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Fracture failure analysis of conductive arm spring of isolation switch in 500kV substation

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Abstract. Through macro inspection, chemical composition analysis, hardness inspection, graphite carbon inspection, metallographic inspection, the causes of spring fracture on conductive arm of isolation switch in a 500kV substation were analyzed. The results show that poor manufacturing technology and anti-corrosion technology of the spring are the main reason for its fracture. Corresponding control measures are put forward to avoid similar failures from happening again.

1. Introduction

The high-voltage isolating switch plays an important role in the power system to isolate the power supply, change the system operation mode, switch small load currents, and perform switching operations. Its working principle and structure are relatively simple, but due to the high frequency of use, wide range, and high working reliability requirements, it has a greater impact on the safe and reliable operation of substations[1-4]. There is a change in the gravitational moment of the horizontal telescopic isolating switch during the opening and closing process. In order to reduce the output torque of the mechanism and make the isolating switch run smoothly, it is necessary to configure a suitable balance spring in the lower conductive tube to match this change[5]. Whether the configuration of the balance spring is scientific or not and the manufacturing quality is good or poor directly affects the stability of the isolating switch system[6].

In this paper, a failure of a spring fracture on conductive arm of isolation switch in a 500kV substation was studied. Through macro inspection, chemical composition analysis, hardness inspection, graphite carbon inspection, metallographic inspection, the causes of spring fracture were analyzed to provide a reference for design and manufacturing, inspection and testing, and operation and maintenance.

2. Experimental Section

A FOUNDRY-MASTER PRO Oxford full-spectrum direct-reading spectrometer was used to analyze the chemical composition of the fracture spring. The hardness test is carried out on the HRS-150M touch screen digital display Rockwell hardness tester. The graphite carbon and microstructure of the fracture spring were observed under the Zeiss Axio Observer A1m metallographic microscope.

3. Results and Discussion

In October 2019, the isolating switch of a 500kV substation failed to operate normally due to a jammed mechanism. After inspection, it was found that the balance spring in the lower conductive arm was damaged. In order to analyze the causes of spring failure, formulate corresponding rectification measures, the spring was sent to a third-party testing agency for testing and analysis. Since the design drawings and manufacturing information of the spring cannot be collected, the original specifications, materials and manufacturing process of the spring are unknown.

3.1. Macro inspection

The balance spring in the lower conductive arm is a cylindrical spiral compression spring, and the large balance spring is severely corroded, as shown in Figure 1. The small balance spring is severely corroded and broken into multiple sections, as shown in Figure 2. The diameters of the large and small balance springs are all over 8mm, and it can be inferred that they are all manufactured by hot-rolling process. The balance spring of the isolating switch was severely corroded after only 9 years of operation, indicating that the anti-corrosion process of the spring was poor when it left the factory. In order to analyze the reasons for the fracture of the small balance spring, the small balance spring was further tested and analyzed.

Figure 1. Big balance spring

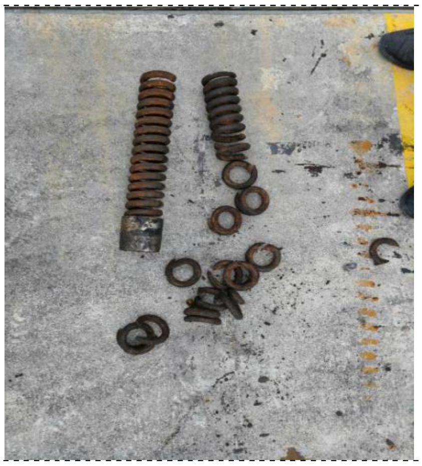

Figure 2. Small balance spring

3.2. Chemical composition testing

The chemical composition of small balance spring were illustrated in Table 1. It can be seen that the average chemical composition of the small balance spring meets the requirements of 60Si2Mn steel in the GB/T 1222-2016 "Spring Steel" standard, so it can be inferred that its design material is 60Si2Mn. The most widely used in China is Si-Mn series alloy spring steel, 60Si2Mn is the most typical grade of this series.The hardenability of 60Si2Mn is much higher than that of carbon spring steel. It is not easy to produce cracks during quenching, has good tempering stability, and is not easy to produce temper brittleness. After quenching and tempering, it has better comprehensive mechanical properties and process properties. It is widely used in industries such as automobiles, machinery manufacturing, and electric power and it is mainly used to manufacture coil springs with medium cross-sections.

Table 1. Chemical composition of small balance spring.

Element content/%	Test point 1	Test point 2	Test point 3	average value	standard for 60Si2Mn
C	0.577	0.581	0.564	0.574	0.56~0.64
Si	1.683	1.714	1.733	1.71	1.50~2.00

Mn	0.701	0.698	0.710	0.703	0.70~1.00
Cr	0.0651	0.0643	0.0644	0.0646	≤0.35
Ni	0.0459	0.0471	0.0474	0.0468	≤0.35
Cu	0.112	0.121	0.118	0.117	≤0.25
P	0.0096	0.0102	0.0096	0.0098	≤0.025
S	0.0183	0.0179	0.0181	0.0181	≤0.020

3.3. Hardness measurement
Since the broken spring failed to be sampled for mechanical performance testing, the Rockwell hardness measurement was performed instead and the results were shown in Table 2. The standard GB/T 1222-2016 "Spring Steel" stipulates that the tensile strength R_m of 60Si2Mn should not be less than 1570MPa. According to the Spring steel tensile strength and hardness conversion tables in Appendix B of standard GB/T 23934-2015 "Hot-wound Cylindrical Spiral Compression Spring Technical Conditions", the tensile strength of 1570MPa corresponds to the Rockwell hardness of 48.2HRC. It can be seen that the hardness of the small balance spring is lower than the lower limit required by the standard.

Table 2. Rockwell hardness test results.

Hardness	Test point 1	Test point 2	Test point 3	average value	standard for 60Si2Mn
HRC	46.3	45.8	46.2	46.1	≥48.2

3.4. Graphite carbon inspection
According to the standard GB/T 13302-1991 "Method for Microscopic Evaluation of Graphite Carbon in Steel", the entire cross-section of the broken spring was taken, after being ground and smoothed, it was carefully polished with velvet. The unetched test surface of the sample was placed under a microscope with a magnification of 250 times for comprehensive observation, as shown in Figure 3. It can be seen that there are obvious fine clusters of flocculent graphitic carbon in the spring steel, and its graphitic carbon grade is rated as 1.0 through comparison with the standard rating chart. The standard GB/T 1222-2016 "Spring Steel" stipulates that the silico-manganese spring steel after heat treatment should not have visible graphite carbon on the fracture surface, so the graphite carbon inspection of the spring steel is unqualified.

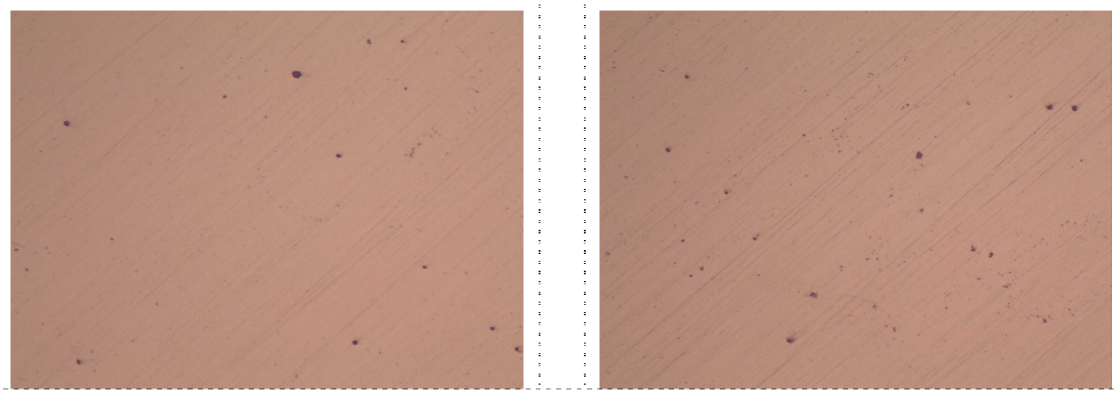

Figure 3. Graphite carbon in spring

3.5. Metallographic inspection

A sample is cut from the spring, ground, polished and etched with a 4% nitric acid alcohol solution, and then the microstructure is observed under a Zeiss Axio Observer A1m metallurgical microscope at 500 times, as shown in Figure 4. By comparing with the medium temperature tempered structure rating chart in the standard JB/T 9129-2000 "60Si2Mn Steel Coil Spring Metallographic Inspection", it can be judged that the microstructure is tempered troostite + massive ferrite, which is rated as Level 5, unqualified.

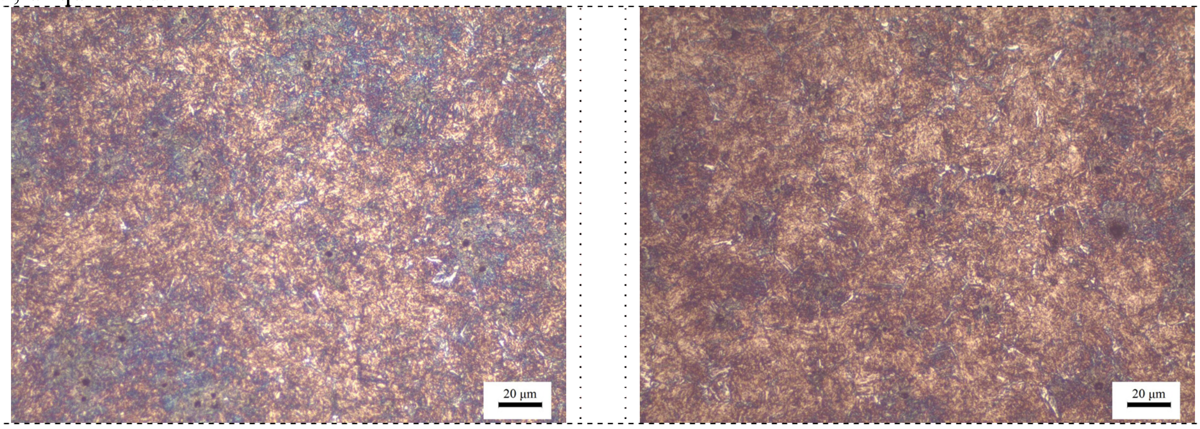

Figure 4. Spring microstructure 500×.

3.6. Cause analysis

3.6.1. Bad spring manufacturing process

As the aforementioned analysis shows, the design material of the spring is 60Si2Mn alloy spring steel. Since silicon is an element that promotes graphitization, graphitic carbon is easily precipitated when the spring is quenched and tempered. If the spring manufacturing process is not well controlled, the precipitation of graphite carbon is equivalent to reduce the carbon content of the spring steel. On the one hand, it will reduce the strength and hardness of the spring. On the other hand, it will cause the spring to be incompletely austenitized during the heat treatment process. After quenching and tempering, a large amount of ferrite will remain, resulting in unqualified microstructure and greatly reducing the toughness of the spring. Due to the poor manufacturing process of the spring, the performance of the spring itself is poor.

3.6.2 Poor spring anticorrosion process

The geographical location where the substation is located is relatively humid, with plenty of rainfall, and the corrosive environment is relatively harsh. The unreasonable structural design of the isolating switch causes water to accumulate in the conductive arm and is not easy to volatilize, which further deteriorates the service environment of the internal spring. The poor anti-corrosion technology of the spring itself made it severely corroded after being put into operation for 9 years in this relatively harsh corrosive environment, which further deteriorated the performance of the spring.

3.6.3 Comprehensive analysis

There are a large number of micro-cracks on the surface of the heavily rusted spring, which increases its notch sensitivity. When the electric operation is performed during the overhaul process, the springs with greatly degraded performance cannot withstand the stress of too fast loading speed, and a large number of micro-cracks rapidly expand and break into multiple segments.

4. Conclusions

1) Poor spring manufacturing process and anti-corrosion process lead to serious deterioration of spring performance, and brittle fracture occurs under the action of the stress of faster loading speed.

2) Check the isolating switches of the same manufacturer, the same batch, and the same type, and replace the balance spring during power outage maintenancein.

3) Strengthen the quality inspection of new replacement springs to ensure that its performance and anti-corrosion quality are excellent.

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