

A Closed Form Method Combined with the Steinberg's Solution to Estimate Number of Fatigue Cycles for Lead-Free Solders

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Abstract

Solder joints of components are normally the most susceptible to the vibration loading conditions. The Steinberg's closed form solution has been widely used in industries to identify high risk components to be candidates for detailed finite element (FE) durability analysis under vibration loads. Unfortunately, the Steinberg's closed form solution is only applicable to the SnPb, not the lead-free materials (SAC); therefore, it would be troublesome to identify high risk SAC components, especially if there are numerous SAC components in the BOM.

This paper is to present a method that would be able to combine with the Steinberg's closed form solution to identify high risk SAC components. This method is developed from comparison between SnPb and SAC fatigue vs. strain range relationship using the high and low cycles of fatigue Coffin Manson closed form equation. In addition, this method can also predict solder joint fatigue cycles of one material using the already-derived fatigue cycles from another material without re-running detailed FE analysis. This additional feature would help, for example, to make prediction if re-ball from SAC to SnPb or vice versa would pose any risks. It is strongly recommended to utilize this method when assessing lead-free components under vibration as currently it is only available method to serve this purpose.

Key words

Coffin-Manson, Lead-Free Solder, SAC, Steinberg, SnPb, PCB

I. Introduction

In any modules or Circuit Card Assemblies (CCAs), solder joints from Surface Mount Technology (SMT) method to mount components directly onto the surface of a board are normally the most susceptible to the vibration loading conditions. In addition to traditional Tin Lead (SnPb) based materials, lead-free materials (e.g., Sn/Ag/Cu, SAC) have been widely used more and more recently. Unlike SnPb materials that mechanical properties appear very stable, SAC materials are aged with time and significantly weaker. Therefore, solder joints using SAC are even more susceptible to vibration.

Any typical CCAs might have many different types of SMT components such as Ball Grid Array (BGA), Lead-less parts (LCCC, QFN), Leaded parts (TSOP, QFP) in the Bill of Material (BOM) list. It has been a common practice to use the Steinberg's closed form solution to scan through the BOM to identify high risk components to be candidates for detailed finite element (FE) durability analysis under

vibration loads. Unfortunately, the Steinberg's closed form solution is only applicable to the SnPb, not the SAC materials; therefore, it would be troublesome to identify high risk SAC components, especially if there are numerous SAC components in the BOM.

With more SnPb components are becoming obsolete and being replaced by SAC components, a closed form method that can be utilized for SAC components is desperately needed and would become tremendously useful tool for component and structural engineers in component selection process.

II. New Closed Form Methodology

The new closed form methodology to be used for SAC solder joint materials is developed by combining both Steinberg's closed form solution and Modified Coffin Manson's formulation. Fatigue assessment results from

these both well-known closed form methods are conservative; therefore, this new closed form method would also result in conservative outcomes.

A brief summary of the Steinberg's closed form and Modified Coffin Manson's formulation is presented before getting into details of the new closed form methodology.

Steinberg's Closed Form Solution

Steinberg's closed form solution has been widely utilized in industries to estimate allowable number of fatigue cycles based on maximum displacement of the Printed Circuit Board (PCB) under applied vibration load. Note that it is a closed form solution so doesn't require solder joint strain or stress value from detailed 3D finite element model. This closed form is very useful to 'scan through' the BOM list that contains numerous components to identify high risk components that don't pass the check.

According to Steinberg, extensive finite element analysis and vibration testing of electronic systems show that the fatigue life of many types of electronic components can be related to the dynamic displacements experienced by the PCBs that support these components. Under vibration, the board is forced to bend back and forth due to PCB resonant frequency is excited. When the PCB displacement amplitudes are high, the relative motion between the components and the PCB can be high, which often results in cracked solder joints and the broken electrical lead wires [Ref. 1].

Steinberg determined a desired single-amplitude displacement of any PCB using its geometry and component's parameters (surface mount type, dimension, location on PCB) as shown in equation 1 below. At this desired displacement, the component can be expected to achieve a fatigue life of about 20 million stress reversals in a random vibration environment, based on the 3σ PCB displacements.

$$Z_d = \frac{0.00022B}{Chr\sqrt{L}} \quad (\text{Eq. 1})$$

where B = length of PCB edge parallel to component (in.)

L = length of electronic component (in.)

H = height or thickness of PCB (in.)

C = constant for different types of electronic components

= 1.0 for standard dual inline package (DIP)

= 1.26 for DIP with side-brazed lead wires

= 1.26 for pin grid array (PGA) with two parallel rows of wires extending from bottom of the PGA

= 1.0 for PGA with wires around the perimeter extending from the bottom surface of the PGA

= 2.25 for a leadless ceramic chip carrier (LCCC)

= 1.0 for leaded chip carriers where the lead length is about the same as for a standard DIP

= 1.75 for a ball grid array (BGA)

= 0.75 for axial-leaded component resistors, capacitors, and fine pitch semiconductors

r = relative position factor for component on PCB

= 1.0 when component is at center of PCB (1/2-point X and Y)

= 0.707 when component is at 1/2 point X and 1/4 point Y on a PCB supported on four sides

= 0.50 when component is at 1/4 point X and 1/4 point Y on a PCB supported on four sides

The actual 3-sigma random dynamic single-amplitude displacement of the PCB can be estimated from equation 2 or derived from finite element analysis.

$$Z_{3\sigma} = \frac{9.8G_{RMS}}{f_n^2} \quad (\text{Eq. 2})$$

Where f_n = resonant frequency of PCB (Hz)

G_{RMS} can be determined from Mile's equation 3 below:

$$G_{RMS} = 3\sqrt{\frac{\pi}{2}Pf_nQ} \quad (\text{Eq. 3})$$

where P = input PSD in unit G^2/Hz at the resonant frequency f_n

Q = transmissibility at the resonant frequency

After the desired board displacement Z_d and actual dynamic single-amplitude displacement Z_{RMS} are determined, number of allowable fatigue cycles under random load requirement can be calculated using the equation 4 below:

$$N_{allowable} = 2E7 \times \left(\frac{Z_d}{Z_{3\sigma}}\right)^4 \quad (\text{Eq. 4})$$

This number of allowable fatigue cycles will then be compared to the required number of fatigue cycles using Miner's rule from equation 5 to determine if the component's solder joint would experience fatigue failure.

$$CDI = \frac{N_{required}}{N_{allowable}} \quad (\text{Eq. 5})$$

where CDI = cumulative damage index

Note that Steinberg's closed form solution is only applicable for SnPb materials and cannot be utilized for lead-free materials.

Modified Coffin-Manson Formulation

The Modified Coffin-Manson equation shows relationship between strain range and number of allowable fatigue cycles. It includes both low cycle and high cycle fatigue terms as shown in equation 6.

$$\Delta\epsilon = a \frac{\sigma_u}{E} N_f^b + D^c N_f^d \quad (\text{Eq. 6})$$

where $\Delta\epsilon$ = effective total strain range

σ_u = ultimate strength, psi

N_f = number of allowable fatigue cycles

E = elastic modulus, psi

D = ductility, $\ln(1/(1-RA))$

RA = reduction in area

a, b, c, d = constant

From detailed finite element analysis results, effective total strain range under any specified vibration load is derived and is placed into the equation 6 to calculate number of allowable fatigue cycles. Then Miner's rule (equation 5) is used to determine if fatigue failure would occur.

Note that Modified Coffin-Manson is a universal formulation that can be utilized for any materials including SnPb and SAC. Constants a, b, c , and d are determined by tests for each material.

New Closed Form Development

Because both Steinberg's and Modified Coffin-Manson closed form solutions are conservative approaches, the new closed form solution that utilizes these both conservative methods shall give conservative results as well.

Following are steps of this new closed form method to estimate number of fatigue cycles of lead-free solder joint materials:

1. Calculate the desired displacement of the board using equation 1.
2. From random vibration load requirement, calculate 3-sigma dynamic single-amplitude displacement of the PCB using equations 2 and 3, or determine this displacement from finite element analysis.
3. Calculate number of allowable fatigue cycles under the required random load using equation 4. Note that in this step, SnPb material is assumed.
4. Using the Modified Coffin-Manson equation 6 with number of allowable fatigue cycles determined from step 3 to calculate effective total strain range. Note that SnPb is still assumed in this step.

5. Estimate effective total strain range of the SAC material using equation 7.
6. Calculate number of allowable fatigue cycles of the SAC material using the effective total strain range from step 5 and Modified Coffin-Manson equation 6.
7. Using Miner's rule (equation 5) with number of fatigue cycles from step 6 to predict fatigue failure of the SAC material.

$$\Delta\epsilon_{SAC} = \frac{G_{SnPb}}{G_{SAC}} \times \Delta\epsilon_{SnPb} \quad (\text{Eq. 7})$$

where G_{SnPb} = shear modulus of SnPb, psi

G_{SAC} = shear modulus of SAC, psi

Because result from this new closed form method is conservative, if it passes Miner's rule in step 7 it can be concluded the SAC solder joint meets the loading requirements. If it doesn't pass the Miner's rule, detailed 3D finite element modeling and analysis will be required for more accurate fatigue assessment.

The new closed form development and procedure have been presented. However, due to having both low cycle and high cycle fatigue terms in the Modified Coffin-Manson equation, it is not easy to back calculate number of allowable fatigue cycles using effective total strain range value in steps 4 and 6 above. To simplify these steps, a much-simpler equation is developed for SnPb and SAC materials using curve-fit regression approach.

In the curve-fit regression approach, for each material, a table of effective total strain range vs. number of allowable fatigue cycles is created using a wide range of different values of effective total strain range. Next, plot data from this table and perform curve-fit regression. Plots for both SnPb and SAC material and curve-fit equations are shown in Figure 1 below.

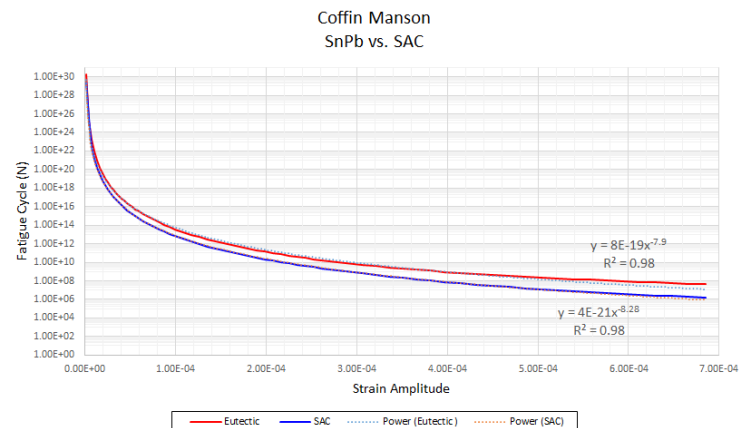


Figure 1

From the Figure 1, curve-fit formulations for SnPb and SAC materials are shown in equation 8 and equation 9, respectively.

$$N_{SnPb} = 8 \times 10^{-19} \times \Delta\varepsilon^{-7.9} \quad (\text{Eq. 8})$$

$$N_{SAC} = 4 \times 10^{-21} \times \Delta\varepsilon^{-8.28} \quad (\text{Eq. 9})$$

Note that each equation has a high R-squared (R^2) value ($R^2 = 0.981$ for SnPb and $R^2 = 0.984$ for SAC) that indicates excellent strength of relationship between effective total strain range and number of allowable fatigue cycles statistically.

Thus, instead of using a complex Modified Coffin-Manson equation 6, one can simply use equations 8 and 9 to quickly calculate for number of allowable fatigue cycles from any values of effective total strain range.

Example

Following is an example using this new closed form method.

Assume:

$$B = 1.19 \text{ in.}$$

$$L = 0.3 \text{ in.}$$

$$h = 0.062 \text{ in.}$$

$$C = 2.25 \text{ (LCCC)}$$

$$r = 1.0$$

$$N_{\text{required}} = 5E6 \text{ cycles: number of required fatigue cycles}$$

$$Z_{3\sigma} = 1.2E-3 \text{ in.}$$

From equation 1, desired displacement is calculated:

$$Z_d = \frac{0.00022B}{Chr\sqrt{L}} = \frac{0.00022 \times 1.19}{2.25 \times 0.062 \times 1.0\sqrt{0.3}} = 3.43E - 3 \text{ in.}$$

From equation 4, number of ‘actual’ fatigue cycles is calculated:

$$\begin{aligned} N_{\text{allowable}} &= 2E7 \times \left(\frac{Z_d}{Z_{3\sigma}} \right)^4 \\ &= 2E7 \times \left(\frac{3.43E - 3}{1.2E - 3} \right)^4 \\ &= 1.33E9 \text{ cycles} \end{aligned}$$

From equation 8, effective total strain range of SnPb material is:

$$N_{SnPb} = 8 \times 10^{-19} \times \Delta\varepsilon^{-7.9} = 1.33E9$$

$$\Rightarrow \Delta\varepsilon_{SnPb} = 3.58E-4$$

From equation 7, effective total strain range of SAC is:

$$\begin{aligned} \Delta\varepsilon_{SAC} &= \frac{G_{SnPb}}{G_{SAC}} \times \Delta\varepsilon_{SnPb} = \frac{1.55E6}{1.17E6} \times 3.58E - 4 \\ &= 4.76E - 4 \end{aligned}$$

From equation 9, number of allowable fatigue cycles of SAC material is calculated:

$$\begin{aligned} N_{SAC} &= 4 \times 10^{-21} \times \Delta\varepsilon^{-8.28} \\ &= 4 \times 10^{-21} \times (4.76E - 4)^{-8.28} \\ &= 1.3E7 \text{ cycles} \end{aligned}$$

Using Miner’s rule (equation 5):

$$CDI = \frac{N_{\text{required}}}{N_{\text{allowable}}} = \frac{5E6}{1.3E7} = 0.038$$

III. Conclusion

Just like the Steinberg’s closed form solution that is used to evaluate SnPb material, this new closed form method will help to identify high risk lead-free components for detailed finite element analysis. New closed form method for lead-free materials is developed utilizing both conservative approaches: Steinberg’s closed form and Modified Coffin-Manson’s formulation; therefore, results derived from this new closed form is also expected to be conservative. It is strongly recommended to use this new closed form as a first cut to scan through BOM lead-free list as it currently might be only closed form available to serve this purpose.

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