Morphological analysis of optocoupler accelerated degradation test data

Xuangong Zhang1*, Xihui Mu2 and Huizhi Li1

1 Department of Ammunition Engineering, Shijiazhuang Campus, Army Engineering University, Shijiazhuang, Hebei 050003, China
2 Institute of Special Service, Army Research Institute, Shijiazhuang, Hebei 050003, China
*Corresponding author’s e-mail: 15132497756@163.com

Abstract. As one of the key components inside the seeker of a certain type of guided missile, optocoupler has attracted much attention for its long storage reliability. In order to accurately assess its storage life, an accelerated degradation test was performed on the optocoupler. Before the processing of the test data, it is necessary to carry out data shape analysis to verify whether the failure mechanism caused by long storage is consistent with the failure mechanism caused by the test. There are many literatures that use mathematical methods to conduct a lot of research on the consistency mechanism of failure mechanism. The method of this paper avoids the lengthy and complicated mathematical derivation, starting from the data morphology analysis, and relies on the failure mechanism obtained by the failure mechanism verification test. The key conclusion that the failure mechanism has not changed is obtained. The method proposed in this paper is portable, and it can provide some reference for the analysis of experimental data of similar products.

1. Description of the test and explanation of the previous conclusions

According to the previously scheduled scheme, the accelerated degradation test uses 10 samples, and the optocoupler is heated in a four-stress step-acceleration degradation test with unequal measurement times. The four stress levels were 70°C, 90°C, 110°C and 120°C, respectively, with 23 measurements, 11 times, 10 times and 9 times. Test parameters were determined as forward voltage drop, reverse breakdown voltage, leakage current, and flip voltage. The overall test time was 424 hours and was tested every 8 hours. The basic test result is that the No.3 optocoupler fails after heating for 408 hours in the fourth stress stage, and the flip voltage cannot be measured; the No.1 optocoupler fails after heating for 424 hours in the fourth stress stage, and the flip voltage cannot be measured. The remaining optocouplers did not fail. From the overall data situation, the degree of change in forward voltage drop, leakage current, and breakdown voltage is relatively intense, and the change in the flip voltage as an indicator parameter is not large. In the next step, data morphological analysis was performed on each parameter of each sample to further obtain its changing trend, failure reason and failure mechanism. Figure 1 is a scatter plot of leakage current over time, where the horizontal axis represents time in hours and the vertical axis represents leakage current in nanoamps. Three vertical lines indicate the division of different temperature stress stages. Due to space limitations, the remaining scatter plots are no longer given.
Through the previous failure mechanism verification test, the following conclusions were obtained:

1. There are two failure mechanisms for optocoupler, namely open circuit failure and leakage failure, respectively. Open circuit failure includes gradual open circuit failure and sudden open circuit failure.
2. The reason for the gradual open circuit failure and the sudden open circuit failure is that the bonding point lead is separated from the bonding point, which is caused by the defect of the bonding process or the poor quality of the transparent adhesive; the leakage failure is caused by the movable ion on the chip to form a surface leakage channel.
3. The key performance parameters are two, namely forward voltage drop and reverse leakage current.
4. The forward voltage drop is affected by two opposite mechanisms, one is an open circuit to increase it, and the other is an increase in leakage current to reduce it. The following data morphological analysis requires these conclusions, so they are given here in advance.

2. Statistical analysis of initial values of samples

The degree of consistency of the sample is reflected in the degree of dispersion of the initial value. In general, the smaller the dispersion of the initial values, the better the consistency of the samples[1]. A frequency histogram was established for the four parameters of the 10 samples, and the mean and standard deviation of the initial values were calculated.

| Parameter                  | μ     | σ      | |σ/μ|
|----------------------------|-------|--------|-----|
| forward voltage drop       | 2.227 | 0.0485 | 0.0218 |
| leakage current            | 25.18 | 58.4086| 2.3196 |
| breakdown voltage          | 78.22 | 11.2392| 0.1437 |
| flip voltage               | -0.3697| 0.0509 | 0.1376 |

Through Table 1, the following conclusions can be drawn: (1) The initial value of forward voltage drop is concentrated, although the initial value of leakage current is concentrated, but its polarization is more serious than the forward voltage drop, and the initial value of breakdown voltage and flip voltage is more uniform. (2) |σ/μ|flip voltage < |σ/μ|breakdown voltage, indicating that the initial value of the flip voltage dispersion is lower than the initial value of the breakdown voltage, but due to they are greater than 0.1, indicating that the initial value of the inversion voltage and the initial value of the breakdown voltage are also relatively discrete with respect to the initial value of the forward voltage drop. (3) The initial value of the leakage current is the one with the largest change among the four parameters, and the|σ/μ|leakage current is >1, and the dispersion is also the largest.

The above three conclusions indicate that the consistency of the samples is not very satisfactory. The poor degree of consistency reflects the need to improve the production process level of the product. On the other hand, it may induce multiple failure mechanisms at the same time, which increases the difficulty of life assessment.
3. Construction of parameter data morphology analysis table and parametric morphological analysis

3.1. Construction of parameter data morphology analysis table

Before the data shape analysis of the forward voltage drop, leakage current, breakdown voltage and flip voltage, respectively, the regression function and the `rcoplot` function in matlab are used to perform the residual analysis to eliminate the abnormal data points, and then through linear fitting[2]:

\[ y = k_1x + k_2 \]

the general trend of the curve is determined. When the trend of the data is upward, there is \( k_1 > 0 \), otherwise \( k_1 < 0 \). Obviously, when the absolute value of \( k_1 \) is larger, the trend of data changes is larger, and vice versa. In addition, the maximum point and the minimum point of the entire curve are obtained, and the change trend of the curve and the degree of oscillation are assisted by judging the difference between the maximum point and the minimum point and the respective positions. Due to the content of the table, due to space, this paper only gives the data morphology analysis table of forward pressure drop.

| Morphological characteristics | \( k_1 \)       | \( k_2 \)       | Minimum point | Maximum point | Overall trend |
|-----------------------------|----------------|----------------|---------------|---------------|--------------|
| 1                           | 4.747 \times 10^{-5} | 2.221          | (0,2.2)      | (360,2.33)   |↗            |
| 2                           | 1.691 \times 10^{-5} | 2.205          | (16,2.19)    | (320,2.23)   |↗            |
| 3                           | -1.775 \times 10^{-4} | 2.349          | (288,2.21)   | (40,2.41)    |↘            |
| 4                           | -1.016 \times 10^{-5} | 2.263          | (0,2.21)     | (152,2.3)    |↗            |
| 5                           | 1.96 \times 10^{-5}  | 2.198          | (96,2.19)    | (312,2.22)   |↘            |
| 6                           | 1.703 \times 10^{-5} | 2.22           | (168,2.21)   | (336,2.24)   |↗            |
| 7                           | 1.626 \times 10^{-5} | 2.205          | (216,2.22)   |               |↗            |
| 8                           | 5.241 \times 10^{-6} | 2.221          | (112,2.21)   | (320,2.24)   |↗            |
| 9                           | 5.947 \times 10^{-6} | 2.221          | (208,2.21)   | (312,2.24)   |↗            |
| 10                          | 9.216 \times 10^{-6} | 2.247          | (2,2)        | (64,2.31)    |↗            |

3.2. Parameter morphology analysis and failure mechanism verification

Since the sample has two forms of degradation failure and sudden failure in the failure mechanism verification test, the samples of the formal test are roughly divided into two groups according to the degradation failure and the sudden failure[3]. A significant feature of degradation failure is a significant increase in leakage current, from nA level to \( \mu \)A level. Therefore, according to the data shape analysis table in the previous section, the 1st, 2nd, 3rd, 4th, 5th, and 10th are grouped into one group, and the 6th, 7th, 8th, and 9th are divided into another group.

First, the parameter of the inversion voltage is analyzed. Among the 10 samples, 9 of the inversion voltages are in a downward trend, and one has an upward trend (sample No. 9). The flip voltage is the only parameter with a failure threshold of -1.8V. However, these two trends are very weak, and the magnitude of \( k_1 \) is between \( 10^{-5} \) and \( 10^{-3} \), and its upward trend is weaker than the downward trend. The maximum difference between the maximum and minimum values is 0.039V (sample No. 4), and the minimum difference is 0.005V (sample No. 9). According to parameter data morphology analysis table, the average value of the inversion voltage is -0.361V. Therefore, flipping the voltage does not characterize the change in optocoupler performance. It is only used as an indicator to reflect the failure of the optocoupler.

Next, the breakdown voltage is analyzed as a parameter. Among the 10 samples, the trend of breakdown voltage showed a polarization. The breakdown voltages of samples 1, 2, 3, 4, 5, and 10 all showed a downward trend, that is, \( k_1 < 0 \), while samples Nos. 6, 7, 8, and 9 were opposite, and all had
an upward trend, that is, $k_1 > 0$. Comparing the morphological analysis table, it can be seen that the data pattern of the breakdown voltage of samples 1, 2, 3, 4, 5, and 10 is roughly opposite to the data pattern of the leakage current, and Table 3 is the correlation coefficient table.

**Table 3 Correlation coefficient between leakage current and breakdown voltage**

| Correlation coefficient | 1   | 2   | 3   | 4   | 5   | 6   |
|-------------------------|-----|-----|-----|-----|-----|-----|
|                         | -0.9637 | -0.9315 | -0.9978 | -0.9578 | -0.9795 | -0.9479 |

As shown in the above table, the breakdown voltage of samples 1, 2, 3, 4, 5, and 10 has a strong negative correlation with the leakage current\(^4\), which is consistent with the results observed in the failure mechanism verification test, that is, leakage current’s dramatic increase is the key cause of the breakdown voltage.

The breakdown voltages of samples Nos. 6, 7, 8, and 9 all have an upward trend. Compared with $k_1$ of samples 1, 2, 3, 4, 5, and 10, the absolute value is smaller than the $k_1$ of the latter. There are approximately 1 to 2 orders of magnitude difference. Although from this point of view, the rising trend of the breakdown voltage is weaker than its downward trend, the $k_1$ of its rising trend is still 1-2 orders of magnitude higher than the trend of the inverted voltage. Moreover, all four samples have an upward trend, so this is not caused by chance. The reduction in breakdown voltage was previously determined and verified by analytical calculations due to the sharp increase in leakage current. According to the data shape analysis table, all the leakage currents $k_1$ are greater than 0. Therefore, for the above two reasons, the increase of the breakdown voltage is not caused by the leakage current. At the same time, the breakdown voltage of samples Nos. 6, 7, 8, and 9 increases while the forward voltage drop increases. Xiao Shiman and Liu Xin pointed out that when the conductive adhesive is poorly bonded, the forward voltage drop and the reverse breakdown voltage will rise synchronously\(^5,6\). Therefore, the breakdown voltage of the samples Nos. 6, 7, 8, and 9 was caused by poor adhesion of the conductive paste.

Finally, the parameter of forward pressure drop is analyzed. The forward pressure drop is affected by two opposite mechanisms. According to the analysis results of the bottom test, the gradual open circuit failure will increase the forward voltage drop, and the leakage current will reduce the forward voltage drop. When the two mechanisms act simultaneously, the mechanisms will compete with each other, and the final curve trend will show a trend of strong mechanism. Among the 10 samples, the forward pressure drop of samples 1, 2, 5, 6, 7, 8, 9, and 10 produced an upward trend. Among them, the breakdown voltage of samples Nos. 6, 7, 8, and 9 also rises synchronously. The specific reason has been given in the foregoing, that is, the conductive adhesive is poorly bonded, which is a kind of gradual open circuit failure. The forward pressure drop of samples 1, 2, and 5 also showed an upward trend, but the leakage current of these three samples showed a large change trend, and the increase of leakage current would decrease the forward voltage drop. Therefore, these three samples must have a mechanism of progressive open-circuit failure to increase the forward voltage drop, and this mechanism is stronger than the forward voltage drop reduction mechanism caused by leakage current.

The forward pressure drop of samples No. 3 and No. 4 is special because the forward pressure drop of both is a downward trend. But the downward trend of the two is not caused by the same mechanism. First, analyze sample No. 3. The initial value of forward pressure drop of sample No. 3 was the highest among all samples, and the mean value of forward pressure drop was around 2.22V, but the initial
value of forward pressure drop of No. 3 was 2.36V. The forward pressure drop curve of sample No. 3 was always oscillating, and the absolute value of $k_1$ was the largest in the forward pressure drop curve of 10 samples. The initial value of the forward voltage drop of sample No. 3 differs from the minimum value by 0.15 V, which is obviously not only due to leakage current. Sample No. 3 was the first of the 10 samples to fail. It was tested for forward current and found that it can only withstand a current of about 500 $\mu$A. Once this value is exceeded, the current representation quickly returns to zero. Apparently there is an open circuit inside sample No. 3. However, this open circuit is not a gradual open circuit. The gradual open circuit will gradually increase the forward voltage drop, and the failure caused by the gradual open circuit will be able to withstand the current to the mA level\cite{7}. Obviously this is a sudden open circuit. The reasons for sudden open circuit have been pointed out before, including poor bonding process or broken connection lines. There is a case in which the bonding process is poor, that is, the conductive adhesive is not positioned properly, which may cause poor contact between the lead gold ball and the electrode, thereby causing poor current expansion\cite{9}. When the temperature rises, the glue gradually overflows, increasing the contact between the lead gold ball and the electrode, resulting in a decrease in the forward voltage drop\cite{9}. However, after the rubber overflows, the bond strength is lowered, and the bond strength is lowered, causing the lead to come off the electrode, thereby causing a sudden open circuit\cite{10}. Therefore, sample No. 3 was actually caused by a sudden open circuit failure. The forward pressure drop of sample No. 4 also showed a downward trend, but the downward trend was weak. As mentioned above, a sharp increase in leakage current causes a decrease in forward voltage drop. It is clear that the forward pressure drop of sample No. 4 is affected by this mechanism.

4. Conclusion
The samples that failed in this test belong to the sudden open circuit failure. There are two specific manifestations of sudden failure: gradual open circuit failure and sudden open circuit failure. Among them, the No. 3 sample belongs to the sudden open circuit failure, and the No. 1 sample belongs to the gradual open circuit failure. Since the two can be attributed to the same failure mechanism, that is, open circuit, the two forms of expression are uniformly summarized as sudden open circuit failure. The consistency level of the sample is not satisfactory, and the production process needs to be improved. Half of the products in this test produced degraded characteristics. The degradation characteristics are consistent with those observed during the bottom test, and the leakage current changes drastically. The inflection points were observed in samples 1, 2, 4 and 5, which were consistent with the mechanism explanation of the movable ion pollution given by the bottom test. There are two failure modes in the sample, so the time of failure is determined by different mechanisms and ultimately determined by the strong mechanism. Different failure mechanisms do not necessarily occur simultaneously on a single sample. For example, the leakage currents of samples Nos. 6, 7, 8, and 9 do not change drastically. When different failure mechanisms occur in the same sample, the mechanisms compete with each other, but the strength is random and varies from sample to sample.

References
[1] Mou S S, Wang L L. Accelerated Life Experiment [M]. Beijing: Science Press, 1995.
[2] Lu C J, Meeker W Q. Using degradation measures to estimate a time-to-failure distribution[J]. Technometrics, 1993:161-174.
[3] Tang S J, Guo X S, Zhou Z F. Modeling and Residual Life Estimation of Step Stress Accelerated Degradation Test[J]. Journal of Mechanical Engineering, 2014, 50(16): 33-39.
[4] Liu J. Research on step-stress accelerated degradation test of electrical connector[D]. Hangzhou: Ph.D. Thesis of Zhejiang University, 2013:20-28.
[5] Xiao S M. Optocoupler Package and Related Failure Mechanisms[J]. Semiconductor Technology, 2011, 36(4): 328-330.
[6] Liu X. Research on Common Failure Modes and Failure Mechanism of LEDs[C]// The 15th
Annual Conference on Reliability, 2010, 122-126.

[7] Si F H. Analysis of Several Common Causes of LED Lamp Failure [J]. Electronic Quality, 2007, 9: 13-14.

[8] Yang S H, LI K L. Analysis of long-term storage degradation characteristics of optocouplers[J]. Electronics Reliability & Environmental Testing, 2013, 31(2): 27-30.

[9] Li H Y, Jin L, Chen C X et al. Long-term storage life of transistor output optocouplers[J]. Semiconductor Optoelectronics, 2014, 35(2): 230-232.

[10] Gao C, X Y Y, Yang D M. Research on storage life evaluation method of plastic encapsulated optocoupler based on POF[J]. Electronic Test, 2018, 2:45-46.