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Failure Analysis of Ultra-High Strength Bolt of Circuit Breaker

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Abstract

Screw mechanism fixing bolt fracture failure of a 500kV circuit breaker spring mechanism running process. By analyzing the installation position and operating environment, and by means of chemical analysis, metallographic examination and other means, the microstructure macro and micro fracture morphology of the fracture bolt were analyzed. The results show that the surface of the bolt is hydrogen-rich and produces hydrogen embrittlement during surface treatment.

Keywords: Circuit breaker; Bolt of high strength; Fracture; Hydrogen embrittlement

1. Introduction

The circuit breaker is one of the most widely used high-voltage electrical equipment in various substations, and is a switching device for closing, carrying and breaking line current 1. The circuit can be automatically cut off to prevent the scale of the accident from further expanding when the power line and motor are faulty, so that all electrical equipment in the power system are protected from damage 2. The failure of the operating mechanism of the circuit breaker will have an impact on the stable operation of the power system, causing serious safety hazards. In the event of a system failure, the circuit breaker operating mechanism may refuse to expand the power outages 3,4.

In the process of manufacture and installation of circuit breakers, the bolts are often used to form detachable joints. The bolts made of high strength steel or which need to be applied with greater pre-tightening force are called high strength bolts. This type of bolt is mostly used in important occasions such as the connection of bridges, rails

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and high-voltage electrical equipment. Therefore, this kind of bolt is different from ordinary standard bolts, and is generally designed and manufactured by the user according to the equipment. The fracture of this kind of bolts is embrittlement during the use process. Only in all steps of bolt design, manufacture and installation, comprehensive technical management and careful implementation of professional technical specifications can ensure the quality of bolts produced without problems such as connection and fracture 5,6.

According to statistics results 7, the mechanical failure accounts for about 25% of the accidents of 110kV and above high voltage circuit breakers in China. Among the many causes of mechanical failure, the circuit breaker body and operating mechanism are the main defects of the circuit breakers 8. In order to determine the fracture reason of high-strength bolts, the literature 9 used the micro-fracture mechanism to analyse the fracture causes of bolts, and determined that the fracture failure property is hydrogen-induced cracking stress corrosion cracking caused by stress, hydrogen and corrosion. The experimental analysis in 10 shows that the reason for the delayed fracture of the grade 10.9 bolt is that the excessive strength of materials caused by insufficient tempering. The literature 11 analyses a series of changes in the bolts under the action of the impact load until the fracture, and concludes that the larger screws should be selected and tightened. In literature 12, the problems existing in a certain type of circuit breaker are sorted out, and corresponding solutions are proposed through experimental analysis, which can provide reference for improving the operation and maintenance of the circuit breakers.

In this paper, a circuit breaker with bolt fracture failure in Hunan Power Grid is analysed. A series of experimental methods are used to determine the two reasons for bolt failure. On the one hand, it comes from external pressure and fluctuating load, on the other hand, it is hydrogen embrittlement caused by hydrogen-rich surface, and the corresponding practical improvements are put forward in the conclusion section to avoid similar failures.

2. Case Study

A 500kV spring mechanism breaker is the original imported product from Sweden. The production date is 2002. The energy storage motor of the circuit breaker mechanism is fixed with other parts of the mechanism through four M8 bolts. After running for a period of time, it was found that two of the circuit breakers broke during the inspection, as shown in Fig. 1.

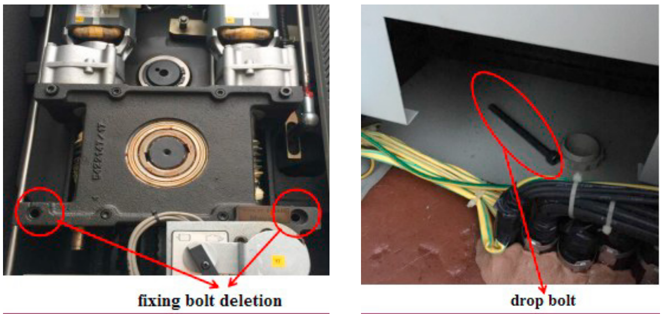

Fig. 1. (a) A circuit breaker electrical energy storage module; (b) Drop bolt of a breaker mechanism.

3. Experiment Analysing

3.1 Macroscopic examination and analysis of fracture

A comprehensive test analysis is carried out on the failed bolt samples. The failure bolt specification is M8, the performance grade is 12.9, and the surface is treated with blackening. Fig. 2 (a) shows the macro morphology of the failure bolt. It can be seen that the fracture position is located at the threaded position, the section is perpendicular to the axial direction of the bolt, the section of the bolt is flat, and there is no obvious macroscopic plastic deformation in the vicinity. Fig. 2 (b) shows a macro-photograph of the cross section after degreasing treatment. No shell-like fatigue front line is found, the shear lip is small, and there is no necking near the fracture. According to the section, it is divided into glossy area and matt area. The matt area is the crack propagation caused by the stress of the bolt. Due to the large size of the area, the crack propagation process is relatively slow. When the crack spreads to a certain extent, it exceeds the bearing value of bolt stress, and then brittle, that is, the glossy area. The above phenomenon can be preliminarily judged that the fracture of the bolt is crack propagation and brittle fracture occurs under the action of stress.

Fig. 2. (a) Macro morphology of motor energy storage bolt; (b) Macro morphology of section.

3.2 Microscopic examination and analysis of fracture

3.2.1 Stereoscopic microscopy

The fractured bolt is examined by the stereoscopic microscope, as shown in Fig. 3. It can be seen that the entire fracture consists of three parts: the crack source area (close to the root surface of the thread, there are obvious rusting marks, accounting for about 5% of the entire fracture surface area), the crack propagation area (accounting for about 75% of the entire fracture surface area) and the final transient fracture area (accounting for about 20% of the entire fracture surface area).

Combined with the service characteristics of less opening and closing times of circuit breakers and more intense vibration during operation, the bolt can be judged as high stress and low cycle fatigue fracture.

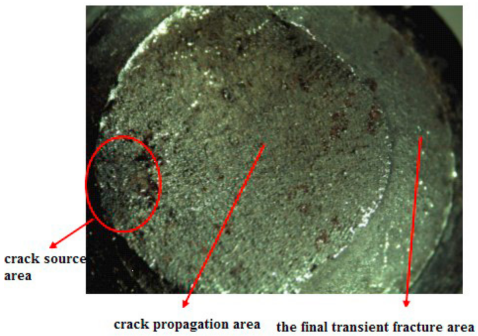

Fig. 3. Fracture of the fracture bolt.

3.2.2 Scanning electron microscopy (SEM) and energy spectrum analysis (EDX)

The fracture bolts are analyzed by SEM. The morphology of crack source area, crack propagation area and final transient fracture area are shown in Fig. 4(a), 4(b) and 5, respectively.

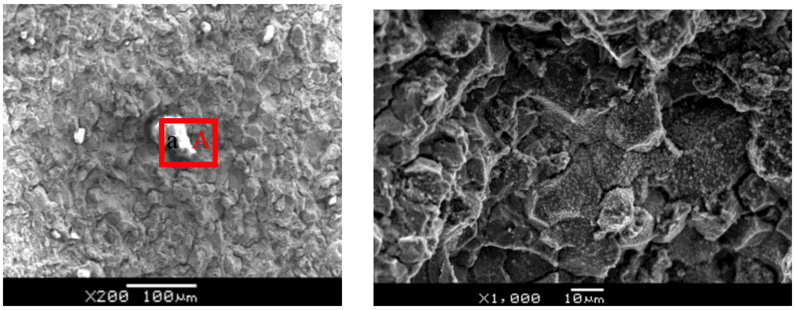

Fig. 4. (a) SEM morphology of crack source area; (b) SEM morphology of crack propagation area.

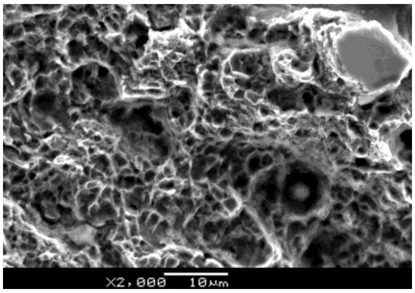

Fig. 5. SEM morphology of the final transient area.

The EDX is carried out for point A where impurities exist in Fig. 5, and the results are shown in Table 1.

Table 1. A point EDX detection results.

Elementary Composition(at%)	Fe	S
A	50.63	49.37

It can be seen that the particulate matter of point A is FeS inclusion, which is located in the crack source area, so it is likely to be the crack source of bolt fracture. In addition, a large number of secondary cracks exist in the crack source area and crack propagation area, and they propagate along grain boundary, which is consistent with the characteristics of hydrogen embrittlement fracture. In the final transient fracture area, there are a large number of small dimples, indicating that the bolt has low plasticity.

3.2.3 Metallographic structure analysis

The metallographic structure of the bolt matrix and thread root are shown in Fig. 6, respectively.

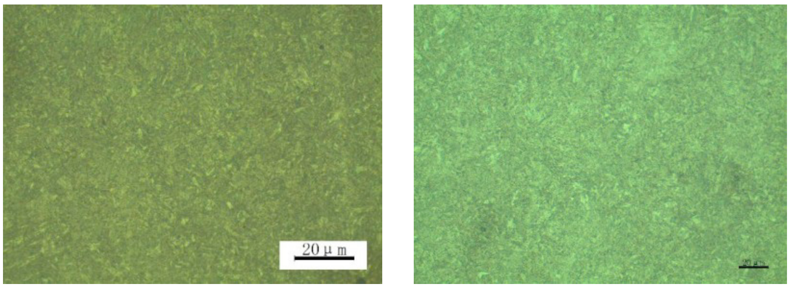

Fig. 6. (a) Metallographic structure of bolt matrix 500×; (b) Metallographic structure of thread root 500×.

It can be seen from Fig. 6 that the metallographic structures of bolt matrix and thread root are tempering sorbite.

3.3 Chemical analysis

3.3.1 Chemical composition analysis

Chemical analysis is carried out on bolts, and the results (mass fraction) are shown in Table 2. According to the test results, it can be inferred that the design material should be alloy structural steel. However, no corresponding grades are found for the broken bolt material according to the alloy structural steel in Chinese national standard GB/T 3077.

Table 2. Chemical composition of fracture bolt.

Element	C	Si	Mn	S	P	Cr	Mo	Ni	Fe
Sample	0.325	0.136	0.973	0.0134	0.0153	1.18	0.0096	0.289	margin

3.3.2 Determination of hydrogen content

The hydrogen content is measured on the outside of the screw and the core of the bolt. The sample location for hydrogen content test is shown in Fig. 7, and the analysis results are shown in Table 3.

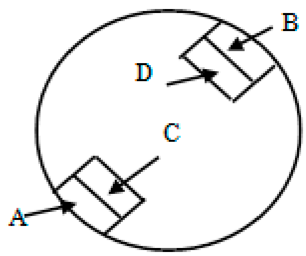

Fig. 7. Sampling location map for hydrogen content test.

Table 3. Analysis results of bolt hydrogen content.

Name	Test location	Hydrogen content /×10-4%
Screw	Area A（1mm area from the surface）	9.34
	Area B（1mm area from the surface）	3.36
	Area C（1~2mm area from the surface）	1.34
	Area D（1~2mm area from the surface）	0.98
Core		0.86

According to the analysis results of bolt hydrogen content in Table 3, the hydrogen content on the surface of the screw is (3.36~9.34)×10-4%, which is high. Since the blackening treatment of the bolt surface, it has to undergo pickling in the process, during which a large amount of hydrogen is absorbed. In the subsequent dehydrogenation process, hydrogen adsorbed on the surface of the bolt due to low temperature and short time. It is too late to diffuse, causing more hydrogen to remain on the surface of the bolt.

4. Analysis and Discussion

In mechanical design, the strength and hardness of the material are generally considered first, and the impact toughness of the material is often insufficiently considered. However, for high-strength bolts, the tensile strength and hardness are higher, while ignoring the toughness of the material. The mechanical properties of steel materials decrease with the increase of strength and hardness, and the toughness gradually decreases 13. The results show that the higher the strength of steel, the greater the crack sensitivity; when the tensile strength is greater than 1200MPa, it is easy to fracture. The fractured bolt reaches 12.9 grade and belongs to the top bolt of the ultra-high strength bolt. The tensile strength is over 1220MPa and the crack sensitivity is very large.

According to the above analysis, the failure of the breaker bolt mainly exists in the following two aspects:

(1) The failed bolt not only bears static load, but also withstands the pulsating load caused by external pressure and temperature changes. Since the circuit breaker adopts the spring mechanism, the operating work is large, and the mechanism vibrates violently in the process of splitting and closing, which causes severe transverse stress to the fixing bolt. Considering that the bolt has a sharp incision during the cutting process and has a high stress concentration coefficient, the cracking of the bolt is easily caused by the severe vibration during the splitting and closing process of the circuit breaker.

(2) The bolt has a high strength and absorbs a large amount of hydrogen during the pickling process. The bolt conducts under the combined action of hydrogen and stress after a period of incubation under the sustained action of low stress of the unit weight and the interaction of high stress during the circuit breaker opening and closing. When the dissolved hydrogen at the crack front reaches the critical value, the bolt cracks due to the combination of hydrogen and stress. As the crack expands, when the crack length reaches the critical value, the crack expands and the material undergoes sudden brittle fracture 9.

5. Conclusion

Ultra-high-strength bolts are sensitive to hydrogen, the hydrogen removal process is not complete or does not meet the standard, and residual hydrogen will lead to bolt fracture. To prevent the occurrence of such things, in the equipment design selection, the spring mechanism circuit breaker and other devices with severe vibrations of closing and closing should fully consider the anti-delay fracture performance and toughness of the bolt in the selection of bolts, in the pursuit of high strength. In the pursuit of high strength and hardness, the properties such as plasticity and impact toughness should be considered at the same time. Special attention should be paid to the processing technology to ensure the safe and stable operation of electrical equipment.

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