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 Kolmogorowa-Smirnowa (testu K-S) i metody symulacji Monte Carlo, w niniejszej pracy zaprezentowano zmodyfikowaną metodę prognozowania niezawodności urządzeń elektronicznych, która hierarchicznie zgrupowana liczby danych testowych o uszkodzeniach. Ilorazową 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 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 fa-
failure physics process of electronic components, i.e., mechanical, electronic, 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 describes quantitatively the uncertainty of product process parameters. It can be calculated by [14]:

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

where $USL$ and $LSL$ are the upper bound and the lower bound of product process parameter criterion, respectively. $\sigma$ is the standard deviation and $\mu$ 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](image)

<table>
<thead>
<tr>
<th>Failure date in test (censored random samples)</th>
<th>Geometric dimensions and material properties of samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Survival ratio method Or Mean rank order</td>
<td>Random values of Geometric parameters</td>
</tr>
<tr>
<td>Practical distribution based on test $F_y(t)$</td>
<td>Monte-Carlo simulation</td>
</tr>
<tr>
<td>Kolmogorov-Smirnov test</td>
<td>Theoretical distribution based on model $F(t)$</td>
</tr>
<tr>
<td>Optimization of Correctional parameter $F$</td>
<td></td>
</tr>
<tr>
<td>$F$</td>
<td>$F_{opt}$</td>
</tr>
<tr>
<td>$C_{pk}$</td>
<td>Optimal value?</td>
</tr>
<tr>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>PoF model after correction</td>
<td>PoF model</td>
</tr>
</tbody>
</table>
### 3.1. Teoretyczna funkcja rozkładu na podstawie modelu F(t)

Teoretyczna funkcja rozkładu to prawdopodobieństwo integralowe funkcji product failure. Oznacza to, że product failure mechanism, wyliczonego przez algorithm failure, można wyznaczyć za pomocą następujących kroków:

1. Obliczenie średnią ocen produktowej geometrycznej dimension i materiałów, polegających na obliczeniu procentu mock-up, w wybranym modelu PoF model.
2. ODBC na losowe wartości geometrycznej dimension i materiałów, otrzymanych przez losowe próbki, np. normalne rozkładu. Obliczyć wartości losowych produktu life przez Monte-Carlo simulation according to the predefined PoF model and F(t).
3. Zbadanie rozkładu teoretycznego F(t) podstawiając do rzeczywistych wartości produktu life.

### 3.2. Praktyczna funkcja rozkładu na podstawie testu Fn(t)

Rozkład teoretyczny produktu w praktyce obliczany jest z użyciem censored model. Zawiera on niektóre ewentualne odpowiedzi. Ta próbka może być wykorzystana do ewentualnych powyższych projektów. Zawiera ona bardzo dużą liczbę próbek, np. n ≥ 20, funkcję rozkładu teoretycznego Fn(t) i reparametrizacji R(t) można obliczyć za pomocą metody przejściowego parametru [1]. Specyficznie, praktyczna rozkład produkcyjny, w danym t, jest obliczana za pomocą:

$$F_{0}(t) = 1 - R(t) = 1 - \sum_{j=1}^{t} S(t)$$

Gdzie S(t) to prawdopodobieństwo, że produkt działa w (t, t+1). S(t) jest prawdopodobieństwem, że product functioning properly at t, może kontynuować swoją pracę w t. Można to obliczyć podając

$$S(t) = \frac{n_{0}(t) - \Delta r(t)}{n_{0}(t)}$$

Gdzie n(t) jest ilością próbek, które działają dobrze w (t, t+1). Przykład jest dowolny z próbek, n(t) można obliczyć za pomocą

$$n_{0}(t) = n - \sum_{j=1}^{t} \Delta r(t) + \Delta k(t)$$

Gdzie n to całkowita liczba próbek, a Δk(t) jest ilością próbek, które nie są widoczne w (t, t+1).

### 3.3. KS-test dla censored random samples

Test Kolmogorov-Smirnov (KS-test) jest używany do określenia, czy dwa zestaw próbki różnią się znacząco [1, 7]. KS-test ma zaletę, że nie wymaga żadnych ewentualnych założeń. KS-test porównuje teoretyczny rozkład i praktyczny rozkład, a następnie, można przeprowadzić test z wykorzystaniem limitowanej ilości danych. Oryginalna hipoteza jest następująca.
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 (125°C) and 15 minutes resident in low temperature (−40°C).

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].

\[
N_f = \frac{1}{2} \frac{F}{2F_c} \frac{L_0}{h} (\alpha_c \Delta T_c - \alpha_s \Delta T_s) \left(1 - \frac{360}{T_0} \right)
\]

\[
c = -0.442 - 0.0006T_{min} + 0.0174 \ln \left(1 + \frac{360}{T_0} \right)
\]

where \(N_f\) is thermal fatigue life (the numbers of temperature cycles before failures), \(c\) is a Material constant and \(c = 0.325\) for eutectic solder materials, e.g., 63Sn37Pb. \(L_0\) is the effective length of the device and is half of external diagonal. \(h\) is the height of solder joint. \(\alpha_c\) and \(\alpha_s\) are the linear thermal expansion coefficients of devices and PCB, respectively. \(\Delta T_c\) and \(\Delta T_s\) are temperature cycle amplitudes of devices and PCB, respectively. \(T_{min}\) is the mean value of cycle temperature and \(T_{min} = (T_{max} + T_{min})/2\). \(T_0\) 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, \(F(t)\) and \(R = nF(t)\) are obtained. Let significance level \(\alpha = 0.05\), and the \(T_{s0}\) corresponding to each correctional parameter \(F\) is obtained. Compare test statistic \(T_{s0}\) with critical value \(T_{s0}\), the correctional parameter which makes \(T_{s0}\) the smallest and \(T_{s0} < T_{s0}\) at the same time is determined.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Array dimension</th>
<th>Pitch (mm)</th>
<th>Diameter of solder ball (mm)</th>
<th>Height of Collapse solder ball (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean value</td>
<td>54 balls</td>
<td>0.8</td>
<td>0.5</td>
<td>0.3</td>
</tr>
<tr>
<td>Upper and lower limits</td>
<td>(6×9)</td>
<td>±0.04</td>
<td>±0.05</td>
<td>±0.06</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Package Size (mm)</th>
<th>Package thickness (mm)</th>
<th>PCB marital and thermal expansion parameters (ppm/ºC)</th>
<th>thermal expansion parameters of Si (ppm/ºC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean value</td>
<td>8×11</td>
<td>0.75</td>
<td>FR4/17</td>
<td>2.6</td>
</tr>
<tr>
<td>Upper and lower limits</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Tab. 1. Geometric dimensions and material properties of PCB and PBGA devices [3]
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 $F_{calc} = 0.54$. 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 $F_{calc}$ 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.
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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6. References


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