Crack Initiation and Propagation Evaluation for Sn–5Sb Solder Under Low-Cycle Fatigue

Noritake Hiyoshi¹

Received: 20 January 2017 / Revised: 13 March 2017 / Published online: 26 July 2017
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Abstract In this study, a crack initiation and propagation behavior of Sn–5Sb lead-free solder under low-cycle fatigue is discussed. Cyclic push–pull loading tests with a single-hole specimen have been conducted at 313 K to investigate the crack initiation and propagation behavior of Sn–5Sb solder which has a higher melting point temperature than that of Sn–Ag–Cu solders. A fatigue life ratio correlates with the crack length within a small scatter. Crack initiates at the early stage, and almost all the life period is crack propagation process independent of strain range and strain rate. The crack propagation rate depends on the strain range and the strain rate. The adaptation of J-integral value for Sn–5Sb solder is also discussed. J-integral value is a suitable parameter for crack propagation rate evaluation.

KEY WORDS: Crack initiation; Crack propagation; J-integral range; Small size specimen; Sn–5Sb solder

1 Introduction

Soldering is an important and a fundamental technique for electronic device mounting. Sn–Pb solders are not allowed to use because it contains lead which is a harmful element for the earth environment and human bodies. There are many kinds of candidate lead-free solders. It is required for an electronic device designing to investigate not only mechanical properties and fatigue life but also crack propagation behavior of the candidate lead-free solders. Some researches argue that almost all the fatigue life of solders occurs at crack propagation stage, so that evaluation of the crack propagation behavior at commercial usage temperature is useful for fatigue life estimation [1–9].

Although Sn–3.0Ag–0.5Cu [10] lead-free solder is widely used all over the world, there are still some issues for this kind of material to be used. One of these issues is that melting point temperature of Sn–3.0Ag–0.5Cu solder is 493 K which is lower than commercially required temperature and also a little lower than the soldering temperature of electronic devices designed for high-temperature environment. Another issue is a high material cost for Sn–3.0Ag–0.5Cu solder due to containing Ag element.

Sn–5Sb solder, which is one of the candidate solders, has a higher melting point temperature and a lower material cost than Sn–3.0Ag–0.5Cu solder. Therefore, it is useful for high-temperature soldering and industrial use. The melting point temperature of Sn–5Sb solder is 516 K, and the material cost is about 4850 JPY (Japanese Yen) per 1 kg which is much lower than that of Sn–3.0Ag–0.5Cu solder costs (about 7450 JPY per 1 kg).

Although it is important for commercial product development and design to clarify not only tensile strength and mechanical properties but also fatigue life of the electronic materials, there are little experimental researches on Sn–5Sb solder. There is also a little research on crack

Available online at <http://link.springer.com/journal/40195>

✉ Noritake Hiyoshi
hiyoshin@u-fukui.ac.jp

¹ Division of Engineering, Faculty of Engineering, University of Fukui, 3-9-1 Bunkyo, Fukui-shi, Fukui 910-8507, Japan

initiation and propagation behavior of Sn–5Sb solder at high temperatures.

The objective of this study is to clarify the crack initiation and propagation behavior of Sn–5Sb solder. Cyclic push–pull loading tests of the specimen with a single hole at the center of the specimen as a stress concentrate part. The stress concentration factor of the hole is calculated to be $K_t = 2.72$ by using Eq. (1) [11].

2 Experimental

The material tested in this study is Sn–5Sb lead-free solder, and its chemical compositions are listed in Table 1. Figure 1 shows the shape and dimensions of the specimen with a single through hole at the center of the specimen as a stress concentrate part. The stress concentration factor of the hole is calculated to be $K_t = 2.72$ by using Eq. (1) [11].

$$K_t = 3.00 - 3.13\left(\frac{d}{W}\right) + 3.66\left(\frac{d}{W}\right)^2 - 1.53\left(\frac{d}{W}\right)^3, \quad (1)$$

where W and d are the width of the specimen and the diameter of the center through hole, respectively. The specimen is produced by a mechanical procedure from a Sn–5Sb solder ingot which was casted under controlled temperature and instruction.

Cyclic push–pull loading tests were conducted under strain control mode with an electric hydraulic fatigue testing apparatus. Since solders have low strength, the testing apparatus has a low-capacity load cell and an actuator in order to conduct accurately fatigue test with solders. The specimen was heated up to 313 K by rubber heaters attached to both upper and lower connecting rods. We had confirmed in advance that temperature distribution and variation of the specimen during test were satisfied for the testing standard of solders [12]. Symmetrically fully reversed triangle waveform with three kinds of strain rates of 0.01, 0.1 and 0.5%/s was used to investigate the effects of strain rates on crack propagation behavior.

An extensometer with linear variable differential transformer was used to measure the axial total strains of 10 mm gage part. To avoid a cracking at the location of the extensometer rod tips, two small bumps of epoxy resin with grooves were formed on the specimen surface and the tips of the extensometer rods were placed on the grooves [12].

Crack initiation and propagation behaviors were observed with a CCD camera and a LCD monitor. Crack

Fig. 1 Shape and dimensions of the specimen (mm)

length ($2a$), which is defined as the length from one end to another end of the crack in a horizontal direction including the center through hole, was also measured with the CCD camera view. Crack initiation cycle (N_i) was defined as the cycle at which a new 0.01 mm length crack was observed at the center through hole. The number of cycles to failure (N_f) was defined as the cycle at which tensile stress amplitude dropped 25% from that at a midlife.

3 Results and Discussion

3.1 Effects of Strain Range and Strain Rate on Crack Initiation Cycle

Figure 2 shows the surface cracks of the failure specimen. Main cracks for all the testing conditions initiated from the center through hole machined as a stress concentration part. Main cracks propagated in the maximum shear direction at strain rates of 0.5 and 0.1%/s. However, the main crack propagation direction at strain rate of 0.1%/s changed from the maximum shear direction to the specimen axis direction encountering huge size slip generated at specimen edge. The huge size slip of the specimen surface was observed clearly at a slow strain rate, but there was a little slip at a fast strain rate testing condition.

Figure 3 shows microstructure of Sn–5Sb solder. The grain size is 200–500 μm . The detailed mechanism of the huge size slip in Fig. 2 is still unknown, but a similar deformation in a single crystal might have occurred due to the large grain size of the Sn–5Sb solder.

Figure 4 shows the relationship between crack length and fatigue life ratio (N/N_f). The fatigue life ratio is the cycle number divided by the failure cycle which is listed in

Table 1 Chemical composition of Sn–5Sb solder (mass%)

Sn	Ag	Cu	Sb	Bi	Pb	Zn	Fe	Al	As
Bal.	<0.0001	0.0002	4.9901	0.0002	0.003	<0.0001	0.0006	<0.0001	0.0024

Fig. 2 Crack propagation observations after the tests

Fig. 3 Microstructure of Sn–5Sb solder tested

Table 2. Figure 4a and b depicts the effect of the strain range and the strain rate on the crack propagation behavior, respectively. Each solid line of Fig. 4 is drawn based on all of the experimental data obtained, and each dotted line indicates data scatter band. The number of crack initiation cycle (N_i) in Fig. 4a and Table 2 is 200, 100 and 88 for the test at the total strain range $\Delta\epsilon$ of 0.3, 0.5 and 1.0%, respectively. The result indicates that there is no strain range effect on the crack initiation cycle. The number of crack initiation cycle in Fig. 4b is 88, 100 and 100 for the

test at strain rate of 0.01, 0.1 and 0.5%/s, respectively. There is also no strain rate effect on the crack initiation cycle. Crack initiated at the early stage, and almost all the life period was crack propagation process which is independent of the strain range and the strain rate. The fatigue life ratio parameter correlates with the crack length within a factor of 1.8 scatter which is independent of not only the strain range but also the strain rate as shown in Fig. 4a and b.

3.2 Effects of Strain Range and Strain Rate on Crack Propagation

Since there were no effects of the strain range and the strain rate on the crack initiation cycle, a crack propagation cycle (N_p) was also considered in this study as a new evaluation parameter. The crack propagation cycle was calculated as subtracting the crack initiation cycle (N_i) from the number of total cycle (N).

Figure 5 shows crack propagation curves of Sn–5Sb solder. Since the experimental crack length data were scattered due to the occurrence of huge size slip and sub-cracks as shown in Fig. 2, an approximation curve was drawn by using only the main crack which initiated from the center through hole. The approximation curve for the test at strain rate of 0.01%/s was drawn based on the experimental data under $2a = 5$ mm, because the crack stagnated due to occurrence of the huge size slip on the

Fig. 4 Crack length as a function of fatigue life ratio **a** effect of strain range, **b** effect of strain rate

Table 2 Crack initiation cycle and failure cycle for Sn–5Sb solder

Strain rate, ε (%/s)	0.01		0.1				0.5			
Strain range, $\Delta\varepsilon$ (%)	0.5		0.3		0.5		1.0		0.5	
N_i : Crack initiation cycle N_f : Failure cycle	N_i	N_f	N_i	N_f	N_i	N_f	N_i	N_f	N_i	N_f
	88	2760	200	3111	100	3967	88	710	100	2870

Fig. 5 Crack propagation curves of Sn–5Sb solder

specimen surface. The crack propagation rate during the test at $\Delta\varepsilon = 1.0\%$ seems to be faster than that at $\Delta\varepsilon = 0.3$ and 0.5% at the same strain rate. The crack propagation rate during the test at the strain rate of $0.01\%/s$ seems to be faster than that at 0.1 and $0.5\%/s$.

Figure 6a and b shows the number of crack propagation cycles when $2a$ reaches 5 mm ($N_{p5\text{mm}}$), depicting the

effects of the strain range and the strain rate on the crack propagation rate, respectively. $N_{p5\text{mm}}$ in Fig. 6a is 3450, 3200 and 565 for the test at $\Delta\varepsilon = 0.3\%$, $\Delta\varepsilon = 0.5\%$ and $\Delta\varepsilon = 1.0\%$, respectively. The larger strain range accelerates the crack propagation rate at strain rate of $0.1\%/s$. $N_{p5\text{mm}}$ in Fig. 6b is 1312, 3200 and 1900 for the test at strain rate of 0.01 , 0.1 and $0.5\%/s$, respectively. These results indicate that a slower strain rate accelerates the crack propagation rate slightly.

3.3 Crack Propagation Rate Evaluation with J-integral Range Parameter

Since electronic material solder has a small proof stress and a small proportional limit, inelastic strain range accounts for a large percentage of total strain range at strain-controlled low-cycle fatigue [13, 14]. Adaptation of J-integral value was discussed in this study. J-integral value was calculated by using Dowling method [15] which is expressed as Eq. (2).

$$\Delta J = \frac{(\Delta K^*)^2}{E} + \frac{S}{Bb}, \quad (2)$$

where ΔK^* , E , B and b are stress intensity factor range, Young's modulus, thickness of the specimen and ligament length of the crack-initiated specimen, respectively. S is the

Fig. 6 Crack propagation cycles when $2a = 5$ mm **a** effect of strain range, **b** effect of strain rate

Fig. 7 Load–displacement curve

half value of the area under the load–displacement curve produced during one cycle of fatigue test, as shown in Fig. 7.

Figure 8 shows the correlation of the crack propagation rate with J-integral value. All the crack propagation data at steady propagation stage are correlated with a small scatter independent of the strain rate. This result indicates that J-integral value evaluates the crack propagation rate independent of the strain rate at 313 K. The approximation line equation is expressed as follows:

$$\frac{da}{dN} = 1.25 \times 10^{-3} \times \Delta J^{0.78}, \quad (3)$$

where a , N and ΔJ are half length of crack, cyclic number and J-integral value, respectively. Therefore, Eq. (3)

Fig. 8 Relationship between crack propagation rate and ΔJ

indicates that there is a linear relationship between crack propagation rate and J-integral value.

4 Conclusions

In this work, the crack initiation and propagation behaviors of Sn–5Sb solder under low-cycle fatigue was evaluated, and the adaptation of J-integral value for the crack propagation rate of Sn–5Sb solder at 313 K was also discussed.

1. There were no effects of the strain range and the strain rate on the crack initiation cycle at 313 K, but the number of crack propagation cycle depended on the

strain range. There was a little effect of the strain rate on the number of crack propagation cycles.

2. Fatigue life ratio parameter was related to the crack length within a factor of 1.8 scatter band independent of the strain range and the strain rate.
3. J-integral value was a suitable parameter for crack propagation rate evaluation. J-integral value evaluated the crack propagation rate independent of the strain rate ranged in 0.01–0.5%/s at 313 K.

Acknowledgments I am grateful to Dr. Takamoto Itoh, a professor in Ritsumeikan University for helpful discussion. I also gratefully acknowledge the work of past members Mr. Hirokatsu Yamamoto, undergraduate student in University of Fukui, and Mr. Kazuki Terahara, graduate student in Ritsumeikan University.

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