EM 388F

Fracture Mechanics

Final Term Paper

Low-Cycle Fatigue Behavior of Lead-Free Solder

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Abstract

Tin-based lead-free solders have been widely used in microelectronic packages today. In electronic packages, solder joints provide not only electrical connection, but also mechanical attachment between the semiconductor devices and substrates. Therefore, the mechanical properties of the solder joints have become critical to the reliability of electronic packaging. Under normal usage, electronic devices are exposed to cyclic temperature load. The thermal expansion coefficient (CTE) difference among materials will transform to a cyclic strain, hence facilitate the commonly seen low-cycle fatigue (LCF) of solder joints.

Under a cyclic load, it has been observed the loading rate and temperature play important roles in LCF of lead-free solders. Further investigation indicated the fatigue life could be represented by a modified Coffin–Manson relationship. In this term paper, the LCF behavior of Sn-Ag lead-free solder alloys will be briefly reviewed, and the LCF properties of bulk lead-free solder and eutectic Sn-Pb solder will be compared as well.

Introduction

The ever rising amount of electronic waste, most of which end up in land-fills, has become a serious worldwide concern. The harmful effect of lead to humans is well known. The recent passage of the European Union "Directive on the Restriction of the Use of Certain Hazardous Substances (RoHS) in Electrical and Electronic Equipment (EEE) " has driven the unstoppable transform from traditional Sn-Pb solder towards lead-free solder for electronics packaging and manufacturing of electronics products. There are many solder alloys that do not contain lead. Currently, the ternary eutectic Sn-Ag-Cu (SAC) alloy is the best candidate for the microelectronics industry to replace the traditional Sn-Pb solder.

As the worldwide electronics industry implements lead-free solder in PCB assembly, reliability issues are critical to a smooth transition to lead-free soldering in high volume manufacturing. Low-cycle fatigue (LCF, $N_f \lesssim 10^4$) is a commonly seen failure mode of solder joint interconnects. Fig. 1 shows an example scheme of a flip-chip packaged microprocessor. When it is subjected to cyclic temperature environments, the difference of thermal expansion coefficient (CTE) between the silicon die (2.6ppm/^{o}C) and the plastic substrate (15ppm/^{o}C) would generate a cyclic shear strain load on solder bumps in between. In most application the strain would generally range from 0.001 to 0.1.

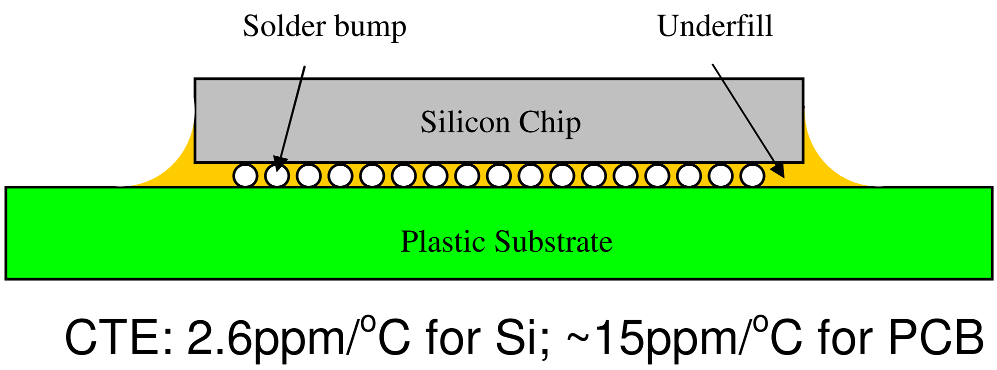

Fig. 1: Scheme of a flip-chip packaged microprocessor

Due to the low melting temperature of solder alloys, the low-cycle fatigue behavior of solder cannot be separated from the time-dependent creep deformation or stress relaxation. Under normal application, the homologous temperature, T/T_{melt}, will be in the range of 0.6~0.87 for use temperature of 25~150°C. Therefore, even at room temperature solder materials are under high temperature service, and the creep deformation or stress relaxation would significantly affect the low-cycle fatigue behavior of solder materials.

Fatigue behavior of bulk solder

The fatigue of solder begins with a stabilization of the microstructure. Most Sn-based solder alloys undergoes cyclic strain softening in strain controlled fatigue test [1]. After the strain softening stage the stress would reach a steady state until final failure. Fig. 2 illustrates the stress softening behavior. The initial stress softening is caused by defect annihilation by dynamic recovery and re-crystallization processes. Fig. 3 shows a general stress-strain curve of solder fatigue test. Near the end of fatigue life, the stress response will drop dramatically. Usually 50% of stress loss is used as failure criteria.

Solder interconnects are most often exposed to cyclic thermal load in normal usage. Nevertheless, fatigue experiments done by cyclic thermal load are much more complicated compared to those done by cyclic load under isothermal condition. For cyclic thermal load experiments, it requires CTE mismatch of the sample itself to transform the thermal load into the strain load, and the entire strain event does not occur at the same temperature. For simplicity there are more researchers studying isothermal fatigue behavior of bulk solder instead of thermal-mechanical fatigue of solder interconnects. Fig. 4 shows an example of cast dogbone-shaped solder specimen used for fatigue test, which is suggested by ASTM.

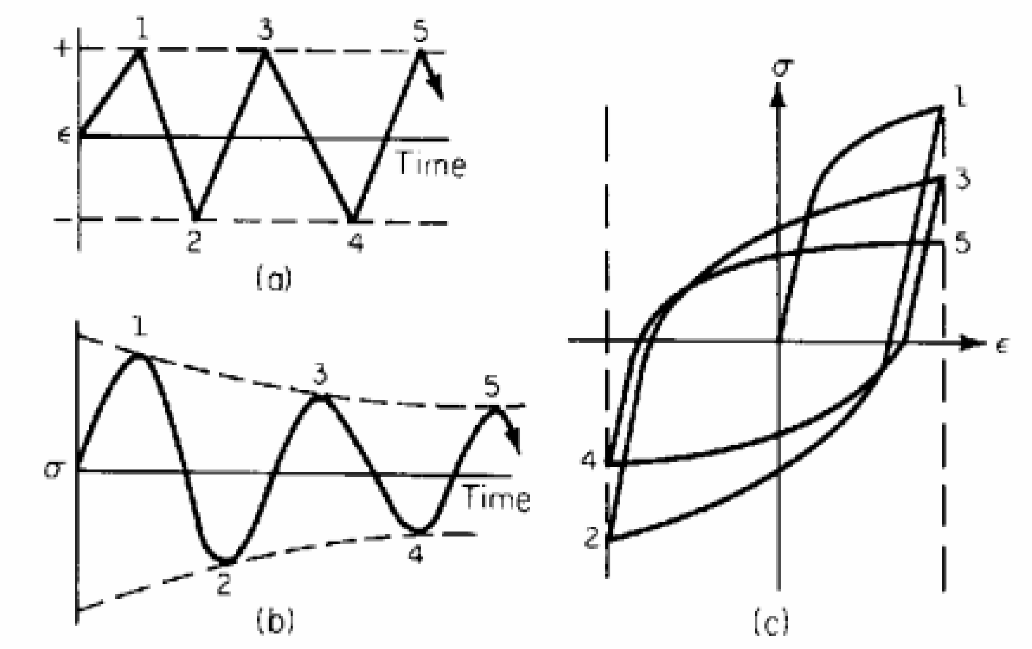

Fig. 2: Stress softening behavior

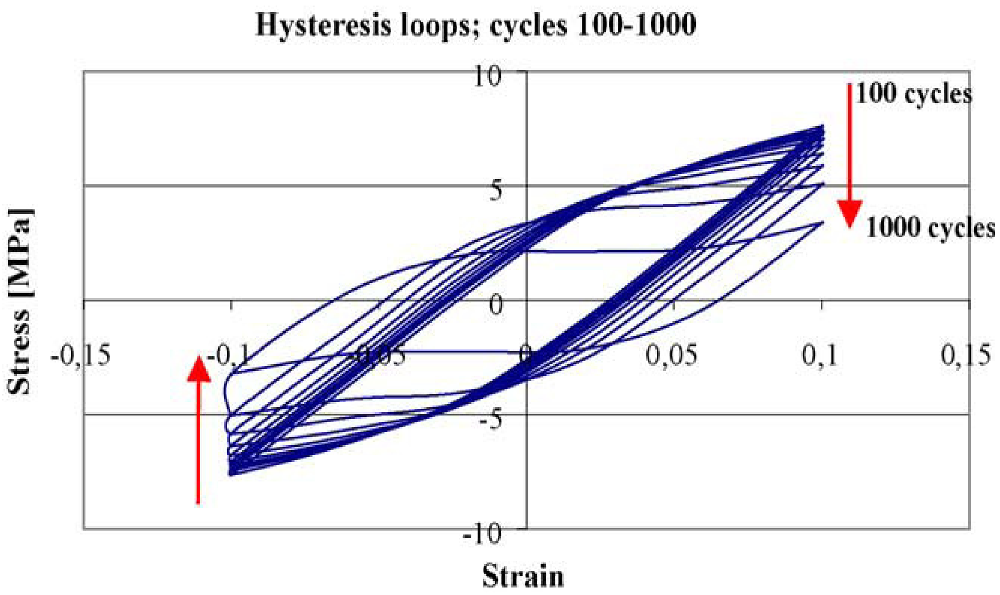

Fig. 3: Stress-strain curve of solder fatigue test

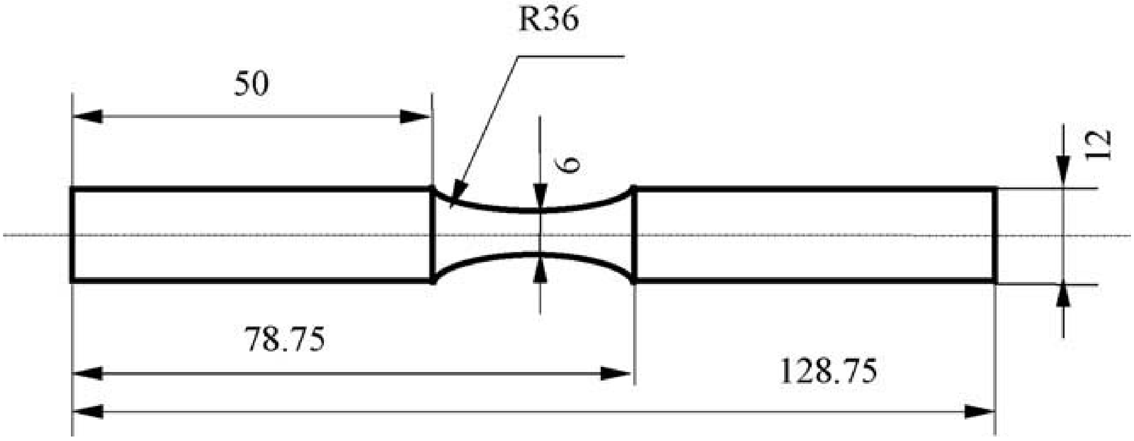

Fig. 4: Dogbone-shaped solder specimen

It has been reported that the low-cycle fatigue behavior of solder alloys can be modeled by Coffin–Manson law:

$$\Delta\varepsilon_p N_f^{\ \alpha} = C \qquad (1)$$

where N_f is the fatigue life, $\Delta\varepsilon_p$ the plastic strain range, α the fatigue ductility exponent and C is the fatigue ductility coefficient. The plastic strain range is the intercept of the stress-strain hysteresis loop with the strain axis. The fatigue ductility coefficient was found to be affected by temperature [2] and frequency of load [3], and both fatigue ductility exponent and coefficient were material dependent.

Frequency effect on fatigue life [3]

Because the high homologous temperature of solder, the time-dependent creep deformation would significantly affect the fatigue life. Fig. 5 shows the stress-strain curve of 96.5Sn-3.5Sn solder under different cyclic loading rates. At 2% total strain, the response stress at 1 Hz is much larger than that at 0.001 Hz, and the plastic strain range, $\Delta\varepsilon_p$, is slightly larger at 0.001 Hz. It shows that lower frequency provides more time for solder to deform plastically. Fig. 6 shows the relationship between stress range and plastic strain range for four different frequencies.

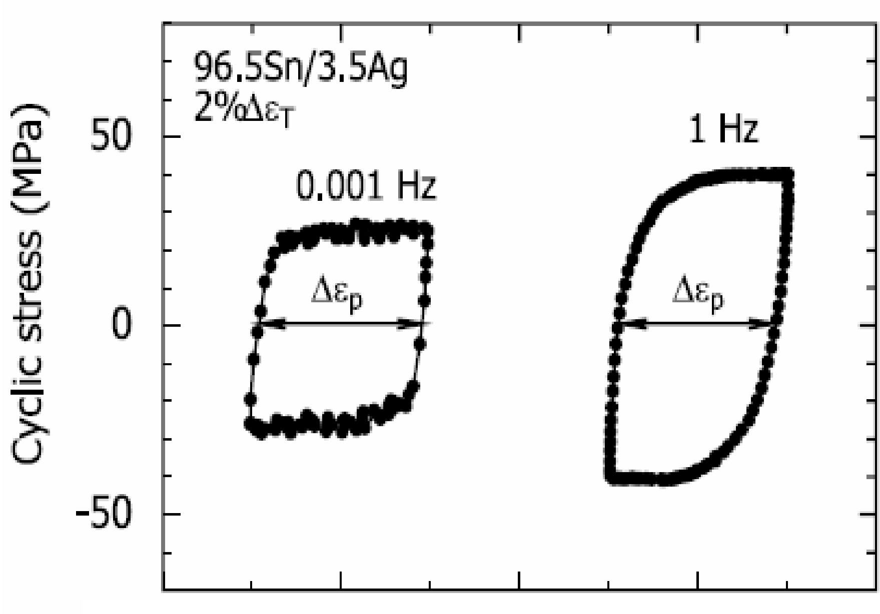

Fig. 5: Stress-strain curve under different frequencies

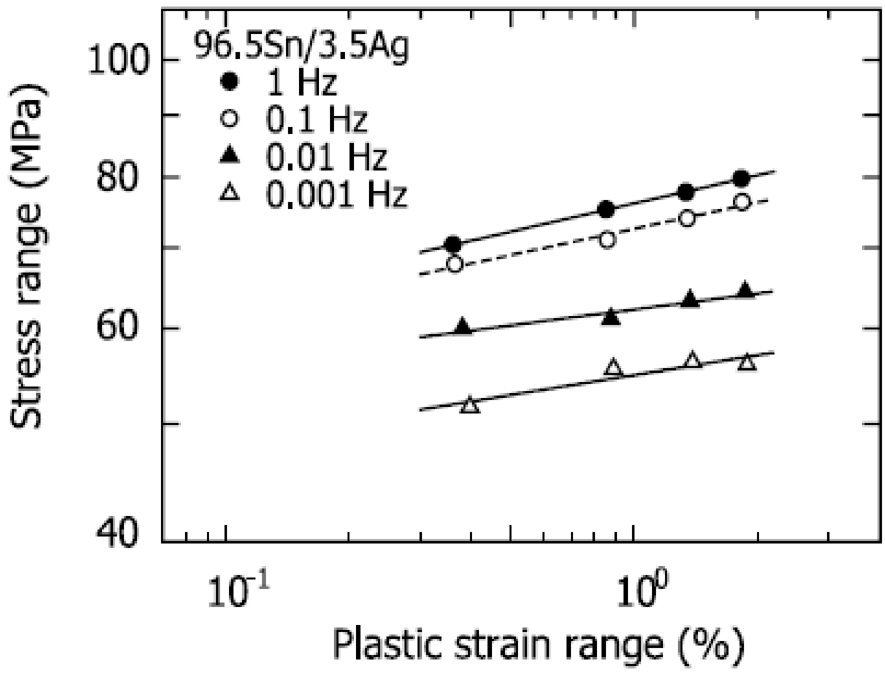

Fig. 6: Stress-strain relationship under different frequencies

The relationship between the plastic strain range and the fatigue life of 96.5Sn-3.5Sn solder for different frequencies is shown in Fig.7. The linear relationship in this log-log plot follows the Coffin-Manson rule. The slope is basically similar for all frequencies, indicating the fatigue ductility exponent is not dependent to frequency, while the fatigue ductility coefficients increase with increasing frequency.

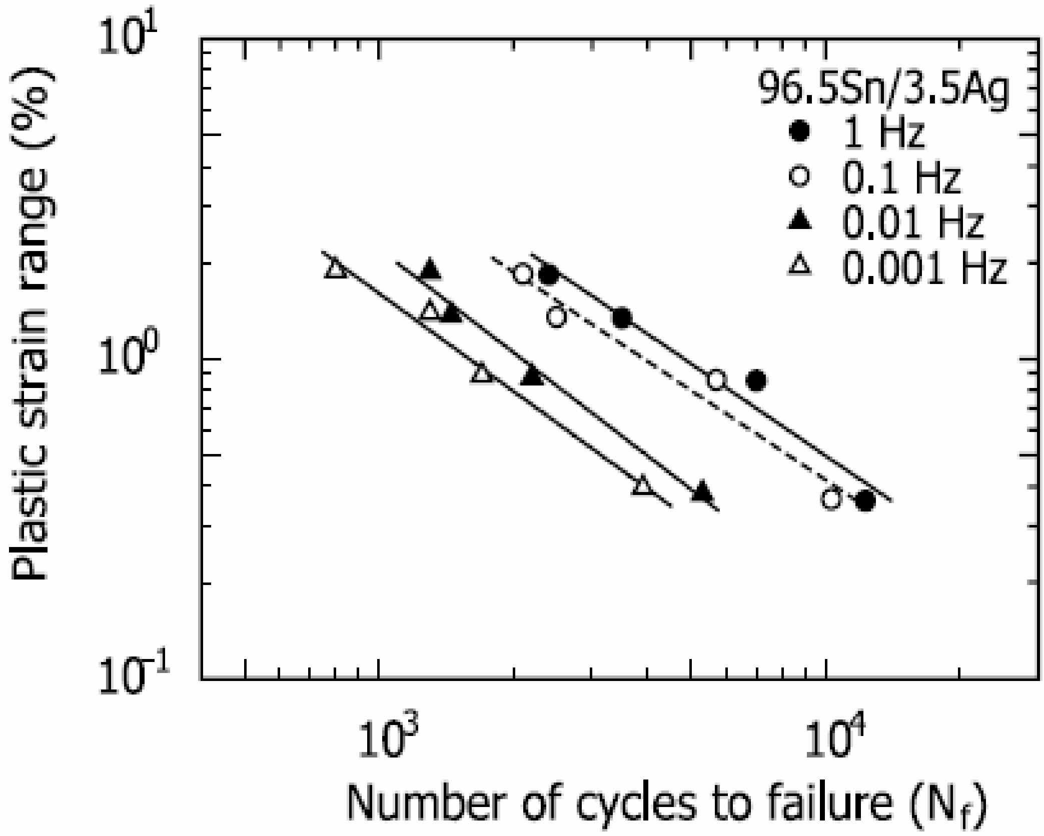

Fig. 7: Plastic strain range and the fatigue life

The relationships between the number of cycles to failure and frequency are shown in Fig. 8. The increase in the number of cycles to failure with increasing frequency can be observed for all total strain ranges. For constant strain range, the Eckel relationship [4], as shown below, can describe the relationship between the number of cycles to failure and frequency:

$$N_f = b\nu^{1-k} \qquad (2)$$

where b is a constant and k is the frequency exponent. These k values ranged from 0.15 to 0.22 for the stain ranges studied. The Coffin-Manson relationship can be therefore modified as shown below:

$$\Delta\varepsilon_p (N_f \nu^{k-1})^{\alpha} = C \qquad (3)$$

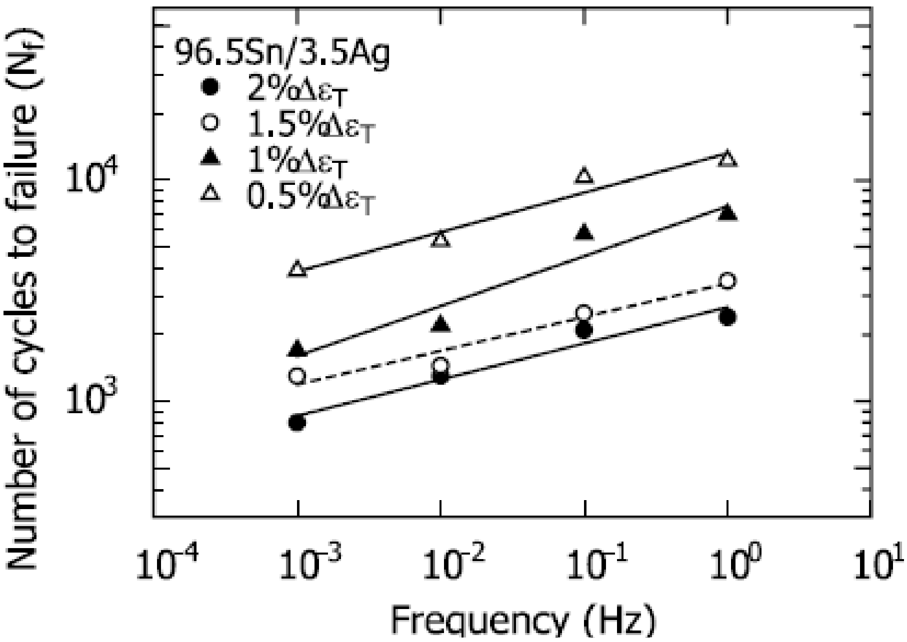

Fig. 8: Frequency and the fatigue life

Fig. 9 shows the relationship between the plastic strain range and frequency-modified fatigue life, $N_f v^{k-1}$. The fatigue results for different frequencies could be fitted to a single curve with exponent α to be 0.89. Therefore, the frequency modified Coffin-Manson relationship can be used for describing the frequency dependence of isothermal low-cycle fatigue behavior of eutectic Sn-Ag solder.

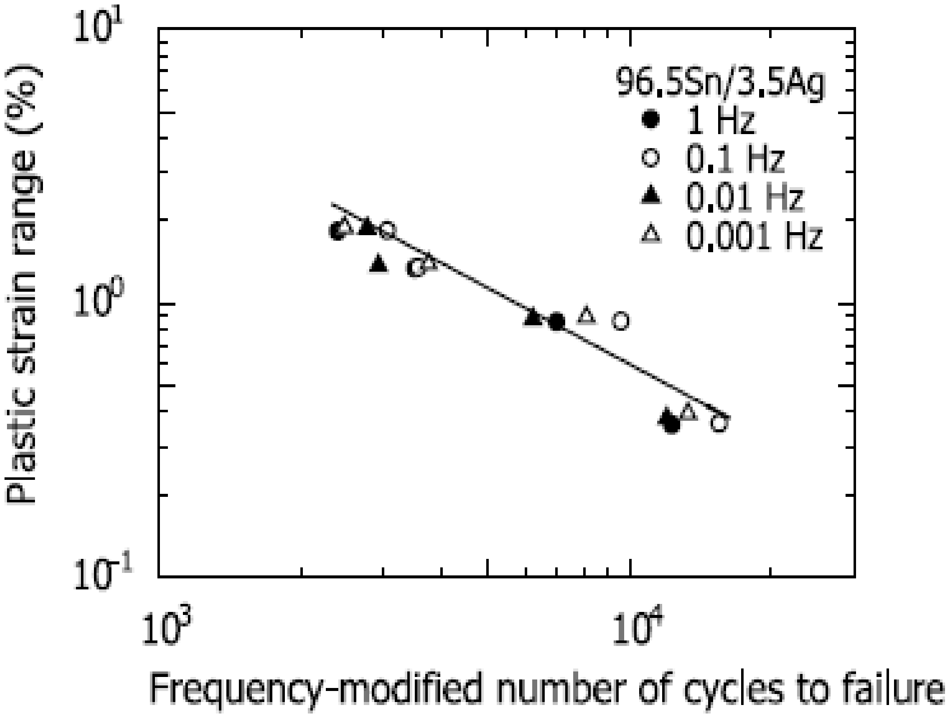

Fig. 9: Frequency modified Coffin-Manson rule

Temperature effect on fatigue life [2]

The creep deformation and stress relaxation of solder materials are also temperature dependent. Increasing temperature is expected to speed up the plastic deformation and shorten the fatigue life. Fig. 10 shows the stress-strain curve of 96.5Sn-3.5Sn solder under different temperatures. At 2% total strain and 0.1 Hz of loading rate, the response stress at 20^oC is much larger than that at 120^oC, and the plastic strain range, $\Delta\varepsilon_p$, is slightly larger at 120^oC. It shows that higher temperature would facilitate plastic deformation/stress relaxation in solder alloys.

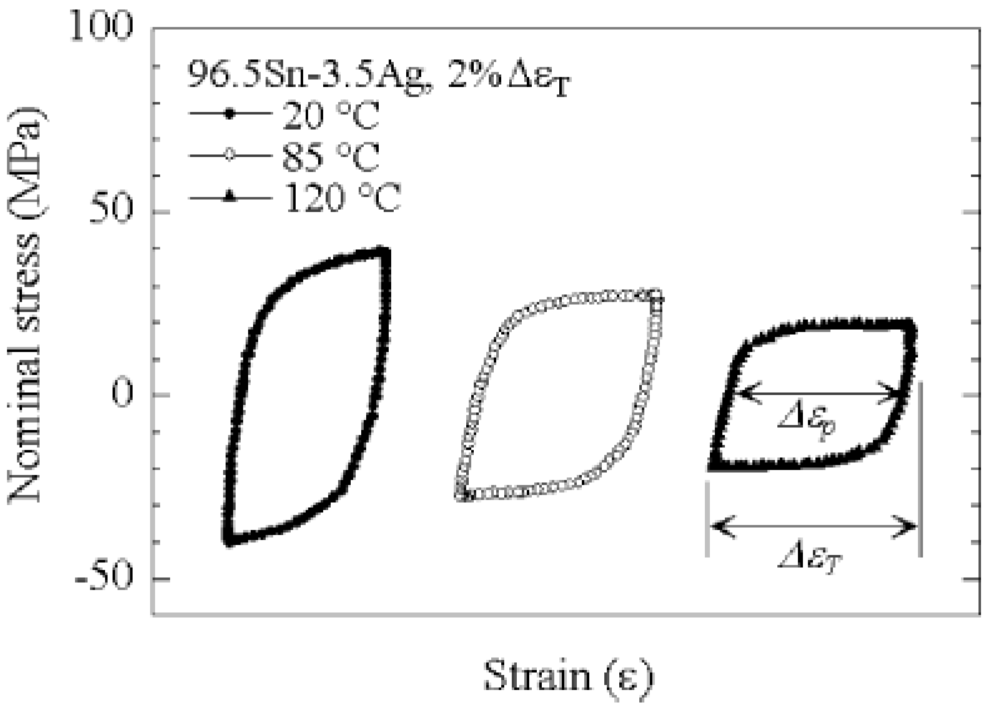

Fig. 10: Stress-strain curve under different temperatures

The reduction in number of cycles to failure with increasing temperature for both 0.5 and 2% total strain ranges ($\Delta\varepsilon_T$) are shown in Fig. 11. The relationship between the plastic strain range and the fatigue life of 96.5Sn-3.5Sn solder for different temperatures is shown in Fig.12. Coffin-Manson rule applies on this relationship, and the fatigue ductility coefficients increase with reducing temperature.

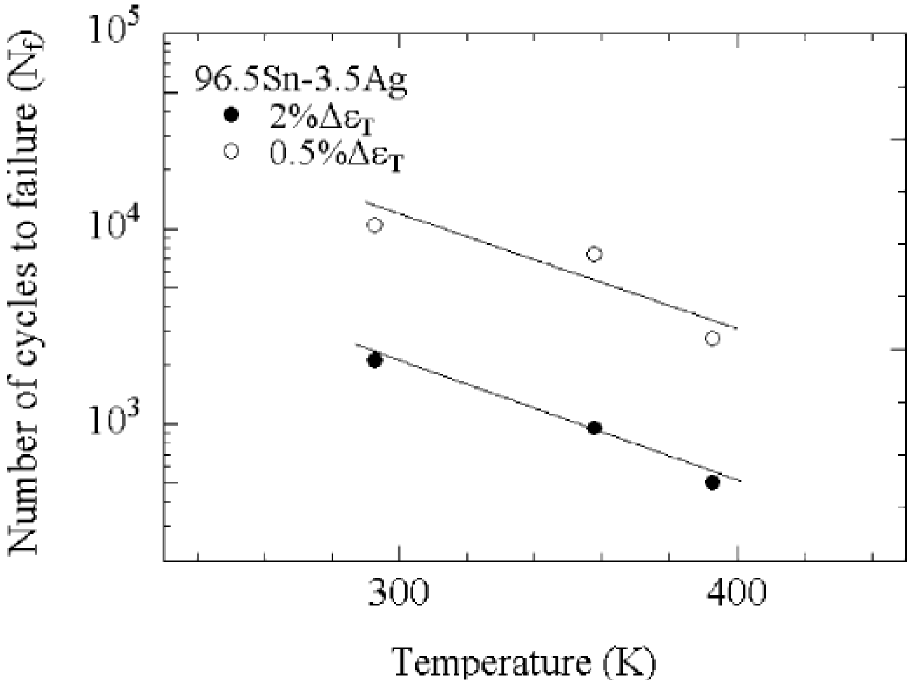

Fig. 11: Fatigue life under different temperatures

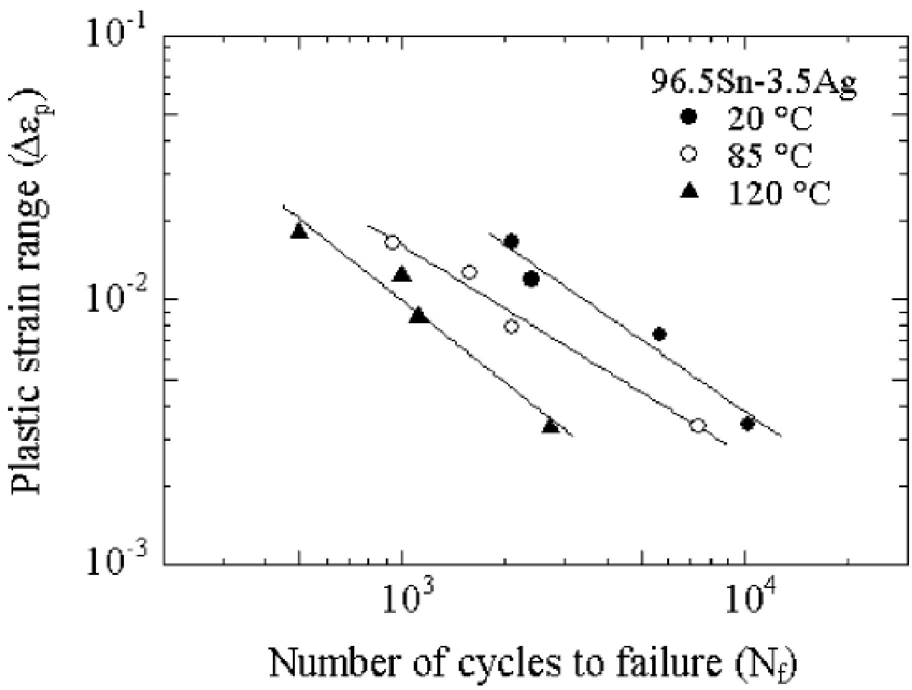

Fig. 12: Fatigue life and plastic strain range

Fatigue life of Sn-Pb and Lead-free solder

Fatigue life of bulk Sn-Pb and Lead-free solder alloys has been studied [5]. Fig. 13 show the isothermal fatigue test results for Sn–37Pb, Sn–3.5Ag and Sn–4.0Ag–0.5Cu solder alloys at different strain range. At all strain level, both lead-free solders exhibit more cycles to failure than eutectic Sn-37Pb solder. The same result has also been confirmed by other researchers [6], as shown in Fig. 14.

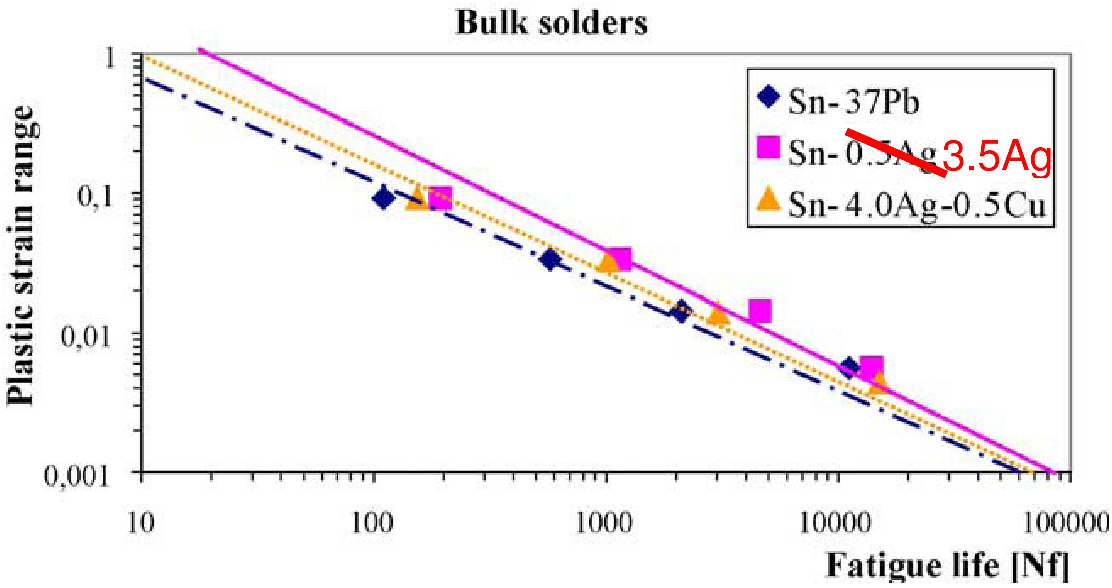

Fig. 13: Sn-Pb and lead-free solder

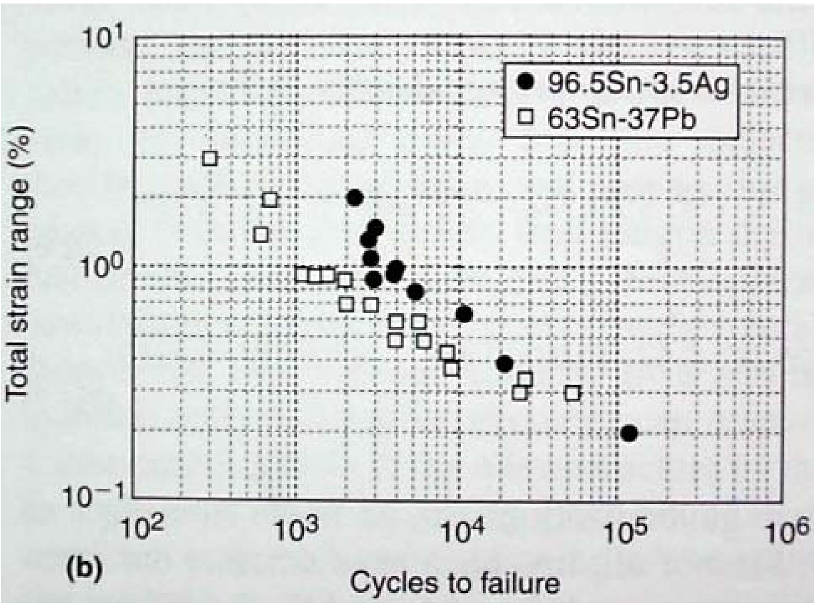

Fig. 14: Sn-Pb and lead-free solder

Summary

Low-cycle fatigue behavior of solder alloys has been briefly reviewed. The relationship between plastic strain range and number of cycles to failure follows the Coffin-Manson equation. Under isothermal test conditions, the frequency as well as temperature has similar effect on the eutectic lead-free solder. Lower frequency and higher temperature enhance the creep deformation and shorten the solder fatigue life. The frequency effect can be further described by a frequency-modified Coffin-Manson equation. The LCF behavior of eutectic Sn-Pb and lead-free solder alloys is compared. Sn-Ag lead-free solder exhibits better fatigue life than traditional Sn-Pb solder.

Reference:

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3. C. Kanchanomai, Y. Miyashita, “Influence of frequency on low cycle fatigue behavior of Pb-free solder 96.5Sn-3.5Ag”, Materials Science and Engineering A345 (2003) 90-983.

4. J. F. Eckel, “The influence of frequency on the repeated bending life of acid lead”, Proceedings ASTM, 51,1951, pp.745-760.

5. C. Anderssona, Z. Laia, “Comparison of isothermal mechanical fatigue properties of lead-free solder joints and bulk solders”, Materials Science and Engineering A 394 (2005) 20–27

6. H. Maroovi et al., *J. Electron. Mater.*, Vol 26, p783-790, 1997.