Multiaxial Study of Notched Component of Sn-3.5Ag Solder in Creep-Fatigue

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ABSTRACT. *This paper studies the creep-fatigue crack initiation and failure lives of Sn-3.5Ag solder notched specimens considering the multiaxial strain at the notch root. Push-pull creep-fatigue tests were performed using three circumferential notched specimens under four kinds of creep-fatigue strain waveforms. The multiaxial strain states were analyzed by finite element (FE) analysis at the notched section in creep-fatigue loading. Couples of creep-fatigue damage laws were applied to evaluate the crack initiation and failure lives based on the multiaxial strains obtained by the FE analysis. Von Mises equivalent strain at the notch root estimated the crack initiation lives with a large scatter as well as the failure lives. Instead, the mean value of von Mises equivalent strain over the cross section of the notch root estimated the crack initiation and failure lives with a small scatter.*

INTRODUCTION

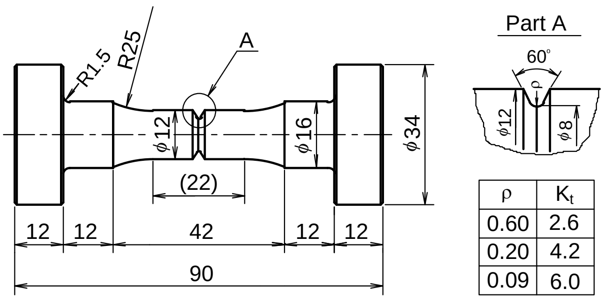
Solder connections in electronic devices undergo low cycle fatigue damage due to the mismatch of thermal expansion coefficient of connecting parts. Solders significantly creep at room temperature, so that solder connections are exposed to creep-fatigue damage during the operation of electronic devices. Solder connections usually have geometrical discontinuities like grooves and fillets that work as notches, and cracks usually initiate and propagate from these geometrical discontinuities. Ball grid alleys and flip-chip joints, for example, mostly have notches with small radius in solder balls near copper pads. Creep-fatigue cracks initiate at the notches and propagate in the solder balls resulting in the open circuit of the joints. Strain state at the notched part is mostly multiaxial so that studies of notch effect taking account of multiaxial strains are essential for the quality assurance of solder connections used in electronic devices.

The objective of this paper is to study the notch effect on creep-fatigue life of

Sn-3.5Ag solder taking account of the multiaxial strains at the notch root. Nominal strain controlled creep-fatigue tests were performed at 313 K using three types of circumferential notched specimens and cycles to crack initiation, for crack propagation and to failure were experimentally obtained. A new method of estimating the crack initiation, the crack propagation and the failure lives is proposed based on the local multiaxial strains in the notch section calculated by FE analysis.

EXPERIMENTAL PROCEDURE

A test material used in this study was Sn-3.5Ag solder of which the chemical composition in weight percent ratio is 3.51Ag, 0.005Sb, 0.001Cu, 0.001Bi, 0.003Fe, 0.008As, 0.026Pb and remainder Sn. Casts of solder round bars were machined to the notched specimens whose shape and dimensions are illustrated in Fig.1. The radii at the notch root are 0.60, 0.20 and 0.09 mm and the elastic stress concentration factors (K_t) of the specimens are 2.6, 4.2 and 6.0. The specimens were annealed at 430 K for one hour to stabilize the microstructure of the solder before testing.



ρ	K_t
0.60	2.6
0.20	4.2
0.09	6.0

Figure 1. Shape and dimensions of the specimen tested (mm).

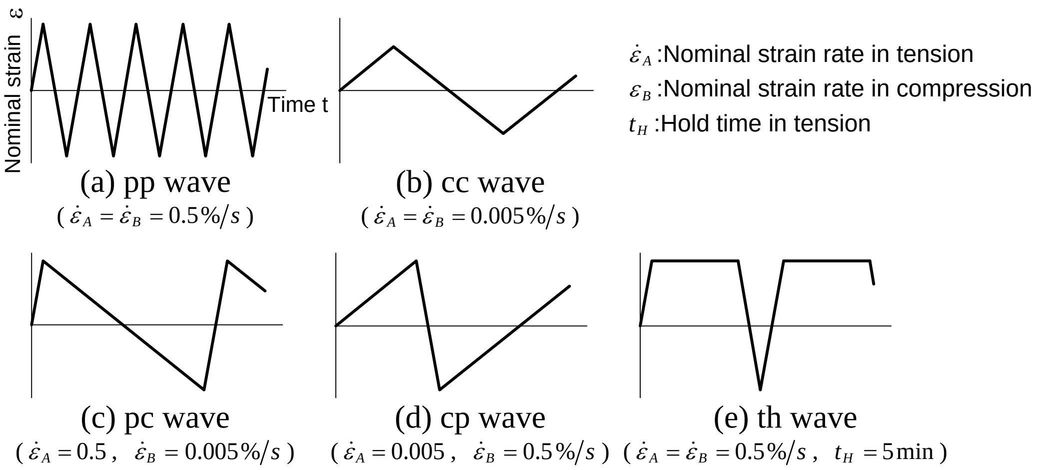


Figure 2. Five nominal strain waveforms used in creep-fatigue tests.

Nominal strain controlled push-pull creep-fatigue tests were carried out at 313 K using five nominal strain waveforms shown in Fig.2 by an electric-hydraulic servo machine. The nominal strain was the strain along 10 mm gage length including the notch part and nominal strain range ($\Delta\varepsilon_t$) used in all the tests was 0.3%.

The number of cycles to crack initiation (N_c) were determined by an a.c. potential method schematically shown in Fig.3. The number of cycles to failure (N_f) was defined as the cycles at which the tensile stress amplitude decreased to 75% of the amplitude from that at half life. The number of cycles for crack propagation (N_p) was calculated by $N_p = N_f - N_c$.

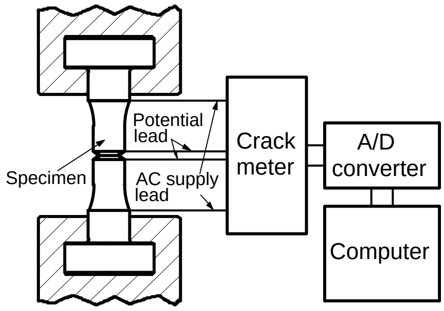


Figure 3. A.c. potential measuring method.

EXPERIMENTAL RESULTS AND DISCUSSION

Evaluation of Crack Length

Figure 4(a) shows a photograph of the fracture surface for $K_t = 2.6$ after the pc test. The fracture surface shows that the crack propagated concentrically from the notch root into the specimen. Figure 4(b) schematically illustrates definitions of the crack length (a), the ligament length (b) and the minimum section radius (R) used in this study.

This study used Eq.1 [1] to convert the a.c. potential measured to the crack length.

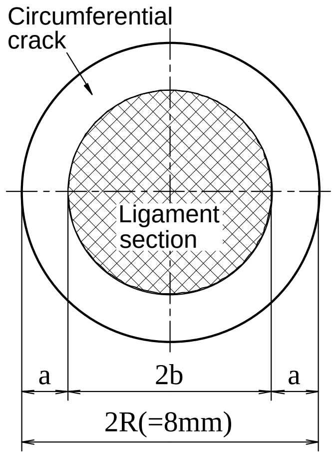
$$\frac{V_{\max}}{V_0} = 1 + 18.0\left(\frac{a}{2R}\right)^{1.88} \qquad (1)$$

V_0 is the potential for non-cracked specimen, i.e. the potential before testing.

Evaluation of Multiaxial Stresses and Strains at Notch Root

Multiaxial strains at the notch root have a significant influence on the multiaxial creep-fatigue life of the notched specimen. Elastic-plastic-creep FE analysis were performed to obtain the strains in the notch section. The element used was an axisymmetric 8-node isoparameteric ring element with 3x3 Gaussian points. The cyclic elastic-plastic constitutive relationship [2] and the Norton type creep constitutive

(a) Photograph of the fracture surface at notch root after test (pc test, $K_t = 2.6$, $\dot{\varepsilon}_A / \dot{\varepsilon}_B = 0.5/0.005\%/s$, $\Delta\varepsilon_t = 0.3\%$)



(b) Schematic of cracking mode

Figure 4. Photograph and schematic of cracking mode in the notch root section after test.

relationship [2], obtained using unnotched specimens, were used in the FE analysis. The Young's modulus, the yield stress and the Poisson's ratio were 35 GPa, 17 MPa and 0.3, respectively. MARC with combined hardening rule that is a combination of the isotropic and the kinematic hardening rules was used in the FE analysis.

Figure 5 shows the distribution of von Mises equivalent strain range ($\Delta\bar{\varepsilon}$) in the notch root section at the peak nominal strain calculated by the FE analysis. There

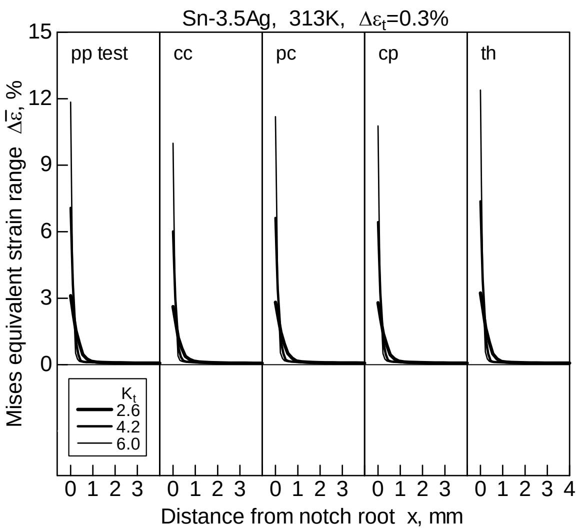


Figure 5. Von Mises equivalent strain range distribution in the notch section obtained in FE analysis.

exists a multiaxial strain state at the notch root section and this paper employs the von Mises equivalent strain to take account of the strain multiaxiality. $\Delta\bar{\varepsilon}$ takes the maximum value at the notch root and sharply decreases with x in the respective strain waveforms. $\Delta\bar{\varepsilon}$ at x larger than 1 mm appears to be very small compared with $\Delta\bar{\varepsilon}$ at x less than 1 mm.

Evaluations of Crack Initiation, Crack Propagation and Failure Lives

The $\Delta\varepsilon_{in} - N_f$ relationship of the Sn-3.5Ag unnotched specimens in the uniaxial five strain waveforms [2] was used to estimate the crack initiation lives of the notched specimens. The relationship is expressed as,

$$\Delta\bar{\varepsilon}_{in} = \alpha \cdot N_f^{-0.569} \tag{2}$$

$\alpha = 169.4$ (pp), 136.7 (cc), 49.48 (pc), 36.05 (cp) or 109.3 (th)

α is the material constant depending on the strain waveform and $\Delta\bar{\varepsilon}_{in}$ the von Mises equivalent inelastic strain range. The equivalent strain range obtained in the FE analysis was substituted in Eq.2 and the cycles of crack initiation of the notched specimens were obtained.

Figure 6 compares the crack initiation lives estimated by the above procedure with those in experiments. Most of the cycles to crack initiation are overestimated, and there is a large scatter in the correlation depending on the stress concentration factor and the strain waveform. The equivalent strain is not a suitable parameter to correlate the crack initiation lives of the notched specimens.

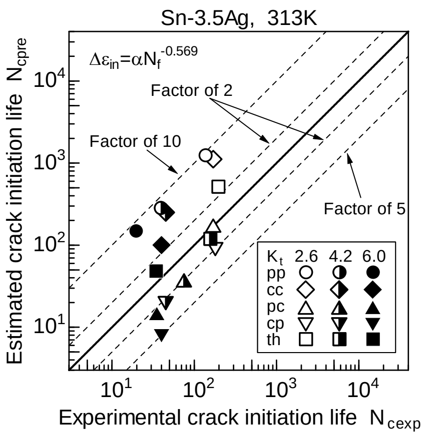


Figure 6. Comparison of crack initiation lives estimated by Eq.2 with the experimental lives.

Notches have an significant influence on crack initiation life and a little influence on crack propagation life [3]. So, the notch effect should be discussed by separating the failure life into the initiation and the propagation lives. Since the peak strain and strain gradient have an influence on the crack initiation lives, the averaged equivalent strain ($\Delta\bar{\varepsilon}_{\lambda i}$) from the notch root to λ_i is applied to estimating the crack initiation and failure lives.

$$\Delta\bar{\varepsilon}_{\lambda i} = \frac{1}{\lambda_i}\int_0^{\lambda_i} \Delta\bar{\varepsilon}\, d\lambda \tag{3}$$

where λ_i is the ratio of the crack length to the minimum radius at the minimum section. The suffix i takes c or f indicating the cycles to crack initiation or to failure.

$$\lambda_i = \frac{\bar{a}_i}{R} \tag{4}$$

Figure 7 shows the variation of λ with the equivalent strain range for $K_t = 2.6$ in the pc test. The values of $\bar{a}_c$ and $\bar{a}_f$ in Eq.4 were taken as 0.056 mm and 1.194 mm, respectively, calculated by Eq.1.

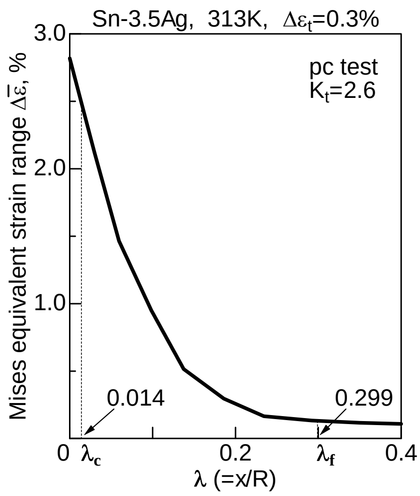
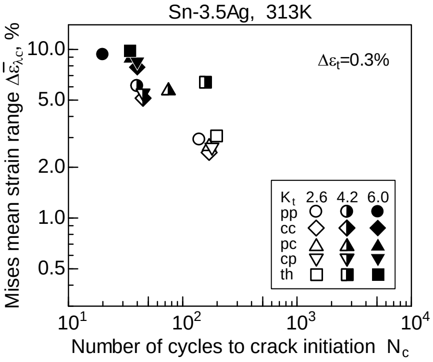
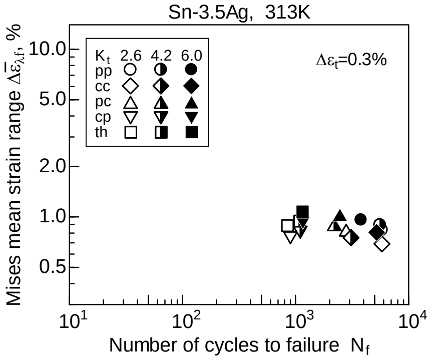


Figure 7. Relationship between λ and von Mises equivalent strain range in pc test for $K_t = 2.6$.

Figures 8(a) and (b) correlate the crack initiation and the failure lives with $\Delta\bar{\varepsilon}_{\lambda i}$. $\Delta\bar{\varepsilon}_{\lambda c}$ satisfactory correlates the crack initiation lives independent on the elastic stress concentration factor and the strain waveform, whereas some scatter is found in the correlation, Fig.8 (a). $\Delta\bar{\varepsilon}_{\lambda f}$, on the other hand, does not well correlate the failure lives of the notched specimens, Fig.8 (b), where the failure lives show small dependence on



(a) Crack initiation life



(b) Failure life

Figure 8. Correlations of the crack initiation and failure lives with von Mises mean strain ranges.

$\Delta\bar{\varepsilon}_{\lambda f}$ and the data appears to be grouped by the strain waveform. Waveform effect should be taken into account to estimate the failure lives.

The authors proposed a method of estimating the creep-fatigue life of the unnotched specimen of Sn-3.5Ag solder fatigued in the pp, cc, pc, cp and th waveforms [2]. The method is expressed by the following equations with a modification applicable to estimating the crack initiation (N_c), the crack propagation (N_p) and the (N_f) failure lives of the notched specimens.

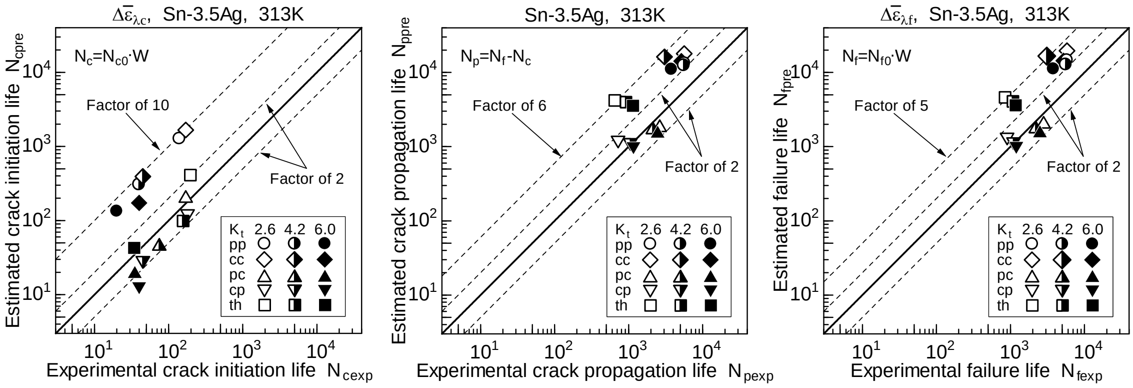
$$N_i = 1.031\times 10^4 \left(\Delta\bar{\varepsilon}_{\lambda i}\right)^{-1.947} \cdot W \tag{5}$$

$$W = 1.01\left(\dot{\varepsilon}_c\right)^{0.0169} + \left(\dot{\varepsilon}_p/\dot{\varepsilon}_c\right)^{-0.444} + \left(\dot{\varepsilon}_p/\dot{\varepsilon}_c\right)^{-0.551} + 0.683\exp\left(-39.2t_H\right) + 0.317 \tag{6}$$

$$N_p = N_f - N_c \tag{7}$$

$\dot{\varepsilon}_p$, in Eq.6, is the fast strain rate, $\dot{\varepsilon}_c$ the slow strain rate and t_H the strain hold-time in creep-fatigue tests. The first term of right hand side in Eq.6 expresses the reduction in failure life caused by the cc wave, the second term by the pc wave, the third term by the cp wave and the fourth term by the th wave [2]. The crack initiation and failure lives in the pp test were estimated with $W = 1$ in Eq.5, that agrees with the cycles to failure of the unnotched specimen obtained in experiments. The crack propagation life (N_p) was calculated by subtracting the crack initiation life from the failure life, Eq.7.

Figure 9 compares the crack initiation, propagation and failure lives estimated by Eqs 5-7 with the experimental lives. The crack initiation lives in the pc, cp and th tests estimated mostly agreed with the experimental lives within a factor of 2 but those in the pp and cc tests were overestimated by a factor of 10, Fig.9 (a). The crack propagation lives in the pc and cp tests were mostly estimated within a factor of 2 but those in the pp, cc and th tests were overestimated by a factor of 2-6, Fig.9 (b). The estimated failure lives in the pc and cp tests agreed well with the experimental lives within a factor of 2



(a) Crack initiation life (b) Crack propagation life (c) Failure life

Figure 9. Comparison of crack initiation, crack propagation and failure lives estimated by von Mises mean strain range with experimental lives.

but those in the pp, cc and th tests were overestimated from a factor of 2 to 5, Fig.9 (c). The crack initiation, the crack propagation and the failure lives of Sn-3.5Ag notched specimen are estimatable with the scatter mentioned above. This means that the equivalent strain is a suitable parameter to express the creep-fatigue damage accumulation at the notch section.

CONCLUSIONS

The creep-fatigue lives of the notched specimens of Sn-3.5Ag solder were discussed using the five nominal strain waveforms. The von Mises equivalent strain was used to express the damage accumulation under multiaxial strain states. The crack initiation lives were satisfactory estimated by the mean equivalent strain up to about 0.06 mm from the notch root and the failure lives were also estimated within a small scatter using the mean equivalent strain up to about 1 mm from the notch root in combination with the strain waveform equation.

REFERENCES

1. Sakane, M., Ohnami, M. (1988) *ASME J. Eng. Mater. Tech.* **110**(3), 247-252.
2. Nozaki, M., Sakane, M., Tsukada, Y., Nishimura, H. (2006) *ASME J. Eng. Mater. Tech.* **128**(2), 142-150.
3. Sakane, M., Ohnami, M. (1986) *ASME J. Eng. Mater. Tech.* **108**(3), 279-284.