Creep-Fatigue Crack Growth in Sn-3.0Ag-0.5Cu Solder*

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Abstract
This paper studies the creep-fatigue crack growth in Sn-3.0Ag-0.5Cu lead-free solder. Strain controlled push-pull low cycle crack growth tests were performed using fast-fast (pp), fast-slow (pc), slow-fast (cp), and slow-slow (cc) strain waveforms at 313K. The fastest crack growth rate was found in the pc waveform, followed by the cp, cc and pp waveforms. Crack growth rates in the pp waveform were well correlated with the cyclic J-integral range and fatigue J-integral range and those in the pc, cp and cc waveforms with the creep J-integral range. No creep-fatigue interaction was found in the correlation of the crack growth rate with the J-integral ranges. The crack grew perpendicular to the specimen axis in the pp waveform. In the cases of the pc, cp and cc waveforms, the crack grew in the perpendicular direction to the specimen axis initially and branched in the direction about 45 degrees to the specimen axis.

Key words: Solder, Creep-Fatigue, Crack Growth Rate, Fatigue J-Integral, Creep J-Integral

1. Introduction
Solder joints in electronic devices undergo low cycle fatigue (LCF) damage by cyclic thermal loading resulting from the mismatch of thermal expansion coefficients of joining materials. Solder joints also sustain creep damage due to the operation at high homologous temperatures\(^{(1)(2)}\). Therefore, creep-fatigue damage occurs in solder joints and development of accurate creep-fatigue damage evaluation method is needed for the quality assurance of solder joints.

Since the use of lead solders in electronic devices is strictly restricted by the RoHS and WEEE legislation, most of lead solders have been replacing with lead-free solders. For seeking suitable lead-free solders, mechanical properties of lead-free solders have been actively investigated\(^{(3)-(12)}\) as well as the other performance of the solders.

Many studies were performed on creep-fatigue lives\(^{(4)(13)-(16)}\) and creep rupture lifetimes\(^{(10)(17)-(22)}\) of solders but these studies only discussed the lifetime of bulk specimens defined by the stress drop or the specimen rupture. Since main failure mode of solder joints under cyclic thermal loading is the crack growth into solder or along solder-copper interface\(^{(23)(24)}\), the crack growth study is essential for predicting the lifetime of solder joints\(^{(2)(3)(5)-(8)(24)-(29)}\). While considerable efforts\(^{(3)(5)(8)-(9)(25)-(29)}\) have been made in studying...
the crack growth for various solders, only a limited number of researches discussed the creep-fatigue crack growth in solders. Especially little study discussed the creep-fatigue crack growth in Sn-3.0Ag-0.5Cu solder that is the most common lead-free solder.

This paper studies the creep-fatigue crack growth in Sn-3.0Ag-0.5Cu lead-free solder. Strain controlled push-pull crack growth tests were performed using fast-fast (pp), fast-slow (pc), slow-fast (cp), and slow-slow (cc) strain waveforms at 313K. This paper discussed the effects of strain waveform and strain rate on the crack growth rates under the four strain waveforms. The stress intensity factor and J-integral ranges were applied for correlating the creep-fatigue crack growth rates under the four strain waveforms. Crack paths were also discussed based on the crack observations after tests.

2. Experiment Procedure

The material tested in this study was Sn-3.0Ag-0.5Cu lead-free solder. The chemical composition of the solder is listed in Table 1. The solder was cast to solid round bars with 50mm in diameter and 200mm in length at 600K using a stainless steel mold. The round bars were machined to the center-cracked-plate specimen whose shape and dimensions are illustrated in Fig. 1. The gage length and the thickness of the gage section of the specimen were 10mm and 5mm, respectively. The specimen had a center notch hole machined by electro discharge machining (EDM) whose shape is shown in Fig. 1. The specimen was annealed at 0.87\(T_m\) (428K) for 1 hour to stabilize the microstructure before testing, where \(T_m\) is the absolute melting temperature of Sn-3.0Ag-0.5Cu solder. The casting and heat treatment methods were the method recommended as a standard testing method by the Japan Society of Material Science. One side of the gage part was polished up to 0.05µm alumina powder for crack length measurement.

### Table 1 Chemical composition of Sn-3.0Ag-0.5Cu solder (wt. %)

<table>
<thead>
<tr>
<th>Element</th>
<th>Sn</th>
<th>Pb</th>
<th>Ag</th>
<th>Sb</th>
<th>Cu</th>
<th>Bi</th>
<th>Fe</th>
<th>As</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sn-3.0Ag-0.5Cu</td>
<td>Bal.</td>
<td>0.026</td>
<td>2.97</td>
<td>0.0075</td>
<td>0.49</td>
<td>0.0025</td>
<td>0.0005</td>
<td>0.0053</td>
</tr>
</tbody>
</table>

An electric-servo hydraulic machine with a 50kN load capacity was used to conduct nominal strain controlled creep-fatigue tests at 313K, where the nominal strain is the strain along the gage length of 10mm including the center notch part. The specimen was heated by
two band heaters wrapped around the lower and upper pull rods. The variation of temperature along the gage length during the test was within ±0.5K. Crack length was measured by a charge-coupled device (CCD) camera with a resolution of 5µm. The crack length (2a) is defined as the length including the initial notch length as shown in Fig. 2.

Figure 3 shows the four types of strain waveforms used in creep-fatigue crack growth tests. They were fast-fast (pp), fast-slow (pc), slow-fast (cp), and slow-slow (cc) waveforms. In the pp, pc and cc waveform tests, the strain rate was set to 0.5%/s for the p part (the “fast” strain rate) and to 0.05%/s for the c part (the “slow” strain rate). In the cp tests, the strain rate of the p part was the same but the c part strain rate was varied to 0.05%/s, 0.01%/s and 0.005%/s to investigate the rate effect. The details of test conditions are listed in Table 2 with circles.

3. Experimental Results and Discussion

3.1 Crack growth rates

Figure 4 shows crack growth curves against the number of cycles in all the tests conducted in this study. Faster crack growth is found at higher strain range in the same waveform and the fastest crack growth is found in the pc waveform, followed by the cp, cc, and pp waveforms at the same strain range and slow strain rate.
Figure 5 plots crack growth rates against the crack length, where the data with the slow strain rate of 0.05%/s is plotted for the pc, cp and cc waveforms. At $\Delta \varepsilon = 0.3\%$, the pc waveform gives the fastest crack growth rate and the pp, cp and cc waveforms show almost the same crack growth rate which is slower than that in the pc waveform. The four waveforms yield almost constant growth rate against the crack length throughout the test. At $\Delta \varepsilon = 0.5\%$, on the other hand, the crack growth rates show a wide variation depending on the waveform. The pc waveform shows the fastest crack growth rates and the cp waveform gives slower growth rates than it. The crack growth rates in the cc waveform are nearly the same as those in the cp waveform. The pp waveform yields the slowest crack growth rates.

Crack growth rates at three slow strain rates are plotted in Fig. 6 at two strain ranges. Faster crack growth rates are observed at slower strain rates. These results indicate that lowering the slow strain rate causes more creep damage at the crack tip that leads to the faster crack growth rate in the cp waveform. This effect is more clearly occurred at the larger strain range.

### 3.2 Cyclic stress-strain response

Figure 7 depicts the stress-strain hysteresis loops at the crack length of 2mm at $\Delta \varepsilon = 0.5\%$ in the four waveforms. The pp waveform gave almost symmetric stress response in tension and compression. The pc waveform produced a larger tensile peak stress but a slightly smaller compressive peak stress compared with the pp waveform. The cp waveform conversely yielded a smaller tensile stress and a larger compressive peak stress than those in the pp waveform. The cc waveform generated smaller peak stresses both in tension and compression. The lower peak stresses are found in the slow straining direction in the pc, cp and cc waveforms and small mean stresses occurred in the fast straining direction in the pc waveform.
and cp waveforms. The lower peak stresses in the slow direction resulted from the creep deformation by the slow straining.

The inelastic strain ranges in the pp, pc, cp and cc waveforms are decomposed into the plastic and creep strain ranges as shown in Fig. 8, following the strain partitioning method proposed by Manson (7)(31). Table 3 summarizes the strain components partitioned at crack length of 2mm in all the waveforms. The inelastic strain range takes up the major portion of the total strain range. The inelastic strain range was partitioned into the plastic and creep strain ranges for the pc, cp and cc strain waveforms and the larger creep strain ranges are found compared with the plastic strain ranges in these three strain waveforms.

![Fig.5 Variation of the crack growth rate with crack length](image)

![Fig.6 Effect of the slow strain rate on the crack growth rate in the cp waveform](image)
Figure 7 shows the variation of tensile and compressive peak stresses with the number of cycles for the four waveforms at $\Delta \varepsilon = 0.5\%$. The stress ranges decreased with the number of cycles which results from the cyclic softening and crack growth. No mean stress exists in the pp and cc waveforms, but tensile and compressive mean stresses are found in the pc and cp waveforms, respectively. The mean stress is in the direction of fast straining and the amount of the mean stress is not so large because of the large inelastic deformation.
Table 3 A summary of the strain partitioned at crack length of 2mm

<table>
<thead>
<tr>
<th>Strain waveform</th>
<th>Strain rate $\dot{\varepsilon}$ (%/s)</th>
<th>Strain range $\Delta \varepsilon$ (%)</th>
<th>Inelastic strain range $\Delta \varepsilon_{in}$ (%)</th>
<th>Plastic strain range $\Delta \varepsilon_{pl}$ (%)</th>
<th>Creep strain range $\Delta \varepsilon_{c}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>pp</td>
<td>0.5 -</td>
<td>0.2 0.117 0.117 0.117 0.0</td>
<td>0.3 0.215 0.215 0.215 0.2</td>
<td>0.5 0.404 0.404 0.404 0.4</td>
<td>0.5 0.404 0.404 0.404 0.4</td>
</tr>
<tr>
<td>pc</td>
<td>0.5 0.05</td>
<td>0.3 0.209 0.089 0.120</td>
<td>0.5 0.366 0.124 0.242</td>
<td>0.5 0.405 0.165 0.240</td>
<td>0.5 0.405 0.165 0.240</td>
</tr>
<tr>
<td>cc</td>
<td>- 0.05</td>
<td>0.3 0.221 0.076 0.145</td>
<td>0.5 0.405 0.165 0.240</td>
<td>0.5 0.405 0.165 0.240</td>
<td>0.5 0.405 0.165 0.240</td>
</tr>
<tr>
<td>cp</td>
<td>0.5 0.05</td>
<td>0.3 0.199 0.094 0.105</td>
<td>0.5 0.385 0.180 0.205</td>
<td>0.5 0.385 0.180 0.205</td>
<td>0.5 0.385 0.180 0.205</td>
</tr>
<tr>
<td>cp</td>
<td>0.5 0.01</td>
<td>0.3 0.209 0.099 0.111</td>
<td>0.5 0.389 0.158 0.231</td>
<td>0.5 0.389 0.158 0.231</td>
<td>0.5 0.389 0.158 0.231</td>
</tr>
<tr>
<td>cp</td>
<td>0.5 0.005</td>
<td>0.3 0.213 0.095 0.118</td>
<td>0.5 0.401 0.167 0.234</td>
<td>0.5 0.401 0.167 0.234</td>
<td>0.5 0.401 0.167 0.234</td>
</tr>
</tbody>
</table>

Fig.9 Variation of the tensile and compressive peak stresses with cycle in $\Delta \varepsilon=0.5\%$ tests

3.3 Creep-fatigue crack growth

This paper applied four fracture mechanics parameters to correlate the crack growth rates discussed above. These parameters are the stress intensity factor, the cyclic J-integral, the fatigue J-integral, and the creep J-integral ranges.

The stress intensity factor range ($\Delta K$) for a center-cracked-plate is given by Eq. (1) \cite{32}. 

\[ \Delta K = \frac{1}{2} \left[ (\sigma_{max} - \sigma_{min})^2 + (\sigma_{max} + \sigma_{min})^2 \right] \]
\[ \Delta K = \frac{\Delta P^*}{BW} \sqrt{\frac{\pi a}{W}} \sqrt{\sec \left( \frac{\pi a}{W} \right)} \]  \quad (1) 

where \( \Delta P^* \) is the load range from the crack opening point to the maximum load in the load-displacement hysteresis loop as shown in Fig. 10. \( B \) and \( W \) are the thickness and the width of the plate, respectively, and \( a \) is the crack length.

The cyclic J-integral range \( (\Delta J) \) for the center-cracked-plate, proposed by Dowling et al. \(^{(33)(34)} \) referring to Rice et al. \(^{(35)(36)} \), is expressed by Eq. (2):

\[ \Delta J = \frac{(\Delta K)^2}{E} + \frac{2S^*}{B(W - 2a)} \]  \quad (2)

where \( S^* \) is the dashed area in the load-displacement hysteresis loop shown in Fig. 10 and \( E \) is the Young’s modulus. \( E=20\)GPa was used for the solder in this paper \(^{(37)} \). Note that the cyclic J-integral range was originally proposed for correlating the crack growth rate under elastic-plastic deformation with no creep deformation. This study applied it to the crack growth under elastic-plastic-creep deformation to examine the extensibility of it.

The fatigue J-integral range \( (\Delta J_f) \) for the center-cracked-plate is expressed by the following equation \(^{(38)(39)} \):

\[ \Delta J_f = \frac{(\Delta K)^2}{E} + \frac{2S_p}{B(W - 2a)} \]  \quad (3)

where \( S_p \) is the dashed area in the load-displacement hysteresis loop shown in Fig. 8. The fatigue J-integral range of Eq. (3) is equivalent to the cyclic J-integral range of Eq. (2) for the pp waveform because \( S_p \) and \( S^* \) are the same in that case. However, when creep deformation takes place, the cyclic J-integral range becomes greater than the fatigue J-integral range because it takes the whole area of the hysteresis loop into account in the computation of \( S^* \).

The creep J-integral range \( (\Delta J_c) \) for the center-cracked-plate is expressed by Eq. \(^{(4)} \):

\[ \Delta J_c = \frac{\alpha - 1}{\alpha + 1} \frac{(S_{c,1} - S_{c,2})}{B(W - 2a)} \]  \quad (4)

where \( S_{c,1} \) and \( S_{c,2} \) are the dashed areas in the load-displacement hysteresis loop in Fig. 8, and \( \alpha \) is the creep exponent in the power creep law. The value of \( \alpha \) at 313K was set to 10.46 \(^{(37)(41)} \). The stress-strain curve under rapid straining is needed to determine \( \Delta J_c \) as indicated in Fig. 8, and the hysteresis loop in the pp waveform was used instead of rapid straining.

Figure 11 correlates crack growth rates in the four strain waveforms with the stress intensity factor range. The solid line in the figure is a linear regression line based on the pp crack growth data. The stress intensity factor range correlates the pp data with a rather small scatter but the regression line underestimates the crack growth rates in the other three waveforms by a factor of up to 7. The stress intensity factor range is basically applicable to only the case of small scale yielding but the well correlated pp data in the figure implies that the stress singularity at the crack tip is close to that expressed by the stress intensity factor ever in the elastic-plastic regime. For the cases of the pc, cp and cc data, on the other hand, the stress intensity factor range gave a large scatter which is attributed to the fact that there exist a large plastic and creep deformation in these strain waveforms.
Figure 12 correlates crack growth rates in all the tests performed in this study with the cyclic J-integral range, where two solid lines were drawn based on the pp data and all the data. Crack growth rates in the pp waveform were correlated with the cyclic J-integral range within the scatter band of factor 2, but the other three waveforms generated a wide scatter. The crack growth rates in the pc, cp and cc waveforms are faster than those in the pp waveform at the same cyclic J-integral range. This results from creep damage at the crack tip induced by slow straining in the former three waveforms. The cyclic J-integral range does not account for creep damage, so that it is not a suitable parameter to correlate crack growth rates in the creep-fatigue regime.

![Fig. 10 Determination of $S^*$ from the load-displacement hysteresis loop for evaluating $\Delta J$ for a center-cracked-plate specimen](image)

![Fig. 11 Correlation of crack growth rates with $\Delta K$](image)
For all the strain waveforms

d\!a/dN = 5.60 \times 10^{-4} \Delta J^{1.816}

For pp waveform

d\!a/dN = 2.50 \times 10^{-4} \Delta J^{1.501}

Fig. 12 Correlation of crack growth rates with \(\Delta J\)

The relationship between crack growth rates and the fatigue J-integral range in the four waveforms is shown in Fig. 13. The results in the figure show that the fatigue J-integral range is not a proper fracture mechanics parameter to correlate the crack growth rates in the creep-fatigue regime. Crack growth rates under creep-fatigue conditions are significantly underestimated from the pp data represented by the solid line. The underestimation is caused by the fact that the fatigue J-integral range does not take the creep deformation into account in the formula. The scatter of the data in Fig. 13 appears to be larger than that found in Fig. 12. The correlation of the pp data with the fatigue J-integral range is the same as the correlation with the cyclic J-integral range since both evaluations are equivalent for the pp data. Both parameters correlate crack growth rates of the pp data within the scatter band of factor 2. The correlation of the pp data alone with fatigue J-integral range is expressed by Eq. (5):

\[
\frac{da}{dN} = 2.50 \times 10^{-4} \Delta J_f^{1.501}
\]  

The parameter \(\Delta J_f\) in this equation is replaceable with the cyclic J-integral range (\(\Delta J\)) for the case of the pp waveform.

The creep J-integral range was used to describe the time-dependent crack growth rates \((38)-(40)\). Figure 14 correlates the crack growth rates in the pc, cp and cc waveforms with the creep J-integral range. Almost all the data are collapsed into the factor-2 scatter band. The relationship between the creep J-integral range and crack growth rates in the three strain waveforms is expressed by Eq. (6):
The satisfactory correlation of the crack growth rates in the pc, cp and cc waveforms with the creep J-integral range physically means that the driving process of crack growth is controlled by the creep damage at the crack tip.

\[
\frac{da}{dN} = 8.26 \times 10^{-3} \Delta J_c^{1.131}
\]  

(6)

Figure 15 shows the correlation of the crack growth rates with the fatigue J-integral range for the pp data and the creep J-integral range for the pc, cp and cc data. The straight lines, representing the pp data and the pc, cp and cc data, are expressed, respectively, by Eqs. (5) and (6). A feature of the results is that crack growth rates in the two groups are correlated separately with two different fracture mechanics parameters, and that there are no cases where both fatigue and creep J-integral ranges need to be considered in crack growth modeling. This is because the crack tip field is either primarily plastic (pp) or primarily creep (pc, cp and cc), and there exist no interaction cases under the test conditions. One of the causes of these experimental results is that the experiments in this study were performed at high homologous temperature for the solder. The homologous temperature was 0.63 that is extremely high compared with the temperature at which conventional heat resistant steels and alloys are used. The creep deformation at the crack tip may dominate the inelastic deformation so that the crack growth rates were uniquely correlated with the creep J-integral range for the pc, cp and cc data.

Taira et al. (40) reported similar correlations as shown in Fig. 15. In their work, the crack growth rates of several heat resistant steels were well correlated with either \( \Delta J_f \) or \( \Delta J_c \), and
no intermediate regime was found. Nozaki et al. (7) and Mukai et al. (42) reported that elastic-creep constitutive equations were sufficient to describe the inelastic deformation under creep-fatigue conditions for solders, which implies that creep deformation dominates inelastic deformation and time-independent plasticity is insignificant.

\[
\text{cp wave } \Delta \varepsilon = 0.5\% , \ \varepsilon_c = 0.05\%/s \quad \text{cp wave } \Delta \varepsilon = 0.3\% , \ \varepsilon_c = 0.01\%/s \\
\text{cp wave } \Delta \varepsilon = 0.5\% , \ \varepsilon_c = 0.005\%/s \quad \text{cp wave } \Delta \varepsilon = 0.3\% , \ \varepsilon_c = 0.005\%/s \\
\text{pc wave } \Delta \varepsilon = 0.3\% , \ \varepsilon_c = 0.05\%/s \quad \text{pc wave } \Delta \varepsilon = 0.5\% , \ \varepsilon_c = 0.05\%/s \\
\text{cc wave } \Delta \varepsilon = 0.3\% , \ \varepsilon_c = 0.05\%/s \quad \text{cc wave } \Delta \varepsilon = 0.5\% , \ \varepsilon_c = 0.05\%/s \\
\text{cp wave } \Delta \varepsilon = 0.3\% , \ \varepsilon_c = 0.05\%/s
\]

Fig. 14 Correlation of crack growth rates with $\Delta J_c$ for the pc, cp and cc waveforms

\[
da/dN = 8.26 \times 10^{-3} \Delta J_c^{1.131}
\]

For pc, cp and cc waveforms

\[
da/dN = 2.50 \times 10^{-4} \Delta J_f^{1.501}
\]

Fig. 15 Correlation of crack growth rates for the fatigue-dominant and creep-dominant waveforms with fatigue and creep J-integral ranges
3.4 Observation of crack paths

Crack paths after test were examined by an optical microscope. Figure 16 shows the macroscopic crack paths in the four waveforms. In the pp waveform, the crack grew in the direction perpendicular to the specimen axis forming a saw-tooth pattern as seen in Fig. 16(a). In the cases of the pc, cp, cc waveforms, the cracks grew perpendicular to the specimen axis in the early phase and then branched in the direction about 45 degrees to the specimen axis as seen in Fig. 16(b)-(f). The creep damage introduced by slow straining increased with crack growth and changed the fracture plane from the maximum principal stress plane to the maximum shear stress plane. This type of cracking mode changes is often observed in ductile metals (43)(44).

(a) pp waveform with $\Delta \varepsilon = 0.2\%$

(b) pc waveform with $\Delta \varepsilon = 0.5\%$ and $\dot{\varepsilon}_c = 0.05\%/s$

(c) cp waveform with $\Delta \varepsilon = 0.5\%$ and $\dot{\varepsilon}_c = 0.05\%/s$
4. Conclusions

(1) The crack growth rate increased with the applied strain range in the same waveform. At the same applied strain range, the fastest crack growth rate was found in the fast-slow (pc) waveform which produces a larger tensile peak stress, followed by the slow-fast (cp), slow-slow (cc), and fast-fast (pp) waveforms. Lowering the slow strain rate which causes more creep damage ahead of crack tip in the slow-fast (cp) waveform accelerated the crack
growth rate. This effect is more pronounced at the larger strain ranges.

(2) Larger tensile and compressive peak stresses were found in the fast-slow (pc) and slow-fast (cp) waveforms, respectively. As a result, nonzero mean stress was generated in the fast straining direction for the fast-slow (pc) and slow-fast (cp) waveforms, but the amount of the mean stress was not so large because the solder gave the larger inelastic deformation under the testing conditions.

(3) The crack growth rates in the fast-fast (pp) waveform were correlated with the cyclic J-integral range and the fatigue J-integral range with the scatter band of factor 2. The crack growth rates in the fast-slow (pc), slow-fast (cp) and slow-slow (cc) waveforms were correlated with the creep J-integral range with the scatter band of factor 2, which physically means that the driving process of crack growth is controlled by the creep damage ahead of crack tip. No creep-fatigue interaction was observed in the correlation of crack growth rates with the J-integral ranges in the fast-fast (pp), fast-slow (pc), slow-fast (cp) and slow-slow (cc) waveforms.

(4) The crack grew perpendicular to the specimen axis forming a saw-tooth pattern in the fast-fast (pp) waveform. In the cases of the fast-slow (pc), slow-fast (cp), slow-slow (cc) waveforms, the crack grew in the perpendicular direction to the specimen axis initially and branched in the direction about 45 degrees to the specimen axis. The creep damage changes the fracture plane from the maximum principal stress plane to the maximum shear stress plane.

Acknowledgments

The specimens used in this study were provided by Advanced Packaging Laboratory, Kyocera SLC Technologies Corporation in a joint research with Ritsumeikan University. Partial support of the Brain Korea 21 program from the Department of Mechanical Engineering of Pohang University of Science and Technology (POSTECH) is also gratefully acknowledged.

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