The study on material defects of structural parts of circuit breaker

ChaoFeng*, YiXie, JunWang, YiLong, DengkeLi, WeikeLiu and KejianOuyang
State Grid Hunan Electric Power Company Limited Research Institute, Changsha 410007, China
*Corresponding author’s e-mail:676459812@qq.com

Abstract. The fault of circuit breaker is caused by the defect of metal material. A series of tests including design drawings, physical and chemical tests, composition tests and metallographic observation, have been carried out for the failed springs. The experimental results showed that the failure of energy storage springs was caused by combination of design flaws and improper heat treatment process. At the same time, the corresponding noteworthy key points in the process of material production were put forward.

1. Introduction
High voltage circuit breaker is an important overload and short circuit protection device in power system[1]. Circuit breakers play an important role in the stable operation of electrical equipment, but they may also break down, posing a threat to the operation of equipment and system[2-5]. In addition, due to the lack of maintenance, the number of failures increases, which is in urgent need of improvement. In the circuit breaker, there are key metal parts that play different roles, such as energy storage spring and transmission connecting rod. Once the instruction cannot operated correctly on account of the material defects of the metal parts in the operation process, the function failure of the circuit breaker will be caused, or even the line will be out of service[6-8].

In this paper, the fault of circuit breaker caused by the failure of energy storage spring is studied, and the failure reason is found out by consulting design, macro inspection, mechanical performance test, composition analysis, metallographic observation and other analytical means, and the corresponding measures are also put forward.

2. Experimental Section
The failed energy storage spring and drive link were collected from transformer substation in service. The sample composition was obtained using a desktop direct reading spectrometer (Oxford instrument). The Brinell hardness is measured on a brinell hardness tester. The morphologies and structures of the samples were analyzed by metallurgical microscopy (Zeiss microscope).

3. Results and Discussion
In September 2014, LW36-126 circuit breaker spring of some 110kV substation failed resulted from the reduction of travel range. At present, the free height of spring is 358 mm, however, the design free height is 367 mm. The design material is 60Si2CrVA.
3.1. Design drawing verification

The material diameter of the spring designed in the drawing is 26 mm, the middle diameter of the spring is 185 mm, the effective number of turns is 5.5, and the free height is 367 mm. Of the above four parameters, all the other parameters are inconsistent with the standard GB/T 1358-2009 except for the effective winding number.

The installed load $F_1$ of spring design is 7082 N, the working load $F_2$ is 22533 N. Hence, the deformation corresponding to the two loads is 55 mm and 175 mm, respectively. The designed stiffness $K_1=K_2$ is 129 N/mm which inferring that the sample is linear spring.

3.2. Macro checking

The spring belongs to the cylindrical spiral spring which the surface paint layer is intact. And no obvious surface defects was observed. The free height of the spring was measured to be 358 mm which is 9 mm lower than the design height. Further measurements showed that the spring material diameter was 26.22 mm which is consistent with the design requirements.

At this time, the installed load $F_1$ of the spring is 5982 N, the working load $F_2$ is 23251 N, the free height is calculated according to 358 mm. Based on this, the deformation amount corresponding to the two loads is 46 mm and 166 mm, respectively. The stiffness $K_1$ is calculated as 130N/mm and $K_2$ as 140N/mm. With the decrease of free height, the linear shape of the spring changed from straight shape to incremental shape.

3.3. Composition analysis

According to the analysis of the composition of spring alloy, all the other measured elements meet the standard requirements of 60Si2CrVA in GB/T 1222-2007 except for the higher content of Si. The specific composition of the material is shown in the following table.

| Element | Content (%) | Standard Requirement(%) |
|---------|-------------|-------------------------|
| Si      | 2.33        | 1.4-1.8                 |
| Mn      | 0.59        | 0.4-0.7                 |
| Cr      | 1.12        | 0.9-1.2                 |
| V       | 0.19        | 0.1-0.2                 |

3.4. Hardness testing

The hardness of the spring was tested and the rockwell hardness was 48.5 HRC. The rockwell hardness conformed to the requirements of design drawing which is 45-52 HRC.

3.5. Metallographic analysis

Microstructure analysis was carried out on the flat end surface of the spring. And the metallographic structure was ferrite, troosite and carbide. The metallographic picture of the compound film was shown in Figure 1.
Typical upper bainite and large block ferrite appeared in the test field, as shown in Figure 2 and Figure 3. The results shows that the metallographic structure of the material is unqualified.

3.6. Failure analysis
The design drawings of the spring were checked and it turned out that the material diameter, mid-diameter and free height of the spring are not in conformity with the standard GB/T 1358-2009.

The Si content of the material is higher than the standard requirements of GB/T 1222-2007. It is generally believed that 1.5% is the optimal composition ratio of Si in spring steel. As a ferritic strengthening element, excessive Si exists in the alloy, which not only increases the austenitizing temperature, but also increases the possibility of free ferrite in subsequent heat treatment.

The microstructure shows that the material has undergone an improper heat treatment process which lead to the production of large amount of carbides, upper bainites and large block ferrites. Too low austenitizing temperature or not enough austenitizing time resulted in large amount of carbides and massive ferrites in the sample. The appearance of upper bainite indicates that the cooling rate is too slow in the quenching process, and the material may not be quenched immediately after austenitization or the quenching liquid may already deteriorated and failed after repeated use. In order to meet the hardness requirements of the design, a lower tempering temperature was chosen under the condition of incomplete quenching. In this situation, the quenching martensite cannot complete the carbon diffusion at low temperature resulting in the unqualified material structure according to the standard requirements of spring steel.

The existence of upper bainite and ferrite makes the strength of spring not enough. The spring material has plastic deformation under the action of compressive stress for a long time which leading to the decrease of free height.
4. Conclusions
In consideration of above discussions, this is a typical case of failure in operation due to unqualified energy storage spring materials of circuit breakers. The control of element content in the alloy is of great significance to the performance of the alloy. Failure analysis conclusion and treatment measures were proposed as follows.

The main reason of spring failure is improper heat treatment process which resulting in the emergence of upper bainite and free ferrite structure in the material. Nonconforming organizational structures weakened the performance of the energy storage spring. As a ferritic strengthening element material, excessive Si in the alloy would directly aggravates the risk of production of free ferrite in subsequent heat treatment. As a result, the early failure is unavoidable.

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