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Optimal Design of Thermal Variant Stress Spectrum Based on Virtual Accelerated Life Test of the Circuit Board

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The spectrum design and lifetime evaluation of high reliability and long lifetime aerospace electronical products has been a puzzled problem for engineering and scientific researcher. The fatigue of these products are caused by complicated environmental and operational conditions. The specific works in this study involve the establishment of fatigue life model of the circuit board under the thermal variant stress, model fatigue virtual accelerated life test (VALT) based on thermal variant stress spectrum, calculation and analysis of model accelerated life based on VALT data, and the method of stress spectrum optimization based on accelerated model.
In this study, focused on the weak node of the circuit board, the fatigue failure model is constructed, and the fatigue life of the model is predicted by accelerated stress spectrum and Coffin-Manson formula. Furthermore, the fatigue degradation data of the model under thermal variant stress are obtained by VALT. Considering that the coefficients of Coffin-Manson formula should be adjusted to different accelerated models, the study combines S-N curve and simulation data to fit the formula parameters, and calculates the optimal stress spectrum of the accelerated model by using the modified Coffin-Manson formula. Finally, the fatigue life of the model under the optimal accelerated stress is obtained. The method and result can be referred to the ALT design for similar products.

Keywords: Thermal variant stress, Virtual accelerated life test, Accelerated life calculation, Coefficient fitting, Optimal design

1. Introduction

With the development of modern science and technology in the field of aeronautics and aerospace, the structure of electronic equipment is becoming increasingly complex, and the working environment of electronic products is getting increasingly strict, which puts forward more stringent requirements on the reliability life of electronic equipment in the complex working environment (Zhou 2021, 37). At present, in the accelerated life testing, thermal variant stress is often applied as the testing environment to obtain the fatigue failure data of the test object (Charki 2011, 1254), and furthermore, calculate its accelerated life. However, it still takes a long time to obtain the accelerated life of products through the accelerated life test. Therefore, this study proposes the virtual accelerated life test (VALT) based on finite element simulation with accuracy and efficiency, which has a wide application prospect in the field of accelerated life test.

Based on fatigue failure of the circuit board (Lin 2020), a method of simulation analysis and accelerated life calculation for the weak node of electronic equipment is proposed in this study, which can effectively solve the problem of stress spectrum optimization during accelerated test. The research will provide theoretical and technical support for the study of service life and storage reliability of electronic equipment.

2. Storage reliability and life simulation

The output information of the tested products is collected by taking the temperature distribution, stress-strain and other accelerated test results of model as characteristic quantities. The collection of output information is carried out by combining theoretical simulation, conventional test and accelerated test (Cheng 2019, 2). The main sensitive stress of the tested products is temperature, and it has the accelerability (Dong 1998, 86). Therefore the degradation performance of tested products is studied by using temperature as the main accelerative stress.

2.1. *Degradation mechanism of tested model*

Electronic products are affected by complex environment in the process of storage and transportation (Wang 2015, 510), especially in aerospace and other fields (Li 2022, 277). In the life cycle of electronic products, a variety of failure factors are usually encountered to cause product failure. According to the United States Air Force statistical analysis of failure causes of electronic equipment (Liu 2003, 1037), 40 percent of failures in electronic equipment are caused by temperature, and 27 percent by vibration and shock, which comes to the conclusion that temperature has the greatest impact on the life of electronic products.

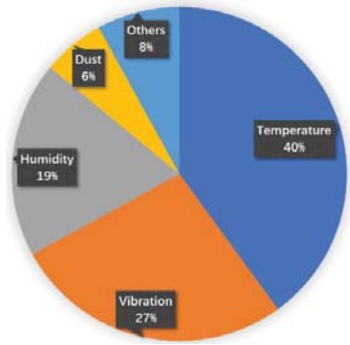

Fig. 1. Failure rate of electronic products under environmental stress

In the failure analysis of electronic products, the reliability of solder joints between components and circuit boards bearing the role of mechanical connection, electrical connection and heat transfer is particularly prominent (Gurumurthy 2014), especially in the case of PCB printed wire with high density, the failure rate of solder joints is often an order of magnitude higher than that of circuit components and devices (Saeed 2019, 64). It directly affects the reliability and stability of electronic products. According to statistics, among the failures of electronic equipment, 50% are caused by PCB welding failures (Salahouelhadj 2014, 206), and the solder joint quality problems are more serious in the form of surface paste packaging which is sensitive to thermal stress (Xu 2011, 52). The defects caused by welding account for 70% of the total defects. As fatigue expert Steinberg puts it (Zhao 2000, 162), "Solder joint reliability is so important that people in the industry think of electronic equipment reliability as solder joint reliability."

2.2. *Requirements and results of the basic Virtual accelerated test*

In normal storage environment, the ambient temperature will change regularly with the day and night. In general, there are values of maximum temperature and minimum temperature in the daily temperature cycle, and the duration of these two values will not be too long. Between the maximum temperature and the minimum temperature, it is approximately believed that the storage temperature is stable at a reference temperature. The time at reference temperature accounts for the largest proportion of a cycle.

According to accelerated test requirements, the basic spectrum of temperature cycle is set as follows: reference temperature 10°C, maximum temperature 80°C, minimum temperature -10°C, rate of temperature changes 3°C/min, time on reference temperature 1h. All above repeats 1000 cycles. The load spectrum is shown as Fig. 2.

According to the feedback of the plastic strain degradation index of the model (Fig. 3), it is found that the plastic strain range of the model, that is, the difference between the maximum strain variable and the minimum value in a single cycle, is small when the cycle is more than 20 times, and basically does not maintain change. Therefore, the first 20 cycles were selected for life prediction analysis in the subsequent accelerated test.

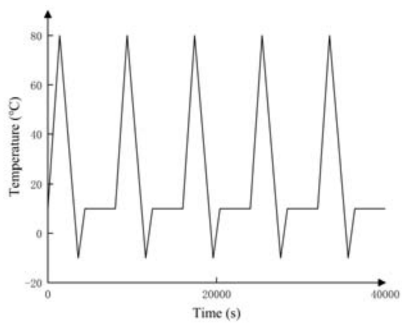

Fig. 2.Reference accelerated load spectrum

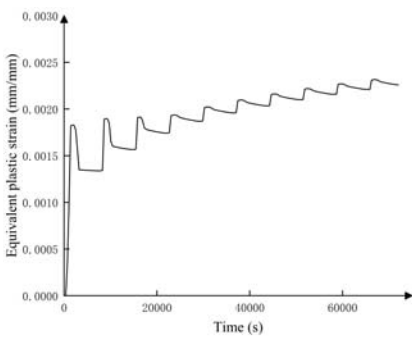

Fig. 3. Strain results under reference stress

3. Accelerated test optimization algorithm and model

In order to not lose generality, the following assumptions should be made in the design and evaluation of accelerated life test under temperature cyclic stress (Li 2015, 815):

(1) Under temperature cyclic stress S_i, the life distribution of the product follows Weibull distribution (E.q.1):

$$F_i(t) = 1 - exp\left\{-\left(\frac{t}{\eta_i}\right)^{m_i}\right\} \quad (1)$$

m_i is the shape parameter, η_i is the character life.

(2) The residual life of the product only depends on the accumulated failure part and the stress level at that time, which has nothing to do with the accumulation method.

(3) Under normal stress S_0 and accelerated stress S_1, S_2, ..., S_k, the failure mechanism of products remains unchanged.

3.1.*Modified Coffin-Manson model*

The Coffin-Manson model, which assumes that the fatigue life is dependent only on the temperature range of the thermal cycle (Cui 2005, 557), is widely used in mechanical and electronic parts to describe the product fatigue failure caused by the thermal cycle (Towashiraporn 2002). While in some applications, the fatigue life is also a function of frequency period and temperature. Norris and Landzberg modified the traditional Coffin-Manson model by integrating the effects of thermal period variables (Lee 2000, 234). Norris-Landzberg model mainly consider the following three factors: the highest temperature cycle T_{max}, temperature variation ΔT, cycle frequency f. The specific form of the model is as follows:

$$N = A \cdot f^{-m} \cdot \Delta T^{-n} \cdot G(T_{max}) \quad (2)$$

Where, N is the number of cycles at the time of failure; A is the model coefficient, which is obtained by regression fitting of relevant literature; m is the cycle frequency index, usually m=1/3; n is the temperature range index, usually n=1.9; $G(T_{max})$ is Arrhenius equation for each cycle under the highest temperature, $G(T_{max}) = \exp(E_a/KT_{max})$, among the function above, E_a is activation energy for material, for soldering material, $E_a = 0.61eV$; K is Boltzmann constant, and K=8.62E-5.

Modified Coffin-Manson model has been successfully applied to temperature cyclic stresses, suitable for mechanical failure, material fatigue or material deformation (Chung 2010).

3.2. *Model accelerated life calculation*

Adopt section 3.1 of the revised Norris - Landzberg model to improve the life prediction, among them, $\Delta T = 90$, $T_{max} = 353.15K$, other parameters are given in section 3.1, into the formula to calculate the failure cycle number N = 119383 cycle. Take the frequency conversion for time into consideration, the life prediction can be calculated as $t = 27.26\ years$.

4. Accelerated life test design and optimization

During the test, the variable stress test scheme is adopted, which needs to control the temperature change interval time (ΔT), temperature change rate (ΔT/t), temperature change amplitude (Tmax-Tmin) and temperature change frequency (n) in the test box.

4.1. *Accelerated test for changing test parameters*

4.1.1. *Accelerated test for varying storage temperature reference*

In the reference load spectrum, the storage temperature reference is 10℃, which is changed to 25℃ and 40℃ respectively. On this basis, the accelerated test simulation is carried out, and the accelerated degradation index of the model represented by equivalent plastic strain is obtained, as shown in the figure below.

According to the comparison of Fig. 4 and Fig. 5, it is found that when the storage temperature baseline increases, the equivalent plastic strain value of the accelerated model under the same number of cycles also increases correspondingly, and the degradation rate of the model with this index also increases correspondingly.

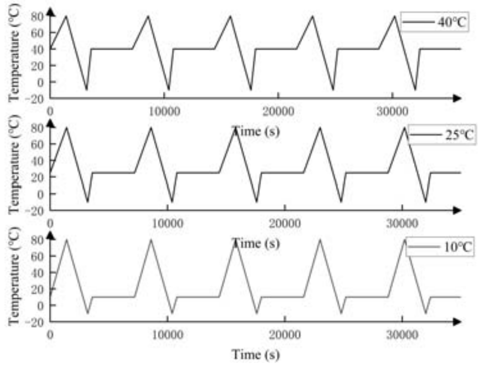

Fig. 4. Accelerated load spectrum with modified storage temperature

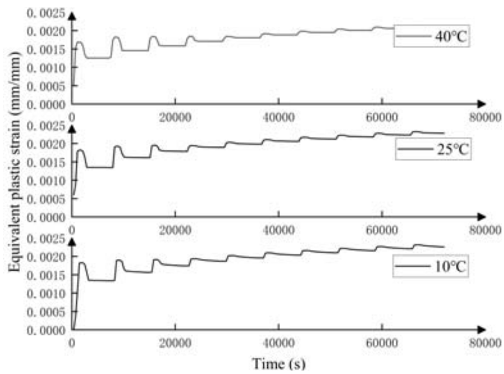

Fig. 5. Strain results under the modified stress

4.1.2. *Accelerated test for varying temperature interval*

In the base load spectrum, the temperature change interval time is 1h, which is changed to 0.5h and 2h respectively. On this basis, the accelerated test simulation is carried out, and the accelerated degradation index of the model represented by equivalent plastic strain is obtained, as shown in the figure below.

According to the comparison of Fig. 6 and Fig. 7, when the temperature change interval time increases, the equivalent plastic strain value of the accelerated model under the same number of cycles will decrease correspondingly, and the degradation rate of the model with this index will also slow down accordingly.

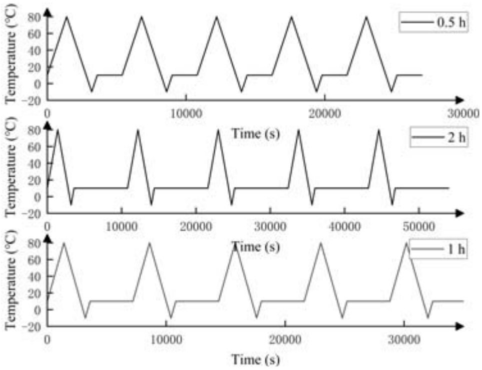

Fig. 6.Accelerated load spectrum with modified temperature change interval time

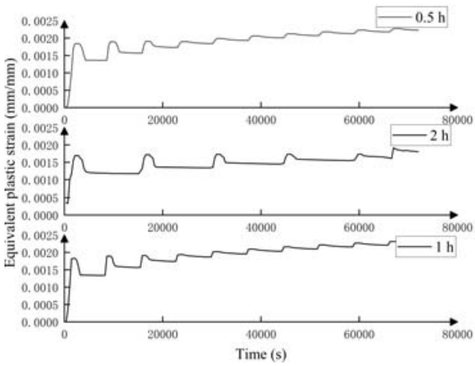

Fig. 7. Strain results under the modified stress

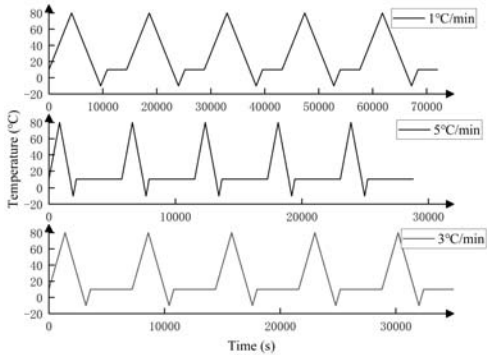

Fig. 8.Accelerated load spectrum with modified temperature change rate

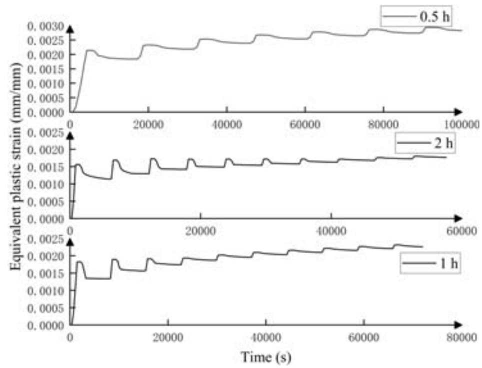

Fig. 9. Strain results under the modified stress

4.1.3.*Accelerated test for varying the rate of temperature change*

In the base load spectrum, the temperature change rate is 3℃/min, which is changed to 1℃/min and 5℃/min respectively. On this basis, the accelerated test simulation is carried out, and the accelerated degradation index of the model represented by equivalent plastic strain is obtained, as shown in the figure below.

According to the comparison of Fig. 8 and Fig. 9, it is found that when the temperature change rate increases, the equivalent plastic strain value of the accelerated model under the same number of cycles will increase correspondingly, and the degradation rate of the model with this index will also increase correspondingly.

4.1.4.*Conclusion of optimization scheme of variable stress experiment*

In this chapter, the degradation data of the model under different stress standards were obtained by changing the parameters of the virtual accelerated life test. According to the data, the following conclusions can be drawn: the temperature change interval time and temperature change rate in the stress spectrum inhibit and promote the model accelerated factor respectively, that is, the smaller the temperature change interval time, the greater the accelerated factor. The greater the rate of temperature change, the greater the accelerated factor. The specific effect ΔT in the stress spectrum will be numerically calculated and analysed in the next chapter.

4.2.*Optimization scheme of stress spectrum for accelerated test*

The optimization scheme of the stress spectrum of the model accelerated test is as follows: (1) By combining the equivalent stress value obtained from the virtual accelerated life test and the S-N curve of the material, the expected accelerated life *N* of the model can be calculated; (2) The N obtained under different accelerated stresses is substituted into the modified Coffin-Manson model, and the coefficient fitting of the Coffin-Manson model can be realized by the multiple linear coefficient fitting method; (3) Optimize the parameters *f*, ΔT and $Tmax$ of the modified Coffin-Manson formula to make the life data N obtain the minimum value, which is the aim of the optimization.

The S-N curve of solder material (Fürtauer 2013, 145) and the modified Coffin Manson model used for optimization analysis are as follows:

$$N = \frac{1.2\times10^{14}}{S^{4.3}} \quad (6)$$

$$N = A \cdot f^{-m} \cdot \Delta T^{-n} \cdot G(T_{max}) \quad (7)$$

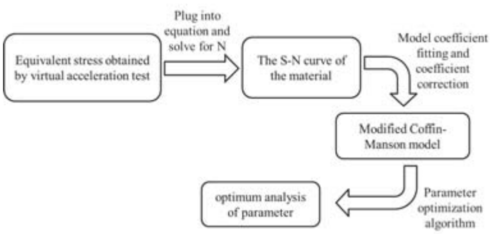

Fig. 10. Stress spectrum optimization scheme

4.3. *Numerical calculation of stress spectrum in accelerated test*

For the modified Coffin-Manson model, linearization is firstly carried out to obtain the following formula:

$$lnN - lnG(T_{max}) = lnA - m\ln f - nln\Delta T \quad (8)$$

First, three unknown coefficients *A*, *f*, *ΔT* in the equation are solved. The five groups of accelerated test data obtained in Section 4.1 were substituted into S-N curves (Pang 2013, 1305) to solve the accelerated life N, and then the linearization formula was fitted according to the N solved under different stress conditions. The results are shown in the table below.

Table 1. Accelerated test data adopted by fitting calculation method

$lnN - G(T_{max})$	$\ln f$	$\ln\Delta T$
-8.838	2.48	4.50
-7.215	2.60	4.25
-7.905	2.54	4.38
-8.776	3.08	4.50
-8.428	2.22	4.50

Table 2. Fitting result

Value	A	m	n
Original	unspecified	1/3	1.9
Modified	1.47e8	0.3207	5.9224

Parameter variance as the coefficient of fitting precision index, calculated parameter variance $R^2 = 0.967$, which shows the fitting result is ideal. The formula deformation after fitting is as follows:

$$lnN - lnG(T_{max}) = 18.8088 - 0.3207\ln f - 5.9224ln\Delta T \quad (9)$$

The problem is now transformed into the optimization problem of the modified linearization formula. Considering the type of parameter *f* is related to parameters ΔT, v and t_0, expand the *f* with the corresponding parameters and substitute into the correction formula.

$$f = 1440/(2\Delta T/v + t_0) \quad (10)$$

$$F(N) = c - 0.3207\ln\frac{1440}{\frac{2\Delta T}{v}+t_0} - 5.9224ln\Delta T = c1 + 0.3207\ln\left(\frac{2\Delta T}{v} + t_0\right) - 5.9224ln\Delta T \quad (11)$$

The problem is transformed into obtaining the minimum value F(N) through the relation among ΔT, v and t_0. With further analysis, according to the accelerated test simulation, t_0 is positively correlated with F(N), while v is negatively correlated with F(N). Take the partial derivative of F(N):

$$\frac{dF}{d\Delta T} = \frac{0.6414}{\frac{2\Delta T}{v} + t_0} - \frac{5.9224}{\Delta T}$$

$$= \frac{0.6414\Delta T - (11.8448/v)\,\Delta T - 5.9224t\_0}{(2\Delta T/v + t_0\,)\Delta T} \quad (12)$$

Where, the denominator is always positive; In specific temperature change rate of v (1℃/min < v < 5℃/min), the molecular keeps negative. So, F(N) is monotonously decreasing about ΔT. Take optimization parameters ΔT = 90 ℃, v = 5 ℃ / min, t_0 = 30 min into Coffin-Manson model of parameters fitted, the optimal stress spectrum of accelerated cycles is obtained as N = 73785.

According to the calculation results above, the optimization method realize the acceleration of the virtual accelerated life test.

Based on the conclusion in section 4.3, optimization parameters are list as follows: ΔT = 90 ℃, v = 5 ℃ / min, t_0 = 30 min. Fig. 12 shows the comparison of test results before and after optimization.

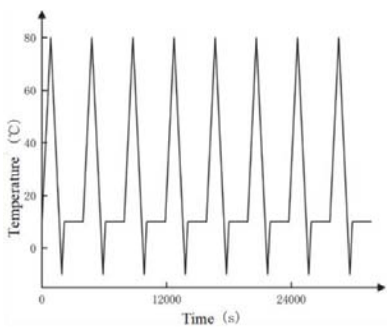

Fig. 11. The optimal accelerated stress spectrum is simulated under existing conditions

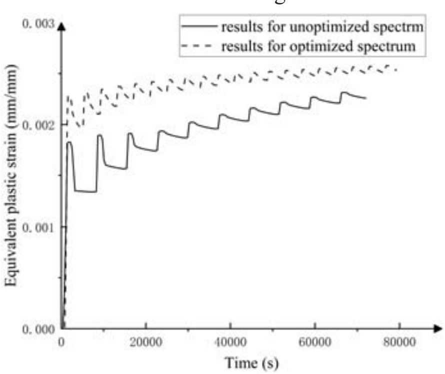

Fig. 12.The equivalent strain degradation trajectory under the optimal accelerated stress spectrum

5. Conclusion

In this paper, two main contents are studied:

(1) plastic deformation is determined as the main failure mode by analysing the influence of storage environment stress and failure mechanism of circuit board,. On this basis, a modified Coffin-Mason model is applied for accelerated data analysis. The virtual accelerated life test is carried out according to the analysis above. The accelerated life of the model can be calculated based on the model accelerated data obtained from the test and the modified Coffin-Mason model.

(2) The ~~model~~ accelerated data under the corresponding modified stress conditions are simulated by modifying the characteristic parameters of the reference accelerated stress spectrum and conducting virtual accelerated tests based on a batch of modified accelerated spectra. Based on the data and the accelerated spectrum optimization scheme and algorithm proposed in this paper, the optimal accelerated spectrum design for the electronic product is realized. The accelerated test under the stress spectrum can achieve the optimal accelerated effect under the existing accelerated conditions, that is, the accelerated life of the model under the test condition of accelerated can reach the minimum value.

Based on virtual accelerated test method and the optimization scheme, the model accelerated lifetime and optimal accelerated spectrum are obtained in this study. The technical route has been verified by simulation model and data. In the following research, the accelerated spectrum based on the virtual accelerated test optimization can be applied in the accelerated test of the real model, and the accuracy of the optimization method and optimization results can be further verified through the actual accelerated test data.

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