100°C, dwell 10 minutes hold at 100°C and ramp down till room temperature of shear strain, normal strain in x and y and maximum shear strain are as shown in figs 7-3,6,7,8

Figure 7-1 Shear stress & shear strain as a function of time

Figure 7-2 Shear stress & shear strain as a function of temperature

Fig7-3 DIP temperature profile and shear strain as a function of time

Figure 7-4 Creep strain rate as a function of time

Figure 7-5 Trend comparison of creep strain rate, total shear strain, temperature and shear stress in solder joint

Fig 7-6 DIP temperature profile and normal strain in x direction as a function of time

Fig7-7 DIP temperature profile and normal strain in y direction as a function of time

Fig 7-8 DIP temperature profile and maximum shear strain as a function of time

Figure 7-9 Maximum shear stress & shear strain of DIP as a function of time

Figure 7-10 Trend comparison of normal strain in x and y direction, shear strain, maximum shear strain in solder joint

Chapter 8 Discussion and Conclusion

8.1 Discussion

8.1.1 Tendency of total shear strain, creep strain rate, shear stress and normal strain in x & y direction

From the results plotted in fig 7-1 SnPb solder joints exhibit shear strain variations with respect to time. During the ramp-up period, thermally induced shear strain in the solder joint increased with rising temperature, where as shear strain slightly went up during the 10-minutes dwell elevated temperature in the test. This means that solder joint showed thermo-mechanical deformation behavior. As temperature increases shown in figure 7-2, the materials in the package begin to expand. The mismatch of coefficient of thermal expansion between pin and copper plating caused the deformation, which is absorbed in the solder joints. Higher the temperature, would result in more shear strain in the solder joint.

As shown in the figure 7-5 with increasing temperature, shear stress in the solder joint quickly initiates and creep strain rate remains very small at the beginning of the test when temperature is low and time duration is short. In the course of ramp up as shear stress reaches maximum, the creep strain rate also reaches to the utmost. The occurrence of maximum creep strain rate was at the end of ramp up when temperature was high. And at this time, shear stress continues relaxing. During dwell time at high temperature, the shear strain was keeping on increasing a little. Shear stress continued relaxing and creep strain

rate was decreasing even though it was at the highest temperature in the testing. This was a the reason that stress relaxation is very small and creep strain rate is the function of stress and temperature.

8.1.2 Elastic Deformation

Elastic deformation is in the order of magnitude of 10^{-4} which occurred at the very beginning of the test when temperature was low and time duration was short. At this period, the elastic strain was the dominant deformation mechanism since plastic strain happens after the yielding point and creep strain needs time and temperature to accumulate. Both plastic and creep strains are negligibly smaller (in the order of 10^{-8} to 10^{-6}) than elastic strain. This is also evidenced by the good linearity shown among the first few data points shown in figure7-1. The elastic strain was small except at the beginning of the test. The maximum elastic strain only accounted for 3-4% of the total shear strain induced in the solder joint. Therefore, it was applicable to ignore elastic strain from total strain during solder joint thermal stress strain analysis in terms of simplicity.

8.1.3 Time Independent Plastic Strain

The time independent plastic strain was less than elastic strain at the beginning of the test when temperature was low and time duration was short as shown in fig 7-1. But started to rise just before the dwell period and was held constant during dwell time and finally began to decrease during ramp down. The study is based on a strain driven, which means that thermal expansion causes stress in

the solder joint. The lead-tin eutectic alloy has a history of use, till recently it changed to lead free alloy. It has a low melting point (183°C) and exhibits better wetting property in the soldering process than any other group of solder alloys.

8.1.4 Solder Creep

From data analyses, as shown in fig7-1,10, creep was a dominant mode of deformation although it took time to show its dominance during a thermal cycle. At the beginning of test, both solder creep strain and creep strain rate were small prior to 50 °C. This may be partially due to the time and temperature required for solder creep. The magnitude of creep strain rate is 10^{-8} to 10^{-6} shown in figure7-5. As the temperature went up, the creep strain was accumulating quickly with time while the sample temperature was increasing. At the end of ramp up, creep strain accounted for about 64% of total strain according to the data analysis. Creep strain discrepancies in solder joint came from the magnitude of plastic strain, since the total inelastic strain including plastic and creep strain are similar in the solder joints. For most of the testing time, creep strain rate was lower. However, at the end of ramp up period, higher creep strain rate resulted from the high temperature and high stress in the solder joint at that time

8.1.5 Normal Strain in X and Y direction

Normal strain in x and y direction was in the magnitude of negative 10^{-4} and

10^{-3} as shown in figure7-6,7. This occurred at the beginning of the test when temperature was low and time duration was short. During the complete testing, dwell time showed a little bit more deformation as compare to other periods. The maximum shear strain was evaluated and compared with the shear strain. Usually normal strain in x and y direction are not a concern in SMT, but in this study it can not be neglected and therefore determined the maximum shear strain to include normal strain x and y and compared it with shear strain.

8.1.6 Effect of shear stress in the solder joint and stress relaxation

The solder joints in the through-hole technology packages during thermal cycling are primarily under displacement controlled boundary conditions. As temperature increased, the component and board in the test vehicle expanded differently since they have different coefficients of thermal expansion. The mismatch of coefficient of thermal expansion between pin (Kovar pin) and copper plating material caused an axial tensile load on the pin, thereby loading the solder joint in shear deformation and shear stresses were also generated between the pin and plated through-hole assembly in axial direction. The coefficient of thermal expansion for pin, copper plating and solder are 5.9, 17 and 21 E-06 respectively. At the same time stress was induced in the solder joint, since solder was compliant part and absorbed the strain induced in the system as shown in figure7-1. High temperature apparently leads to high shear stress in the solder joint and the maximum shear stress reaches (5.519 MPa) at

87°C (or 14 minutes after the start of the test). Dasgupta, Barker & Pecht [9] interpreted their results.

Due to differential coefficient of thermal expansions of the pin, solder, copper and FR4 in the radial direction, the shear loads were superposed by an extensive encircle and radial stresses in the solder. Hence forth indicating that this site undergoes maximum strain cycling and thus accumulating the maximum fatigue damage.

As the temperature continued rising, the creep developed with the time and the stress might have started to relax .During dwell at elevated temperature, the stress relaxes, which avoided the stress to continuously build up in the solder joint and the creep strain kept accumulating and the stress continued to relax over time. The shear stress was plotted as functions of time and temperature in the fig 7-1,2. During the ramp up, at the lower temperature, the solder was subjected to more severe stress and displayed less deformation while at relatively higher temperature the solder tolerated less stress and showed larger deformation. Pan et al [22] stated the more the deformation is accumulated, the more the strain and geometry of the solder joint changes, consequently the distributions of strain and stress are changed accordingly and complicate subsequent deformation.

8.2 Conclusions

Thermo mechanical strains in the eutectic tin-lead solder joint of pin through hole are evaluated using DSC technique for dual in line package. Applying the R Darveaux's constitutive model for solder material, the approach devised for strain partitioning that has led to calculation of the shear stress, elastic, plastic and creep strains from the measured total strain. The analysis does show that creep strain was the dominant deformation mechanism. The analysis also provided insights of the solder behavior under thermal load. In particular, the following points are worth addressing:

- Pin through-hole solder joint solder shows different deformation trends under temperature profile. With temperature increases, thermally induced deformation, especially shear strain in the solder joint was increasing.
- Under thermal load conditions, mismatch of pin and copper plating material resulted in shear deformation of solder and a dominant deformation mode. It was as well verified by experimental results using the DSC computer vision technique.
- Creep strain was the dominant deformation mechanism in the solder joint (2.84×10^{-3}) that occurred at the high temperature dwell period. And the maximum shear stress that occurred was 5.519MP during the end of ramp up period.

- It showed that higher shear strain, shear stress and creep strain based on the experimental data and calculation using the strain partitioning method.
- The elastic strain dominated in the beginning of the thermal cycle, but in the whole period of testing profile, it was negligible in comparison to the creep strain.

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DSC results of dual in line package solder joint

Fig A-1 Results of Ramp Up DSC shear strain at 35,42,50C

Fig A-2 Results of Ramp Up DSC shear strain at 58,68,77C