Storage Failure Mechanism Analysis and Reliability Improvement Measures for Electromagnetic Relay

Zhaobin Wang*, Weiyan Li*, Kangning Chen, Zhen Li and Shang Shang

School of electronic information, Jiangsu University of Science and Technology, Zhenjiang, China

E-mail: wangzb@just.edu.cn; 1825339708@qq.com

Abstract: In order to solve the problem of unknown cause of parameter degradation and incomplete failure mechanism, and to obtain the data support required for the storage life evaluation of the whole machine system, a certain type of electromagnetic relay was selected for accelerated storage degradation test. The failure mode, the law and mechanism of electrical parameter change under storage condition were studied. On this basis, the improvement measures of relay reliability are put forward, which is of certain significance to improve the reliability of electromagnetic relay and system.

1. Introduction
Electromagnetic relay is an electronic device which uses low voltage and small current to control high voltage and large current [1]. It is widely used in the field of automatic control. In power electronic devices and systems, relay is often used as the final executive part of control system to control the action of the system. In the national defense weapon equipment system, the relays are mostly in the state of storage [2]. Therefore, it is necessary to study the reliability of the relays in the storage process to meet the requirements that whenever needed.

The failure of storage relay generally includes three elements: environmental stress, failure mode and failure mechanism [3]. At present, the research on the storage failure mechanism of electromagnetic relay is not very comprehensive, and the improvement design measures for the failure mechanism are also very few. In view of this, this paper carried out accelerated storage test, focused on the failure mode in the experiment, and put forward the improvement measures.

2. Accelerated storage degradation test of relay

2.1 Overall structure of accelerated storage test
There is no large current flowing through the relay during storage, so the test storage parameters are different from the working parameters. Most of the existing relay parameter testing systems are based on the working state of the relay [4], and few of them have studied the storage state parameter. Among them, Wang Z and others proposed a relay accelerated storage experimental system in reference [3]. This storage degradation test system can test the contact current of up to 40 relay samples under four different temperature stresses. Resistance and time parameters (pull-in time, release time, overrun time, bounce time, etc.) are detected and analyzed with high precision and automation. Later, many scholars used this system to conduct accelerated storage experiments. For example, in literature [5], Wang Z et al. used this system to study the pick-up time model of aerospace relay. However, there are few researches on the changes of voltage parameters, mechanical parameters and their causes. It is difficult to exclude that if these parameters have an important impact on the storage performance of relays. Based on this, this paper will study the relationship between relay failure and performance degradation parameters such as coil resistance, contact resistance, action/release voltage, action/release time, etc. These parameters need to be tested first. Based on the references [5], the design is improved to add a module that can specifically test voltage parameters. It is expected that more parameters related to performance can be tested. The overall structure of the system is shown in figure 1.

![Figure 1. Overall structure of accelerated storage test.](image)

2.2 Voltage parameter test unit

According to the corresponding standards, the pull-in (action) voltage test should start from zero until the relay acts, and record the voltage at this time as the action value (voltage). When testing the release voltage, first add rated voltage to the coil, then gradually reduce the voltage until all contacts return
to the de-excited state, and record the voltage value at this time as the specified release value (voltage). The step function of voltage as shown in figure 2 is used to test the specified action voltage and release voltage.

![Voltage Parameter Measurement](image)

**Figure 2.** Step function of voltage parameter measurement.

The measurement steps of voltage parameters are as follows:
- When the step rises to the specified action value (voltage), the contact shall be converted and all normally open contacts shall be closed.
- Step up to rated coil voltage.
- Step down the voltage to the specified holding value (voltage), and the normally open contacts must be kept closed.
- Step down the voltage to the specified release value, all contacts shall be converted and all normally closed contacts shall be closed.
- Step down the voltage to zero.

According to the above principle, the voltage parameter module is designed. Figure 3 is the voltage parameter testing unit. The output voltage of the relay is detected by Hall sensor, and then the voltage following circuit composed of RC low-pass filter and operational amplifier is sent to AD port of ARM processor.

![Voltage Parameter Test Unit](image)

**Figure 3.** Voltage parameter test unit.

The software part is ARM programming for voltage parameter testing. The algorithm flow chart of the pull-in/release voltage is shown in figure 4.
3. Degradation trend of test parameters

Through statistical graph analysis, the degradation trend of each data was analyzed. Among them, coil resistance and contact resistance showed a trend of decreasing and increasing with the increase of storage time and temperature stress respectively, which were sensitive parameters. As a sensitive parameter, the operating voltage decreases slowly with the increase of storage time and temperature stress. According to the overall trend diagram of time parameters with the increase of storage time and temperature stress, the degradation trend of relay action and release time with the storage time increasing is not significant and the degradation is not sensitive. The relay action and release bounce time of the relay have strong fluctuation, great randomness in the storage process and low trend, so it is not considered as the key degradation parameter of the test. The experimental data are shown in figure 5, and only the trend charts of the sensitive parameters under four temperature stresses are given. Among them, at 210℃, the contact resistance in the later period exceeds the limit seriously, which affects the observation of the degradation trend of the contact resistance at the other three temperatures. So it is not shown in the trend diagram.

Figure 4. Algorithm flow chart of pull in / release voltage.
4. Failure tree analysis

4.1 Excessive contact resistance

It can be seen from figure 5 (b) that the contact resistance seriously exceeds the standard or even fails in the later stage of the test. The relays in the accelerated degradation test are all balanced armature structure, belonging to 1/2 crystal cover series. According to the structural characteristics of this series of relays, without considering the design defects, the fault tree of over standard contact resistance (contact not conducting) is shown in figure 6.

![Fault tree of over standard contact resistance](image)

**Figure 6.** Fault tree of over standard contact resistance.

- Rough surface or mechanical damage of relay reed

  From the microscopic point of view, when the moving and static reeds contacts each other, only a few protruding contact points have real contact, and only a part of conductive spots can conduct electricity. If the roughness of the reed surface is poor, the number of pits at the contact position will increase correspondingly, and the number of contact bumps will reduce accordingly, that is, the current conduction path will be reduced, and the contact resistance value of the relay will also increase accordingly. It can be seen from the SEM pictures of the reed in figure 7 that the appearance quality of the relay reed is good except for the imprint at the contact position, and there is no rough or obvious mechanical damage on the surface of the relay. Moreover, according to the test results of the initial state of the relay, the contact resistance has good consistency and meets the requirements of the
standard. Therefore, the factors of surface roughness and mechanical damage of the reed can be ruled out.

**Figure 7.** Scanning morphology of reed under electron microscope.

- Oxide film pollution on reed surface
  
  When the sealed relay of crystal cover series is packaged, the inert gas (pure nitrogen) is first filled, and the inert gas is sealed inside the relay by laser fusion welding. In the accelerated degradation test, the actual storage time of the relay is short and under the premise of good sealing, there is little gas exchange inside and outside of the relay that is the oxygen and corrosive gas in the external environment are not easy to enter the relay shell.

  According to the gas component analysis report inside the relay, the gas in the actual relay sample contained a certain amount of oxygen and moisture. At normal temperature, the oxidation effect of trace oxygen and water vapor on the reed surface of relay is weak, but will be intensified at high temperature. By analyzing the SEM morphology of the moving reed in figure 7, it is not difficult to find that with the increase of temperature, the degree of oxidation corrosion on the surface of relay gradually increases. Especially at the contact position of the reed, it can be seen that temperature accelerates and promotes the formation of oxide film on contact during storage of relay.

**Figure 7.** SEM morphology of moveable reed surface after 36 days storage under different temperature stress.
In addition to the size of the temperature stress of contact resistance degradation, the length of the storage time is also affected, as shown in figure 8 for under 175 °C temperature stress, the storage test to 0 h, 864 h and 3456 h after sample relay static reed surface SEM photos, can be seen from the graph, with the increase of time, contact oxidation corrosion increase constantly. Therefore, it cannot be ruled out that excessive contact resistance (or contact not conducting) is caused by reeds surface oxide film pollution.

![Figure 8. SEM morphology of static reed surface after different storage time.](image)

- Organic film pollution on reed surface

In order to achieve electrical isolation between the input end and the output end, there are several non-metallic parts (or auxiliary materials) in relay, such as coil frame, PTFE sleeve, polyimide gasket, enamels and glass in addition to metal parts. Glass is a kind of inorganic nonmetallic material with high melting point, good stability and no volatile organic gas at high temperature. Coil frame, PTFE sleeve, polyimide gasket and enameled wire coating are organic and non-metallic materials. In particular, a lot of lubricants are added to enameled wire during the processing process. There are lot of organic matter remaining on the surface of enameled wire layer, especially the high-temperature gas release is significant. Moreover, with the increase of temperature, the release of organic gas also increases.

In order to verify the conclusion, a domestic brand of enameled wire commonly used in the relay industry was taken for organic gas composition analysis (GC-MSD determination). The test results are shown in Table 1. It can be seen that there is a certain proportion of organic gas composition in the enameled wire of relay. Moreover, due to the closed structure of the relay, the organic gas diffuses in the relay for a long time, which may adsorb to the contact surface and form an organic pollution film, which may cause corrosion on the contact surface. As shown in figure 7 and figure 8, the black imprint on the contact surface includes not only the oxidation corrosion film, but also the organic pollution film. The organic pollution film cannot eliminate the insulation layer by itself, which can lead to the increase of the contact resistance. Therefore, this factor cannot be excluded.

| Number | R.T./min | Name of organic gas | Sample A | Sample B | Average value of organic gas |
|--------|----------|---------------------|----------|----------|----------------------------|
| 1      | 2.196    | toluene             | 0.14     | 0.14     | 0.14                       |
| 2      | 3.223    | ethylbenzene        | 0.10     | 0.09     | 0.10                       |
| 3      | 3.296    | m-xylene            | 0.23     | 0.25     | 0.24                       |
| 4      | 3.611    | styrene             | 0.19     | 0.16     | 0.17                       |
Surface oxidation of lead-in foot

The pin surface of relay adopts tin-stained or tin-plated technology, and the tin layer is easy to oxidize when it is stored in high temperature and non-vacuum environment for a long time. Too thick oxide film may cause contact resistance test errors. This problem has been identified in the test process, so after each test sample is taken out from the oven, the oxide layer on the surface of the lead-in foot needs to be removed with a blade and sandpaper. Figure 9 shows the morphology of the leading-foot oxide layer before and after taking out of the relay. Therefore, this factor can be excluded.

![Figure 9. Morphology before and after removal of the oxide layer.](image)

Contact static pressure decreases

The contact resistance can be expressed as the sum of shrinkage resistance and film resistance. According to the formula $R_0 = \rho/D$, the shrinkage resistance depends on the diameter of the contact point. When the static closing pressure of the contact decreases, contact between reeds is in the form of point contact, so the contact diameter $D$ is smaller, and the shrinkage resistance increases correspondingly. It can be seen from figure 10 (a) and (b) that after the first storage cycle, the static closing pressure of the relay presents a significant downward trend, and the greater the temperature stress, the greater the downward trend. Therefore, this factor cannot be excluded.

Through the analysis of the fault tree of the over-standard contact resistance, it can be known that the reasons for the high contact resistance of the relay contact (contact not conducting) are as follows:

a. oxidation and organic corrosion of the reed surface;

b. decrease of the static closing pressure, which leads to a larger shrinkage resistance at the reed contact point. The temperature stress and storage time both have influence on the contact resistance.

![Figure 10. Tendency of static closing pressure and restoring reaction](image)
4.2 fault tree analysis of vibration failure samples

The breakdown fault tree of relay under sinusoidal vibration excitation is shown in figure 11.

![Fault Tree Diagram](image)

**Figure 11.** Breakdown fault tree of relay under sinusoidal vibration excitation

According to the terminal factors listed in fault tree, test conditions and internal structure of relay, the analysis is carried out as follows:

- **Contact static closing pressure is small**

  It can be seen from figure 10 that the static closing pressure of the test relay presents a significant downward trend after the first storage cycle, and the greater the temperature stress, the greater the decline range, and then the change of static closing pressure tends to be stable. The test samples have been inspected by PIND before storage test, and the vibration performance meets the requirements. According to the vibration strength formula for $N = F_0 / (P_k + 0.3\pi P_{kl} / \Delta)$ after the storage test contact static pressure $F_0$ decreased, the anti-vibration strength of the reed also decreases. In condition of high frequency, the reed is easy to produce resonance, and the contact group in the closed state is chattering open failure. Therefore, this factor cannot be excluded.

- **The initial restoring reaction is small**

  Observe the internal mechanism of the relay after the cover is removed, and restoring reed of the test relay is a wire reed structure. The stress points of the linear reed structure are relatively dispersed, so the reaction force changes not significantly after the stress release. According to the change trend of initial restoring reaction in figure 10, the restoring reaction of linear reed structure decreases with the increase of temperature stress and storage time, and the change trend is that the initial change is large, and then the change tends to be flat. After the initial restoring reaction is reduced, the fixed force of armature is insufficient, which makes it easier to start vibration under high frequency vibration, and may lead to the opening of closed contact by pushing the moving reed. Therefore, this factor cannot be excluded.

- **The free stroke of armature is small**

  In order to ensure that there is enough thrust and speed at the moment when the armature pushes the ball to push away the moving reed, there is usually a certain clearance between the pushing ball and the moving reed when the armature is open. According to the data of removing the cover, the distance parameters such as the contact clearance and overtravel of the relay remain basically unchanged. It can be inferred that the creep rate of the internal parts of the relay is slow under high
temperature storage conditions. Therefore, the free stroke in the initial state is basically unchanged, which can be excluded.

The reason of sinusoidal de-excitation chattering of relay is that the static closing pressure of contact decreases after high temperature storage, which makes the resonant frequency of reed decrease, and jitter occurs under high frequency vibration.

4.3 Analysis of action voltage change reason and failure mechanism

The operating voltage (current) of a relay refers to the minimum voltage (current) that enables the relay to operate. In addition to the above failure conditions, the operating voltage also has a slow downward trend, so it is necessary to explore the reasons for the voltage parameter decline. In general, the operating voltage of relay is mainly affected by initial restoring force, contact static closing pressure, contact clearance and overtravel. Through the measurement of coil resistance before and after storage, it is found that the coil resistance shows a slow downward trend, as shown in figure 5 (a) and table 2. It can be seen that the coil resistance has decreased significantly after the first few storage cycles, and the maximum decrease range is about 1%. It is considered that the change trend is related to the ambient temperature of the test. Therefore, the electromagnetic attraction only increased slightly in the first few storage cycles.

| Storage time(h) | Initial state | The fifth cycle | The tenth cycle | The fifteenth cycle | The twentieth cycle |
|-----------------|---------------|-----------------|-----------------|--------------------|---------------------|
| coil resistance (Ω) | 124.36 | 123.88 | 122.81 | 123.69 | 122.59 |

According to the degradation trend of action voltage in figure 5 (c), it can be seen that the operating voltage under four different temperature stresses all show a significant decrease in the first cycle, and then tends to be stable in 19 cycles. Under the temperature stress of 210 ℃, the decrease trend is the most obvious in the first storage cycle, the average operating voltage decreased about 0.8V.

At the same time, through the measurement of mechanical parameters of relay before and after storage, the trend diagram of contact static closing pressure and restoring reaction force under 175 ℃ temperature stress is shown in figure 5. The other three temperature stresses have the same trend. It can be seen that contact static closing pressure and initial restoring reaction decrease significantly after the first storage cycle, and then decrease slowly. The decrease trend of contact static closing pressure and initial recovery reaction force is the same with operating voltage. Because the contact clearance and overtravel remain unchanged during the whole test, the change of relay operating voltage is mainly affected by the static closing pressure and the magnitude of restoring reaction force. Under the condition of storage degradation test, the stress relaxation at the deformation of dynamic reed of relay is the main reason for the decrease of static closing pressure. In the early stage of test, the stress release of reed (dynamic reed and recovery reed) is more obvious, so the change of static closing pressure and recovery reaction force is also obvious. After that, the stress release tends to be stable, and the change of static closing pressure and recovery reaction force tends to be gentle. Therefore, it can be considered that the stress relaxation at the deformation of the moving reed is the main reason for the decrease of the voltage parameters of the relay.
When the electromagnetic relay is stored for a long time, its electromagnetic system, contact reed system and mechanical system will degrade to a certain extent, which will affect the normal operation characteristics of the relay. Due to the numerous factors that influence relay action characteristics, Wan B conducted a comprehensive analysis and comparison of all influencing factors through the bottom test[6], and considered that among many factors, the variation of reed reaction characteristics had the greatest influence on relay contact characteristics[7]. The reed itself of the relay has certain elastic force, which can guarantee the reliable contact. However, when the relay is stored, the reed material will experience stress relaxation, which will reduce the reaction force provided by the reed, and then affect the fit of suction reaction force, thus affecting the contact process.

With the stress relaxation of reed material, the reed reaction will decrease. The relative decrease of suction force is needed to compensate the decline of reaction force to maintain the coordination of suction reaction force. However, it has been known in the above analysis that the decline trend of coil resistance is not obvious, and the electromagnetic suction only slightly increases. Then only the voltage parameter drop causes the electromagnetic suction drop to compensate for the drop of reaction caused by stress relaxation. When the stress relaxation is not compensable, the relay fails.

5. Reliability design and improvement measures
The failure analysis of the test relay has been carried out in the previous several summaries. In this section, the reliability design and improvement of the electromagnetic relay are analyzed. The reliability design and improvement measures are the problems that manufacturers should pay attention to. On the one hand, they should improve the components themselves, design the components with no fault, good maintainability and low cost, and also provide good suggestions for the designers of equipment and systems. On the other hand, it is necessary to formulate the corresponding use specification for the user to operate correctly. Component manufacturers should also work closely with the whole machine factory to provide the best design data. The purpose of obtaining these data is not only to provide the whole machine factory, but also to improve the test method and the components and materials themselves.

5.1 Failure mode and improvement measures of test relay
Table 3 shows the improvement measures of relay storage reliability according to the failure forms in accelerated storage test and the results of fault tree analysis. The products from the factory should be screened in strict accordance with the national military standards, which can improve the ability of environmental stress resistance during storage. Strengthen the factory inspection and eliminate the products with defects, so as to improve the reliability of batch products in non-working state.

| Failure modes | Improvement measures of relay reliability |
|---------------|------------------------------------------|
| Contact resistance exceeding standard | Screen |
| The reed surface is subject to oxidation | Improvement measures |
| Analysis of internal gases and organics | Clean up leftovers and residues in the |
5.2 Reliability design of relay

Figure 12 is the relationship between reliability technology and failure analysis. Batch products, test samples, on-site failure, failure in maintenance and overhaul, poor process, etc. can be used as the basis and data source for system reliability analysis and evaluation. The information related to reliability is analyzed and evaluated with appropriate reliability indexes, and to improve the reliability of the original, material, products, including materials, component specification, procurement, and filter, etc. Next, the improvement measures of relay storage reliability will be put forward from three aspects.

| and organic corrosion | package |
|-----------------------|---------|
| The static closing pressure of the relay decreases, the shrinking resistance of the reed contact point increases | Eliminate the samples with obvious failure (contact resistance exceeding the standard seriously, sine de excitation shaking off, and abnormal operation due to voltage parameter change) | Use high conductivity, high thermal conductivity contact and reed material, such as silver magnesium nickel alloy |

| Sinusoidal de-excitation chattering | Stress relaxation of reed in long-term storage |
|-----------------------------------|---------------------------------------------|
| The contact static closing pressure decreases at high temperature | |

5.2.1 Improvement and analysis of mechanical parameters.

First of all, it is necessary to ensure the safety factor matching the suction and reaction characteristics. The fixed part should be made as a whole as possible to reduce the unreliable factors and non-working air gap brought by the connection, so as to make full use of the magnetic circuit efficiency and improve the overall structural rigidity. After the transition of spring root spot welding, combined with the new technology of foot spot welding, the contact reed is vertically and uniformly distributed on
the base, avoiding the contamination of relay surface by brazing. A special spot welding fixture was designed to ensure the contact gap and static closing pressure, improve the correction efficiency of the contact system, reduce the adjustment stress at the root of the reed, and improve the stability of the mechanical parameters (contact pressure, contact clearance, etc.) in the whole life test process of the contact reed.

5.2.2 Structural design improvement and analysis.

The whole metal welding encapsulation is adopted to replace the original tin sealing process, so as to eliminate the pollution of rosin and other flux on the contact and improve the sealing performance. Control the welding parameters of each welding place to avoid the failure caused by internal unstable welding; Improve the installation process and technology of mechanical parts, improve the mechanical precision of mechanical parts, prolong the mechanical stress release period, and strictly control the mechanical damage in the processing process and leave enough margin for the coil lead.

Take protective measures to improve the environmental resistance of products, improve the storage environment, often check the sealing of electromagnetic relay, and prevent the residual into the cavity after damage. For relays stored in corrosive gases, the products shall be manufactured with corrosion resistant materials or sprayed with corrosion resistant materials as required. To reduce the vibration during the transfer of the storage site, buffer measures should be taken to prevent external and internal mechanical damage.

5.2.3 Improvement and analysis of contact material.

The failure of electromagnetic relay is closely related to the static closing pressure of contacts and the stress relaxation of reed. Therefore, materials with high conductivity and high thermal conductivity can be used as contact and reed materials, such as silver magnesium nickel alloy. Currently, only alloys containing a small amount of magnesium and nickel (less than 0.3%) are used in silver magnesium nickel alloy. It has "internal oxidation" characteristics, the most outstanding characteristics of silver magnesium nickel alloy after internal oxidation are: good elasticity, low resistivity, thermal conductivity and corrosion resistance, its hardness does not change with temperature (because the hardening is irreversible), and the creep speed is very small (about 1/10 of pure silver). This material not only has excellent electrical and mechanical properties, but also has the characteristics of large temperature range and stable performance, so it is suitable for making reed material of electromagnetic relay.

6. Summary

This paper studies the storage reliability of electromagnetic relay and puts forward improvement measures:

- Firstly, the accelerated storage test system of relay is optimized, and the voltage parameter test unit is added, so that the accelerated storage test system can obtain more data related to degradation, such as coil resistance, contact resistance, pull-in/release time, pull-in/release voltage and so on.
- During the test, failure modes such as excessive contact resistance and sinusoidal vibration de-excitation chattering occurred. At the same time, the voltage parameters had a significant change...
trend. The fault tree analysis was carried out for the above failure modes and parameter changes. The results show that the reasons for the high contact resistance of the relay were oxidation and organic corrosion of the reed surface and decreases of relay static closing pressure. The reason of sinusoidal de-excitation chattering is that the static closing pressure of contact decreases after high temperature storage. The stress relaxation at the deformation of the moving reed is the main reason for the decrease of the relay voltage parameters.

- Improvement measures of relay reliability design are proposed from three aspects: mechanical parameters, structural design and contact material. This is of great significance to the design and manufacture of relay manufacturers and the reliability of the user research system.

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