A crack initiation and propagation simulation and the fatigue characteristics of solder joints considering the material property changes

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Abstract. The re-working of the manufacturing process from the reliability evaluation after the production process is a significant cost and loss of energy. In-vehicle electronic devices are exposed to multiple environmental loads such as thermal and vibrational loads. The effects of the material property changes in the thermal cycle load on the fatigue life of solder joints were estimated with our fatigue simulation for the purpose of constructing a design method considering the fatigue characteristic changes in the thermal cycle. The fatigue lives were estimated with and without considering the creep property changes measured by indentation tests. The fatigue ductility index and the coefficients increased toward the reported values by considering the creep property changes.

1. Introduction
In recent manufacturing, sustainability for reducing the environmental load is necessary, as is the cost reduction against the worldwide economic depression. The re-working of the manufacturing process from the reliability evaluation after the prototyping or the production process is a significant cost and loss of energy. Estimating the fatigue life at the design step is a huge contribution toward reduction of the environmental load.

It is experimentally known that the low cycle fatigue life of solder joints in electronic devices is fit by Coffin-Manson’s law [1][2]. The fatigue life of solder joints under thermal cycle loading estimated by Coffin-Manson’s law has been reported [3][4]. In the condition of high acceleration such as resonance frequency, the fatigue life can also be estimated by Coffin-Manson’s law [5]. For these estimations, the inelastic strains are calculated with the finite element method (FEM) by applying the initial material properties and structure. However, the inelastic strain changes according to the structural changes by crack initiation. In vibration tests after thermal cycle loading, the degradation of the fatigue life is impossible to estimate by a simple cumulative damage rule [5]. Furthermore, the material properties of the solder under thermal cycle loading changes according to the microstructural changes [6]. Analyses considering the structural changes with crack initiation and propagation have been executed [7]; however, the property changes described above were not considered.

In this paper, we perform a crack simulation considering the material property changes according to the microstructural change with strain and thermal loading as well as the structural change with crack initiation and propagation in addition to the initial stress-strain distribution during the construction of
electronic devices. This simulation clarifies the effects of material property changes on fatigue life and is used to construct a fatigue life estimation system against multiple environmental stresses.

2. Sample and experimental method

2.1. Sample
Sn-3Ag-0.5Cu solder joints of a ball grid array (BGA) package with 272 terminals in 1.27 [mm] pitch assembled at the center of a glass epoxy board (FR-4 100 [mm] x 100 [mm] x 1.6 [mm]) are the target of this research (Figure 1). The BGA packages were assembled with the temperature profile in which the peak temperature is 240 [°C], which is 20 [°C] over the melting point of Sn-3Ag-0.5Cu solder.

2.2. Thermal cycle loading
A thermal shock test chamber (Espec TSV-40S) is used for the thermal cycle test. The temperature ranges are -40/80 [°C], -40/125 [°C], and -40/150 [°C]. The cycle time of 30 [min] consists of the 4 [min] ramp times and 11 [min] hold times. The failure criteria is the threshold of voltage (20 [mV]) of the daisy chain circuit connecting every solder bump in series during the passage of a 1.0 [mA] current.

2.3. Dynamic indentation test
The dynamic indentation test was executed to estimate the material property changes under thermal cycle stress. A bonding tester (RHESCA PTR-1100) with a Vickers’ indenter was used for the test, in which a constant load of 0.15 [N] was held for 15, 50, and 100 [s].

3. FEM model and analysis

3.1. FEM model
The FEM analysis is executed to estimate the stress and strain distribution generated in the solder joint under thermal loading. Figure 2 shows the 1/8 model for the analysis. The corner solder bump, which is first loaded with the maximum stress and fractures in the experiments, is meshed in detail with 50 [μm] elements. The crack of approximately 10 [μm] is also modelled in the corner bump for the crack propagation analysis. The mesh size around the crack tip is 5 [μm]. Table 1 shows the material properties used in the simulation. The solver is ANSYS 11.0 SP1.

Figure 1. Size and position of BGA package on the substrate.

Figure 2. Finite element model of the BGA assembled board. (a) 1/8 model overview, (b) the corner solder bump in the crack initiation phase and (c) the corner solder bump in the crack propagation phase.
Table 1. Initial material properties used in the simulation.

| Material          | FR-4 | Package | Sn-3Ag-0.5Cu | Cu    |
|-------------------|------|---------|--------------|-------|
| Young’s Modulus   | 19   | 15      | (See Table 2)| 129.8 |
| Poisson’s ratio   | 0.18 | 0.24    | 0.38         | 0.3   |
| Mass density [kg/m³] | 1930 | 2300    | 2100         | 8800  |
| Linear expansion coefficient [ppm] | 15   | 27      | 21.7         | 16.5  |

Table 2. Temperature dependent mechanical properties of Sn-3Ag-0.5Cu.

| Temperature [°C] | Young’s modulus [GPa] | Yield stress [MPa] | Tangent modulus [MPa] |
|------------------|------------------------|--------------------|-----------------------|
| -50              | 41.3                   | 48                 | 1100                  |
| -15              | 40.8                   | 36                 | 900                   |
| 25               | 38.2                   | 30                 | 700                   |
| 75               | 35.5                   | 23                 | 450                   |
| 125              | 33.8                   | 17                 | 250                   |

3.2. Thermal cycle analysis

The temperature profiles in the thermal cycle analysis are generated with the same conditions as in the experiments. The temperature ranges are -40/80 [°C], -40/125 [°C], and -40/150 [°C]. The temperature is held for 11 [min] at the maximum and minimum temperature and is changed in the 4 [min] ramp time.

3.3. Material properties

Table 1 shows the initial material properties used in the simulation. The elasto-plastic creep analysis is executed with the solder properties shown in Table 2. The bilinear kinematic hardening rule with the parameters in Table 2 and the Norton Law expressed by the following equations are applied in the elasto-plastic creep analysis [8]:

\[
d\varepsilon /dt = A\sigma^n, \tag{1}
\]
\[
A = \exp(-0.008T^2 + 0.3313T - 58.923), \tag{2}
\]
\[
n = -0.0481T + 13.575, \tag{3}
\]

where \( T \) expresses the temperature (°C).

4. Crack initiation and propagation simulation

4.1. Simulation and assumptions

The crack initiation and propagation simulation method is developed to investigate the effect of material property changes on the fatigue characteristics. The process leading to the failure of solder joints is divided into two phases: the crack initiation phase and the crack propagation phase. The crack simulation method is suggested in accordance with hypotheses about the relationship between the inelastic strain range under fatigue stress and the crack initiation life \( N_i \) or the thermal fatigue life \( N_f \), described later. The thermal fatigue life is estimated based on the strain changing with crack initiation in the simulation. The effects of material property changes are considered by the changed properties in the calculation of the strain range.

Figure 3 is the algorithm of the crack initiation and propagation simulation. The circles in Figure 2(b) and (c) are the strain concentrated points at the solder bump in each phase, respectively, where \( \Delta \varepsilon_{in}(N) \), \( \Delta \varepsilon_{in,crack}(N) \) express the inelastic strain range at the \( N \)th cycle in each phase. The changing
material properties in the thermal cycle such as yield stress $\sigma_y$, and Young’s modulus, are applied to the FEM analysis to calculate the inelastic strain range $\Delta \varepsilon_{in}(N)$ and $\Delta \varepsilon_{in\_crack}(N)$ at the concentrated point. The crack initiation life $N_c$ and the thermal fatigue life $N_f$ are based on these inelastic strain ranges. The hypotheses in the simulation are as follows.

[Hypothesis 1] Crack initiation phase

It is reported that the ductile crack of structural steel is generated when the cumulative strain reaches a certain value [9]. In the crack initiation phase in our simulation, it is hypothesized that the crack initiates when the cumulative strain ranges reach the constant value of the critical cumulative inelastic strain $\varepsilon_{crack}$, as in the following equation:

$$\sum_{N=1}^{N_c} (2 \times \Delta \varepsilon_{in}(N)) = \varepsilon_{crack}.$$  \hspace{1cm} (4)

[Hypothesis 2] Crack propagation phase

It is also reported that the crack simulation shows good correspondence between the crack tip opening displacement (CTOD) and the crack propagation rate $\Delta a$ in the simulation and the experiment with the hypothesis that the crack propagates when the inelastic strain at the crack tip reaches a certain value [10]. In our simulation, the crack propagation rate is decided from the inelastic strain at the tip of the crack, shown in the following equations:

$$\frac{da(N)}{dN} = 2 \times \Delta \varepsilon_{in\_crack}(N) \times \alpha,$$  \hspace{1cm} (5)

$$\sum_{N=N_c}^{N_f} a(N) = a_f,$$  \hspace{1cm} (6)

where $da(N)/dN$ is the crack propagation rate at the Nth cycle, $\alpha$ is the crack propagation coefficient, and $a_f$ is the critical crack length to failure.

4.2. Inelastic strain range in crack propagation

Elasto-plastic creep analyses were executed using the corner bump model with 10, 100 and 200 [$\mu$m] crack lengths under thermal cycle loading. The inelastic strain range at the tip of the crack changed...
only a few percent with the different lengths of the cracks. Therefore, the inelastic strain range \( \Delta \varepsilon_{\text{in, crack}}(N) \) is calculated using the model with the 10 [\( \mu \)m] crack in the corner bump in our simulation.

4.3. Crack initiation and propagation condition

The critical crack initiation inelastic strain \( \varepsilon_{\text{crack}} \) and the crack propagation coefficient \( \alpha \) are defined based on observation of the intersection of the BGA assembled board after the thermal cycle with the temperature range of -40/150 [°C] is loaded. The 10 [\( \mu \)m] crack is observed after 300 [cycle]. Therefore, \( \varepsilon_{\text{crack}} \) is defined as the following equation using the inelastic strain range at the first cycle \( \Delta \varepsilon_{\text{in}}(N=1) \) of the same temperature condition:

\[
\varepsilon_{\text{crack}} = 2 \times \Delta \varepsilon_{\text{in}}(N=1) \times 300. \tag{7}
\]

The crack propagation rate is calculated to be approximately 0.46 [\( \mu \)m/cycle]. The \( \alpha \) is hypothesized in the following equation using the inelastic strain range at the first cycle \( \Delta \varepsilon_{\text{in, crack}}(N=1) \) of the same load condition:

\[
\alpha = 0.46 / \{2 \times \Delta \varepsilon_{\text{in, crack}}(N=1)\}. \tag{8}
\]

The criterion of failure in the simulation is that the crack beginning at one end of the solder bump reaches the other end. Therefore, the failure crack length \( a_f \) is the diameter of the solder bump, 600 [\( \mu \)m].

If every change of the inelastic strain range in the thermal cycle is calculated by applying the changed material properties, the calculation cost would be tremendous. Therefore, the crack initiation process was divided into several steps and the inelastic strain ranges are calculated in the first cycle of each step using the material properties at that point. The inelastic strain ranges during each step are calculated with linear interpolation.

5. Material property changes under thermal cycle stress

5.1. The method of investigating the fatigue characteristics according to the material property changes

The fatigue lives under the three temperature ranges of the thermal cycle loadings, -40/80 [°C], -40/125 [°C], and -40/150 [°C], are estimated using the suggested crack initiation propagation

![Figure 4. Investigating the effects of material property changes on the simulated fatigue characteristics.](image)

![Figure 5. Creep stress exponent changes under thermal cycle stress.](image)
simulation. Figure 4 shows the concept of the method to investigate the effects of material property changes on the fatigue characteristics. The figure shows the actual fatigue characteristics and the ones estimated in the simulation with/without considering material property changes. The inelastic strain range $\Delta\varepsilon_{in}$ on the vertical axis and the thermal fatigue life $N_f$ on the horizontal axis are both logarithmic. The bold line shows the actual fatigue characteristics for the relationship between the initial $\Delta\varepsilon_{in}$ calculated in the FEM analysis and the fatigue life obtained by the thermal cycle test. The broken line shows the simulated fatigue characteristics with the fatigue life calculated in this simulation based on the inelastic strain ranges $\Delta\varepsilon_{in}$ and $\Delta\varepsilon_{in\_crack}$.

The actual fatigue characteristics are expected to be obtained as the result of material property changes in the thermal cycle stress. Therefore, the effects of material property changes on the fatigue characteristics are investigated by comparing the fatigue characteristics simulated with and without material property changes in the simulation.

5.2. The material property effects on the fatigue characteristics
Each material property, such as yield stress, Young’s modulus, tangent modulus, and creep exponent, is changed. Then, the crack initiation and propagation simulations with the range -40/75 [°C] as the in-use environment for in-vehicle electronic devices [11] are executed to investigate the effect of each material property change on the fatigue characteristics. The results are shown in Table 3. The variables $m$ and $C$ in the table are the fatigue ductility exponent and the fatigue ductility coefficient of Coffin-Manson’s law, respectively, represented by the next equation:

$$\Delta\varepsilon_{in}^m \cdot N_f = C.$$ (9)

The creep properties have a larger influence on the fatigue characteristics compared with the yield stress, Young’s modulus, and tangent modulus. The fatigue life changes are approximately 2.8 [%] at most with the yield stress, Young’s modulus, and tangent modulus changes; however, the fatigue life changes 17 [%] with the creep exponent change.

5.3. The measurement of creep property changes by indentation tests
The actual creep property changes are measured in the solder bump of the BGA assembled board after the thermal cycle is loaded. Although the tensile test of the solder bump in the actual assembled board is impossible, Sargent et al. confirmed good correlation between the creep exponents and the time dependent results of the indentation test [11]. We also executed the indentation test to measure the creep property changes. Figure 5 shows the creep exponent measured by indentation tests at 25 [°C] and 75 [°C] after the thermal cycle stress with -40/80 [°C], -40/125 [°C], and -40/150 [°C] temperature ranges. The initial properties are the results of Sakai’s measurement of bulk solder [8]. The properties after thermal cycle loading are calculated with the change ratio of our measurement results. The
approximated curves are also indicated in Figure 5 by considering the changes as exponential. The
creep exponent degradations are observed and the changes are larger in the thermal cycle test with the
higher maximum temperature.

5.4. The fatigue characteristics considering the measured creep property changes
The fatigue characteristic changes are calculated with the suggested simulation using the measured
creep exponents. The creep exponents at the temperatures -35 [°C], 75 [°C], and 125 [°C] are assumed
to change according to the thermal cycle with the same exponential ratio and creep exponents obtained
at room temperature (25[°C]).

The fatigue characteristics considering the creep exponential changes are shown in Figure 6 with the
fatigue characteristics calculated with constant material properties. The fatigue characteristics of the
SnAgCu solder joint estimated in the suggested simulation show changes such as the fatigue ductility
exponent from 1.05 to 1.19 and the fatigue ductility coefficient from 62.2 to 135.2. The values
calculated by considering the creep property changes are closer to the reported fatigue ductility
exponent and coefficient, respectively [12].

Figure 7 shows the crack behavior expected by the simulation and the thermal cycle test results at
the conditions of temperature range -40/150 [°C], -40/125 [°C], and -40/80 [°C]. The simulation
results with and without considering the creep property changes are both shown. The results of the
condition
-40/150 [°C] are, of course, corresponding because the crack propagation rate is defined based on the
experiment result. The simulation results by considering the creep property changes for the other two
conditions show better expectations than those without considering the material property changes,
although they are about 10% on the safer side.

6. Summary
The crack simulation to estimate the fatigue life of solder joints in electronic devices considering the
strain distribution changes due to crack initiation and the material property changes due to material
microstructural changes under thermal cycle stress is constructed. The suggested crack initiation and
propagation simulation clarifies that the creep property influence on the fatigue life is larger than are
the influences of the yield stress, Young’s modulus, and tangent modulus. The actual creep property
changes in the solder joints in the BGA assembled board are measured with indentation tests. The
creep exponents decreased by the thermal cycle, and the degradation of the sample loaded with the

![Figure 6](image6.png)

**Figure 6.** Fatigue characteristics under thermal cycle stress evaluated by thermal cycle stress model.

![Figure 7](image7.png)

**Figure 7.** Simulated crack initiation and propagation with and without creep degradation compared with the experiment.
higher temperature thermal cycle is more significant. The fatigue characteristics are estimated with the measured creep property changes in the suggested simulation. The fatigue ductility exponent and the coefficient become closer to the reported values than the simulation result with constant material properties. The crack behaviors are simulated with the thermal cycle test of temperature ranges -40/150, -40/125 [°C], and -40/80 [°C]. The estimation results considering the creep property changes are better than those with a constant value.

From the results described above, the fatigue ductility exponent $m$ and the fatigue ductility coefficient $C$ are affected by the creep property changes under thermal cycle loading. The fatigue life simulation can be constructed without measuring the material property changes by estimating the changes from the stress-strain distribution in a thermal cycle analysis.

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