Low-Cycle Fatigue Prediction Model for Pb-Free Solder 96.5Sn-3.5Ag

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Low-cycle fatigue (LCF) data of Sn-Ag eutectic solder (96.5Sn-3.5Ag) under various temperatures and frequencies has been described using three different prediction models, i.e., Coffin–Manson model, Smith–Watson–Topper (SWT) model, and Morrow energy model. The LCF behavior represented by the present prediction models showed temperature and frequency dependences, i.e., the fatigue ductility coefficient increased with increasing frequency and decreasing temperature. In order to better correlate the LCF data, a flow stress and/or frequency-dependent modifications were introduced to the Coffin–Manson and Morrow energy models. The frequency-modified Coffin–Manson model could not describe the influence of temperature on LCF behavior, while the flow stress–modified frequency-modified Morrow energy model, into which the metallurgical response (flow stress and frequency) was introduced to account for the effect of temperature and frequency on LCF behavior, gave reasonable predictions of LCF data under various temperatures and frequencies.

Key words: Low-cycle fatigue, lead-free solder material, 96.5Sn-3.5Ag, Coffin–Manson model, Smith–Watson–Topper model, Morrow energy model

INTRODUCTION

Surface mounting technology (SMT) is an electronic packaging methodology, where the devices are directly soldered to pads on one or both sides of a printed wiring board. This technology increases the number of devices that can be mounted and decreases the processing cost. However, the ability for absorbing the thermal and mechanical strains is decreased. Thermal strain is induced by the mismatch of thermal expansion coefficient between components during processing and in service. The solder is softer than other components, so most of the cyclic stresses and strains take place in solder. Therefore, fatigue failure, especially thermally induced low-cycle fatigue (LCF) failure, is likely to occur in the solder.

Due to the environmental and health concerns about lead used in conventional solder materials, lead-free solder 96.5Sn-3.5Ag (Sn-Ag eutectic alloy) is one of the candidates for SMT in the next generation. Therefore, understanding LCF behavior and the mechanisms of deformation and fracture in the LCF of the Sn-Ag eutectic solder is important for developing reliable SMT electronic packaging. Kariya and Otsuka[1] reported that the fatigue life of Sn-3.5Ag-Bi in a total axial strain-controlled test was determined by true fracture ductility, and could be represented by a ductility-modified Coffin–Manson relationship. Solomon[2] found that the fatigue life of 96.5Sn/3.5Ag was generally greater than that of 60Sn/40Pb solder in total shear-strain-controlled fatigue tests at 35°C and 150°C. Kanchanomai et al.[3] reported that the LCF behavior in the frequency range of 10^{-3} to 10^{-1} Hz could be described successfully by using the frequency-modified Coffin–Manson model. However, little is known about the influence of temperature on the fatigue behavior of Sn-Ag eutectic solder.

It is the objective of this work to study the effect of temperature and frequency on LCF behavior and

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then to verify various parameters for LCF life predictions for Sn-Ag eutectic solder. These parameters, which aim to predict the fatigue life for a wide range of temperatures and frequencies, are based on the stabilized stress-strain response of LCF data.

MATERIALS AND EXPERIMENTAL PROCEDURES

Sn-Ag eutectic alloy (96.5Sn-3.5Ag) was used in the present study. Ingots of 99.9% Sn and 99.9% Ag were melted in air under temperature of 400°C and cast into a steel mold. The material then was left to cool in air. To reveal the microstructure, the solder was etched with etchant 10 g of $FeCl_3$, 2 mL of HCl, and 100 mL of water. Scanning electron microscope (SEM) micrographs of the Sn-Ag eutectic alloy are shown in Fig. 1. In the Sn-Ag eutectic alloy, β-Sn phase is the major phase, which comprises over 90% by volume. The microstructure can be characterized by primary β-Sn dendrites (dark) and Sn-Ag eutectic structures (light). By means of the linear intercept method, the average size of β-Sn dendrites was determined to be 80 μm. Some needles and particles of Ag_3Sn, approximately 0.3 μm in diameter, can be observed in the Sn-Ag eutectic phase. Monotonic tensile tests were conducted at 20°C up to a small strain (about 0.03% strain) with a strain rate of 10^{-2} s^{-1}. The resultant modulus of elasticity was 50 GPa and the hardness obtained in this study was 11.5–12 HV. The melting temperature of 96.5Sn/3.5Ag is 221°C.[4]

From bulk solder bar materials, fatigue specimens were machined on a numerical-controlled lathe machine. The configuration of the specimen, which was designed according to the ASTM recommendation,[5] has a diameter of 12 mm at the two ends, a center diameter of 6 mm, and a gage length of 8 mm. In order to remove lathe machining marks as well as any possible residual stresses from the specimen surface, the specimen gage lengths were electrolytically polished at room temperature at 8 V DC for 3 minutes in a solution of ethanol (80%) 800 mL, distilled water 140 mL, and perchloric acid (60%) 60 mL. The specimens were then left to fully age at room temperature for more than 30 days. Since the homologous temperature at room temperature is above 0.5 for the solder studied here, this aging treatment also stabilized the microstructure.[6] The total strain controlled fatigue tests were performed by using a servo-hydraulic fatigue machine under 55% relative humidity. A triangular waveform with a strain ratio R = –1 and total strain range 0.5–2% were used for the fatigue tests under various temperatures (20–120°C). In order to avoid the local deformation and stress concentration at contact point induced by the conventional displacement-measuring device, a digital image measurement system[7] was used in the present strain-controlled fatigue tests. The induction-type heaters, above and below the gage of the specimen, were used for high-temperature tests. Before high-temperature fatigue tests, the temperature variation during fatigue tests was confirmed to be within ±1°C. The cycle loading was started from the tensile side. The fatigue failure was defined as 25% reduction of maximum tensile load.[8] Three types of prediction models were verified by using the present results and the LCF data for various frequencies, published previously.[3,9] The predictive capability was discussed.

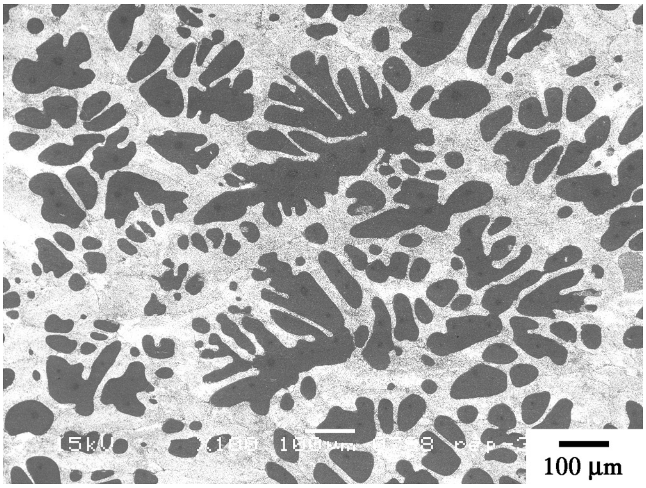

Fig. 1. SEM micrographs of Sn-Ag eutectic alloy (96.5Sn-3.5Ag).

RESULTS AND DISCUSSION

Coffin–Manson Model (Plastic Strain Range–Life Model)

The hysteresis loops, as shown in Fig. 2, were plotted and used for determining the plastic strain range ($\Delta\varepsilon_p$) by subtracting the elastic strain range ($\Delta\varepsilon_e$) from the total strain range ($\Delta\varepsilon_T$). This plastic strain range is equivalent to the width of the hysteresis loop and was constant during the fatigue test. For the same strain range, the plastic strain range increases with increasing temperature, while the stress range ($\Delta\sigma$) decreases with increasing temperature.

The relationship between the plastic strain range and the number of cycles to failure follows the Coffin–Manson equation:[10,11]

$$\Delta\varepsilon_p N_f^{\alpha} = \theta \tag{1}$$

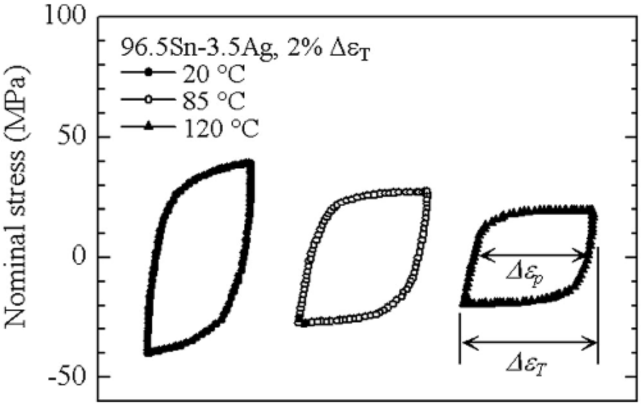

Fig. 2. Hysteresis loops of 96.5Sn-3.5Ag tested at 2% $\Delta\varepsilon_T$ under various temperatures.

where $\Delta\varepsilon_p$ is the plastic strain range, N_f is the fatigue life, α is the fatigue ductility exponent, and θ is the fatigue ductility coefficient. The relationships between the plastic strain range and the fatigue life for 96.5Sn-3.5Ag solder for different frequencies and temperatures are shown in Fig. 3a and b. The fatigue ductility exponents for different frequencies are similar, while the fatigue ductility coefficients increase with increasing frequency and decreasing temperature.

The influence of frequency on fatigue life can be described in terms of a frequency-modified Coffin–Manson relationship:

$$\left(N_f \nu^{k-1}\right)^{\alpha} \Delta\varepsilon_p = \theta \qquad (2)$$

where ν and k are the frequency and frequency exponent, respectively, evaluated from the fatigue life–frequency relationship.[3] The relationship between the plastic strain range and frequency-modified fatigue life ($N_f\nu^{k-1}$) is shown in Fig. 3c and d. The results for different frequencies can be fit to a single curve, while those under different temperatures indicate temperature dependence. Therefore, only isothermal LCF behavior for Sn-Ag eutectic solder with frequency effects can be described by the frequency-modified Coffin–Manson relationship.

Smith–Watson–Topper Model

The Smith–Watson–Topper (SWT) model[12] assumes that the fatigue life for any situation of mean stress depends on the product $\sigma_{max}\Delta\varepsilon_T$:

$$(\sigma_{\max}\Delta\varepsilon_T) N_f^n = d \qquad (3)$$

where σ_{max} is the maximum stress, $\Delta\varepsilon_T$ is the total strain range, n is the fatigue ductility exponent, and d is the fatigue ductility coefficient. The relationships between the product of maximum stress and the total strain range (SWT parameter) and the fatigue life under various temperatures and frequencies are shown in Fig. 4a and b, respectively. It is seen that the fatigue ductility exponents for different temperatures and frequencies are basically similar, while the fatigue ductility coefficient increases with decreasing temperature and increasing frequency. Therefore, the SWT parameter cannot characterize the effects of temperature and frequency on LCF behavior of Sn-Ag eutectic solder.

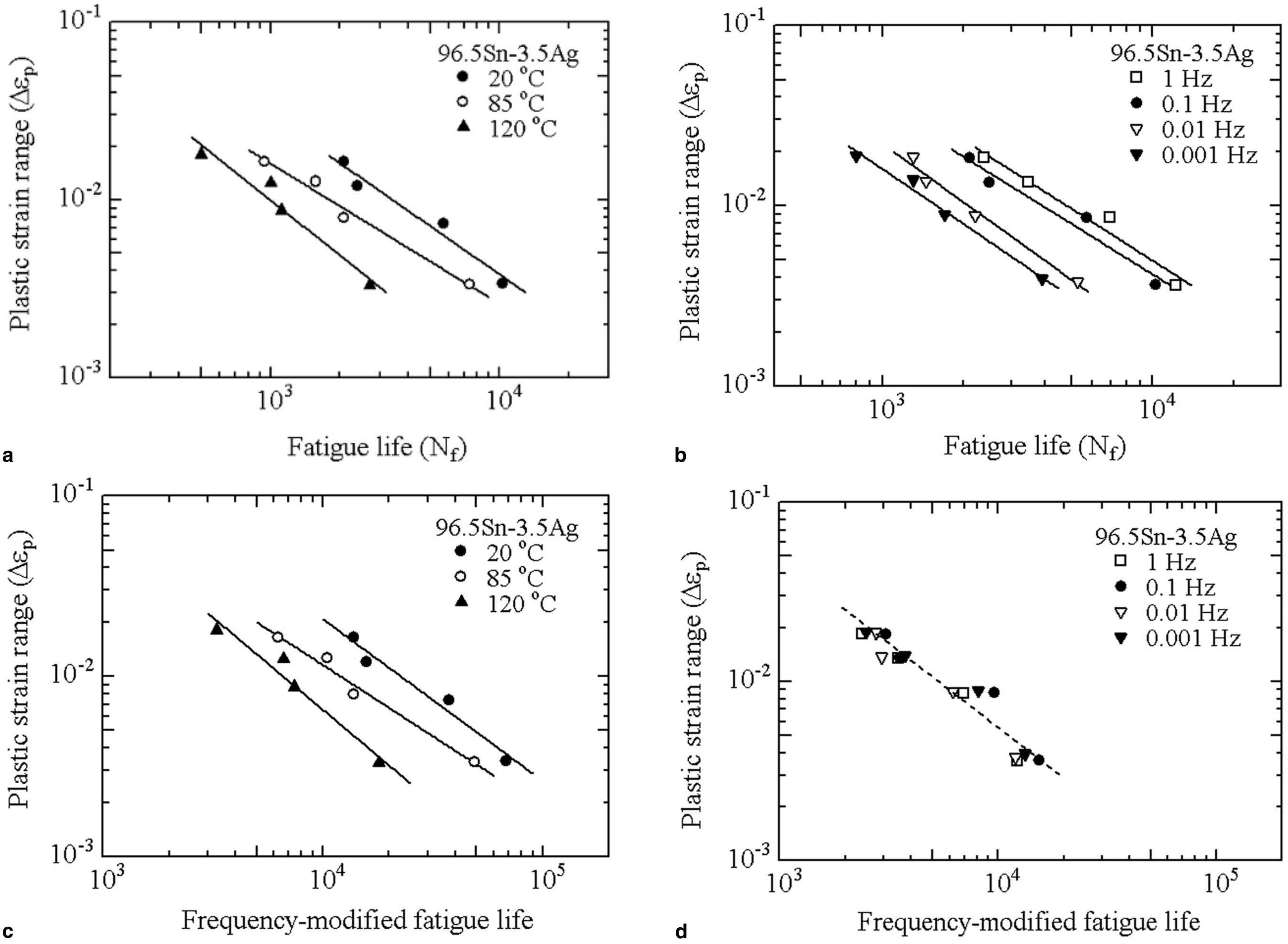

Fig. 3. Relationships between (a) and (b) plastic strain range and fatigue life under various temperatures and frequencies, and (c) and (d) plastic strain range and frequency-modified fatigue life under various temperatures and frequencies.

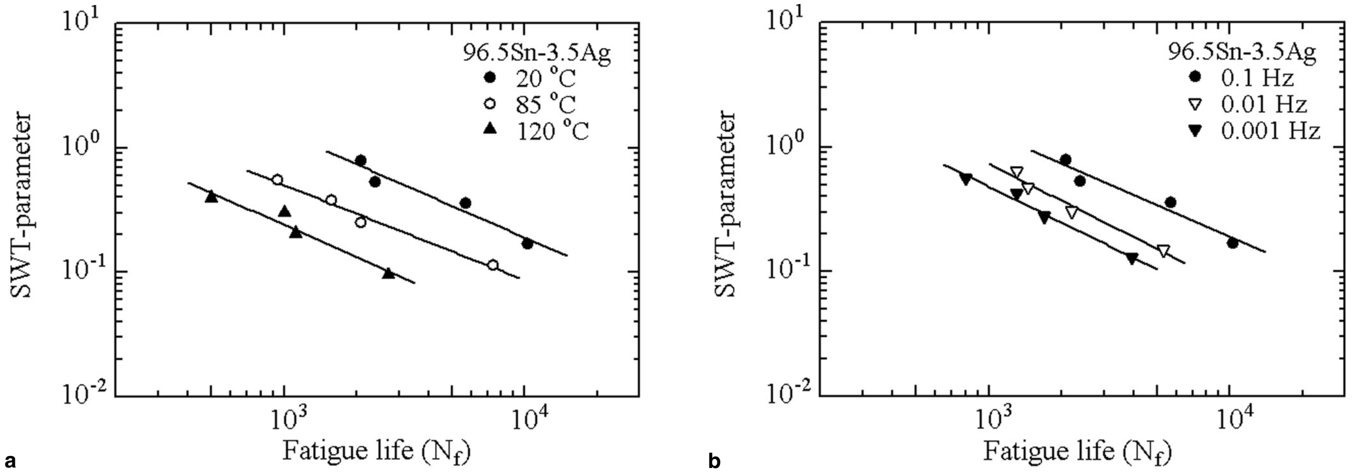

Fig. 4. Relationships between SWT parameter and fatigue life under (a) various temperatures and (b) various frequencies.

Morrow Energy Model (Plastic Strain Energy Density–Life Model)

The plastic strain energy density can be physically interpreted as distortion energy associated with the change in shape of a volume element and related to failure, particularly under conditions of ductile behavior. It can be evaluated numerically as the inner area (W_p) of the saturated stress-strain hysteresis loop for the uniaxial fatigue tests. At a given total strain range, the area within the hysteresis loop decreases with decreasing temperature (Fig. 2) and increasing frequency.[3] The fatigue life can be described in terms of the plastic strain energy density:[13]

$$N_f^m W_p = C \tag{4}$$

where W_p is the plastic strain energy density, N_f is the fatigue life, and m and C are the fatigue exponent and coefficient, respectively. The relationships between plastic strain energy density and fatigue life under various temperatures and frequencies are shown in Fig. 5a and b, respectively. The fatigue exponents for different temperatures and frequencies are similar, while the fatigue coefficient increases with decreasing temperature and increasing frequency. It is clear that plastic strain energy density cannot characterize the effects of temperature and frequency on LCF behavior of Sn-Ag eutectic solder.

In order to describe the effects of frequency, a frequency-modified Morrow energy model was examined. The model predicts fatigue life (N_f) in terms of the plastic strain energy density (W_p):

$$\left(N_f \nu^{k-1}\right)^m W_p = C \tag{5}$$

where ν and k are the frequency and frequency exponent evaluated from the fatigue life–frequency relationship,[3] respectively. The relationship between plastic strain energy density (W_p) and frequency-modified fatigue life ($N_f \nu^{k-1}$) is shown in Fig. 6a. The results for different temperatures and frequencies locate within a narrow band, where no obvious dependency of temperature and frequency was observed.

Shi et al.[14] proposed a flow stress-modified frequency-modified Morrow energy model, in which both temperature-dependent and frequency-dependent material parameters were introduced into the plastic stain energy density model:

$$\left(N_f \nu^{k-1}\right)^m \frac{W_p}{2\sigma_f} = C \tag{6}$$

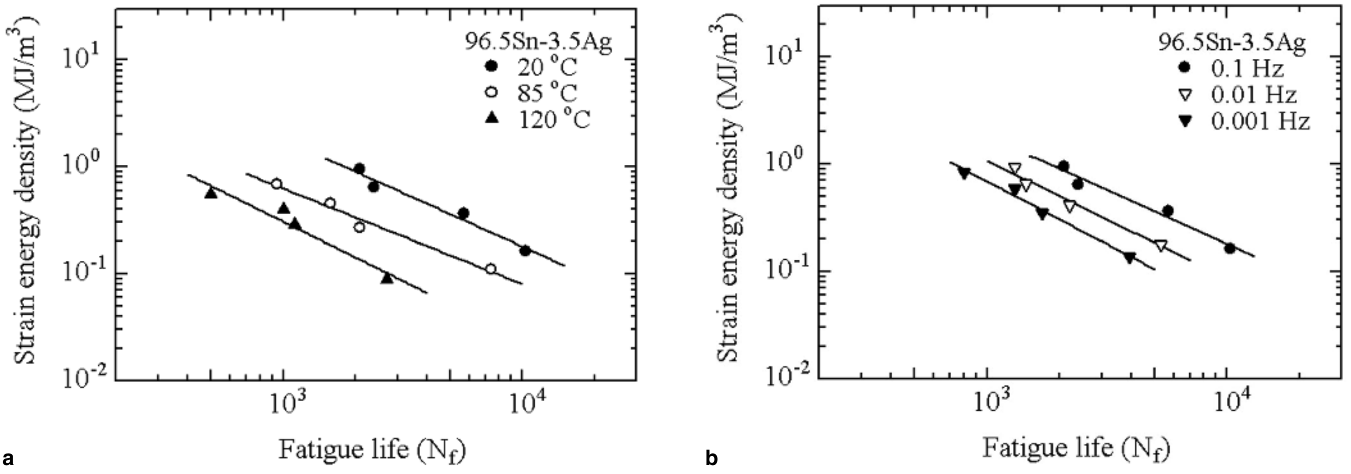

Fig. 5. Relationships between strain energy density and fatigue life under (a) various temperatures and (b) various frequencies.

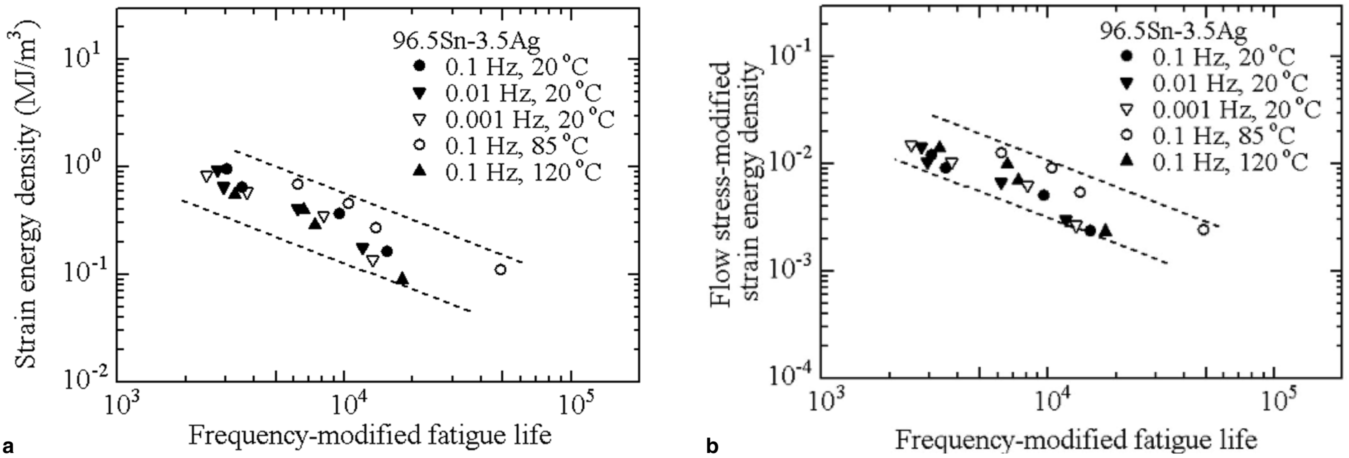

Fig. 6. Relationships between (a) strain energy density and frequency-modified fatigue life under various temperatures and frequencies, and (b) flow stress–modified strain energy density and frequency-modified fatigue life under various temperatures and frequencies.

where σ_f is the flow stress, i.e., the averaged value between the yield point and the highest stress of hysteresis loop, and m and C are constants. The flow stress is highly dependent on temperature and strain rate,[15] so this prediction model includes the flow stress to reflect the effect of temperature and frequency on LCF behavior of a visco-plastic material, such as solder. The relationship between the flow stress–modified plastic strain energy ($W_p/2\sigma_f$) and frequency-modified fatigue life ($N_f\nu^{k-1}$) is shown in Fig. 6b. The LCF results for different temperatures and frequencies are located within a narrow band with less scatter compared to the frequency-modified Morrow energy model shown in Fig. 6a. It is clear that the flow stress–modified frequency-modified Morrow energy model, into which the metallurgical response (flow stress and frequency) was introduced to account for the effect of temperature and frequency on LCF behavior, gives a better prediction for the fatigue life (N_f) of Sn-Ag eutectic solder in the temperature range of 20–120°C and frequency range of 10^{-3} to -10^{-1} Hz than other models studied here.

CONCLUSIONS

The LCF data of Sn-Ag eutectic solder (96.5Sn-3.5Ag) under various temperatures (20°C, 85°C, and 120°C) and various frequencies (10^{-3} Hz, 10^{-2} Hz, and 10^{-1} Hz) have been described using three different prediction models. The main conclusions obtained are as follows.

- The LCF behavior in the temperature range of 20–120°C and frequency range of 10^{-3} to -10^{-1} Hz followed the Coffin–Manson equation, SWT equation, and Morrow energy equation. The fatigue ductility exponents were similar. However, the fatigue ductility coefficient was dependent on temperature and frequency, i.e., increased with increasing frequency and decreasing temperature.
- The frequency-modified Coffin–Manson model successfully described the LCF behavior under various frequencies; however, it could not describe the influence of temperature. On the other hand, the SWT model could not describe both effects of temperature and frequency on fatigue life.
- Under the condition studied, reasonable predictions of LCF data under various temperatures and frequencies can be achieved with the flow stress–modified frequency-modified Morrow energy model. It can be concluded that this model, into which the metallurgical response (flow stress and frequency) was introduced to account for the effect of temperature and frequency on LCF behavior, is the most promising LCF prediction model for Sn-Ag eutectic solder.

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