Material Strength and Applied Mechanics
A. Khotsianovsky and Y. Chen (Eds.)

doi:10.3233/ATDE240536

Benchmark Analysis of Plastic Strain-Based Lifetime Estimation Fatigue Models in Aspect of SMD Component Standoff Height

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Abstract. Thermomechanical fatigue is one of the most common cause of the failure in microelectronic technology in the solder joints. The lifetime prediction for microelectronic components is a very important area in nowadays automotive industry, because the lifetime estimation fatigue models in the literature differ in their results by orders of magnitude. However, developing an accurate lifetime estimation methodology for microelectronic components is not straightforward, because the failure mechanism of the solder joints under cyclic thermomechanical load is not fully understood. In addition, there are numerous tolerances and uncertainties during the designing and manufacturing processes, such as component size, copper pad area, solder material volume or the formed standoff height of the component from the copper pad. These parameters can hugely affect the lifetime of the solder joint. In this paper a benchmark analysis based on finite element method were carried out with four plastic strain-based fatigue models to understand the impact of the standoff height to the estimated lifetimes. Three CAD models were created with identical parameters, except the standoff height of the components. Creating the solder geometries for the 3D models, Surface Evolver software were used. The result shows that the fatigue models give the same tendencies varying the standoff height values. However, changing the standoff height increases the differences between models, even if they are tuned so that the estimated lifetime matches for a certain standoff height.

Keywords. fatigue models, finite element method, microelectronics reliability, lifetime estimation, solder joint, SMD components, standoff height

1. Introduction

Nowadays, the automotive industry is experiencing a strong trend towards electronification, which is accompanied by downsizing and an increase in the use of electronic components. The reliability of these microelectronic devices is becoming more difficult due

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to miniaturisation, in addition the wider use of microelectronic devices in the automotive industry is also increasing the demands on the devices.

The most common failure cause for microelectronic devices is thermomechanic fatigue at the solder joints, which occurs because of the mismatch of Coefficient of Thermal Expansion (CTE) values between the parts of the microelectronic assemblies during temperature changes. This fatigue failure mechanism is still not fully understood, because the complex behaviour of the leadless solder material at room or higher temperature [1].

Many lifetime estimation fatigue models [1,2] have been developed by researchers over the last 50 years to estimate the lifetime of microelectronic components, but all models are based on different approaches, their parametrisation requires model preparation and they have a large variance in terms of lifetime estimation. With the advances in computing technology, simulation-aided lifetime estimation has come to the fore. In addition to measurements, a finite element method approach to the development of life estimation methodologies has been used in the literature [3,4,5]. In the literature, there are several life estimation models for either vibration or thermomechanical stresses [4,6,7], but none of them focus specifically on the effect of component standoff height only.

The standoff height of components is relevant parameter in the lifetime of the solder joints [8] and can be influenced by several factors, apart from the manufacturing parameters, the misalignment, the size of the copper pad, the size of the component [3,5,9,10,11]. The dimensions mentioned above are provided with a tolerance, and the standards do not specify either their exact size or the resulting solder joint standoff height. Due to the previously mentioned causes the value of the component standoff height can be highly uncertain. The influence of the component standoff height to the calculated lifetime is not really in focus in the literature, however its impact is significant.

In this study, four different plastic strain-based fatigue models, were compared in the case of three different standoff heights for capacitor C1005. The geometry of the solder joint was created using Surface Evolver software to make it as realistic as possible, and then finite element method were used to calculate the different type of strains, which were used as inputs for the fatigue models. Component misalignment, creep phenomenon and material inhomogeneity were neglected in the study.

2. Simulation and lifetime estimation

2.1. 3D CAD model

The 3D CAD assembly consists a PCB, two Solder masks, two copper pads, the C1005 capacitor with its two terminations, and the SAC305 solder joints, as shown in Fig. 1. The PCB sizes are: 3 mm length, 1.5 mm width, 1 mm thickness. The solder masks thickness is 0.03 mm. The copper pad sizes are 0.5 mm length, 0.6 mm width, the thickness of the pads are the same as the solder mask thickness, the gap between the two copper pad is 0.5 mm. The C1005 termination length is 0.2 mm, the height and the width of the component is 0.5 mm, and the full length is 1 mm.

The three cases with the 9 μm, 12 μm and with 15 μm standoff height is created with the above mentioned dimensions.

2.2. Solder geometry prediction

Surface Evolver generates the solder joint geometry from an initial geometry based on an energy minimization method as a result of a sequence of different numerical commands as a function of the defined energies [12]. The defined energy in the case of the present model is the sum of the energy due to surface tension, capillary pressure and gravitational potential energy. The surface tension of the solder material is 544.9 mN/m, the volume is 28452 μm^3, the contact angle is defined as 24 degrees for each surface in all three test cases. After running the defined command sequence on the Surface Evolver model the solder geometry is created from the initial solder geometry in aspect of the defined constraints in the model, as shown in Fig. 2.

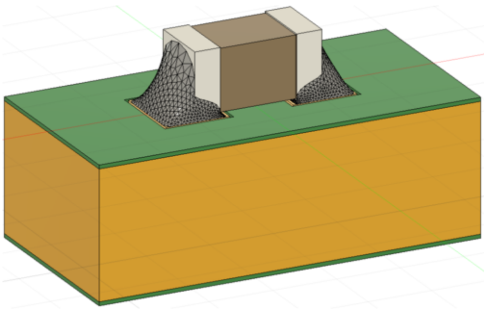

Figure 1. The CAD model of the assembly

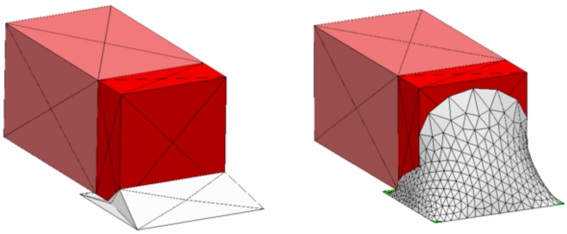

Figure 2. Initial and predicted solder joint shape with Surface Evolver

2.3. Finite element model

The 3D CAD models created were imported into Abaqus finite element method (FEM) software. In the Abaqus software the two defined temperature sets are -50 °C as initial temperature and 125 °C as final temperature. Dwell times were neglected from this simulation. The investigated volume of the solder joint was the under component portion for the strain values. Volume weighted average values are used in this paper. The meshed finite element model can be seen on Fig. 3.

The material parameters are shown in Table 1 for the element of the microelectronic assembly.

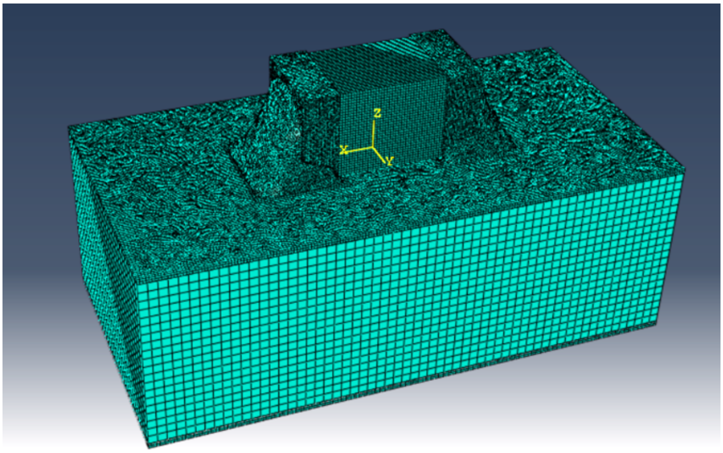

Figure 3. The meshed finite element model

Table 1. Finite element model material properties [3,4,5,13]

Part	Young's Modulus [GPa]	Poisson's Ratio [-]	CTE [ppm/°C]
PCB	19	0.39	16.5
Solder Mask	3.75	0.3	43
Copper Pad	121	0.34	16.7
Termination	83	0.37	18.9
Passive Component	282.7	0.22	6

2.4. *Fatigue lifetime prediction*

In this section four plastic strain-based lifetime estimation fatigue models are introduced [1,2].

First the Coffin-Manson equation, which model was introduced for general lifetime estimation for solder joints gives the connection between the plastic strain range $\Delta\varepsilon_p$, and the low-cycle fatigue life N_f is

$$N_f^m \Delta\varepsilon_p = C\,, \qquad (1)$$

where m is the fatigue exponent and C is the ductility coefficient. The chosen parameters for the Coffin-Manson model is: $m = 0.4$, $C = 0.1$.

Shi et al. introduced a frequency-modified Coffin-Manson equation, which also gives the connection between the fatigue life and the plastic strain range, however the estimated lifetime is the function of the load cycle frequency. Thus the fatigue life is decreasing with the frequency as the formula shows

$$[N_f \nu^{(k-1)}]^m \Delta\varepsilon_p = C\,, \qquad (2)$$

where ν is the frequency, k is the frequency exponent. The chosen parameters for the Shi model is: $m = 0.35$, $C = 0.3156$, $\nu = 0.0005556$ Hz, $k = 0.91$.

Engelmaier model has been introduced for ceramic chip carriers and leadless chip carriers. Engelmaier equation is calculating with cyclic frequency, solder material parameter and with the substrate temperature, as follows

$$N_f = \frac{1}{2}\frac{\Delta\gamma}{2\zeta_f'}^{1/c}, \tag{3}$$

where N_f is the mean cycle to failure, $\Delta\gamma$ is the cyclic shear strain range, ζ_f' is the fatigue ductility coefficient, c is the fatigue ductility exponent which is the function of the solder joint mean temperature. The chosen parameters for the Engelmaier model is: $\zeta_f' = 0.0956$, $c = -0,39156$.

Fourth, the Solomon equation calculating the lifetime N_f from the plastic shear strain range $\Delta\gamma_p$ is

$$\Delta\gamma_p N_f^{\alpha} = \theta\,, \tag{4}$$

where α and θ are constants. The chosen dimensionless parameters for the Solomon model is: $\alpha = 0.6938$, $\theta = 1.14$. Solomon fatigue model has been originally introduced for calculating 60/40 Tin-lead solder joints lifetime estimation.

3. Result and discussions

3.1. Estimated fatigue lifetimes

Three CAD model were created with different standoff heights, with 9μm, 12μm and with 15μm. The investigated set of geometry for calculating the volume weighted average was in all of the cases the portion of the solder between the copper pad and the capacitor component. The volume weighted average strains were the input for the fatigue models. With the knowledge of the plastic equivalent strains and plastic shear strains in the different cases, the lifetime estimations can be made.

As the Fig. 4 shows, the tendency of lifetime growth with the higher standoff height, were proven with simulation result. In the case of 9μm the estimated lifetime is 1071 cycle for Coffin-Manson, 1002 cycle for Shi, 1175 for Engelmaier and 1277 for Solomon fatigue model, while in the case of 15μm standoff height the Coffin-Manson model estimated 3434 cycles, the Shi model estimated 3793 cycles, the Engelmaier model estimated 3481 cycles and the Solomon model calculated 2598 cycles. It can be seen, that with the change of component standoff height, the difference in the calculated lifetimes with different fatigue models will be hugely increase.

3.2. Benchmarking of the fatigue models

For benchmarking the four plastic strain-based fatigue models, an exponential curve was fitted with least squares method for each models. As the result from the Fig. 5 shows, the Coffin-Manson, Shi and Engelmaier fatigue model were much more sensitive in estimated lifetime to the change in standoff height than the Solomon method with the used parametrization in this paper, and in this inverval of component standoff height.

With the fitted exponential curve it can be seen in Fig. 5 that the Shi fatigue model is the most sensitive estimating about 3.2 times higher lifetime for 15 μm standoff height than in the case of 9 μm, and the slope of the fitted curve is exponentially growing. The least sensitive fatigue model to the change of the standoff height was the Solomon model, estimating 2.03 times higher lifetime for 15 μm than in the case of 9 μm. It can be seen that the overall change in the estimated lifetime of fatigue models which use shear strain as inputs are not so large than the overall change in the lifetime estimated of fatigue models which are use equivalent strains as inputs, so the fatigue models which inputs are the shear strains are less sensitive to the change of standoff height in this case of tuning.

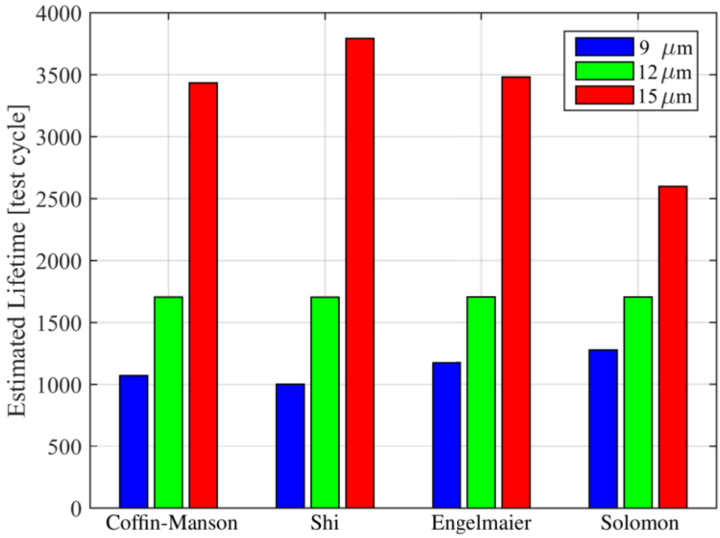

Figure 4. Estimated lifetimes with different fatigue models in the case of different component standoff height

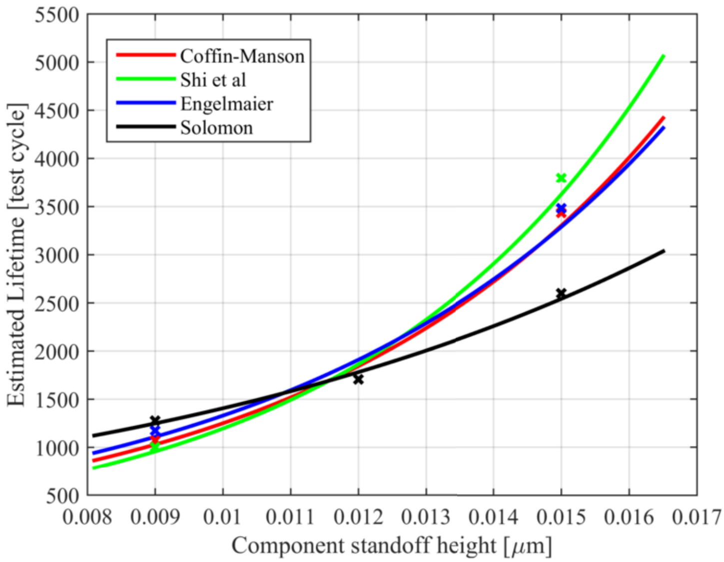

Figure 5. Fitted curves for the different standoff heights and prediction models

4. Conclusion

In this study, the simulation results for the chosen C1005 component showed that the plastic strain and the plastic shear strain increase rapidly with the decrease of standoff height of the capacitor components for thermocyclic test. The benchmark analysis of the four plastic strain-based fatigue models showed that the estimated lifetime increases rapidly if the standoff height is higher in all cases. In the cases of Coffin-Manson and Shi fatigue models, when we calculate with the plastic strain range, the lifetime is much more sensitive to the change of the standoff height than in the case of Engelmaier and Solomon fatigue models when the plastic shear strains are considered as input. In further research this lifetime change could be experimentally validated with tests in aspect for the copper pad design, which can have impact on the standoff height.

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