Analysis on Stress Corrosion Cracking of Brass Connecting Nut Utilized in Pneumatic Mechanism for 500kV Tank Circuit Breaker

Hao Chen¹,a, Tao Zhang¹,b, Yingjun Wang¹,c and Jianjun Zheng¹,d

¹ Inner Mongolia Electric Power Science & Research Institute, Hohhot, Inner Mongolia, 010020, China
a chenhao3@impc.com.cn
b chenhao1984223@163.com, cdkyzhangtao@163.com, dkywangyingjun@163.com,
dzhengjianjun27@126.com

Abstract. Circuit breaker is an on-load device that can interrupt load or short-circuit current. Recently, failure of component used in circuit breaker occurs frequently, thus the safety and stability of power grids is severely affected. In this paper, the fracture cause of a brass connecting nut of tank circuit breaker for 500 kV substation was investigated by means of macro-morphology inspection, chemical composition analysis, microstructure analysis, fracture morphology analysis, numerical simulation and energy spectrum analysis. The result showed that the fracture of the brass connecting nut was mainly caused by stress corrosion and stress concentration. Meanwhile the poor mechanical properties due to improper manufacture process, accelerated the development of the stress corrosion cracking of the brass connecting nut.

1. Introduction
The circuit breaker plays a crucial role in control and protection of main device for power system, which requires higher reliability of the operation mechanism. Once the operation mechanism of circuit breaker could not work well, it would cause huge economic and social losses to the power grid [1].

Since a 500kV substation was put into operation, the brass connecting nuts used in the pneumatic circuit of operating mechanism for tank circuit breaker have cracked many times, which cause air leakage and pressure drop in the pipeline. Therefore, it makes the pneumatic operating mechanism unable to operate normally. The fractured brass connecting nuts is used as a sealed connection in the pneumatic operating mechanism for 500kV circuit breaker. The brass connecting nut is composed of a hexagon nut with inner thread diameter of 15mm and a male connection with external thread diameter of 12mm, which is made of HPb59-1 lead brass alloy and bears 1.55Mpa compressed air pressure under normal working situation. In order to find out the reason leading to the brass connecting nut fracture and ensure the stability and security of other similar equipment, the fractured brass connecting nut of tank circuit breaker for 500 kV substation was investigated by means of different test methods.

2. Experiment results and analysis

2.1. Macroscopic observation
Figure 1 shows the macro-morphology of the fractured brass connecting nut. And it is clearly observed that the nut fractured at the joint of hexagon nut and male connection. For the joint surfaces are
perpendicular to each other without smooth transition, it is easy to crack due to stress concentration at the variable cross-section step. The grey fracture surface is even and rough without obvious plastic deformation, which presents typical brittle characteristics. Moreover, defects such as mechanical damage and arc strike are not found near the fracture. In addition, there is a mass of light green powder at the step of variable section of the nut, which should be the basic copper carbonate produced by the reaction of copper with oxygen, carbon dioxide and water in the air.

2.2. Fracture morphology analysis
The fracture morphology of the brass connecting nut is investigated by means of scanning electron microscope (SEM) and the result is shown in Figure 2. The result shows that the fracture initiates from the outer surface of the transition region with varying cross-section and the main fracture mode is intergranular fracture accompanied by secondary crack. Meanwhile, a crack is found at the end of the hexagon nut, which almost penetrated the whole nut.

2.3. Chemical composition analysis
The chemical compositions of fractured brass connecting nut are determined by means of chemical composition analysis and the testing result (mass fraction) is shown in Table 1. The result shows that the copper content of brass connecting nut is lower than the requirement of standard GB / T 5231-2012 for HPb59-1 lead brass, while the contents of lead, iron and impurities are higher than the standard requirements.

| Chemical element | Cu  | Pb  | Fe  | Zn  | Impurities |
|------------------|-----|-----|-----|-----|------------|
| Standard requirements | 57.0~60.0 | 0.8~1.9 | ≤ 0.5 | / | ≤ 1.0 |
| Test values      | 55.60 | 4.30 | 0.96 | 36.86 | 2.28 |
2.4. Metallographic structure Analysis
Figure 3 shows the metallographic microstructure of the brass connecting nut. In the whole longitudinal section, the metallographic structure of the nut is a two-phase structure of \( \alpha+\beta \), and the \( \alpha \) phase is distributed along the grain boundary in massive or feathery morphology. According to standard YS/T 347-2004, the average grain diameter of brass nut is determined as 0.11mm, and the grain fineness number is 3.5, which illustrates the grain size is relatively larger. In addition, it is clearly seen that the crack at the end of hexagon nut expands along the crystal boundary, which is consistent with the microscopic characteristics of stress corrosion cracking for copper alloy [2, 3].

![Figure 3 The metallographic structure of fractured brass nut](image)

2.5. Finite element analysis
There is a variable cross-section step at the joint of hexagon nut and male connection, which is easy to form stress concentration when right angle transition is adopted. Thus, in order to analyse the stress characteristics and compare the stress level under different transition forms, geometric models of brass connecting nuts with right angle and fillet transition are constructed according to the actual measurement data. Based on actual conditions, the numerical simulation models with tetrahedral elements are established, as shown in Figure 4. In simulation model, the influence of residual stress is ignored, and the bottom of nut is considered as fixed. Meanwhile the pressure in the nut cavity and the pre tightening force of the connecting nut are set as 1.55Mpa and 1000N respectively [4].

![Figure 4 Numerical simulation model for brass connecting nut with different transitional form](image)
Figure 5 shows the stress distributions of brass connecting nuts under different transition forms. It can be seen that the maximum stress of brass connecting nut appears in the transition region with varying cross-section for different schemes. For the brass connecting nut adopted right angle transition, the maximum stress is about 67 MPa. While the maximum stress of the brass connecting nut with round angle transition is only 32 MPa, which is less than half that of brass nuts with right angle transition. Therefore, the introduction of fillet transition for the connecting nut could reduce the stress level at the variable cross-section region effectively and avoid the occurrence of stress concentration cracking.

2.6. Energy spectrum analysis
The corrosion product within the crack of the fractured brass connecting nut is analysed by energy spectrum analyser, and the testing results are shown in Figure 6 and table 2. The result shows that the sulphur content of the corrosion product in the crack tip of the nut is as high as 1.64%. Generally, the stress corrosion of brass is closely related to the corrosive sulphur element in the contact medium [5, 6].
3. Analysis and discussion

In the chemical composition of the fractured brass connecting nut, the copper content is lower than the standard requirement, while the content of lead, iron and impurities is obviously higher than the standard requirements. Therefore, it the toughness of the nut declines due to lower copper content, on the other hand higher content of lead, iron and impurities makes the brittleness increase and the strength and toughness decrease. Recent research shows that when the zinc content in copper alloy is lower than 20%, stress corrosion cracking would not occur in natural environment generally. Once the zinc content is higher than 20%, the higher the zinc content, the greater the stress corrosion cracking sensitivity [7-9]. The zinc content of the fractured brass connecting nut is about 37%, which is much higher than 20%, thus the possibility of stress corrosion cracking is extremely high.

In addition, smooth transition is not considered for the variable cross-section step of the brass connecting nut, so that under the combined action of the internal medium pressure, pre tightening force and residual stress during operation, stress concentration cracking takes place easily at the tip of step with variable cross section.

The fractured brass connecting nut have been installed in the manufacturer and been supplied to the substation with the operating mechanism directly. Moreover, the substation is located in a good environment without any industrial pollution. Therefore, the corrosive medium with high sulphur content, which caused stress corrosion of the brass connecting nut, is related to the process of manufacture, storage and transportation.

In conclusion, the main reasons for the fracture of the brass connecting nut used in the pneumatic circuit of tank circuit breaker are as follows.

At first, the chemical composition of brass connecting nut does not meet the standard requirements, which makes its strength and toughness decrease. Secondly, owing to higher forging temperature or larger forging ratio of the brass connecting nut, the α phase distributes along the grain boundary and the crystalline grains relatively is coarse, which makes the intergranular bonding force weaken obviously. Thus, the strength and toughness of the brass connecting nut is further reduced as a result of improper manufacture process. Moreover, for adopting right angle transition in the step with variable cross-section of the fractured brass nut, thus it is easy to form crack initiation at the tip of the step due to stress concentration. Finally, the nut is exposed to the corrosive medium with high sulphur content which is more sensitive to the stress corrosion of brass alloy in the process of manufacture, storage and transportation. Therefore, affected by tensile stress together with corrosion medium, stress corrosion...
cracking occurs along the stress concentration area with varying cross section of brass connecting nut, and the crack expands to the internal surface of the male connection by the way of intergranular cracking.

4. Conclusions
In this paper, the reason for fracture of the brass connecting nut was systematically investigated and analysed. Through comparing and analysing the experimental results, the following conclusions are drawn.

1) As a result of poor material quality and improper manufacture process, the strength and toughness of the brass connecting nut was not sufficient enough. Meanwhile, in the process of manufacture, storage and transportation, the nut had been in contact with the corrosive medium with high sulphur content. Under the comprehensive action of inner pressure, preload and residual stress during operation, stress corrosion cracking occurred along the stress concentration area of the whole brass nut, which led to leakage of compressed air.

2) The brass connecting nuts of the same batch should be completely replaced, and the chemical composition of the newly replaced nuts should contain aluminium, nickel and tin elements to decrease tendency of stress corrosion.

3) Considering that the brass connecting nuts of the pneumatic circuit of operating mechanism have cracked many times in the power grid, the supports used in other similar equipment should be comprehensively inspected and the cracked ones should be replaced in time.

4) According to the results of numerical simulation, fillet transition should be considered for the variable cross-section step at the joint of hexagon nut and male connection of the brass connecting nut, in order to decrease the degree of stress concentration.

5) When replacing brass connecting nuts, the standardized and unified pre tightening force should be used in order to avoid stress corrosion cracking, which ensures safety and stability for circuit breaker.

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