ORIGINAL RESEARCH ARTICLE

Low-Cycle Fatigue Behavior of Sn-0.3Ag-0.7Cu-0.5CeO$_2$ Composite Solder Alloy

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Abstract

The low-cycle fatigue behavior of Sn-0.3Ag-0.7Cu-0.5CeO$_2$ composite solder alloy was studied. The results show that the fatigue life exponent and material ductility coefficient of the composite solder alloy are dependent on both temperature and frequency. A modified Coffin-Manson model considering the influence of frequency and temperature was put forward, and the relationship between temperature and the frequency exponent, low-cycle fatigue life exponent, and material ductility coefficient was established. The modified model has a good elimination effect on the influence of different frequencies and temperatures on the low-cycle fatigue life of the composite solder alloy.

Introduction

Solders are commonly used in microelectronic products, acting as electronic link and mechanical connect between the printed circuit board and components. During service load conditions, solder joints are subjected to thermal stress due to thermal mismatch between the components and printed circuit board. If alternating high and low temperatures occur inside the electronic products, the solder joints will be subjected to periodic thermal stress. Under the action of periodic thermal stress and strain, permanent local cumulative damage will gradually occur in one or several parts of interconnecting solder joints. After a certain number of cycles, fatigue failure is likely to occur in the solder joints.[1] Hence, the service life of microelectronic products is usually limited by the low-cycle fatigue behavior of solder joints.

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In recent years, the low-silver-content tin-silver-copper (SAC) solder alloys are widely used in electronic products due to their excellent solderability and mechanical properties.[2] Hence, understanding the low-cycle fatigue behavior of deformation of low-silver-content SAC solder joints is of great significance to improve the reliability of electronic packaging. In the published reports, the low-cycle fatigue behavior of SAC solder alloys with high silver content was proposed.[1,3–5] Although the effects of temperature and frequency on low-cycle fatigue behavior in high-silver-content lead-free solder have been studied, the temperature dependence of the fatigue exponent and ductility coefficient, the mathematical relations between the fatigue exponent and temperature, and the ductility coefficient and temperature in low-silver-content composite lead-free solder have not been not reported.

Our previous work reveals that adding 0.5wt.% CeO$_2$ nanoparticles into Sn-0.3Ag-0.7Cu low-silver-content solder can effectively refine the microstructure and improve the shear properties of the solder joints.[2,6] Therefore, in this work, the composite solder Sn-0.3Ag-0.7Cu-0.5CeO$_2$ with optimized CeO$_2$ nanoparticle addition was chosen to be used for the research of low-cycle fatigue behavior of the solder joints because composite solders have been identified as the potential materials that may provide higher strength and reliability.[7–16] In order to better understand the effects of temperature and frequency on the low-cycle fatigue lifetime and failure mechanisms, low-cycle fatigue testing and analysis of

Fig. 1 Schematic illustration of shear-lap solder joint specimen.

Fig. 2 Reflow temperature profile.

Fig. 3 Relationship between stress amplitude and number of cycles at 1% total strain, 25°C and 0.01 Hz.
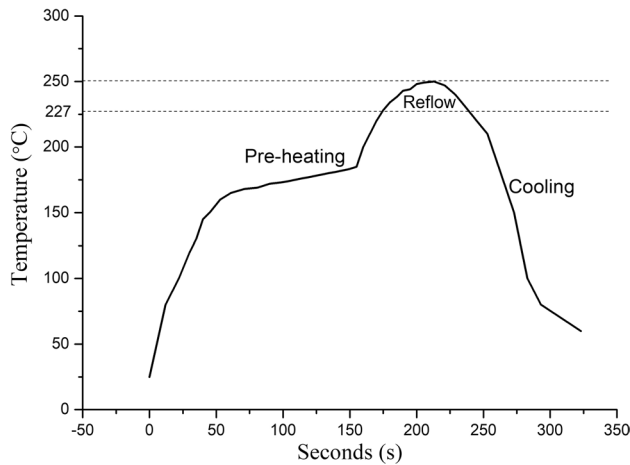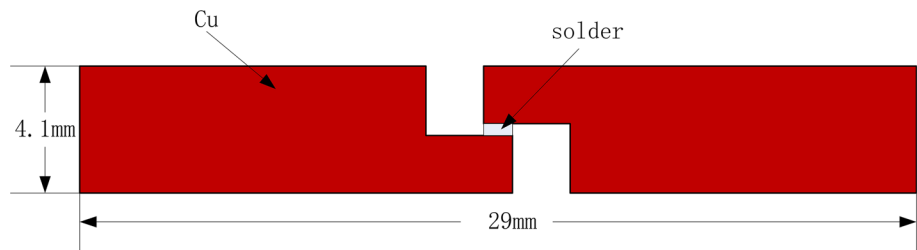
Sn-0.3Ag-0.7Cu-0.5CeO$_2$ solder joints were carried out for a range of test temperatures and frequencies, and a modified Coffin-Manson model is proposed.

Experimental Procedures

The composite solder alloy used in this work is Sn-0.3 wt.%Ag-0.7 wt.%Cu-0.5 wt.%CeO$_2$. In this study, in order to study the low-cycle fatigue condition experienced by the actual solder joint, lap joint dimensions of 1.0 mm × 1.0 mm × 0.1 mm were chosen based on previous works,[3,17,18] and the shear-lap solder joint specimen was designed as shown in Fig. 1. Pure copper (> 99.5% purity) was selected as the substrate. The Cu substrates were ground and polished with diamond paste until a mirror surface was obtained. The composite solder paste of Sn-0.3Ag-0.7Cu-0.5CeO$_2$ with dimensions of 1.0 mm × 1.0 mm × 0.1 mm was then applied between the two Cu plates. After that, they were all placed in an aluminum fixture, which was then passed through a reflow oven. The reflow temperature profile is presented in Fig. 2. The fixture was finally taken out of the oven and cooled in air. In order to relieve the residual stress before testing, samples were placed under an air atmosphere for 2 weeks.
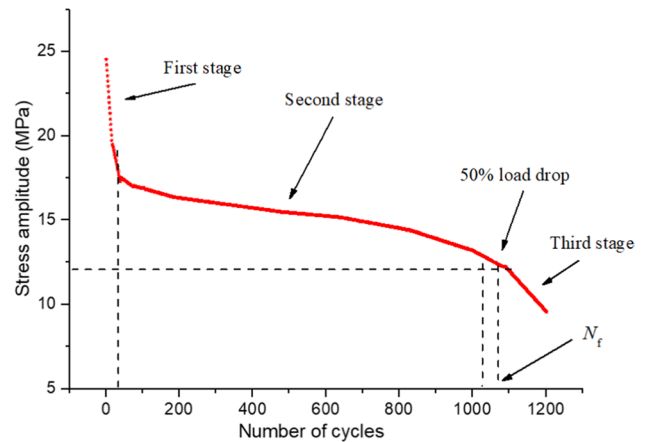
Fatigue tests were conducted using a micro-force fatigue testing machine. The tests were carried out under symmetrical uniaxial tension–compression loading with total strain control. The fatigue testing was carried out at three different temperatures (25°C, 75°C and 125°C) and at three different frequencies (0.1 Hz, 0.01 Hz and 0.001 Hz) with total strain set at three different values (1%, 2% and 5%). Each set of condition was conducted at least three times and the results were averaged. The low-cycle fatigue failure criterion was defined as 50% reduction of maximum tensile load, as recommended by the ASTM [1].

Results and Discussion

Cyclic Stress–Strain Behavior

The representative relationship between the stress amplitude and number of cycles for Sn-0.3Ag-0.7Cu-0.5CeO$_2$ solder at 1% total strain, 25°C and 0.01 Hz is shown in Fig. 3. Here it can be seen that stress amplitude can be clearly divided into three stages. In the first stage, stress amplitude decreases rapidly, which may due to the crack initiation and aggregation. At the second stage, the stress amplitude decreases slowly and steadily with increasing cycles. This indicates that there is a stable fatigue crack propagation process in

the second stage. After entering the third stage, the stress amplitude decreases rapidly, resulting in the ultimate ductile fracture of the specimen.[19–23]

A low-cycle fatigue process of the solder alloy usually includes plastic strain and elastic strain.[24,25] The ranges of plastic strain and elastic strain can be obtained through the stress–strain hysteresis curve. Hence, the stress–strain hysteresis curve of the composite solder alloy is plotted. Figure 4 shows the typical stress–strain hysteresis curve of the composite solder alloy tested at 125°C, 5% total strain and 0.01 Hz. The result of the hysteresis curve is similar to that reported by other researchers.[18] There is slight asymmetry in the hysteresis curve, which is caused by the material hardening under tension and the material softening under compression loading.[25]

On the basis of plastic flow law,[26] the relationship between the applied stress range $\Delta\sigma$ and plastic strain range $\Delta\varepsilon_{plastic}$ can be described as follows:

$$\Delta\sigma = A\Delta\varepsilon_{plastic}^{\eta}\lambda_{plastic}^{\omega} \tag{1}$$

where $\lambda_{plastic}$ is frequency, A, η and ω are constants.

Equation 1 can be linearized by taking natural logarithms of both sides as:

$$\ln\Delta\sigma = \ln A + \eta\ln\Delta\varepsilon_{plastic} + \omega\ln\lambda_{plastic} \tag{2}$$

For a given frequency, the cyclic strain-hardening exponent η can be determined from the slope of the plot by linear regression method. In order to investigate the strain hardening of composite solder alloy during low-cycle fatigue process, the relationship between $\ln\Delta\sigma$ and $\ln\Delta\varepsilon_{plastic}$ at 10^{-2} Hz, 5% total strain for different temperatures are plotted in Fig. 5. Here it can be seen that the strain-hardening exponent η at different temperatures is
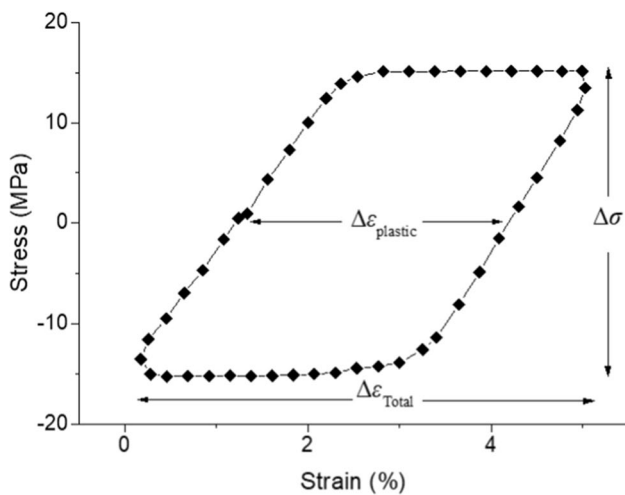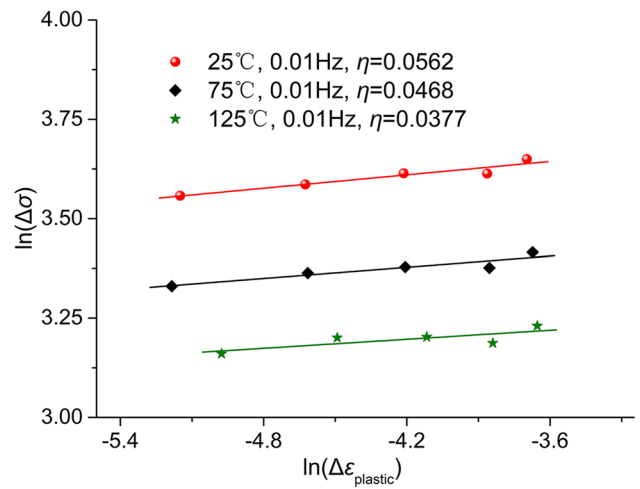

Fig. 5 Relationship between $\ln\Delta\sigma$ and $\ln\Delta\varepsilon_{plastic}$ at 10^{-2} Hz, 5% total strain for different temperatures.

between 0.0377 and 0.0562. With the increase in temperature, the strain-hardening exponent decreases, which means that at high temperature, the material hardening effect of the composite solder alloy is weakened and the applied stress decreases. This phenomenon is consistent with our previous research conclusion[2]. At high temperature, the weakening of the pinning effect of the second phase particles will cause an increase in dislocation activity and a faster decline in applied stress[2]. According to the definition of low-cycle fatigue life, the faster decline of applied stress means shorter low-cycle fatigue life. Therefore, it is necessary and meaningful to improve the strain-hardening exponent to obtain a longer fatigue life.

Since the study of cyclic strain-hardening exponent of solder alloy is scarce, the data of cyclic strain-hardening exponent of high silver solder Sn-3.5Ag which is close to the experimental conditions in this work are selected for comparison. According to the study of Kanchanomai et al.,[26] the cyclic strain-hardening exponent of Sn-3.5Ag is 0.08 at 20°C and 0.02 at 120°C. The value of the cyclic strain-hardening exponent of Sn-3.5Ag at low temperature is higher than that at high temperature, which may indicate that Sn-3.5Ag has better material hardening ability at low temperature. Meanwhile, the cyclic strain-hardening exponent of Sn-3.5Ag is higher than that of Sn-0.3Ag-0.7Cu-0.5CeO₂ at low temperature, indicating that the material hardening of Sn-0.3Ag-0.7Cu-0.5CeO₂ composite solder alloy after CeO₂ doping is only close to and still does not reach the level of high--silver-content solder alloy. However, the decrease in the cyclic strain-hardening exponent of Sn-3.5Ag at high temperature is more obvious than that of Sn-0.3Ag-0.7Cu-0.5CeO₂, indicating that the material hardening of Sn-3.5Ag solder alloy is significantly weakened at high temperature, which may be

Fig. 4 Stress–strain hysteresis loop of composite solder alloy at 125°C, 5% total strain and 0.01 Hz.

due to the weakening of the pinning effect of the second phase particles.

The cyclic strain-hardening exponent of Sn-0.3Ag-0.7Cu-0.5CeO$_2$ solder alloy at high temperature is greater than that of Sn-3.5Ag, which may indicate that the material hardening ability of Sn-0.3Ag-0.7Cu-0.5CeO$_2$ solder alloy at high temperature is better than that of Sn-3.5Ag. The reason for this phenomenon may be that doping CeO$_2$ nanoparticles inhibits the growth of intermetallic compound (IMC) grains in the composite solder alloy, so the pinning effect in the composite solder alloy decreases less at high temperature [2]. However, due to the high silver content, the rapid growth of IMC grains in Sn-3.5Ag solder alloy at high temperature makes the pinning effect significantly weakened, resulting in a significant reduction of the cyclic strain-hardening exponent of Sn-3.5Ag solder alloy. Therefore, it can be concluded that the temperature sensitivity of the composite solder alloy can be reduced by doping CeO$_2$ nanoparticles especially at high temperature, and the temperature sensitivity of composite solder alloy may be better than that of high-silver-content Sn-3.5Ag solder alloy.

The different values of cyclic strain-hardening exponent η at different temperature reveal that temperature has a great influence on the low-cycle fatigue life of the composite solder alloy. Therefore, in the next section, the influence mechanism of temperature on the low-cycle fatigue behavior of the composite solder alloy is discussed.

Effect of Temperature on Low-Cycle Fatigue Behavior

The low-cycle fatigue life of the Sn-0.3Ag-0.7Cu-0.5CeO$_2$ composite solder alloy under different test conditions is listed in Table I. The plastic strain range of the composite solder alloy under different test conditions is presented in Table II.

Table I Fatigue life of composite solder alloy under different test conditions

Temperature frequency		Fatigue life (cycles)		
		$\Delta\varepsilon_{Total} = 1\%$	$\Delta\varepsilon_{Total} = 2\%$	$\Delta\varepsilon_{Total} = 5\%$
25°C	10^{-1} Hz	1203	679	106
	10^{-2} Hz	1091	531	89
	10^{-3} Hz	307	115	13
75°C	10^{-1} Hz	934	421	47
	10^{-2} Hz	708	356	36
	10^{-3} Hz	77	41	9
125°C	10^{-1} Hz	276	98	34
	10^{-2} Hz	178	75	24
	10^{-3} Hz	31	13	3

Table II Plastic strain range of composite solder alloy under different test conditions

Temperature	Total strain range	Plastic strain range		
		10^{-1} Hz	10^{-2} Hz	10^{-3} Hz
25°C	$\Delta\varepsilon_{Total} = 1\%$	0.00198	0.00201	0.00205
	$\Delta\varepsilon_{Total} = 2\%$	0.00531	0.00614	0.00803
	$\Delta\varepsilon_{Total} = 5\%$	0.01704	0.01914	0.02215
75°C	$\Delta\varepsilon_{Total} = 1\%$	0.00231	0.00275	0.00315
	$\Delta\varepsilon_{Total} = 2\%$	0.00784	0.00963	0.01014
	$\Delta\varepsilon_{Total} = 5\%$	0.02679	0.02781	0.02916
125°C	$\Delta\varepsilon_{Total} = 1\%$	0.00697	0.00716	0.00781
	$\Delta\varepsilon_{Total} = 2\%$	0.01784	0.01845	0.01964
	$\Delta\varepsilon_{Total} = 5\%$	0.02873	0.02961	0.03211

In order to further investigate the relationship between temperature and low-cycle fatigue life of composite solder alloy, the linear regression analysis was carried out and the results are presented in Fig. 6. It can be seen that with the increase in temperature, the fatigue life under different experimental conditions decreases. Obviously, the low-cycle fatigue life of the composite solder alloy is dependent on temperature. In general, the plastic strain range and low-cycle fatigue life obtained at different temperatures follow the Coffin-Manson model.[26] Hence, the influence of temperature on low-cycle fatigue behavior is discussed based on the Coffin-Manson model.

The Coffin-Manson model is the most widely used model for predicting fatigue life of metals.[25] The expression is as follows:

$$N_f^{\beta} \Delta\varepsilon_{plastic} = \theta \tag{3}$$

where N_f is the fatigue life of composite solder joint, $\Delta\varepsilon_{plastic}$ is the plastic strain range, β is the fatigue life exponent and θ is the fatigue ductility coefficient. Fatigue ductility coefficient θ and fatigue life exponent β are constants.

Figure 7 shows the curve fitted with the Coffin-Manson model for the experimental data of plastic strain range and fatigue life. From the curve fitting analysis results, it can be seen that the Coffin-Manson model has a good curve fitting result for the Sn-0.3Ag-0.7Cu-0.5CeO$_2$ composite solder alloy, and the goodness of fit R^2 of the curve reaches 0.86–0.97.

The fitting results of fatigue life exponent β and fatigue ductility coefficient θ are shown in Table III. In order to further study the relationship between fatigue life exponent, fatigue ductility coefficient and temperature, the linear regression analysis method is carried out, and the results are shown in Fig. 8. From the results, it can be seen that with the increase in temperature, the fatigue life exponent β shows a significant downward trend at
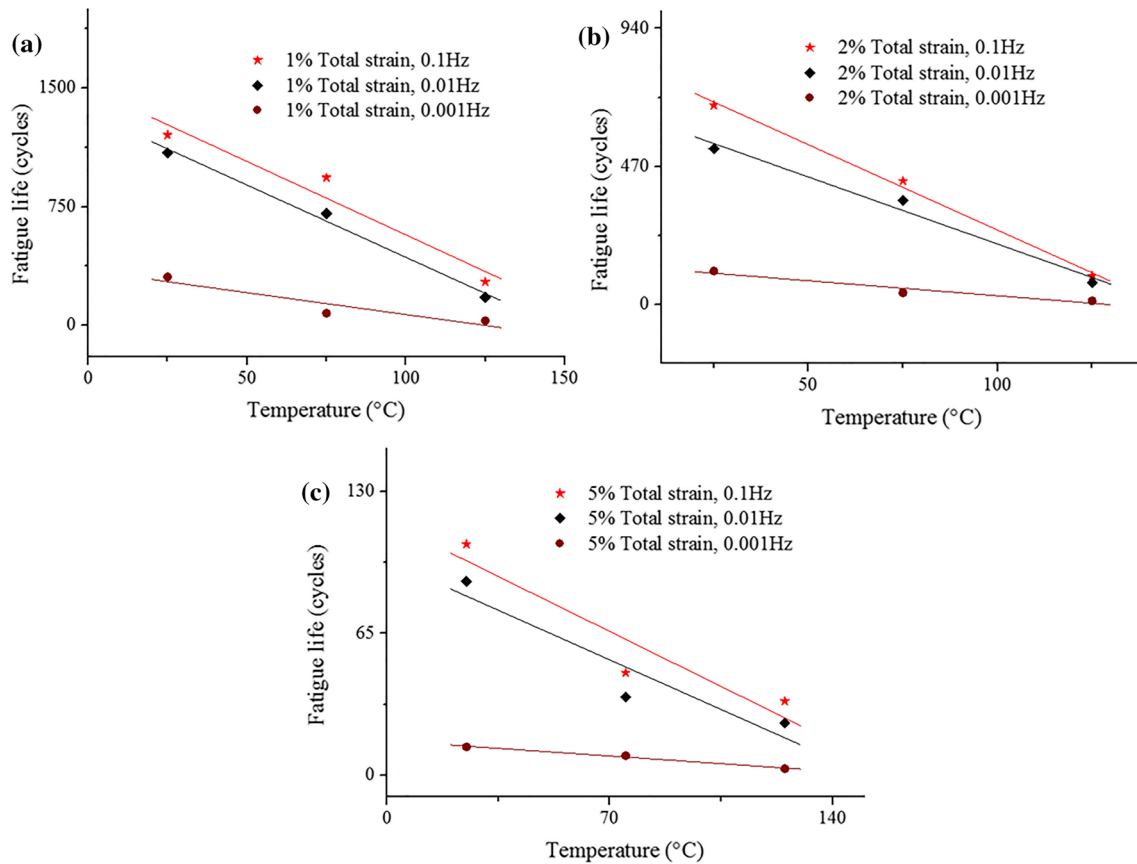
Fig. 6 Fatigue life versus temperature at total strain of (a) 1%, (b) 2% and (c) 5%.

different frequencies. This phenomenon is similar to other reports.[24,25] The decrease in the fatigue life exponent with the increase in temperature indicates that the fatigue life of the composite solder alloy will be shortened at higher temperature. This is due to the coarsening of IMC grains in the composite solder alloy at higher temperature, which weakens the pinning effect.[6] Therefore, dislocation slip and grain boundary slip occur more easily, resulting in the decrease in applied stress and the shortening of fatigue life.

The fatigue life exponent β decreases with the increase in temperature, and the low-cycle fatigue life N_f decreases with the increase in temperature. Hence, the fatigue ductility coefficient θ which is proportional to the low-cycle fatigue life N_f in the Coffin-Manson model is expected to decrease with the increase in temperature. From Table III, it can be seen that with the increase in temperature, the fatigue ductility coefficient θ shows a significant downward trend, which is consistent with the theoretical analysis and similar to the fatigue life exponent. Additionally, this phenomenon reveals that the ductility of composite solder alloy will be affected by temperature. This is because the mobility of grain boundaries and dislocations is strengthened at high temperature, which

makes the solder alloy more prone to crack and fracture, thereby reducing the ductility of the solder alloy.[2]

The fatigue life exponent is of great significance for analyzing the fatigue performance of solder alloys and predicting the fatigue life of solder alloys. Therefore, the fatigue life exponents of Sn–Ag–Cu solder alloys with different silver content, which are close to the experimental conditions (25°C, 0.01–0.03 Hz) in this work, are chosen for comparison. The values of fatigue life exponent of different Sn–Ag–Cu solder alloys are shown in Table IV. From the data in Table IV, it can be seen that the fatigue life exponent of Sn-0.7Cu (0 wt.% Ag) is the minimum value, only 0.43. After adding 1 wt.% Ag, the fatigue life exponent increases to 0.62, and the fatigue life exponent of Sn-3.5Ag-0.75Cu (3.5 wt.% Ag, the highest content) increases to 0.74, the highest. Since there is no report on the fatigue exponent of Sn-0.3Ag-0.7Cu at present, the fatigue life exponent of Sn-0.3Ag-0.7Cu may be between 0.43 (0 wt.% Ag, Sn-0.7Cu) and 0.62 (1 wt.% Ag, Sn-1.0Ag-0.5Cu). After adding CeO$_2$ nanoparticles, the fatigue life exponent of composite solder alloy is 0.72, which is close to that of Sn-3.5Ag-0.75Cu. Therefore, it may mean that the fatigue performance of the composite solder alloy is improved after CeO$_2$ addition,
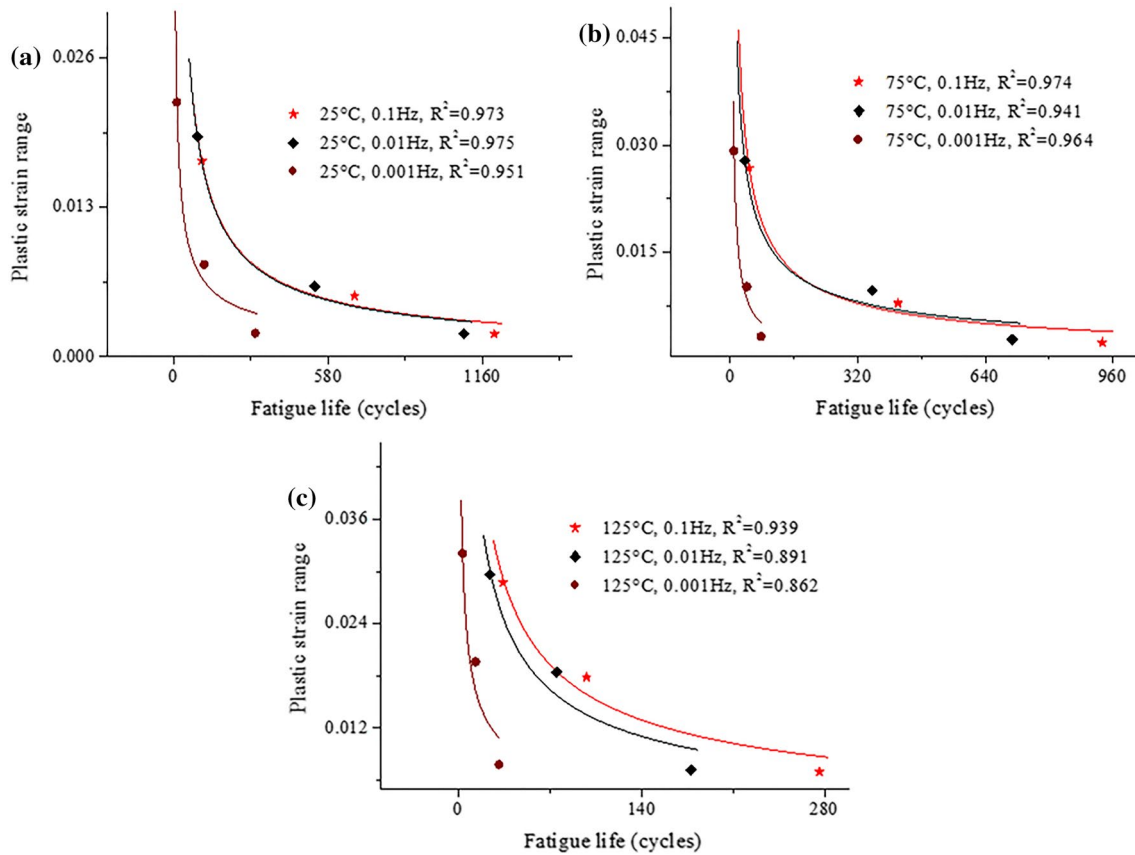
Fig. 7 Modeling results of the Coffin-Manson model at temperatures of (a) 25°C, (b) 75°C, (c) 125°C.

Table III Values of fatigue life exponent and ductility coefficient

Temperature	10^{-1} Hz		10^{-2} Hz		10^{-3} Hz	
	θ	β	θ	β	θ	β
25°C	0.496	0.722	0.504	0.727	0.143	0.560
75°C	0.321	0.644	0.215	0.570	0.142	0.515
125°C	0.223	0.576	0.184	0.569	0.054	0.471

and the improved fatigue performance is close to that of Sn-3.5Ag-0.75Cu.

From Fig. 4, it can be seen that the fatigue life of composite solder alloy is dependent on frequency obviously. Therefore, in order to better understand the relationship between frequency and low-cycle fatigue behavior of composite solder alloy, the effect of frequency on low-cycle fatigue behavior of composite solder alloy will be discussed in the next section.

Effect of Frequency on Low-Cycle Fatigue Behavior

As mentioned above, the plastic strain range is determined by the hysteresis loop, and the hysteresis loop is mainly determined by the applied stress and total strain range.

Generally, at a given total strain range, different strain rates are generated at different frequencies. According to our previous study,[2] the strain rate has a great influence on the applied stress. Changing the strain rate, the applied stress changed. Hence, by changing the frequency of low-cycle fatigue experiment, the plastic strain range changed.

In order to better describe the influence of frequency on the plastic strain range, linear regression analysis was conducted on the relationship between the plastic strain range and frequency under different total strain ranges. The analysis results are shown in Fig. 9. It can be seen that with the increase in frequency, the plastic strain range decreases. This phenomenon indicates that the plastic strain range is dependent on frequency: the higher the frequency, the smaller the plastic strain range. This phenomenon occurs because at
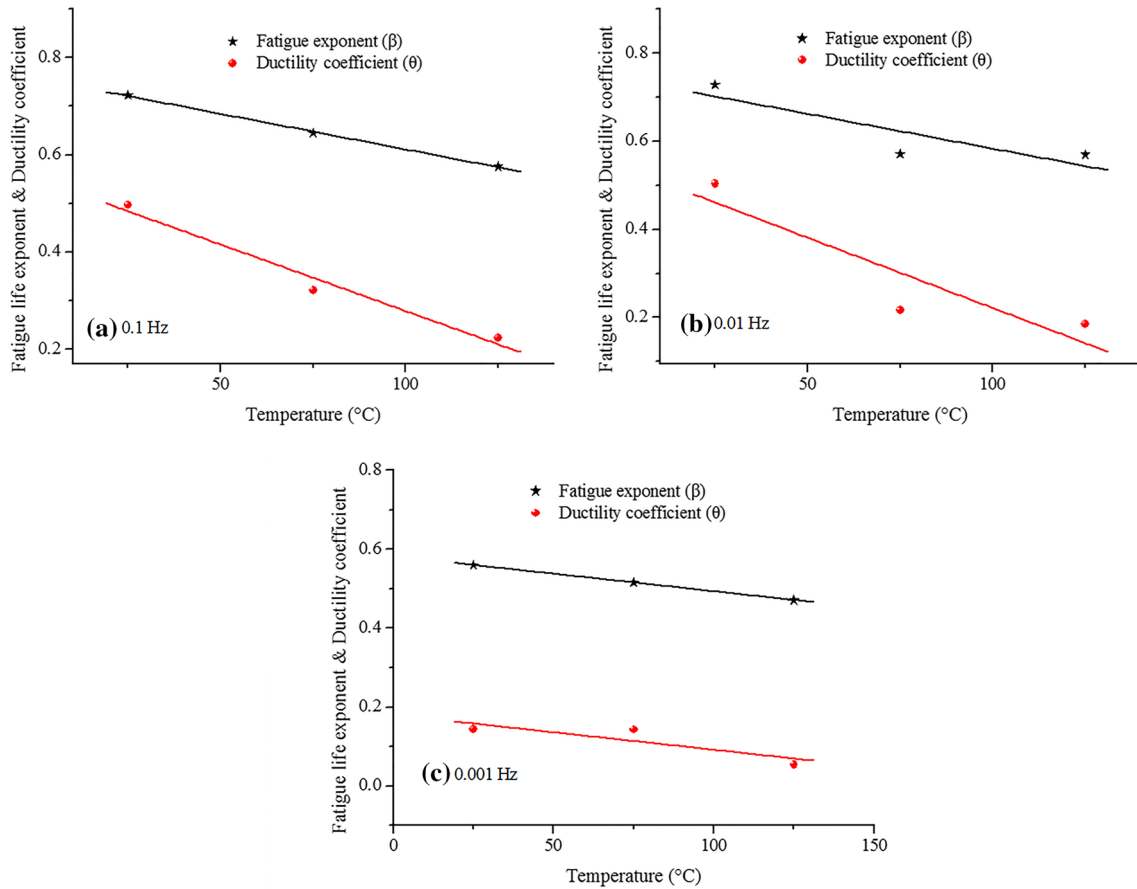
Fig. 8 Constants β and θ obtained at different conditions (a) 0.1 Hz, (b) 0.01 Hz, (c) 0.001 Hz.

Table IV Fatigue life exponent of different Sn–Ag–Cu solder alloys

Alloy	Temperature (°C)	Frequency (Hz)	β
Sn-0.7Cu	25	0.03	0.43 [27]
Sn-0.3Ag-0.7Cu-0.5CeO₂	25	0.01	0.72
Sn-1.0Ag-0.5Cu	25	0.01	0.62 [28]
Sn-3.5Ag-0.75Cu	25	0.03	0.74 [27]

a lower frequency, the concentrated stress has more time to be released through plastic deformation. Therefore, the longer the plastic deformation time, the larger the plastic strain range. Hence, with the frequency increases, the plastic deformation time becomes shorter, and the plastic strain range becomes smaller.

In the previous discussion, the fatigue life exponent β and fatigue ductility coefficient θ were determined by the Coffin-Manson model, and the effect of temperature on low-cycle fatigue behavior of composite solder alloy was discussed. Similarly, the effect of frequency on low-cycle fatigue behavior of composite solder alloy can be understood by the fatigue life exponent β and fatigue ductility coefficient θ obtained by the Coffin-Manson model. The relationship between fatigue life exponent β, fatigue ductility factor θ and frequency is shown in Fig. 10. Here it can be seen that with the increase in frequency, the fatigue life exponent and fatigue ductility coefficient at different temperatures show an upward trend. The fatigue life exponent increases with the frequency, indicating that the higher the frequency, the longer the fatigue life. This is because with the increase in frequency, the strain rate increases. With the increase in strain rate, the dislocation proliferation and interaction in the composite solder alloy are enhanced. Therefore, the mechanical properties of the composite solder alloy are improved and the low-cycle fatigue life is prolonged. The ductility coefficient θ also increases as the frequency increases, revealing that the composite solder alloy can obtain higher ductility at higher fatigue frequency. The reason for this phenomenon is consistent with the influence of frequency on plastic strain range mentioned above.
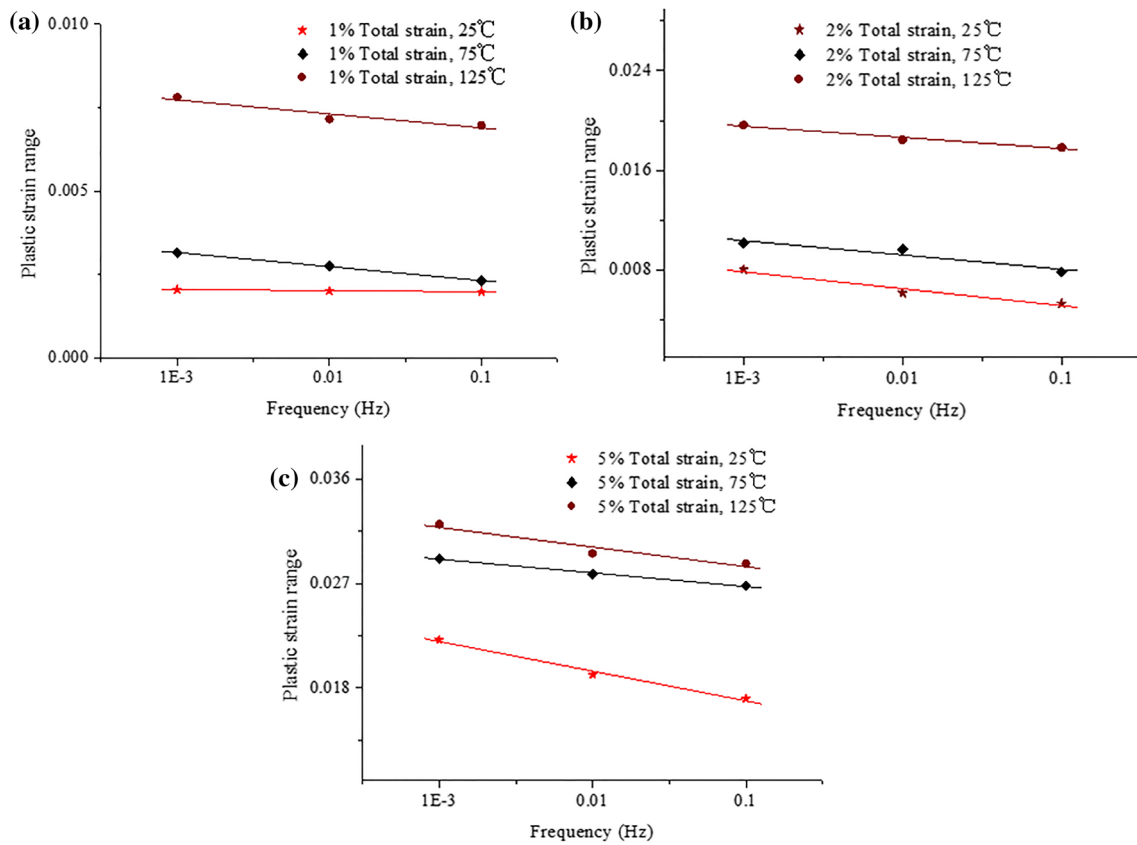
Fig. 9 Relationship between plastic strain range and frequency at total strain of (a) 1%, b 2% and c 5%.

From the above results, it can be seen that the fatigue life exponent β and fatigue ductility coefficient θ are obviously dependent on frequency at any temperature, which are in agreement with the phenomenon observed by Shi et al.[25] Other researchers reported that the effect of frequency on low-cycle fatigue life can be described by a frequency-modified Coffin-Manson model[1]:

$$(N_f \nu_{plastic}^{k-1})^\beta \Delta\varepsilon_{plastic} = \theta \qquad (4)$$

where $\nu_{plastic}$ is the frequency, k is the frequency exponent.

The relationship between low-cycle fatigue life and frequency of composite solder alloy Sn-0.3Ag-0.7Cu-0.5CeO$_2$ is shown in Fig. 11. Here it is found that the low-cycle fatigue life of composite solder alloy is slightly frequency-dependent in the frequency range 10^{-2} to 10^{-1} Hz but is strongly frequency-dependent in the frequency range 10^{-3} to 10^{-2} Hz. This phenomenon is consistent with the results of other studies.[4,5,24] Therefore, in order to better analyze frequency exponent k, it is more reasonable to divide it into two intervals: a strongly frequency-dependent region and a slightly frequency-dependent region.

In order to analyze the frequency exponent k in different frequency-dependent intervals and on basis of our experimental results, Eq. 4 can be modified as

$$\begin{cases} (N_f \nu_{plastic}^{k_1-1})^\beta \Delta\varepsilon_{plastic} = \theta & (10^{-1} \geq \nu_{plastic} \geq 10^{-2}) \\ \left[N_f \left(\dfrac{\nu_{plastic}}{10^{-2}}\right)^{k_2-1}(10^{-2})^{k_1-1}\right]^\beta \Delta\varepsilon_{plastic} = \theta & (10^{-2} > \nu_{plastic} \geq 10^{-3}) \end{cases}$$

$$(5)$$

After dividing into two frequency intervals, the frequency exponent k is replaced by k_1 and k_2. The frequency exponents k_1 and k_2 can be obtained from the relationship between frequency and low-cycle fatigue life as shown in Fig. 12. According to previous studies, the frequency exponents are dependent on temperature.[25] Additionally, as mentioned above, low-cycle fatigue life has a strong dependence on temperature. Hence, it is necessary to establish the relationship between frequency exponent and temperature, which can help to better understand the effect of temperature on low-cycle fatigue behavior of composite solder alloy.
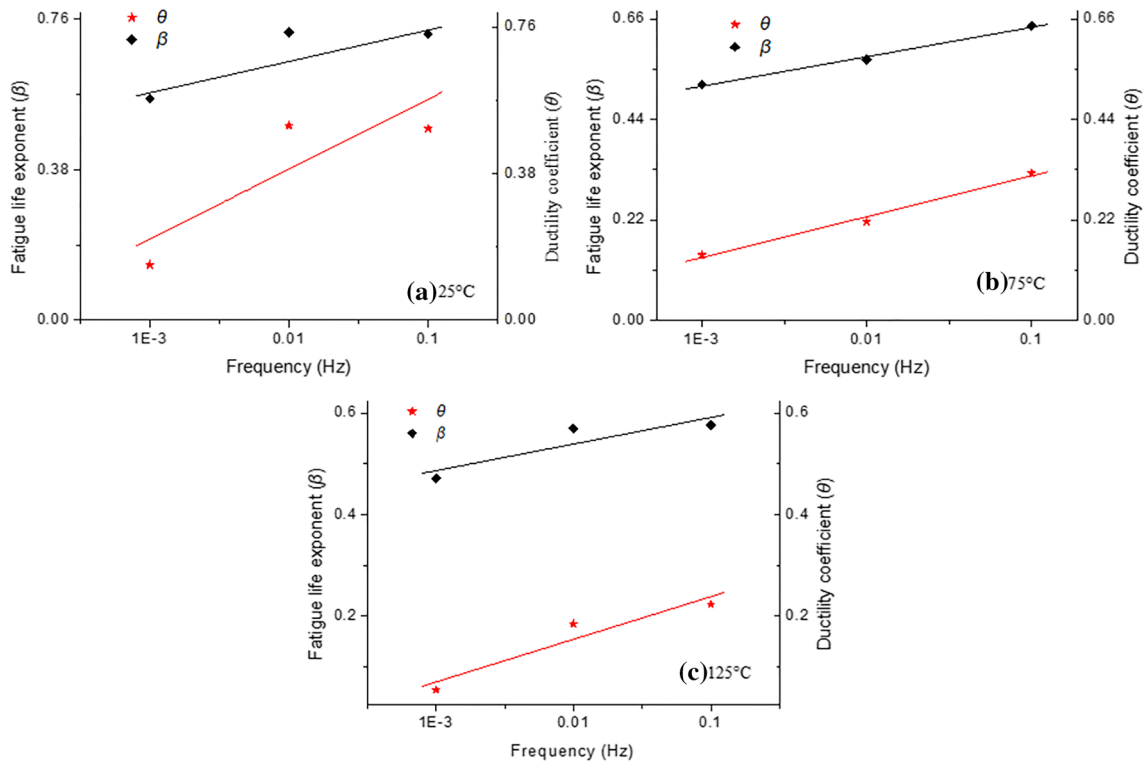
Fig. 10 Values of fatigue life exponent and fatigue ductility coefficient at temperature of (a) 25°C, (b) 75°C, (c) 125°C.

The relationship between frequency exponents and temperature can be described by polynomial fitting method and the relationship can be expressed as

$$k_1 = 0.9308 - 1.2426 \times 10^{-4}T - 4.3447 \times 10^{-6}T^2 \quad (6)$$

$$k_2 = 0.459 - 6.59 \times 10^{-3}T + 3.5649 \times 10^{-5}T^2 \quad (7)$$

where T is the temperature.

The fitting results of Eqs. 6 and 7 are shown in Fig. 13. On the other hand, it should be noted that from Fig. 8, the fatigue ductility coefficient θ and the fatigue life exponent β are also dependent on temperature. Therefore, these factors need to be taken into account in order to better understand the effect of temperature on low-cycle fatigue behavior of composite solder alloys. In this regard, the relationship between fatigue life exponent β, fatigue ductility coefficient θ and temperature is expressed by polynomial fitting method as follows:

$$\beta = 0.7647 - 1.73 \times 10^{-3}T + 1.78 \times 10^{-6}T^2 \quad (8)$$

$$\theta = 0.6129 - 5.02 \times 10^{-3}T + 1.5241 \times 10^{-5}T^2 \quad (9)$$

The fitting results for Eqs. 8 and 9 are shown in Fig. 14. Consequently, based on the above polynomial expressions and Eq. 5, the fatigue life of composite solder alloy can be predicted and analyzed. Because at the low temperature, the experimental time is longer than that of high temperature, the influence of frequencies on fatigue life is more obvious. On the other hand, at the low frequency, the experimental time is longer, the impact of temperatures on the fatigue life is more significant. Hence, in order to verify the modified Coffin-Manson model, the experimental data at low temperature and low frequency are selected for analysis.

Figure 15 shows the curve fitted with the modified model for the experimental data at low temperature and low frequency. From Fig. 15, it is obvious that the modified Coffin-Manson fatigue model fits the experimental data well. In addition, it can be seen that the modified Coffin-Manson model has basically eliminated the influence of frequency and temperature on the low-cycle fatigue behavior of composite solder alloys.

In order to verify the rationality of the modified Coffin-Manson model, the research data reported by Zhu et al.[18] with similar experimental conditions were chosen for verification. The solder alloy in their study is Sn-3.0Ag-0.5Cu, and the experimental temperature, frequency and sample
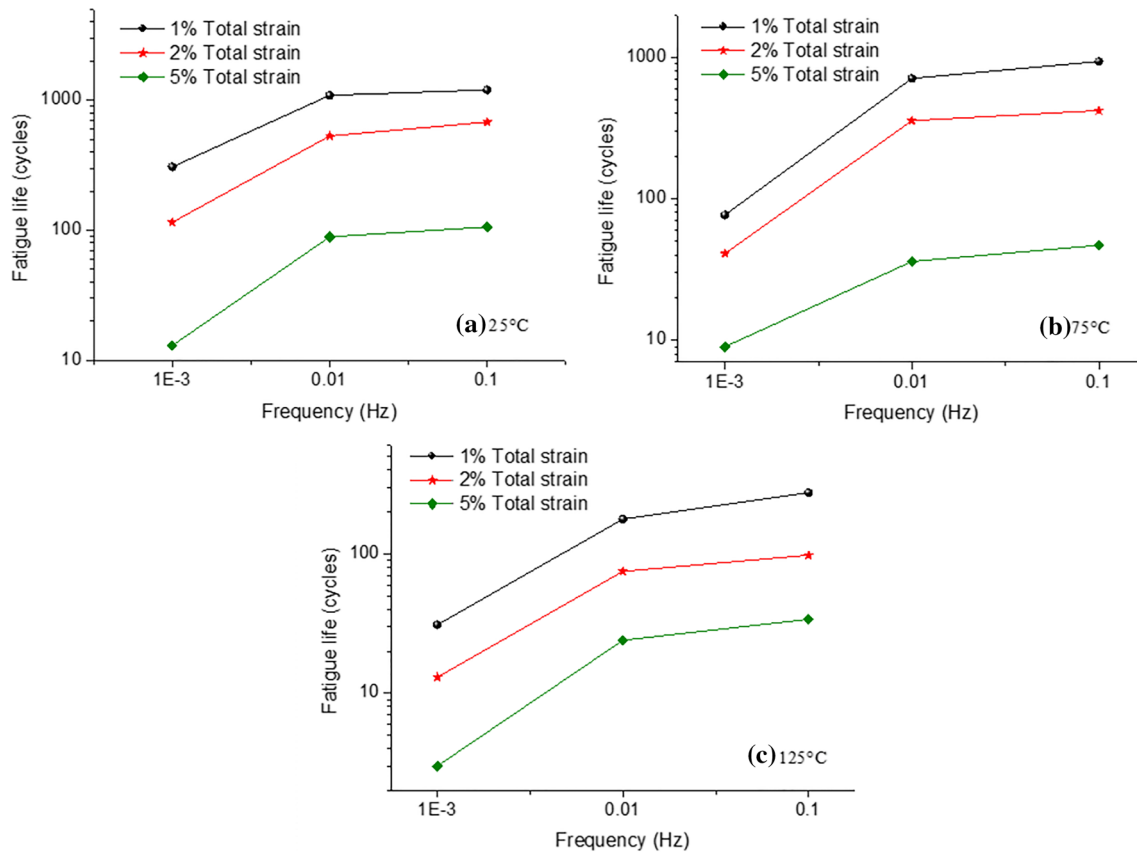
Fig. 11 Relationship between fatigue life and frequency for different strain ranges at temperature of (a) 25°C, (b) 75°C, (c) 125°C.
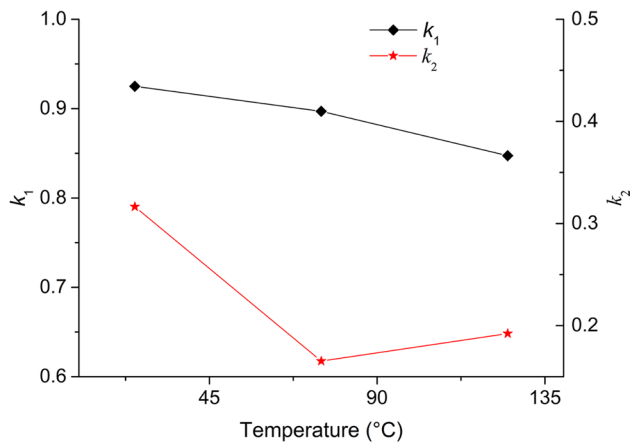

Fig. 12 Frequency exponent k_1 and k_2 versus temperature.
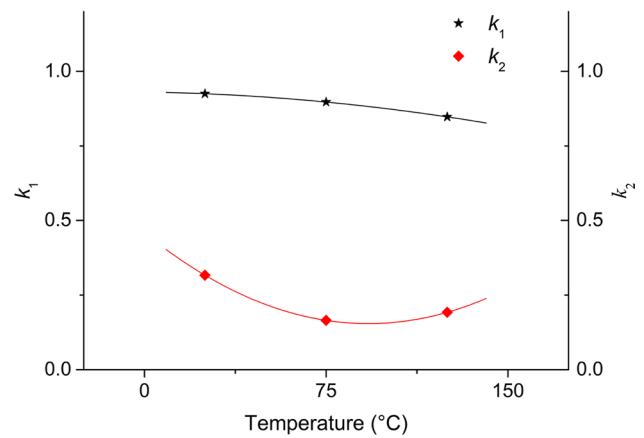

Fig. 13 Polynomial expression fitting results of frequency exponent and temperature.

size are close to this paper. Figure 16 shows the curve fitted with the modified Coffin-Manson model for the research data of Zhu et al.

From Fig. 16, it is apparent that the modified Coffin-Manson model fits the test data well and the influence of temperature is basically eliminated. From the figure, it is also found

that the results obtained from the modified Coffin-Manson model are close to the actual data in the low-cycle region, but there are small deviations in the high-cycle region. This may be due to the experimental results of Zhu et al. which are based on the complete fracture of the sample as a
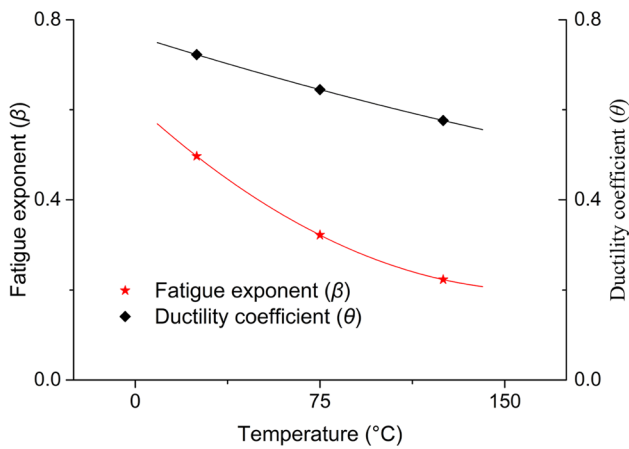
Fig. 14 Fatigue exponent and ductility coefficient versus temperature.

low-cycle fatigue life rather than reduction of applied stress by 50%. The fitting results reveal that the experimental data of Zhu et al. agree well with the modified Coffin-Manson model, which means that the modified model is applicable to further understand the low-cycle fatigue behavior of other Sn–Ag–Cu solder alloys.

Conclusion

In the present study, the low-cycle fatigue behavior and related mechanism of Sn-0.3Ag-0.7Cu-0.5CeO₂ lead-free composite solder alloy were studied. The main conclusions are summarized as follows:

1. The cyclic strain-hardening exponent of the composite solder alloy decreases with the increase in temperature, indicating that at high temperature, the material hardening phenomenon of the composite solder alloy is weakened, resulting in a decrease in applied stress. This is because at high temperature, the pinning effect of IMC grains is weakened, and the dislocation activity is enhanced, resulting in the weakening of material hardening. After doping of CeO₂ nanoparticles, the pinning effect is strengthened, and the material hardening is enhanced.

2. The low-cycle fatigue life exponent β of composite solder alloy decreases with the increase in temperature, which reflects that the increase in temperature will reduce the low-cycle fatigue life of composite solder alloy. Compared with the data of other researchers, the fatigue life exponent of Sn-0.3Ag-0.7Cu-0.5CeO₂ is 0.72, which is higher than 0.43 of Sn-0.7Cu and 0.62 of Sn-1.0Ag-0.5Cu, and close to 0.74 of Sn-3.5Ag-0.75Cu. This may mean that the fatigue performance of the com-
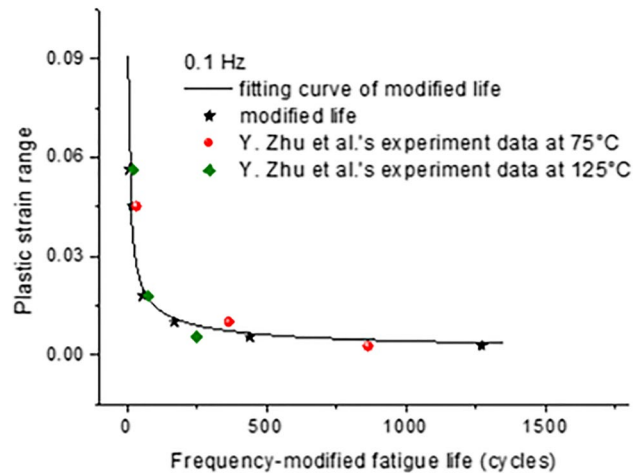

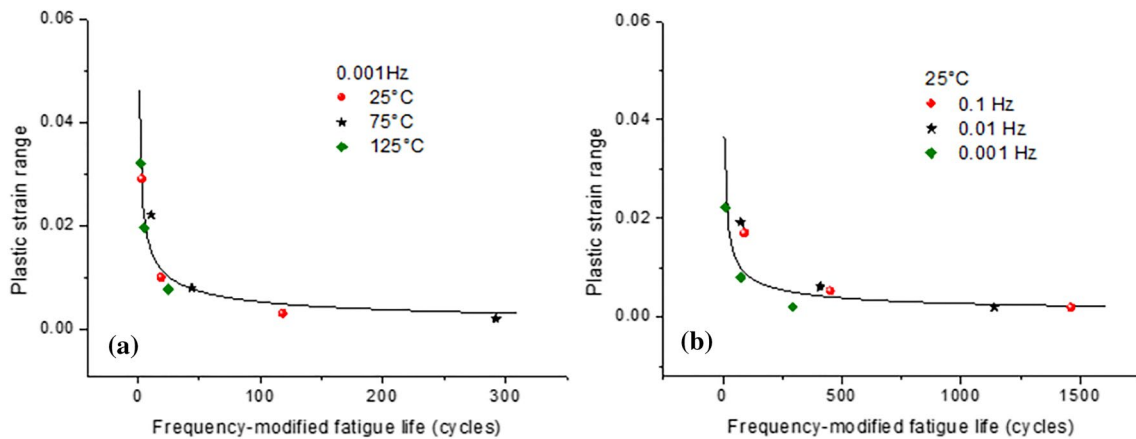**Fig. 16** Verification results of the modified model, data from Zhu et al.[18]

Fig. 15 Plastic strain range versus modified fatigue life at different conditions of (a) temperature, (b) frequency.

posite solder alloy after adding CeO_2 nanoparticles is close to that of the high-silver-content Sn-3.5Ag-0.75Cu solder alloy.

3. In the frequency range of 10^{-2} to 10^{-1} Hz, the low-cycle fatigue life is slightly dependent on the frequency, while in the frequency range of 10^{-3} to 10^{-2}, the low-cycle fatigue life is strongly dependent on the frequency. Meanwhile, the fatigue life exponent β and ductility coefficient θ are strongly dependent on the frequency. Therefore, a modified Coffin-Manson model was proposed, and the relationship expressions between temperature and frequency exponent, low-cycle fatigue life exponent, and material ductility coefficient were established. The modified model can effectively eliminate the influence of different frequencies and temperatures on the low-cycle fatigue life of composite solder alloys.

Author Contributions LL and ZL: performed the experiment and performed the data analyses and wrote the manuscript; YT and GL: helped perform the analysis with constructive discussions. All authors have read and approved the content, and agree to submit for consideration for publication in the journal.

Data availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

Ethical standard The authors declare that this manuscript is original, has not been published before, and is not currently being considered for publication elsewhere.

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