Failure analysis and improvement of tact switch in smart meter after accelerated life testing (ALT)

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ABSTRACT

The smart meter requires a long lifetime and high reliability. Accelerated Life Test (ALT) is an important reliability acceptance method. The switch is an important human-machine interface for electricity meters, and its reliability will directly affect the reliability of the meter. In the article, scanning electron microscopy (SEM), X-ray energy dispersive spectroscopy (EDS), and ion chromatography were used to analyze the failure mechanism and source of failure factors of the light touch switch that failed after ALT testing with the intelligent meter. The results indicate that the deionized water used in the production process of the switch is contaminated with K^+, resulting in excessive residual K^+ inside the switch. In the ALT environment, water vapor enters the interior of the switch, forming a pathway between the high-voltage and low-voltage terminals inside the switch. Under the action of the electric field, K^+ gradually accumulates to the low-voltage terminals, forming potassium salts with other substances inside the switch. During the ALT cooling and dehumidification phase, the solubility of potassium salt decreases, the solvent decreases, and potassium salt precipitates. Due to the poor conductivity of potassium salts, the switch fails. The article proposes improvement methods for such failures from the perspectives of pollution source control and improving product protection capabilities, which can effectively improve the reliability of smart meters.

Keywords: Tact switch, accelerated life test, failure analysis, ionic contamination, reliability, waterproof

1. INTRODUCTION

Smart meters are used in complex environments and have the characteristics of multiple functions, complex structures, and long life. Accelerated life test (ALT[1,2] is commonly used to verify and evaluate the reliability of the whole product and its internal components (including tact switches).

Tact switch is a kind of component which can convert mechanical signal into electrical signal. It has the advantages of small size, small operating force and short operating distance. It is widely used in electronic equipment, instrumentation, power system, electrical system and other industries. It is an important man-machine interface. Its reliability is an important factor affecting the reliability of the whole product. Li et al.[3] statistically found that 36.47% of the company's defective products in the first half of 2019 are logic on-off problems, and the switch failure is the main cause of unqualified logic on-off detection. However, there are few literatures on the reliability research and failure analysis of tact switch. Therefore, it is of great significance to analyze the failure of the tact switch, reveal the root cause and mechanism of its failure, and put forward effective improvement methods and preventive measures to improve the reliability of the whole product.

This paper analyzes the failure of the tact switch after ALT test with the whole machine, reveals its failure mechanism, and finds out the failure source. In view of this kind of question, proposed the improvement plan, effectively enhanced the intelligent electric meter reliability.

1.1 Test conditions

The failure of the tact switch comes from the smart meter product one week after the completion of the ALT test. Equation (1) is an accelerated test model proposed by Luis[4]. In equation (1), L is the product life, AF is the acceleration factor, and T is the test time of ALT. Acceleration factor model is referred to GBT 17215. 9311[5] and IEC 62059-31[6] using the Peck temperature-humidity model[7], see equation (2). Figure 1 shows the temperature and humidity curve of each cycle of ALT test. The test temperature is 70°C and the test humidity is 85% RH. There are 8 cycles in total.

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$$L = AF \times T \tag{1}$$

$$AF = \frac{RH_u}{RH_s}^{-n} \times e^{\frac{Ea}{k}(\frac{1}{T_u} - \frac{1}{Ts})} \tag{2}$$

where

RH_u is the percent relative humidity at use conditions;

RH_s is the percent relative humidity at stress conditions;

T_u is the temperature in K at use condition;

T_s is the temperature in K at stress conditions;

k is the Boltzmann constant (8.617×10^{-5} eV/K)

Ea is the activation energy in electron volts;

n is a constant.

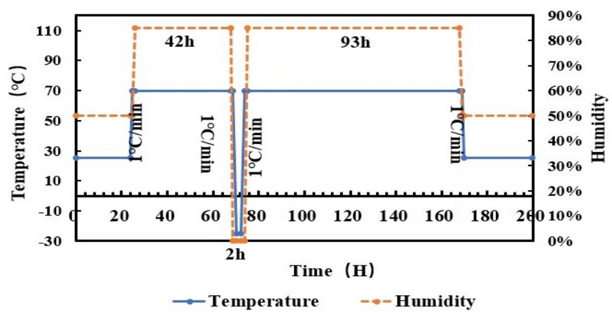


Figure 1. Temperature and humidity curve of ALT test.

1.2 The structure of switch

Figure 2 is a schematic diagram of the internal structure of the switch. wherein the part 1 is a handle of the switch, which is made of a plastic material FR52, and the part 2 is a cover plate, which is commonly made of stainless steel or plastic materials. Part 3 and part 4 are the core parts of the tact switch. Part 3 is called the reed, which is shaped like a pot cover, concave downward, made of stainless steel, silver-plated on the surface, and also known as the pot piece in the industry. The part 4 is a terminal made of brass with a surface treatment of Ni plating and then silver plating. Part 5 are the pins of the switch. The internal terminal has three contact points, position 2 and position 3 are in contact with the reed. When the handle bounces up, position 1 is disconnected from the reed, and the switch is in the disconnected state. When the handle is pressed down, the reed is in contact with position 1, and the switch is connected[8]. In this article, the performance of the failure switch is when the handle bounces up, the switch is in the open state, and when the handle is pressed down, the switch is still unable to conduct.

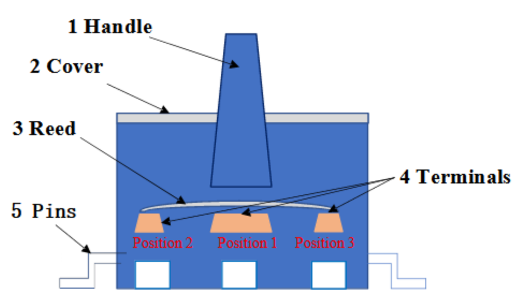


Figure 2. Schematic diagram of the internal structure of the switch.

2. ANALYSIS PROCESS

2.1 Circuit analysis

A digital multimeter is used to measure the impedance of the pins of the 1-3# failed switches in the conduction state. As shown in Table 1, the test values of the conduction impedance of the 1-3# failed switches are 5.7 KΩ, 5.1 KΩ and 6.3 Ω respectively, which are much greater than 0.06 Ω of the new sample 4# switch. The failure cause was analyzed as open circuit failure.

Table 1. Test value of conduction impedance.

Sample number	Test value of on-resistance (Ω)
1# Failed switch	5700
2# Failed switch	5100
3# Failed switch	6300
4# New switch	0.06

2.2 Appearance analysis

Disassemble the failed switch 1#. Figure 3 is the photo of the internal terminal and reed of the failed switch. Figure 3a is the top view of the brass terminal, the core component of the switch. White deposits are found near one of its contact surfaces, as shown in Figure 3b. Figure 3c is a photograph of the concave surface of the reed, and it was found that there are also white deposits near the contact positions between the concave surface and the two ends of the copper terminal and in the center. After the foreign matter was removed, the function of the switch returned to normal, and it was speculated that the white deposit might be the cause of the poor contact of the switch.

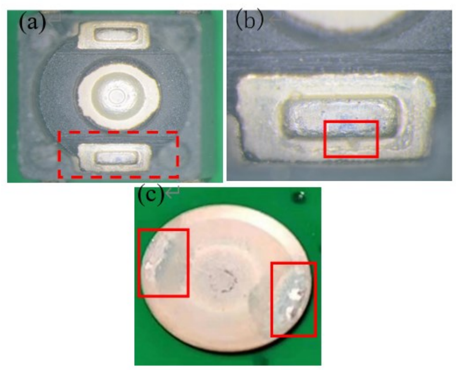
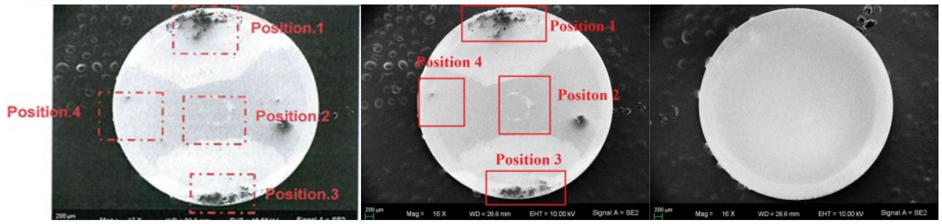


Figure 3. Reed and terminal photos of 1# failed switch.

2.3 Analysis by scanning electron microscope (SEM) and energy dispersive spectrometer (EDS)

In order to further analyze the composition of the white deposit, the failed switch (2# and 3#) and the new sample (4#) without reliability test were sent to the third-party reliability research and analysis center for analysis by AUPRA 55VP scanning electron microscope. As shown in Figure 4, it was observed under the scanning electron microscope that there was foreign matter near the contact positions (positions 1 and 3) between the reed and the terminal of the failed samples 2# and 3#, and there was also a small amount of unknown foreign matter near the center (position 2). The surface of sample 4# was smooth and free of foreign matter. As shown in Figures 4-6, for samples 2# and 3#, position 1, position 2, position 3 with foreign matter and position 4 without foreign matter were selected for component analysis, and the central position was selected for sample 4# when component analysis.



(a) (b) (c)

Figure 4. Photo of the surface morphology of the spring. (a) 2#; (b) 3#; (c) 4#.

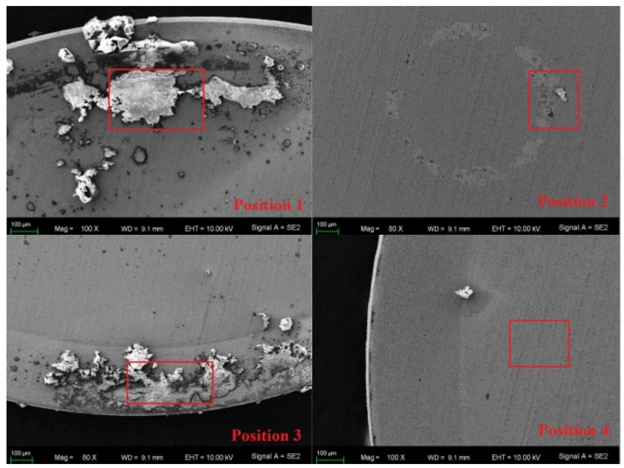


Figure 5. Surface morphology photos and 4 EDS testing positions on sample 3#.

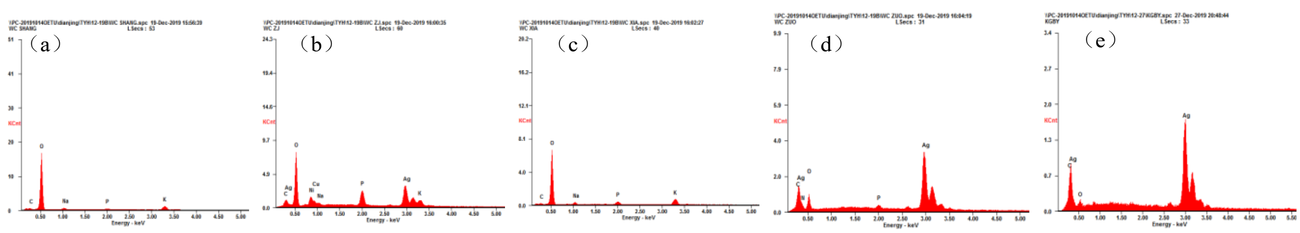


Figure 6. X-ray energy spectrum of switch spring (a) Position 1 of 3#; (b) Position 2 of 3#; (c) Position 3 of 3#; (d) Position 4 of 3#; (e) Sample 4#.

Analyzing the test data in Table 2, as shown in Figure 7, the marked elements in the red solid coil represent the common elements detected at the 6 foreign matter positions of the failed switch, the marked elements in the blue short coil represent the elements detected at the 2 non-foreign matter positions of the failed switch, and the marked elements in the green dotted coil represent the elements detected at the new switch. It was found that element C was the common element tested in six foreign matter positions, two non-foreign matter positions of the defective product and the new switch. 3# Failure sample position 1 and position 3 did not detect the Ag element on the concave surface of the reed because the surface foreign matter has completely blocked the surface of the Ag layer below. Ag element was detected in both the foreign matter free positions of the two failed samples and the new switch. The O and P elements were detected at the 6 foreign matter positions and the non-foreign matter positions of the 2 failed switches. the K element was the only element that was detected at the 6 foreign matter positions but not at the non-foreign matter positions of the new samples and the failed switches, and the content of O element at the 6 foreign matter positions increased, so it was speculated that the white foreign matter might be potassium salt.

Table 2. EDS test data for switch reed (At%).

Test location information	Position name	C	N	O	Ni	Cu	Na	P	Ag	K	Total
Foreign matter location of failed switch	Position 1 of 2#	6.08	0	72.94	0	0	1.58	1.69	14.51	3.2	100
	Position 2 of 2#	12.33	0	77.35	0	0	0	0.69	0.82	8.81	100
	Position 3 of 2#	6.73	0	84.62	0	0	0	0.59	2.54	5.53	100.01
	Position 3 of 3#	5.97	0	85.6	0	0	1.69	0.9	0	5.84	100
	Position 3 of 3#	9.25	0	61.85	5.32	1.19	1.22	6.48	11.95	2.75	100.01
	Position 3 of 3#	6.12	0	81.6	0	0	1.88	2.34	0	8.06	100
No foreign matter location of failed switch	Position 4 of 2	17.35	5.12	42.44	0	0	0	2.49	32.61	0	100.01
	Position 4 of 3#	18.79	4.54	33.42	0	0	0	1.65	41.6	0	100

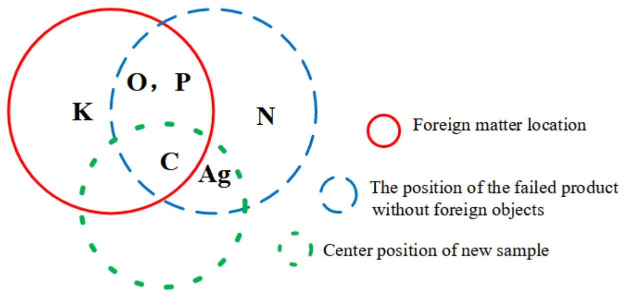


Figure 7. Schematic diagram of EDS result analysis.

3. FAILURE MECHANISM AND IMPROVEMENT MEASURES

3.1 Failure mechanism analysis

According to the above analysis, it is speculated that the deionized cleaning solution used in the production process of the switch is contaminated by K^+, so that more K^+ remains in the switch reed and terminal after cleaning, and exists inside the switch after assembly. As shown in Figure 8, the voltage of the three internal terminals of the switch on the whole product is grounded at both ends and +3.3 V at the center. In the ALT experiment, the high humidity makes the water vapor enters the switch, which weakens the insulation capacity between the switch terminals. Two paths are formed from the center to the two ends, and the direction of the electric field points from the center to the two ends, as shown by the arrow in Figure 8. Under the action of an electric field, K^+ gradually migrates and aggregates on the surface of the terminals at both ends[9], dissolves in water vapor, and forms a potassium salt solution.

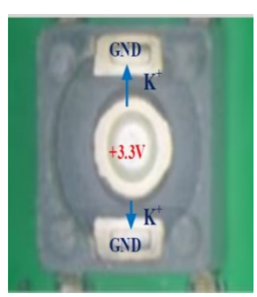


Figure 8. Schematic diagram of K^+ migration under high temperature and humidity.

As shown in Figure 9, the solubility of several common potassium salts in water increases with the increase of temperature. With the rapid cooling and dehumidification after each cycle of the ALT experiment, the solubility of potassium salt decreases and the solvent decreases, causing potassium salt to precipitate and adhere to both ends of the reed. Due to the poor conductivity of solid potassium salts, the switch fails to conduction.

It can be seen that the impurity and ion contamination of the reed and terminal of the tact switch seriously affect the reliability of the switch. Using switches of the same model from different batches, the same reliability test was conducted again, and no related failures occurred.

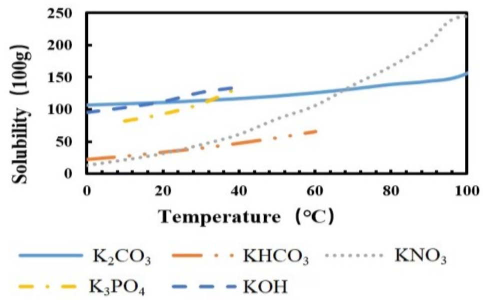


Figure 9. Solubility curves of common potassium salts in water.

3.2 Improvement measures

Ionic pollution that hinders the transfer of substances and energy will have a serious impact on product performance. In 2015, Young Joon Cho found that potassium contaminated solar cell samples had a shorter lifespan[10,11]. In 2020, Aidi HanFound that cobalt ion pollution had a negative impact on proton conduction in ultra-thin Nafion membranes[12]. To avoid similar failure phenomena and improve the reliability of switches and the entire machine, the following aspects can be taken into consideration.

(A) Supplier raw material monitoring

(a) Test the composition of key raw material samples by batch;

(b) Batch monitoring of key production materials.

(B) Supplier production phase

(a) Improve the automation degree of key processes to avoid pollution caused by manual contact;

(b) It is not allowed to throw materials directly into the production line;

(c) Regularly check the flow of deionized cleaning solution, and test whether the conductivity of cleaning solution meets the requirements.

(C) Complete machine design optimization

(a) Spraying conformal paint (commonly known as three-proof paint) on the surface of PCB can effectively improve the moisture problem of SMD thin components and the micro-short circuit problem of small pin spacing under high temperature and humidity conditions[13];

(b) Shell ultrasonic welding. Through ultrasonic technology, mechanical energy is converted into thermal energy[14,15], keeping the internal circuit board of the product in a closed environment, which helps to improve the moisture-proof performance of the entire product under high temperature and humidity conditions.

(D) Waterproof design optimization of switch

The reliability of the switch can be improved through the waterproof design of the switch. The common waterproof design methods are as follows.

(a) Add of waterproof membrane design. The waterproof membrane is added between the reed and the button, so that the cavity where the concave surface of the reed is in contact with the terminal forms a sealed cavity, which plays a certain role in dust prevention and water prevention[16].

(b) Add of rubber pad inside. By adding a rubber pad in the switch base, the switch can also form a sealing structure to play a waterproof role[17]. In 2021, a rubber pad is added in the switch base design by Kaihua Electronics, so that the switch forms a sealing structure, and the dustproof and waterproof grade can reach IP56 grade[18].

(c) Optimization the structural design. In 2023, Zhejiang Electronics designed an installation groove with a circular step at the edge of the opening, allowing the dust film to seal the installation groove and achieve the effect of dust and water prevention[19]. The sealing effect of the product can also be enhanced by increasing the size of the reed, increasing the upper limit of the reed pressure, and adding a convex rib structure of the upper cover.

(d) Optimization of the processing technology. In 2022, Jiang proposed that the hardware terminal and the base should be connected by injection molding, and the base and the plastic shell should be welded by plastic laser welding technology, which can effectively play a waterproof role[20].

4. CONCLUSION

Through circuit analysis, it is found that the failure position of the switch is the contact position between the reed and the terminal. The failure reason is that there is some white foreign matter with poor conductivity at the contact position between the reed and the terminals. The white foreign matter at the contact position between the reed and the terminals was speculated to be potassium salt by scanning electron microscope (SEM) and energy dispersive X-ray spectrometer (EDS) analysis. The source of abnormal potassium content was found by ion chromatography analysis. The failure mechanism of tact switch after ALT test is revealed.

To ensure the reliability of tap switches intended for application in high-reliability products, the following three aspects can be considered. firstly, the selection of raw materials should pay attention to avoid containing inorganic salts or corrosive ions that are easy to form with substances in the air; Secondly, ion contamination of components is avoided during production, such as contact component reeds and terminals. Thirdly, the switch with waterproof design or the waterproof design of the whole machine is adopted to prevent water vapor from entering the switch.

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