Fracture failure analysis of driving crankshaft of substation circuit breaker

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Abstract. Fracture failure analysis of the driving crankshaft of a substation circuit breaker was conducted by means of macroscopic inspection, magnetic particle testing, spectroscopic analysis, mechanical property test and metallographic examination. The analysis results show that the fractured crankshaft is in the cast state, the manufacturer has not carried out follow-up heat treatment after casting, and there are large residual stresses and even cracks in the castings. Finite element analysis shows that the new driving crankshaft produced by Q235-A forged steel plate has higher safety performance and can replace the driving crankshaft produced by casting process.

1. Introduction
The opening and closing operation of circuit breaker is realized by the contact and separation between the moving contact and the static contact, and the movement of the moving contact is driven by the crankshaft. Therefore, the role of the crankshaft in the circuit breaker is very important. The quality of the crankshaft will directly affect the accuracy of the circuit breaker opening and closing. If the crankshaft breaks suddenly during operation, it will lead to unsuccessful opening and closing of circuit breaker, and will cause major safety accidents [1].

Driving crankshaft of the 508 circuit breaker broke during the pre-commissioning test of a 110 kV transformer substation. The circuit breaker was operated only less than 100 times before the fracture. The circuit breaker manufacturer is Shandong Tai’an Taishan High Voltage Switch Co., Ltd. The spring mechanism model of the operating mechanism is CTB-I, and the design material of the crankshaft is ZG 310-570. In this paper, the fracture reasons of the driving crankshaft are analyzed and the improvement measures are put forward.

2. Fracture Cause Analysis
2.1. Macroscopic inspection
The driving crankshaft of the circuit breaker spring mechanism is completely broken, as shown in figure 1. The crack zone with obvious rust and the silver-white final fracture zone can be seen on the fracture surface. The crack zone almost runs through the whole cross section, as shown in figure 2,
which means that there are serious cracks in this crankshaft before the field test. Thus, the driving crankshaft suddenly broke after only a few dozen actions.

Visual inspection of the fractured crankshaft and the same batch of crankshaft shows that there are rust and holes on the inner surface, as shown in figure 3, which means that there are some problems in the manufacturing process of this batch of crankshaft.

![Figure 1. Fracture of the driving crankshaft.](image1)

![Figure 2. Macroscopic fracture morphology.](image2)

![Figure 3. Rust and holes on the inner surface.](image3)

2.2. Magnetic particle testing
Two driving crankshafts in the same batch were sampled and the paint film was polished off for magnetic particle testing. It was found that there were dense cracks in both crankshaft. The maximum crack length was about 20 mm, as shown in figure 4. According to GB/T 9444-2007 "Magnetic Particle Detection of Steel Castings", the quality grade is determined as LM5, which means Linear Defect Grade 5. Therefore, the manufacturing quality of this batch of driving crankshafts is not up to standard.
2.3. Spectroscopic analysis

Spectroscopic analysis was carried out on the fractured crankshaft. The experimental results are shown in Table 1, and the composition of the cast steel brand ZG 310-570 in GB/T 11352-2007 standard is also listed for comparison. It can be concluded that the chemical composition of the fractured crankshaft meets the standard requirements.

| Samples             | Chemical Composition/ % |
|---------------------|--------------------------|
|                     | C  | Si  | Mn  | P  | S  |
| The fractured crankshaft | 0.210 | 0.295 | 0.505 | 0.0176 | 0.0125 |
| ZG 310-570          | ≤0.50 | ≤0.60 | ≤0.90 | ≤0.035 | ≤0.035 |

2.4. Mechanical property test

Room temperature mechanical properties of the fractured crankshaft was carried out. The experimental results are shown in Table 2, and the mechanical properties of the cast steel brand ZG 310-570 in GB/T 11352-2007 standard is also listed for comparison. It is found that the prescribed plastic elongation strength $R_{p0.2}$ and tensile strength $R_m$ of the fractured crankshaft are far greater than the lower limit value of ZG 310-570 in the standard, while the elongation after fracture is significantly lower than the standard value. Therefore, it is concluded that the room temperature mechanical properties of the fractured crankshaft are abnormal.

| Samples             | Mechanical Properties Parameters |
|---------------------|---------------------------------|
|                     | $R_{p0.2}$/MPa | $R_m$/MPa | A/% |
| The fractured crankshaft | 720           | 992       | 7.7 |
| ZG 310-570          | $\geq$310      | $\geq$570 | $\geq$15 |
2.5. Metallographic examination
The metallographic structure of the fractured crankshaft is shown in figure 5. It is composed of Widmanstatten structure of fine strip ferrite, massive ferrite and pearlite, showing typical metallographic morphology of ZG 310-570 castings [2].

![Figure 5. Metallographic structure of the fractured crankshaft.](image)

ZG310-570 cast steel has medium carbon content, and it is easy to form Widmanstatten structure in as-cast state, which results in poor mechanical properties. Heat treatment can improve its metallographic structure and comprehensive mechanical properties. Heat treatment can also eliminate the residual stress of the castings and avoid deformation and cracks in the process of using the castings. ZG 310-570 steel castings are usually heat treated by annealing, normalizing or normalizing plus tempering. The heat treatment specification is to heat the furnace to 900±20°C and cool it after holding for 4 hours. The cooling mode can choose furnace cooling or stacking air cooling according to site specific conditions and operation requirements, which are also known as annealing and stacking normalizing, respectively [3]. Because the internal stress of normalized castings is larger than that of annealed castings, the heat treatment process of tempering after normalizing can be adopted for some important parts. The normal normalizing structure of ZG310-570 cast steel is white fine ferrite with uniform distribution and black fine pearlite, so that the casting has the best comprehensive mechanical properties [3].

Therefore, it can be judged that the metallographic structure of the fractured crankshaft is not qualified. Based on the above mechanical properties test results, it can be concluded that the basic reason for the unqualified structure and abnormal mechanical properties of the castings is that the castings are not annealed, normalized or normalized plus tempered. That is to say, the fractured crankshaft is directly put into use without any heat treatment after casting.

The above analysis shows that the fundamental reason for the fracture of the driving crankshaft is that the crankshaft in this batch is in as-cast state. The manufacturer has not carried out follow-up heat treatment for the castings, and there are large residual stresses or even cracks in the castings, which can not meet the quality standards of the castings [4].

3. Improvement measures
Fracture analysis of driving crankshaft shows that the quality of this batch of crankshaft manufactured by casting method is not up to standard, and the long-term safe operation can not be guaranteed. After communication and coordination with the manufacturer, it is proposed to replace all the six driving crankshaft of the substation in the same batch. The material of the new driving crankshaft is Q235-A steel plate, and the manufacturing process is forging.

In order to ensure the quality of the new driving crankshaft, one is randomly selected for experimental testing. Tensile tests at room temperature show that the lower yield strength, tensile strength and elongation after fracture of the new crankshaft are 322 MPa, 452 MPa and 40.3%
respectively. The metallographic structure of the new crankshaft is shown in figure 6, showing a streamlined shape, indicating that it is a typical forging structure\cite{5}.

![Image](image1.png)

**Figure 6.** Metallographic structure of the new crankshaft.

![Image](image2.png)

**Figure 7.** Finite element calculation of the new crankshaft (a) total deformation (b) equivalent stress.

The finite element method is used to calculate the stress and deformation of the new crankshaft, as shown in figure 7. The calculation results show that under service conditions, without considering the stress concentration, the deformation is 0.1 mm and the stress is 108 MPa. If the yield strength of the material is 322 MPa, the safety factor is 3. Therefore, the mechanical properties of the new crankshaft can fully meet the application requirements.

4. Conclusions

Reason for fracture of the driving crankshaft of the circuit breaker in this substation is that the crankshaft in this batch is in as-cast state, the manufacturer has not carried out follow-up heat treatment for the castings, and there are large residual stresses or even cracks in the castings, which can not meet the quality standards. The new driving crankshaft produced by Q235-A forged steel plate has higher safety performance and can replace the driving crankshaft produced by casting process.

The driving crankshaft of circuit breaker bears large impact load during its service. If a sudden fracture occurs, it will lead to serious electrical equipment accidents. In view of the better comprehensive mechanical properties and better safety performance of forged steel parts than cast steel parts, it is suggested that forgings be used for important load-bearing parts in substation, such as driving crankshaft of circuit breaker, operating abutment and driving connecting rod, etc.
References

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