Analysis of heat treatment defect of load-bearing metal parts of high voltage circuit breaker mechanism

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Abstract. Failure analysis was carried out on the circuit breaker gear damaged in operation. Various detection methods were applied including composition analysis, hardness testing, metallographic observation, fracture scanning analysis and so on. The failure reason was found out to be improper heat treatment process, and corresponding rectification opinions were also put forward.

1. Introduction
High voltage circuit breaker is an important electrical appliance in the circuit protection of high voltage equipment. It is used in power systems to switch on and off normal loads and overloads load, short circuit load, which playing arc extinguishing function and cutting off capacity roles[1-3]. High voltage circuit breaker operation delay or fault will cause serious damage to equipment and even endanger the power grid[4,5]. Energy storage gear, energy storage spring and vertical connecting rod are important metal parts in circuit breaker mechanism, which carrying the power storage and transmission of circuit breaker[6-8]. In addition, the metal bearing parts of the mechanism suffer great impact in the opening and closing action of the circuit breaker, which directly affects the operating performance and reliability of the circuit breaker.

In this paper, the failure behavior of circuit breaker gear is thoroughly analyzed which improper heat treatment is considered to be the key cause. Corresponding technical means are put forward to improve the safety and stability of the equipment.

2. Experimental Section
The failed gear samples were collected from transformer substation in service. The Brinell hardness is measured on a brinell hardness tester. The sample composition was obtained using a desktop direct reading spectrometer (Oxford instrument). The morphologies and structures of the samples were analyzed by metallurgical microscopy (Zeiss microscope) and field emission scanning electron microscope (FE-SEM). FESEM characterization and inclusion composition characterization was performed on a JSM-7600F.

3. Results and Discussion
On December 2, 2014, the substation maintenance class of some power supply company carried out the installation and acceptance of some 110kV substation. During the tripping and closing operation and debugging, a tooth of manual energy storage gear fell off during the electric tripping.
3.1. Composition analysis
The design material of manual energy storage gear is 45# steel, and its composition test results are shown in the following table. The composition meets the standard requirements of 45# steel in GB/T 699-2015.

| Element | Content (%) | Standard Requirement(%) |
|---------|-------------|-------------------------|
| C       | 0.495       | 0.42-0.50               |
| Si      | 0.220       | 0.17-0.37               |
| Mn      | 0.597       | 0.50-0.80               |
| P       | 0.0312      | ≤0.035                  |
| S       | 0.0331      | ≤0.035                  |
| Cr      | 0.106       | ≤0.25                   |
| Ni      | 0.30        | ≤0.30                   |
| Cu      | 0.0476      | ≤0.25                   |

3.2. Hardness testing
After sampling near the fracture of the gear and grinding the cross section, rockwell hardness test was carried out uniformly on the tooth top and gear core. The average rockwell hardness of the tooth tip is 45.8HRC, and the average rockwell hardness of the gear core is 45.6HRC, which is higher than the design requirements provided by the manufacturer (28~35HRC).

3.3. Metallographic analysis
Metallographic tests were carried out after sampling near the gear fracture and section grinding. No abnormal metallographic structure was found at the tooth tip and the gear core, as shown in Figure 1 and Figure 2. Gray sulfide inclusions were found existing in the tissue, as shown in Figure 2. The sulfide grade is 1.5, which meets the requirements of gear manual.

3.4. Fracture analysis
Samples were taken near the gear fracture and observed by FE-SEM, as shown in Figure 3 – Figure 6. Figure 3, 4, 5 shows that the fracture source is an obvious brittle intergranular fracture, and there are secondary cracks at the grain boundary. However, as is displayed in Figure 6, the fracture has been oxidized, the inclusion at the crack source cannot be judged. The fracture toughness nest which exhibiting typical brittle fracture characteristics differed from fracture of conventional 45# steel. At the same time, as you can see most of the fracture morphologies are intergranular fractures except for a small number of transgranular fractures. There is no obvious striations morphology was observed, so
as fatigue fracture characteristics. Considering the tooth was also not subjected to serious wear and tear, the possibility of fatigue fracture was finally ruled out.

3.5 Failure analysis
The chemical composition of the manual energy storage gear submitted for inspection meets the standard requirements of 45# steel in GB/T 699-2015. The metallographic structure is normal, but the hardness value is higher than the design requirements provided by the manufacturer. The heat treatment process of 45# steel gear generally requires quenching and tempering which the sample should be undergone high temperature tempering after being quenching treated. The hardness of 45# steel tempered parts is generally HRC56~59, and the hardness after quenching is generally HRC22~34. The hardness value of the gear sent for inspection is 45.8HRC which beyond the design requirement scope of 28~35 HRC. Furthermore, the gear structure is tempered sorbite. Therefore, the high hardness of the gear is caused by improper heat treatment process, which may be due to the low tempering temperature in the quenching and tempering process.

In the service process, the stress state of the gear is repeated load. Due to the mutation of the section at the root of the tooth, the bending stress here is comparatively large. And improper heat treatment process led to the abnormally high hardness of sample which weakening the performance of toughness and impact resistance properties macroscopically. At the same time, internal stress may not be completely eliminated resulting from insufficient tempering treatment. Based on this situation,
micro cracks firstly emerged in the non-metallic inclusions being located at surface or subsurface of gear root. Subsequently cracks extended along the grain boundary. Brittle fracture occurred when the crack extended to a particular section which the load is already greater than the gear capacity.

4. Conclusions
In consideration of above discussions, the production process of load-bearing metal parts in circuit breaker and corresponding necessary testing should be paid attention to. Failure analysis conclusion and treatment measures were proposed as follows.

a) The hardness value of the manual energy storage gear is higher than the design requirement, its impact toughness is significantly reduced, and brittle fracture occurs under the action of load.

b) The hardness of manual energy storage gear of the same batch and model is checked, and the gear with high hardness value is replaced.

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