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ZMODYFIKOWANY MODEL PROGNOZOWANIA NIEZAWODNOŚCI URZĄDZEŃ ELEKTRONICZNYCH

A MODIFIED MODEL OF ELECTRONIC DEVICE RELIABILITY PREDICTION

Prognozowanie niezawodności urządzeń elektronicznych oparte na modelu fizyki uszkodzeń (PoF) jest obarczone niepewnościami. Opierając się na połączeniu testu Kołmogorowa-Smirnowa (testu K-S) i metody symulacji Monte Carlo, w niniejszej pracy zaprezentowano zmodyfikowaną metodę prognozowania niezawodności urządzeń elektronicznych, która bierze pod uwagę ograniczoną liczbę danych testowych o uszkodzeniach. Ilościową charakterystykę głównych czynników niepewności modelu stworzono na podstawie wskaźnika zdolności procesu (Cpk). W pierwszej części pracy badano stopień dopasowania pomiędzy teoretycznym rozkładem podobieństwa uszkodzeń urządzeń elektronicznych obliczanym w oparciu o PoF przy użyciu metody symulacji Monte-Carlo a empirycznym rozkładem podobieństwa uszkodzeń urządzeń elektronicznych uzyskanym na podstawie testowych lub terenowych danych o uszkodzeniach przy użyciu metody K-S. W części drugiej, dokonano optymalizacji skorygowanego współczynnika modelu. Wreszcie, na podstawie przykładu modelu oceny termicznej wytrzymałości zmęczeniowej połączenia lutowanego oraz wybranych danych testowych o uszkodzeniach dokonano weryfikacji proponowanej metody. Wyniki prognoz uzyskane na podstawie zmodyfikowanego modelu są zgodne z wynikami testowymi.

Słowa kluczowe: *prognozowanie niezawodności, modyfikacja modelu, fizyka uszkodzeń, urządzenie elektroniczne, test K-S, testy cenzurowania losowego.*

There exist uncertainties in the prediction of electronic device reliability based on PoF (physics of failure) model. Based on the combination of Kolmogorov-Smirnov test (KS-test) and Monte-Carlo simulation method, this paper presents a modified method for reliability prediction of electronic devices considering limited test failure data. The process capability index (Cpk) is used to quantitatively characterize the main factors of model uncertainties. Firstly the degree of fitting between the theoretical probability distribution of electronic device failures based on PoF by using the Monte-Carlo simulation method and the practical probability distribution of electronic device failures based on test or field failure data is tested by using K-S test method. Secondly the corrected coefficient of the model is optimized. Finally, a solder thermal fatigue life assessment model and some test failure data are used to verify the proposed method in the illustrative example. The prediction results calculated by modified model are consistent with test results.

Keywords: *reliability prediction, model modification, physics of failure, electronic device, K-S test, random censored tests.*

1. Introduction

The reliability prediction of electronic device based on U.S. military standards MIL-HDBK-217F has been widely used in practice [4, 6]. However, there are some disadvantages of this method, e.g., the delayed update of model parameters, product failures due to the neglect of non-components failures, and the design misleading due to imprecise prediction. Moreover it has been under increasing doubt recently [11, 13]. As a result, the update of MIL-HDBK-217F was terminated in 1995, and MIL -HDBK-217F was eliminated from supplier contracts by the Army in February 1996, which marked the end of a time for MIL-HDBK-217F in reliability prediction.

The fade of MIL-HDBK-217F provided the impetus to the rising of *physics of failure*. This approach can be applied in various reliability fields, i.e., electronic device reliability design, analysis, test, assessment and failure prediction [5, 12]. Failure physics models of electronic components are the basis of reliability prediction methods based on physics of failure and various failure physics models have been developed with the development of microelectronic technology. These models can describe quantitatively failure physics process of electronic components, i.e., mechanical, electronical, thermodynamic and chemical process.

However, due to the limitation of human cognitive ability and the complexity of objective world, it is difficult to build a perfect model to accurately describe the failure process of electronic components. Moreover some improper assumptions are used for facilitating the calculation in the modeling of PoF.

Therefore some subjective coefficients or modified parameters are considered in the PoF model. These coefficients have great impact on the accuracy of prediction and must be determined before using the PoF model to predict reliability of electronic devices. Generally speaking, a recommendable value interval or mean value can be determined through the comparison between mean value of experimental results and mean value of model prediction. However, due to sample disparity, the prediction of the model with the coefficients determined by mean comparison is far away with the practical results. Furthermore, not all the technological parameters of various electronic components can be obtained through the measurement in engineering practice. Some technological parameters are difficult to be measured in some extreme situations. Therefore it demands that group characteristics should be considered in the determination of model empirical coefficients. The modification and optimization of these parameters are essential and critical to obtain precise reliability prediction by using PoF model.

This paper presents a modified method of PoF model with limited test failure data to deal with the above-mentioned problems. Based on the source analysis of PoF model uncertainty, the proposed method combines Kolmogorov-Smirnov test (KS-test) and Monte-Carlo simulation techniques. In the numerical example, a solder thermal fatigue life assessment model and some failure data obtained in solder accelerated life testing of Plastic Ball Grid Array (PBGA) are utilized for case study and method verification. The modified method proposed in this paper is a general method and can be extended to PoF model parameters modification and optimization of other electronic components.

2. Model uncertainty and product process capability

Common source of model uncertainty comprises two categories: cognitive uncertainty and product uncertainty. Firstly, failure of electronic products is a complex process and involves multi-discipline, e.g., mechanics, thermodynamics, electrics and chemistry. Due to the limitation of human cognitive ability, firstly it is impossible to obtain precise physics model to describe product failure mechanism quantitatively. Secondly, due to different process conditions, there exist different process parameters of electronic products, e.g., geometric dimensions and material properties, inherent uncertainties. Even though process condition can be the same, process parameter of a product may have some certain disparity. These uncertainties can lead to deflection of prediction, even unreasonable results. To guarantee a reasonable prediction in practice, it is necessary to properly modify and optimize PoF model to reflect product failure mechanism.

In the production process of electronic products, some assessment methods can be used to manage quality and reliability of electronic components, e.g., process capability index assessment, statistical process control (SPC), Parts per Million (PPM). Process capability index, represented as C_{pk}, reflects practical Process capability of electronic components and describe quantitatively the uncertainty of product process parameters. It can be calculated by [14]:

$$C_{pk} = \min\left[\frac{USL-\mu}{3\sigma}, \frac{\mu-LSL}{3\sigma}\right] \tag{1}$$

where USL and LSL are the upper bound and the lower bound of product process parameter criterion, respectively. σ is the standard deviation and μ is the mean of process parameter distribution.

The larger C_{pk}, the higher process capability, which reflects the uniformity of products. Generally speaking, when $C_{pk} = 2$, it corresponds to 6σ of process level. Based on the PoF model, the uncertainty of products is the chief factor. Therefore in the following section, C_{pk} is used to represent the uncertainty of product process parameters.

3. Model modification

Accounting for the above model uncertainty, a new model based on the modification method is presented in this paper. The main process is shown in Fig. 1.

Generally, based on empirical knowledge of failure mechanism, firstly failure physics models, describing failure process of electronic products quantitatively, can be obtained. Secondly theoretical distribution function of failure is determined according to corresponding failure physics model. Meanwhile, the practical probability distribution of electronic device failures can be evaluated based on test or field failure data of a product. Due to model uncertainty, practical probability distribution and theoretical distribution function can not be always consistent. Therefore a reasonable approach is to find an optimized modified parameter so as to make two distributions as similar as possible. In this paper, the Kolmogorov-Smirnov test (KS-test) is used to optimize the model and obtain modified parameters. The modified method will be illustrated in detail in the following sub-sections.

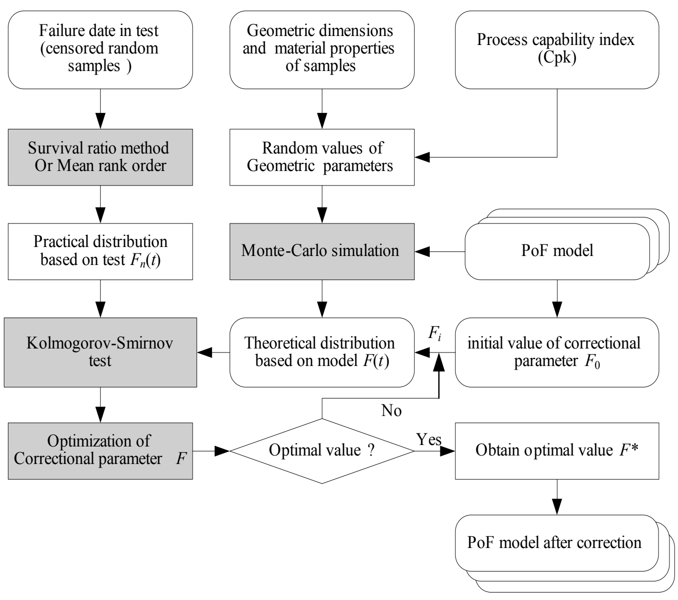

Fig. 1. The process of model modification method

3.1. Theoretical distribution based on model F(t)

Theoretical distribution function is the probability cumulative function of product failure. Determined by product failure mechanism beforehand, it can be determined by the following steps:

(1) According to the mean assessment of product geometric dimension and material properties, determine the initial value of modified parameter F_0 in the given PoF model.

(2) Obtain the random values of product geometric dimension and material properties through random samples, e.g., normal distribution. Calculate random values of product life through Monte-Carlo simulation according to the predefined PoF model and F_0.

(3) Determine theoretical distribution function $F(t)$ according to the random values of product life.

(4) Different theoretical distribution functions can be obtained according to different modified parameters. The optimum modified parameter corresponds to the most desirable theoretical distribution function. In this case, the degree of fitting between theoretical distribution function and practical distribution function will match best.

3.2. Practical distribution based on test $F_n(t)$

Reliability test for electronic product in practice usually uses censored random model, which has some deleted samples. These deleted samples can be the lost data for some reasons in the product process, or some data which are not product life data are inserted. When the total number of samples is very large, e.g., $n \geq 20$, practical distribution function $F_n(t)$ and reliability function $R(t)$ can be calculated by survival ratio method [1]. Specifically, a practical distribution function at t_i is given as follows:

$$F_n(t_j) = 1 - R(t_{i-1})S(t_j) = 1 - \prod_{j=1}^{i} S(t_j) \quad (2)$$

where $S(t_i)$ is survival probability of the product in (t_{i-1},t_i). $S(t_i)$ is a conditional probability and represents probability that the product functioning properly at t_{i-1} can continue to work at t_i. It can be calculated by

$$S(t_i) = \frac{n_s(t_{i-1}) - \Delta r(t_i)}{n_s(t_{i-1})} \quad (3)$$

where $n_s(t_{i-1})$ is the number of samples which operate properly at t_{i-1}. $\Delta r(t_i)$ is the number of samples failed in (t_{i-1},t_i). $n_s(t_i)$ can be obtained by

$$n_s(t_i) = n - \sum_{j=1}^{i} \left[\Delta r(t_j) + \Delta k(t_j) \right] \quad (4)$$

where n is the total number of samples and $\Delta k(t_j)$ is the number of deleted samples in (t_{i-1},t_i).

3.3. K-S test of censored random samples

The Kolmogorov-Smirnov test (KS-test) is used to determine whether two data sets differ significantly [1, 7]. The KS-test has the advantage that no basic assumption is necessary about the distribution of data. Therefore, K-S test between theoretical distribution and practical distribution can be undergone with limited failure data. The original hypothesis is as follows.

H: theoretical distribution function $F(t)$ = practical distribution function $F_n(t)$, K-S test has group characteristic. Considering the difference D_n between theoretical distribution and practical distribution in each point, the larger D_n is used to determine whether the hypothesis can be validated.

Test statistic can be constructed by using censored random samples:

$$T_0 = \sup_{t \leq t_0} \left| F_n(t) - F(t) \right| \quad (5)$$

where t_0 is the censored time of the test.

Further, denote by $R_c = nF(t_0)$ censored point, which is the theoretical failure number at censored time t_0. The criterion is

$$P\left\{ T_0 \geq T_{n,\alpha} \right\} = \alpha \quad (6)$$

where α is the significance level and $T_{n,\alpha}$ is critical value needed to be tested. $T_{n,\alpha}$ can be obtained by $T_{n,\alpha} = k/n$, where k can be obtained by checking " Reliability Test Table" [2] according to R_c and α. If test statistic T_0 satisfies $T_0 < T_{n,\alpha}$, the original hypothesis can be accepted, which means theoretical distribution and practical distribution are consistent .

4. Numerical example

Surface Mount Technology (SMT) has been widely applied in modern electronic products. Modified Coffin-Manson model can be used to evaluate thermal fatigue life of solder joints in Ball Grid Array (BGA). Generally speaking, failure physic models have some degree of similarities. Without loss of generality, 54-pin device of Plastic Ball Grid Array (PBGA) is chosen to validate the proposed modified method.

4.1. Test samples and preparation before the test

4 PCBs (Printed Circuit Boards) and 15 PBGA devices are prepared before the test. Solder of the 15 PBGA devices to the PCB and set up monitoring circuit of test samples are shown in Fig. 2. There are two monitoring circuits in each device and there are 30 monitoring circuits in total. Geometric dimensions and material properties of PCB and PBGA devices are shown in Table 1.

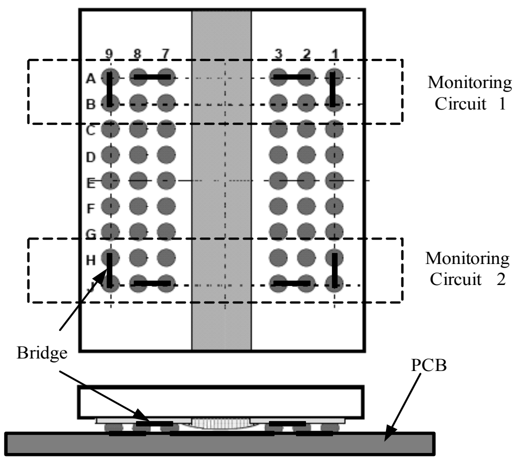

Fig. 2 Monitoring circuit with bridge

Tab. 1. Geometric dimensions and material properties of PCB and PBGA devices [3]

Parameters	Array dimension	Pitch (mm)	Diameter of solder ball (mm)	Height of Collapse solder ball (mm)
Mean value	54 balls	0.8	0.5	0.3
Upper and lower limits	(6×9)	±0.04	±0.05	±0.06
Parameters	Package Size (mm)	Package thick-ness (mm)	PCB marital and thermal expansion parameters (ppm/ºC)	thermal expansion parameters of Si (ppm/ºC)
Mean value	8×11	0.75	FR4/17	2.6
Upper and lower limits		±0.05		

4.2. Test condition and results

Temperature stress is the main environment stress which affects fatigue failure of PCB. In the test, high-low temperature cycle box is used to simulate the changing of environment stress. The typical temperature stress profile is shown in Fig. 3. In Fig. 3, The temperature cycle is 60 minutes, including 15 minutes resident in high temperature (125ºC) and 15 minutes resident in low temperature (–40ºC).

In the test, 4 PCBs are placed at the box and the function of circuits is in real time monitoring. In 1500 temperature cycles, there were 26 monitoring circuits failed, including 4 circuits which were confirmed as bridge failures and were deleted. The numbers of temperature cycles before failures in 30 monitoring circuits are shown in Table 2.

4.3. Fatigue life assessment model

On the basis of simplification and assumption, Engelmaier model, called as corrected Coffin-Manson model, is used to evaluate thermal fatigue life of electronic devices. Thermal fatigue life can be represented by the numbers of temperature cycles before failures caused by thermal fatigue fracture of solder joint. The following model is applicable to all types of BGA solder joints [8, 9].

$$\begin{cases} N_f = \dfrac{1}{2}\left(\dfrac{F}{2\varepsilon_f} \times \dfrac{L_D}{h}\left(\alpha_c \Delta T_c - \alpha_s \Delta T_s\right)\right)^{\frac{1}{c}} \\ c = -0.442 - 0.0006 T_{sj} + 0.0174 \ln\left(1 + \dfrac{360}{t_D}\right) \end{cases} \tag{7}$$

where N_f is thermal fatigue life (the numbers of temperature cycles before failures). ε_f is a Material constant and $\varepsilon_f = 0.325$ for eutectic solder materials, e.g., 63Sn37Pb. L_D is the effective length of the device and is half of external diagonal. h is the height of solder joint. α_c and α_s are the linear thermal expansion coefficients of devices and PCB, respectively. ΔT_c and ΔT_s are temperature cycle amplitudes of devices and PCB, respectively. T_{sj} is the mean value of cycle temperature and $T_{sj} = (T_{max} + T_{min})/2$. t_D is the residence time in high temperature. F is empirical correction coefficient of the model and recommended values range from (0.5~1.5) [9].

4.4. Model modification and results

Simulation is conducted in MatLab according to the above modified method and process. Geometric dimensions and material properties of PCB and PBGA devices are shown in Table 1. Due to the process level of samples in the test, let $C_{pk} = 0.33$ and a set of random values of geometric technical parameters are obtained in each sampling. Each value of modified parameter F corresponds to a group of random life. Repeat this process and theoretical distribution based on model F(t) can be obtained.

In the test, let censored random time of the test 1500 cycles and $n = 30$, according to steps discussed in section 3.1, $F(t_0)$ and $R_c = nF(t_0)$ are obtained. Let significance level $\alpha = 0.05$, and the $T_{n,\alpha}$ corresponding to each correctional parameter F is obtained. Compare test statistic T_0 with critical value $T_{n,\alpha}$, the correctional parameter which makes T_0 the smallest and $T_0 < T_{n,\alpha}$ at the same time is determined.

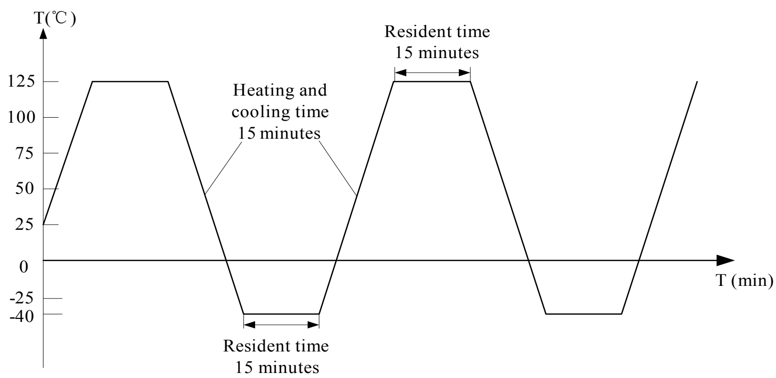

Fig.3 The typical temperature stress profile in the test

Table 2. Failure data of PBGA in the test [3]

Circuit Number	The number of cycles before failures	Circuit Number	The number of cycles before failures	Circuit Number	The number of cycles before failures
1	752	11	NF**	21	947
2	589 BD*	12	1098 BD*	22	1376
3	1411	13	1143	23	385
4	903	14	883	24	995
5	687 BD*	15	892	25	1269
6	773	16	931	26	NF**
7	1034	17	1452	27	467
8	1187 BD*	18	1328	28	NF**
9	1357	19	NF**	29	1132
10	994	20	871	30	635

BD*: Bridge Defect NF**: No Failure

4.4.1. Modification results of the model

According to the above simulation and K-S test, the optimized modified parameter corresponding to the case is calculated and F^* = 0.76 shown in Fig. 4. From the view of this point, the difference of theoretical distribution function (deep dotted line shown in Fig. 4) and practical distribution function (Solid line shown in Fig. 4) is the smallest and the K-S test is accepted (H = 0). In Fig.4, the distribution functions (shown in light dotted line) when F = 0.7 and F = 0.8 are given. It can be seen that the difference between two distribution functions is very large and the K-S hypothesis is rejected (H=1).

4.4.2. Modification results comparison

In practice, mean comparison method is often used to determine modified parameter, i.e., compare the mean value of test results of samples in accelerated life test with the prediction value of the model, and determine modified parameter. In the numerical example, using mean comparison method, modified parameter F_{avg} = 0.67. In [10], the recommended modified parameter of PBGA device F_{calce} = 0.54. In Fig. 5, Cumulative failure probability distribution curves corresponding to three correctional parameters are given. From Fig. 5, the K-S test with F_{avg} and F_{calce} can not be accepted (H=1). However, the K-S test with the correctional parameter F^* = 0.76 using the proposed method is accepted (H=0), which means that the prediction using the model with F^* has smaller difference with the practical result.

In addition, the PBGA samples used in [10] are the solder joint in the form of full area array, which is different with the samples used in this paper. It is one of the reasons causing difference of modified parameters. According to the practical use in the project, the samples in the form of non-full area array are chosen for study.

5. Conclusion

In this paper, according to the failure data in accelerated life test, PBGA solder thermal fatigue life assessment model is optimized and modified using the proposed modified method. From the result of the numerical example, the conclusions are given as follows:

1) After discrete process of parameters, the PoF model can be used to predict/assess reliability and obtain the confidence interval. However, the determination of modified parameter is critical for reliability prediction accuracy. The mean comparison method based on correctional parameter can not obtain precise prediction due to product uncertainty.
2) K-S test has group characteristic. In this paper, combining KS-test and Monte-Carlo simulation, a modified method of electronic device reliability prediction model with limited test failure data is presented. The prediction result has smaller difference with test result and this method can be applied into practical use caused by more accurate reliability prediction or assessment.

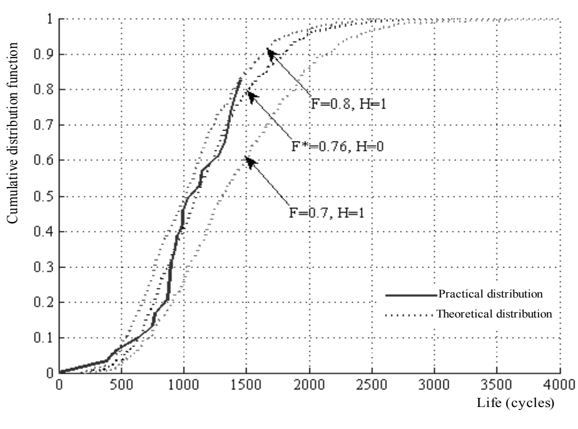

Fig. 4 Modification results of the model

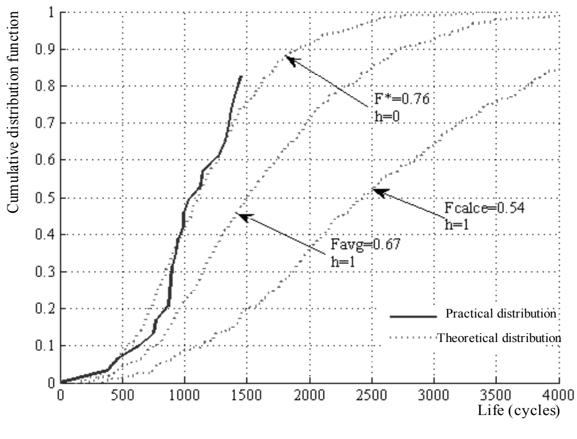

Fig.5. Comparison of modification results in different methods

3) The modified parameter using the proposed method can be used to predict reliability of other products of the same type in design phase, as well as assessing reliability and predicting failure in test phase and using phase.

4) When assessing reliability or predicting failures, the proposed method uses group data and can be applied in practical use, no matter how much the influence of product uncertainty.

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