Fracture failure analysis of coal mill shaft

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Abstract. During the operation of No.2 boiler in a power plant, the fracture of a coal mill shaft occurred. The fracture causes of the coal mill shaft were found by macroscopic inspection, metallographic inspection, chemical composition analysis, fracture morphology analysis and mechanical property inspection. The experimental results showed that: 1. The external surface of the coal mill shaft had been welded, and the poor welding process resulted in a large number of welding defects such as cracks, slag inclusions and lack of fusion in the overlaying layer; 2. The improper hot working process of the coal mill shaft resulted in the abnormal metallographic structure of the shaft, and the existence of serious reticulated ferrite and brittle widmanstatten structure resulted in the low strength of the shaft. 3. Because of the existence of the cyclic torsion and bending stress of large load, the initial crack source occurred at the welding position of the hardfacing layer, and then extended in the form of fatigue, eventually causing the coal mill shaft to break. Three factors led the high cycle and low stress fatigue fracture of the coal mill shaft.

1. Introduction
During the grid connected power generation of boiler 2 in a power plant, the operators found that there was abnormal noise at the bearing box of coal mill, and then stopped the operation of the coal feeder, carried out maintenance on the coal mill, found that there was no coal accumulation and pressure grinding in the mill, checked the striking wheel, and found that there was no abnormality in the shell, striking plate, striking wheel rivets and front plate surface, and further checked that the ground angle bolt of the shell of the coal mill was not loose. Then, the striking wheel was pulled out and the bearing box was disassembled for inspection. The grease, oil level and bearing were all normal. The bearing box and motor ground angle bolts were not loose. When the sealing fan of the bearing box was removed, it was found that the large shaft of the pulverizer was broken in the free end cover of the bearing box. The model of coal pulverizer was EVT-S12.75, belonging to fan coal pulverizer, which was composed of inlet pipe, seal partition baffle, gate, striking wheel, case, bearing box base, bearing box, coupling, main motor, separator and lubricating pipeline, as shown in Figure 1. The striking wheel was cantilever mounted on the main shaft supported by double row bearings. The main motor and the main shaft of the bearing box can drive the striking wheel to rotate at high speed through the coupling, crushing the raw coal. The coal powder was finally sent into the boiler combustion chamber through the powder feeding pipeline. Therefore, the bearing box of the pulverizer bore the front and rear impact, bending and torsion stress. It was put into operation in December 1990 and has operated 136000 hours. The main shaft of bearing box has not been replaced so far. The main shaft of the pulverizer was $\Phi$ 250 × 1790mm, and the material was 45 steel.
2. Test method
The fracture morphology and fracture characteristics of the coal mill shaft were observed and analyzed to determine the fracture mode and fracture mechanism. HITACHI S-3700N scanning electron microscope was used to analyze the fracture morphology of coal mill.

According to GB/T 4336-2016 Determination of multi-element content of carbon steel and low and medium alloy steel by using spark discharge atomic emission spectrometry (routine method), the chemical composition of the broken coal mill shaft samples was analyzed by using the spectrometer desk type direct reading spectrometer to determine whether the chemical composition met the requirements of the standard.

According to the requirements of GB/T 228.1-2010 Metallic materials tensile test Part 1: room temperature test method, the room temperature tensile test was conducted on the CMT5305 electronic universal testing machine to determine whether the strength and plasticity of the coal mill shaft met the standard requirements.

According to GB/T 229-2007 Metallic materials Charpy pendulum impact test method, the coal mill shaft samples were tested at room temperature on ZBC-300B digital impact test machine to determine whether its impact toughness met the standard requirements.

According to the requirements of DL/T 884-2019 Technical guide for metallographic examination and evaluation of thermal power plants, the microstructure of the fractured coal mill shaft is tested by Bxio Observer Blm metallographic microscope to determine whether the metallographic structure was normal.

3. Test results and discussion
3.1. Observation and analysis of macromorphology
Analyze the macroscopic appearance of the broken coal mill shaft. The pulverizer shaft was broken in the free end cover of the bearing box, and there was no obvious change in the shaft diameter at the fracture. The fracture was vertical to the axis, and the fracture surface was flat, and there was no obvious macroscopic plastic deformation. The fracture surface was composed of initial fracture area(1), fatigue growth area(2) and instantaneous fracture area(3). The crack growth area was smooth and bright, and the fatigue striae like "rings" could be clearly observed, which accounted for most of the fracture area. The instantaneous fracture area was small and the surface was uneven. It was observed that there was a certain degree of corrosion on the fracture surface, and there was no obvious mechanical damage and corrosion damage on the surface of shaft near the fracture. On the fracture surface close to the initial fracture area, obvious defects such as lack of fusion and slag inclusion formed by welding could be observed, as shown in Figure 2,3,4.
Figure 2. Overall appearance of coal mill shaft.

Figure 3 Macroscopic fracture morphology of coal mill shaft.

Figure 4. Fracture welding defect

3.2. Scanning electron microscopy.
Scanning electron microscope (SEM) was used to detect the micro fracture of the pulverizer. The micro characteristic morphology of the fracture was shown in Figure 5. From the electron micrograph, it can be seen that the fracture morphology presented a river pattern, the fracture direction came along the cleavage plane of different heights, and the cracks between the cleavage planes of different heights converge to form a river pattern. At the same time, the cleavage crack presented a tongue pattern due to the result of propagation along the interface between the contracture crystal and the matrix. Therefore, from the overall macro morphology and micro fracture characteristics of the pulverizer fracture, the fracture of the pulverizer was brittle.

Figure 5. Scanning electron micrograph of coal mill shaft.
3.3. Analysis for Chemical Composition

The chemical composition of the broken coal mill shaft was tested, and the results are shown in Table 1. The material of the shaft was 45 steel. It can be seen that the content of each element in the chemical composition of the coal mill shaft sample met the standard requirements GB/T 699-2015.

| Detection elements | Carbon C | Silicon Si | Manganese Mn | Phosphorus P | Sulfur S | Chromium Cr | Nickel Ni | Copper Cu |
|--------------------|---------|------------|--------------|-------------|---------|-------------|----------|----------|
| Sample             | 0.46    | 0.25       | 0.63         | 0.004       | 0.012   | 0.09        | 0.05     | 0.10     |
| ~                  | 0.42    | 0.17       | 0.50         | ~           | ~       | ~           | ~        | ~        |
| Standard           | 0.50    | 0.37       | 0.80         | ~0.035      | ~0.035  | ~0.25       | ~0.30    | 0.25     |

3.4. Microstructural examination and analysis

Metallographic microscope[1-4] was used to inspect the microstructure of the coal mill shaft sample, and the metallographic morphology was shown in Figure 6, 7, 8, 9, 10. In the initial fracture zone, the surface structure of the axis was obviously welded, and there were a lot of welding defects such as cracks, slag inclusions and lack of fusion. The structure of the axis matrix from the surface to the center was coarse reticulated ferrite + pearlite, accompanied by severe widmanstatten structure, and the grain size was grade 5. No serious slag inclusion was found in the tissue. This kind of structure led to the decrease of the strength and toughness of the material, and brittle fracture occurred easily.
3.5. Analysis of mechanical properties
The normal temperature impact test and tensile test were carried out on the coal mill shaft. As shown in Table 2 for test results. According to the analysis of the structure and structure state of the coal mill shaft, it was a heat treatment process of normalizing + tempering. Under this heat treatment process, the strength and impact toughness allowance of the coal mill shaft material were insufficient.

| Detection elements | tensile strength $R_m$ (MPa) | Yield strength $R_e$ (MPa) | elongation at break $A$ (%) | Impact fracture energy $A_kU$ (J) |
|-------------------|-----------------|-----------------|-----------------|-----------------|
| Sample            | 723             | 415             | 22              | 40              |
| Standard          | ≥ 600           | ≥ 355           | ≥ 16            | ≥ 39            |

4. Summary
According to the analysis of fracture morphology, the initial fracture area, propagation area and instantaneous fracture area were relatively clear, and the fatigue striation morphology of propagation area was obvious. The fracture of initial crack area is close to the external surface of shaft, and there were weld defects such as crack, slag inclusion and lack of fusion. The expansion area was larger, and the instantaneous fault area was smaller. It showed that the primary load on the coal mill shaft was not very large. The fracture of the coal pulverizer was river pattern, and the brittleness was large. By observing the density of fatigue striations in the extended region, it was concluded that the axial fracture belonged to high cycle and low stress fatigue fracture.

From the metallographic structure analysis[5,6], the structure of the surface layer of the coal mill shaft was welding structure. There were many welding defects such as cracks, slag inclusions and lack of fusion in the structure. The structure of the shaft base from the surface layer to the center was coarse reticulated ferrite + pearlite structure, accompanied by serious widmanstatten structure, and the grain size was grade 5.

From the analysis of mechanical properties, although the mechanical properties of the coal mill shaft materials met the requirements of relevant standards, the strength and impact toughness indexes were close to the lower limit, and the allowance of the coal mill shaft material was insufficient.

To sum up, the coal mill shaft should be normalized + tempered in the manufacturing process. But under the hot working process with high normalizing temperature, long holding time and slow cooling speed, the network ferrite and widmanstatten structure distributed along the austenite grain boundary formed. When austenite transformation occurred in hypo-eutectoid steel, primary ferrite was preferentially formed at austenite grain boundary. When the cooling speed was too slow, it would form network ferrite at austenite grain boundary according to the diffusion transformation law. Network ferrite would increase the brittleness of steel. The widmanstatten structure was a coarse-grained austenite formed at high temperature. During the cooling, some ferrite extended from the grain boundary to the crystal or precipitated along a certain direction in the crystal according to the shear mechanism, and distributed on the pearlite as acicular ferrite. The formation conditions of
Widmanstatten structure were low carbon content (generally lower than 0.2%), high undercooling and coarse austenite grains. In general, due to the low carbon content of low-carbon steel and low-carbon alloy steel, the pre-reticulated ferrite was preferentially formed at the austenite grain boundary during continuous cooling of austenite. Due to the high transformation temperature, the precipitation is mainly diffusion transformation at this time. Further cooling would cause a large number of widmanstatten ferrite to grow rapidly from the reticulated ferrite side of the austenite grain boundary to a certain coarse acicular ferrite, which points to the austenite body. The reticular ferrite and widmanstatten structure were overheated structures, which can reduce the strength and toughness of the material and make the material brittle. The external surface of the shaft in the initial crack area was subject to surfacing treatment, and the welding process was poor, and there were welding defects. Furthermore, the pulverizer had been put into operation for 132000 hours, under the action of long-term cyclic torsion and bending stress. The crack source of hardfacing layer expanded continuously. Finally, high cycle and low stress fatigue fracture of coal mill shaft occurred.

References

[1] Zhang, Z., Yin, Z., Han, T., & Tan, A. C. (2013). Fracture analysis of wind turbine main shaft. Engineering Failure Analysis, 34, 129-139.

[2] Savković, M., Gašić, M., Petrović, D., Zdravković, N., & Pljakić, R. (2012). Analysis of the drive shaft fracture of the bucket wheel excavator. Engineering Failure Analysis, 20, 105-117.

[3] Eder, M. A., & Bitsche, R. D. (2015). Fracture analysis of adhesive joints in wind turbine blades. Wind Energy, 18(6), 1007-1022.

[4] Chou, J. S., & Tu, W. T. (2011). Failure analysis and risk management of a collapsed large wind turbine tower. Engineering Failure Analysis, 18(1), 295-313.

[5] Zangeneh, S., Ketabchi, M., & Kalaki, A. (2014). Fracture failure analysis of AISI 304L stainless steel shaft. Engineering Failure Analysis, 36, 155-165.

[6] Fuller, R. W., Ehrrott Jr, J. Q., Heard, W. F., Robert, S. D., Stinson, R. D., Solanki, K., & Horstemeyer, M. F. (2008). Failure analysis of AISI 304 stainless steel shaft. Engineering Failure Analysis, 15(7), 835-846.