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## RESEARCH ARTICLE

# RELIABILITY ANALYSIS OF LEAD FREE SOLDER

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**ABSTRACT**

The reliability of electronic assemblies is highly dependent on the quality of solder joints, and the latter's response to temperature excursions. Finite element modeling (FEM) has been widely used for the estimation of the lifetime of solder joints subjected to temperature cycling. Thanks to the expertise of decades, a significant number of companies, universities and research institutes were able to have a relatively accurate estimation of life time for SnPb solder. For the lead-free solder materials, first attempts for correlation models show up but there are several problems. First of all, there is a wide range of alloys and alloy compositions, which have a different material behavior (E-modulus, CTE) but also a different resistance to thermal fatigue. Second, it is shown in several papers that lead-free solders have different failure modes compared to SnPb. In particular at low temperatures (-20°C, 50°C), some lead-free materials show brittle behavior and this is not covered by the current simulation models based on creep fatigue at high temperature. Experiments show that the trends in lead-free solder joint reliability are cycling-condition and package dependent. In this paper, the simulation results for commonly used solder alloys are presented and the thermal fatigue reliability of lead-free solder joints has been investigated. An isothermal fatigue test method was used in this study to improve the efficiency of fatigue study, and two different lead-free solder alloys, Sn-Ag-Cu, Sn-Ag were investigated. It was found that the lead-free solder alloy was more reliable compared to the lead alloy and this is package dependent.



## INTRODUCTION

The function of reliability engineering is to develop the reliability requirements for the product, establish an adequate reliability program, and perform appropriate analyses and tasks to ensure the product will meet its requirements. A key aspect of reliability testing is to define "failure". Soldering is distinguished from brazing by use of a lower melting-temperature filler metal; it is distinguished from welding by the base metals not

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being melted during the joining process. In a soldering process, heat is applied to the parts to be joined, causing the solder to melt and be drawn into the joint by capillary action and to bond to the materials to be joined by wetting action (Zahn Bret, 2002). After the metal cools, the resulting joints are not as strong as the base metal, but have adequate strength, electrical conductivity, and water-tightness for many uses. Currently, mass-production printed circuit boards (PCBs) are mostly wave soldered or reflow soldered, though hand soldering of production electronics is also still standard practice for many tasks. In wave soldering, parts are temporarily adhered to the PCB with small dabs of adhesive, and then the assembly is passed over flowing solder in a bulk container (Bart Vandevelde *et al.,* 2001). Reflow soldering is a process in which a solder paste (a sticky mixture of powdered solder and flux) is used to stick the components to their attachment pads, after which the assembly is heated by an infrared lamp, or (more commonly) by passing it through a carefully-controlled oven, or soldering with a hot air pencil. Since different components can be best assembled by different techniques, it is common to use two or more processes for a given PCB; the surface mounted parts may be reflow soldered, followed by a wave soldering process for the through-hole mounted components, with some of the bulkier parts hand-soldered on last (Laura *et al.,* 2000). For hand soldering of electronic components, the heat source tool should be selected to provide adequate heat for the size of joint to be completed. A 100 watt soldering iron may provide too much heat for printed circuit boards, while a 25 watt iron will not provide enough heat for large electrical connectors, joining copper roof flashing, or large stained-glass lead came. Using a tool with too high a temperature can damage sensitive components, but protracted heating by a tool that is too cool or under powered can also cause extensive heat damage. Environmental legislation in many countries, and the whole of the European Community area, has led to a change in formulation of both solders and fluxes. Water soluble non-rosin based fluxes have been increasingly used since the 1980s so that soldered boards can be cleaned with water or water based cleaners. This eliminates hazardous solvents from the production environment, and effluent. There is no easy answer to why the industry has become so pre-occupied with lead-free solders as of late, since there is no imminent legislation; the most simple explanation is FEAR: Fear of (potential) Legislation, Fear of Trade Barriers, and Fear of Competition. It is likely that most of the companies currently concerned with the lead-free issue are motivated by a combination of these three.

- The WEEE directive in Europe and similar mandates in Japan have instilled fear that a legislative body will prohibit the use of lead in electronics soldering.
- If a particular country disallows lead from electronics, then a de facto trade barrier is created between that country and anyone not capable of providing lead-free electronics solutions. Of course, this also could take place between individual companies or industries.
- Some companies already are producing electronics products with lead-free solder alloys and marketing them as such. This has led to fears of being caught behind in the marketing game.

## Reliability analysis of lead-free solder joint

Solder Joint Reliability, or SJR, is the ability of solder joints to remain in conformance to their visual/mechanical and electrical specifications over a given period of time, under a specified set of operating conditions. Solder joint reliability has two aspects - 1) component-level solder joint reliability; and 2) board-level solder joint reliability. Component-level SJR deals basically with the reliability of solder joints within the package structure itself prior to board mounting, and is primarily assessed by performing reliability tests on unmounted parts. Board-level SJR deals with the reliability of the solder joints of a package after it has been mounted on a board or substrate, encompassing both the solder-to-package and solder-to-board interfaces. There are three major mechanisms of solder joint failure, although these often interplay with each other simultaneously. These are: 1) tensile rupture or fracture due to mechanical overloading; 2) creep failure, or damage caused by a long-lasting permanent load or stress; and 3) fatigue, or damage caused by cyclical loads or stresses. Thus, solder joint reliability consideration.

**Table 1. Factors for failure**

| Factor | Failure % |
|---|---|
| Sand and dust | 6 |
| Moisture | 19 |
| Shock | 2 |
| Temperature | 40 |
| Salt | 4 |
| Altitude | 2 |
| Vibration | 17 |

ANSYS is chosen as the FEM package because of the fact that is used in the analysis foe the following reasons:

- ANSYS Workbench Capabilities for geometry processing and meshing
- Material models in ANSYS Mechanical
- APDL scripts for GUI based user inputs for Material models and Fatigue Model

In this work, fatigue life based on strain-energy density (Darveaux methodology) will be utilized for characterizing the fatigue life of the compliant interconnect and solder.

Crack Initiation, $N_0 = K_1 (\Delta W_{avg})^{K_2}$ .....(1)
Crack Growth, $da / dN = K_3 (\Delta W_{avg})^{K_4}$ …. (2)
Characteristic Life, $\alpha_w = N_0 + a / [da / dN]$ .... (3)

The characteristic life, $\alpha_w$ is then related to the failure free life and cycles to first failure for failure prediction.Here, K1 through K4 are parameters estimated by correlating ΔWavg from simulation predictions to test data of N and crack growth rate a is the joint diameter at the interface ('final crack length') ΔW is the plastic work per cycle. However, since the fatigue life prediction methodology developed by Darveaux was derived using measurement data taken from actual solder joints, which presumably contained similar intermetallic structures, their influence is believed to be indirectly incorporated into the predicted results.

# MATERIALS AND METHODS

By measuring the crack growth rate of actual solder joints, Darveaux was able to establish four K4) along with two equations by which finite element simulation results could be used to calculate thermal cycles to crack initiation along with crack propagation rate per thermal cycle. However, the methodology is sensitive to the finite element modeling procedure. First, care must be taken in controlling the element thickness at the interface between the eutectic solder and copper pad. Second, element volumetric averaging of the stabilized change in plastic work within this controlled eutectic solder element thickness must be used. This procedure reduces singularity issues whereby the size of the finite element mesh affects plastic work simulation results. It should also be noted that Darveaux's methodology requires that the solder ball and solder mask material elements not be joined in the finite element model. This is due to the non-adhesion between solder and mask materials. Given a solder mask defined solder joint at the package substrate, Darveaux recommends a 0.0127mm (0.5mil) gap between the solder ball and solder mask material in the finite element model. Corresponding K1 through K4 crack growth correlation constants for a 0.0254mm (1mil) solder joint element thickness are given in Table 2.

**Table 2. Thermal Cycle**

| Time(s) | Temp(°C) |
|---|---|
| 0 | 25 |
| 300 | -40 |
| 2100 | -40 |
| 2400 | 85 |
| 4200 | 85 |
| 4500 | -40 |
| 6300 | -40 |
| 6600 | 85 |
| 8400 | 85 |
| 8700 | -40 |

From the above table the following details are evident:

- $T_{max}$= 85 °C
- $T_{min}$=40 °C
- Ramp up/down time, $T_R$= 300s
- Dwell Time, $T_D$= 1800s

-40°C ~ 85°C cycle is chosen as it is the industry standard **JEDEC JESD22-A108.** Since Darveaux

English units, it is important to remember to convert the simulated ΔWave (ANSYS constant "dwavg") from units of MPa to units of psi by multiplying by 6.894757x10-3. Also, the solder joint diameter should be converted from units of mm to units of inches by dividing by 25.4. These values can then be substituted into equations (1) through (3) to obtain cycles to crack initiation, crack propagation rate, and solder joint characteristic fatigue life respectively.

**Table 3. Darveaux K1 Through K4 Crack Growth Correlation Constants**

| Constant | Value |
|---|---|
| $K_1$ | 22400 cycles/psi |
| $K_2$ | -1.52 |
| $K_3$ | 5.86x10-7 in/cycle/psi |
| $K_4$ | 0.98 |

## Modeling:

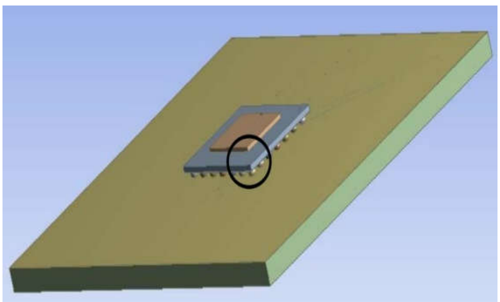

**Fig. 1. Modeling**

A 10x8mm, 72-ball (9x8 Full Matrix), 0.80mm pitch package was modeled using ANSYS ™ DESIGN MODELER.

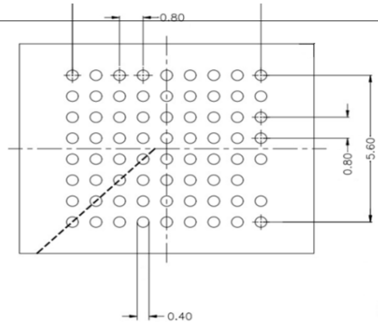


**Fig. 2. Board dimensions in MM**

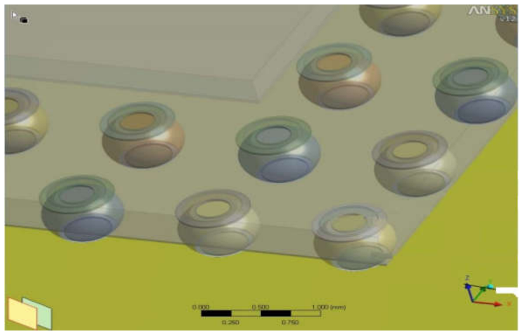

**Fig. 3. Solder ball modeling**

## Materials

The paper considers FR2 and FR4 board materials and Sn(63)Pb(37) and Sn(96.5)Ag(3.5). FR2 is usually used for 1-layer PCBs because they are not good for passing through holes. Flame resistant - 2consists of Paper material with phenolic binder. FR4 (FR = Flame Retardant) is a glass fiber epoxy laminate. It is the most commonly used PCB material. 1.60 mm (0.06 inch). FR4 uses 8 layers glass fiber material. The maximum ambient temperature is between 120° and 130°C, depending on thickness. FR4 is widely used because it is good enough to make anything from one- layer to multi-layer PCBs. With only FR4, PCB companies can make all kinds of PCBs, which makes the management and quality control much easier, and eventually reduces cost. Tin/lead solders, also called soft solders, are commercially available with tin concentrations between 5% and 70% by weight. The greater the tin concentration, the greater the solder's tensile and shear strengths. At the retail level, the two most common alloys are 60/40 Sn/Pb which melts at 370 °F or 188 °C and 63/37 Sn/Pb used principally in electrical work. The 63/37 ratio is notable in that it is a eutectic mixture, which means:

1. It has the lowest melting point (183 °C or 361.4 °F) of all the tin/lead alloys; and
2. The melting point is truly a point — not a range.

This alloy exhibits adequate wetting behavior and strength and is used in electronics as well as plumbing. Several sources have also reported good



Thermal fatigue damage in solders is accelerated at elevated temperatures. In the Sn/Pb system, the relatively high solid solubilities of Pb in Sn and vice versa, especially at elevated temperatures, lead to microstructural instability due to coarsening mechanisms. These regions of inhomogeneous microstructural coarsening are known to be crack initiation sites. It is well-documented that these types of microstructures in Sn/Pb alloys fail by the formation of a coarsened band in which a fatigue crack grows. By comparison, the Sn/Ag system, has limited solid solubility of Ag in Sn, making it more resistant to coarsening. As a result, Sn/3.5Ag eutectic forms a more stable, uniform microstructure that is more reliable. Although the Sn/3.5Ag alloy itself exhibits good microstructural stability, when soldered to copper base metal, the combination of a higher Sn content (96.5Sn compared to 63Sn) and higher reflow temperature environments accelerate the diffusion rates for copper base metal in Sn. As its corresponding composition is reached, the brittle Cu6Sn5 intermetallic compound is nucleated and begins to grow.

## Properties Used

The following material properties have been extracted from various research papers and are used in the analysis:

**Table 4. Structural Properties**

| Part | Properties | | | | | | |
|---|---|---|---|---|---|---|---|
| | DENS | EX | EY | EZ | PR XY | PR YZ | PR XZ |
| PCB board | 2,000 | 1.68e10 | 1.685e10 | 7.73e9 | 0.11 | 0.39 | 0.39 |
| Solder Sn Pb | 7,500 | 30641.69e6 | | | .35 | | |
| Solder SnAgCu | 9250 | 3.08e9 | | | 0.45 | | |
| Copper (Lead) | 8,960 | 128931.96e6 | | | .344 | | |
| Top Pad | 1,900 | 16.8e9 | 16.8e9 | 7.4e9 | 0.11 | 0.39 | 0.39 |

There are four possible combinations for the materials chosen:

- FR2+SnPb
- FR2+SnAg
- FR4+SnAg

**Table 5. Thermal Properties**

| Part | Properties | | | | |
|---|---|---|---|---|---|
| | CTEY | CTEZ | KXX | KYY | KZZ |
| PCB board | 1.45e-5 | 6.72e-5 | 1 | 1 | 3 |
| Solder Sn Pb | | | 0.05 | | |
| Solder SnAgCu | 23e6 | | 0.03 | | |
| Copper (Lead) | | | .086 | | |
| Top Pad | | | 1 | 1 | 1 |

**Table 6. Darveaux Modified Anand Constants**

| Constant | Parameter | Value | Definition |
|---|---|---|---|
| $C_1$ | $S_o$(MPa) | 12.41 | Initial value of deformation Resistance |
| $C_2$ | Q/R(1/K) | 9400 | Activation Energy |
| $C_3$ | A(1/s) | 4.0E-6 | Pre-Exponential Factor |
| $C_4$ | ξ(dimless) | 1.5 | Mulitiplier of Stress |
| $C_5$ | m(dimless) | .303 | Strain Rate Sensitivity of Stress |
| $C_6$ | $h_o$(MPa) | 1378.95 | Hardening Constant |
| $C_7$ | s(MPa) | 13.79 | Coeff. of Deformation Resistance Saturation Value |
| $C_8$ | n(dimless) | .07 | Deformation Resistance Value |
| $C_9$ | a(dimless) | 1.3 | Strain Rate Sensitivity of Hardening |

There are four possible combinations for the materials chosen:

- FR2+SnPb
- FR2+SnAg
- FR4+SnPb
- FR4+SnAg

## RESULTS AND DISCUSSION

ANSYS window and the von mises stress is found.

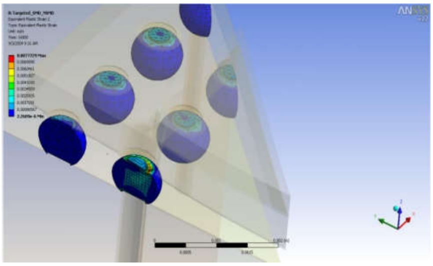

**Fig. 3. Plastic Work**

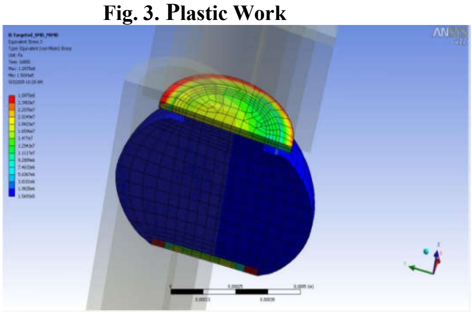

**Fig. 4. Von-mises stress distribution**

A total of four package models were created to evaluate corresponding solder joint fatigue effects.

| Data Description | A | B | C | D |
|---|---|---|---|---|
| Failure Joint (From Center) | 4 | 4 | 4 | 4 |
| Delta Plastic Work/Cycle (MPa) | 0.94E-01 | 0.72E-0 | 0.84E-01 | 0.70E-0 |
| Delta Plastic Work/Cycle (psi) | 13.69 | 10.57 | 12.30 | 10.16 |
| Crack Initiation (cycles) | 4200 | 6220 | 4940 | 6610 |
| Crack Growth Rate (mm/cycle) | 0.19E-03 | 0.15E-0 | 0.17E-03 | 0.14E-0 |
| Solder Joint Diameter (mm) | 0.2700 | 0.2700 | 0.2700 | 0.2700 |
| Crack Propagation (cycles) | 13960 | 17990 | 15500 | 18710 |
| Characteristic Life (cycles) | 18160 | 24210 | 20440 | 25320 |

From the above table, it is clear that the combination FR4+SnAg is the most reliable for the given configuration having a characteristic life of 25320 cycles. Table 10 indicates the detailed simulation results for the 10x8mm, 72-ball (9x8 Full Matrix), and 0.80mm pitch package. The worst-case results are shown for the solder ball failure solder joint occurred at the outside solder ball (4th ball from model center). Simulation results indicate that the solder joint characteristic life is best when combination D (FR4+SnAg) and worst when using combination A (FR2+SnPb). From the package deformation trend at the maximum Δtemperature from the zero strain reference temperature it is evident that the outside solder ball will absorb the bulk of the plastic strain. Another trend is evident in that the ends of the two active die (i.e. top and bottom die) are pushed in opposite directions away from the center spacer die due to the expansion of the mold cap material that fills the gap between these die. This trend may lead to wire bond separation failures during thermal cycling qualification. The fatigue life of the solder joints increased by 25-33% when FR4 is used. This dramatic improvment can be attributed to the packages increased flexibility, thus reducing the amount of plastic strain absorbed by the solder structures during accelerated temperature cycling.

### Conclusion

A finite element analysis based methodology for estimating accelerated temperature cycling solder joint characteristic fatigue life has been developed and applied to predict the reliability performance of a same die size, stacked, chip scale, ball grid array package. The method uses the ANSYS finite element analysis tool along with Anand's Viscoplastic constitutive law. Darveaux's crack growth rate model was applied to calculate solder joint characteristic life using simulated Viscoplastic strain energy density results at the package substrate and printed circuit board solder joints.

Four material combinations were evaluated.

- FR2+SnPb
- FR2+SnAg
- FR4+SnPb
- FR4+SnAg

Simulations indicate material combinations D (FR4+SnAg) provides the best solder joint characteristic fatigue life performance that are 25-33% greater than the other three. This dramatic



life is believed to be due to the increased flexibility of the thinner package thus reducing the amount of plastic strain absorbed by the solder structures.

Overall it is seen that lead-free solder is more reliable than lead solder for the same package configuration and die and board materials.

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