Damage Degree analysis of storage failure modes for plastic encapsulated microelectronic devices

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Abstract. After long-term storage, plastic sealing devices must have good performance when installed on the whole machine. Identifying the risk of failure mode and taking preventive measures before failure can effectively improve storage reliability. To ensure the quality of military products, this paper studies the storage failure modes of plastic sealed micro-electronic devices, and uses the method of FMECA to calculate the damage degree of each failure mode and determine the key failure modes. The case analysis shows that the damage degree of failure mode is ranked as external lead corrosion, aging of packaging material, chip corrosion and bonding ball corrosion. The evaluation result accords with the actual situation of the method. The improved FMECA model can better deal with the relative importance of risk factors, improve the accuracy of risk ranking, and quantify risks more reasonably.

1. Introduction
Micro-electronic devices are microminiaturized electronic system chips and devices realized by micro-electronic technology, which determine the internal performance and performance of equipment. Packaging can avoid the destruction of devices by external mechanical forces and harmful environmental factors. Plastic packaging refers to the packaging of devices with materials such as resin. Studies show that more than 99% of microelectronic devices are packaged in plastic [1].

Plastic sealed micro-electronic devices are mainly composed of chip, bonding wire, lead frame, encapsulation resin and external lead. Because of the water absorption of plastic sealing materials, CET mismatch between materials and other problems, lamination and corrosion will occur [2]. For example, the potential storage failure modes of chips are chip corrosion, chip cracking and so on. The potential storage failure modes of bond wires are bond wire breakage, bond ball corrosion and so on. As an important strategic resource, the reliability of the system will be greatly reduced if the failure occurs in the whole machine or system. How to improve the storage reliability of plastic sealing devices has become one of the research focuses.

The improvement of plastic sealing devices has been mainly focused on plastic sealing materials and processes. Yang Xiulun proposed the selection of plastic sealing materials with moderate fluidity and other solutions [3]. Meng Bo et al pointed out that the optimization of the composition ratio of the plasticizer can solve the problem of lamination [4]. He Bing pointed out that the closer the coefficient of thermal expansion between materials is, the less failure occurs [5].

To sum up, existing studies lack a methodological perspective to quantify the risk of storage failure mode of plastic sealing micro-electronic devices. The plastic sealed microelectronic devices must have
good performance after long-term storage. In the case of limited resources, corresponding measures should be taken for key failure modes. FMECA is a reliability analysis method widely used in aerospace [6], ship [7] and other fields. In this paper, the improved FMECA method is used to determine the critical fault mode, which provides a basis for improving product reliability.

2. Methods
FMECA is a widely used reliability assessment method. The influence of potential failure modes that cause system failures is analyzed. Traditional FMECA by calculating the risk priority number (RPN), prioritize and failure mode of the worst failure mode for corrective measures [8]. However, traditional FMECA does not consider the weight of risk factors when calculating RPN, the product of different risk factor values might yield the same RPN, but the underlying risk profile is quite different.

To solve the above defects, many scholars have improved FMECA. LIU et al. improved the calculation method of RPN based on the relationship of hesitancy and fuzzy preference [8]. REZA F et al. combined FMECA with fuzzy analytic hierarchy process to obtain S, O and D weights [9]. Li H et al. used fuzzy theory and grey correlation theory to determine the priority of risk decision-making [10].

In this paper, FMECA was improved as follows: 1) The weights of S, O and D in FMECA are calculated by using order relation analysis method; 2) According to the index weight given by the experts in the order relation method, the weight of the experts is calculated by using the grey correlation analysis method; 3) The calculation method of risk priority coefficient in FMECA is improved, and the ranking of potential failure modes during storage of plastic sealed microelectronic devices is carried out to realize the health management of devices.

3. Improved FMECA model

3.1 The determination of bottom events evaluation criteria
Severity S describes the severity of the failure mode’s impact on the product. Degree O is generally used to describe the vulnerability of the site. Detection D reflects how easily failure modes can be detected. In this paper, detection is defined as the possibility of detecting failure modes using reliability analysis technology. RPN=S×O×D. The greater the RNP, the greater the risk.

| Severity S | Occurrence O | Detection D | Score |
|------------|--------------|-------------|-------|
| Loss of system function | Failure is inevitable | Failure modes cannot be detected | 10 |
| Impact on the system function is very serious | Failure usually occurs | Failure modes are almost impossible to detect | 9 |
| System functions are seriously affected | Failures occur frequently | The probability of detecting a failure mode is extremely low | 8 |
| System functions are adversely affected | More failures occur | The probability of detecting failure modes is relatively low | 7 |
| System functions are moderately affected | Failures occur relatively frequently | Low probability of failure mode detected | 6 |
| The impact on system functions is low | Failure occurs occasionally | The probability of failure mode detected is moderate | 5 |
| System functions are slightly affected | Failures occur relatively infrequently | High probability of failure mode detected | 4 |
| Very low impact on system functions | Less failure | Detect the probability of failure mode is on the high side | 3 |
The impact on system functions is negligible
Failure is rare
The probability of failure modes being detected is very high

The system is not affected
Failure is not possible
Definitely detect a failure mode

3.2 The order relation method is used to calculate the weight of risk factors
The group judgment method of order relation analysis refers to that multiple experts are invited to make comparative judgment on the same problem at the same time, and the judgment results of various experts are integrated to reduce the interference of human judgment.

3.2.1 Problem description
For a group evaluation problem, it is assumed that the evaluator set is \( S = \{s_1, s_2, \ldots, s_n\} \), the set of evaluation indicators is \( X = \{x_1, x_2, \ldots, x_m\} \), the set of evaluato weights is \( \Omega = \{\mu_1, \mu_2, \ldots, \mu_n\} \), and \( \sum_{k=1}^{m} \mu_k = 1 \), \( j = 1, 2, \ldots, m; k = 1, 2, \ldots, n \).

3.2.2 Calculation of weight
Step 1: Determine the order relationship of evaluation indexes according to G1 method
If the importance of the evaluation index \( x_a \) is greater than or equal to that of a criterion, remember as \( x_a \geq x_b \), \( x_a \in X \). If the indicators \( x_1, x_2, \ldots, x_m \) has a relation with respect to a criterion \( x_1 > x_2 > \ldots > x_m \), the order relation among evaluation indexes is established.

Step 2: Determine the ratio of relative importance between adjacent indicators
Expert K's judgment of adjacent indicators inter-importance degree can be expressed as
\[ r_{lb} = \frac{w_{k(b-1)}}{w_{kb}} \]

Table 2 Reference table of \( r_b \)

| \( r_b \) | Instructions |
| --- | --- |
| 1.0 | Indicators are as important as indicators \( x_{b-1} = x_b \) |
| 1.2 | Indicators are slightly more important than indicators \( x_{b-1} > x_b \) |
| 1.4 | Indicators are obviously more important than indicators \( x_{b-1} > x_b \) |
| 1.6 | Indicators matter more strongly than indicators \( x_{b-1} > x_b \) |
1.8 Indicators $x_{b-1}$ are more important than indicators $x_b$

Step 3: Calculate the weight distribution of each expert to the evaluation index
If expert $K$ gives $r_{kb(b-1)} > 1/r_{kb}$, then the weight of the $m$ indicator is:

$$w_{km} = 1/1 + \sum_{k=2}^{m} \prod_{i=1}^{k} r_i$$  \hspace{1cm} (2)

Step 4: Comprehensive weight of each evaluation index

$$w_j = \frac{1}{n} \sum_{k=1}^{n} w_{kw}$$  \hspace{1cm} (3)

3.3 Grey correlation method is used to calculate expert weight
G1 method is a quantitative method to describe the trend of system change. The specific calculation steps are as follows.

Step 1: Selective reference sequence

$$x_{oj} = (w_1, w_2, \ldots, w_n)$$  \hspace{1cm} (4)

Step 2: Calculate the difference sequence

$$\Delta = |x_{oj} - x_{kj}|$$  \hspace{1cm} (5)

Step 3: Calculate the grey correlation coefficient

$$\delta_{ij} = \frac{\min_j \min_k |x_{oj} - x_{kj}| + \rho \max_j \max_k |x_{oj} - x_{kj}|}{|x_{oj} - x_{kj}| + \rho \max_j \max_k |x_{oj} - x_{kj}|}$$  \hspace{1cm} (6)

Step 4: Calculate the grey correlation degree

$$r_{ij} = \frac{\sum_{j=1}^{n} \delta_{ij}}{n}$$  \hspace{1cm} (7)

Step 5: Calculate expert weights

$$\mu_k = \frac{r_{kj}}{\sum_{j=1}^{k} r_{kj}}$$  \hspace{1cm} (8)

3.4 Failure mode sorting
Failure modes are ranked from large to small according to the risk priority index $RPN$.

$$RPN = \sum_{k=1}^{n} \sum_{j=1}^{3} w_k (w_1 S_{kj} + w_2 O_{kj} + w_3 D_{kj})$$  \hspace{1cm} (9)

4. The example analysis
In order to prove the practicability of the method mentioned above, an example analyzes the failure mode risk of a certain type of plastic sealed microelectronic device.

4.1 Brief introduction of a model of plastic sealed microelectronic device

4.1.1 Device information
1) Lead-tin eutectic welding is used in SMT process, and the lead frame is made of Cu.
2) Aluminum wire wedge welding is adopted for packaging process, and the welding quality of internal and external bonding points is good.
3) The whole product is completely sealed by epoxy resin molding plastic, the matrix is epoxy resin,
the curing agent is phenolic resin, and other components are mixed in a certain proportion.
4)  Lead wire tin plating, coating quality is good.
5)  The passivation layer of the chip is silicon oxide, and good process without defects.
6)  The encapsulation of the chip is well sealed.

4.1.2 Storage environment and failure mode
The main stress of this type of microelectronic device in actual storage environment is temperature, humidity, day and night temperature change, etc. The main failure modes are chip corrosion, packaging material aging, bonding ball corrosion and external lead corrosion.

4.2 The calculation of RPN
Group evaluation should select experts with certain professional knowledge and rich experience. In consideration of the accuracy of the results, five influential experts in the field of plastic sealed microelectronics devices were employed for this study. Table 3 shows the scoring results, and Table 4 shows the weight results of risk factors.

Table 3  Analysis diagram of FMECA for a certain type of plastic sealed microelectronic device

| Failure mode             | Expert1 | Expert2 | Expert3 | Expert4 | Expert5 |
|-------------------------|---------|---------|---------|---------|---------|
| Chip corrosion          | S       | O       | D       | S       | O       |
| Aging of packaging material | 4   | 5       | 2       | 5       | 3       | 4       | 6       | 3       | 4       | 6       | 2       | 5       | 4       |
| Bonding ball corrosion  | 5       | 3       | 1       | 6       | 4       | 1       | 7       | 3       | 1       | 6       | 2       | 1       | 5       | 4       |
| External lead corrosion | 8       | 7       | 1       | 9       | 8       | 1       | 7       | 7       | 1       | 9       | 6       | 1       | 7       | 8       |

Table 4 Order relation of risk factors, relative importance ratio of adjacent factors and index weight

| Expert | Order relation | The ratio of importance | Index weight value |
|--------|----------------|-------------------------|--------------------|
| 1      | X₁>X₂>X₃       | 1.2                     | 0.41               |
| 2      | X₁>X₃>X₂       | 1.0                     | 0.35               |
| 3      | X₂>X₁>X₃       | 1.2                     | 0.41               |
| 4      | X₃>X₂>X₁       | 1.4                     | 0.43               |
| 5      | X₃>X₁>X₂       | 1.4                     | 0.41               |

The weight of each risk factor is Wj=(0.35, 0.38, 0.27). The correlation coefficient matrix is

\[
\begin{bmatrix}
0.5 & 0.6 & 0.33 \\
0.6 & 0.43 & 0.75 \\
0.33 & 0.75 & 0.55
\end{bmatrix}
\]

The correlation degree is r=(0.48,0.73,0.62,0.48,0.48). The expert weight is \( \mu_k=(0.172,0.262,0.222,0.172,0.172) \). The improved risk priority number is RPN=(3.8, 4.2, 3.6, 5.8).

Table 5  Comparison of FMECA

| Failure mode             | Traditional FMECA | The improved FMECA |
|-------------------------|-------------------|--------------------|
| Chip corrosion          | 21.6              | 3                  |
| Aging of packaging material | 55.0            | 2                  |
| Bonding ball corrosion  | 21.6              | 3                  |
| External lead corrosion | 57.4              | 1                  |

4.3 Result
Through comparison, it can be seen that: 1) The same RPN appears in the traditional FMECA, which cannot be compared and the evaluation accuracy is low. The evaluation accuracy is improved after
improvement. 2) The risk of chip corrosion is higher than that of bonding ball corrosion, because the former failure has a greater impact on the storage reliability of plastic sealed microelectronic devices than the latter, and experts agree that the probability of chip corrosion being detected is slightly lower. 3) Both conventional and modified FMECA have shown that external lead corrosion is the most risky failure mode. This is due to the capillary effect makes the water vapor in inherent coating metal coating surface coating, further lead to corrosion of lead. The evaluation result is consistent with the actual situation.

4.4 Suggestions for improving storage reliability
Improve the composition of plastic sealing material and improve the performance of plastic sealing. The purity of plastic can be improved by adding ion trapping agent to the plasticizer. Particle filled resin matrix composites have the advantages of improving dielectric properties and are potential materials for improving plastic sealing properties.

For example, in the chip pin daub three anti paint to prevent oxidation of coating and moisture from the pin gap into the chip; Process defects can be reduced by sealing the solder ball with a moisture resistant coating before packaging after welding.

Strengthen storage environment control, reduce environmental stress. During the storage period to take strict protection measures, in the specified conditions of storage, at the same time to develop inspection plans, regular or irregular inspection of the storage environment.

5. Conclusion
Failure mode hazard analysis is one of the means to improve device performance and quality. As an effective tool for systematic risk analysis, FMECA model can directly and concretely evaluate the risk, compare high-risk failure modes, and find out what's behind them, so as to prevent future failure.

In this paper, the order relation analysis method and grey relation analysis method are combined to modify the RPN to ensure the weight of important risk factors, reduce the subjectivity to a certain extent, and analyze the risk of the storage of plastic sealed microelectronic devices more accurately, which provides a basis for improving the storage reliability.

In the future research, the risk analysis model of deeper dimension can be established by combining various risk analysis techniques, so as to further improve the fault mode risk analysis of plastic sealed microelectronic devices, and make a more comprehensive analysis of the formation of storage failure process, change track and multi-field coupling effect, which can provide help to improve the packaging process and storage reliability of devices.

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