Failure Analysis of 2Cr13 Blade in a 135MW Low Pressure Steam Turbine

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Abstract: The failure mode and causes of low-pressure rotor 2Cr13 stainless steel blades in a power plant steam turbine were analyzed using fracture analysis, SEM, chemical composition analysis and metallographic techniques. The fracture characteristics and mechanism of the blades were discussed. The results show that the failure mode is fatigue which was caused by the machining tool mark at R corner of blade root and tenon transition area.

1. Introduction
The reliability of the last stage blade of the steam turbine has a great influence on the safe operation of steam turbine. The main cause of the steam turbine accidents is blade damage, accounting for 30% [1]. The abnormal vibration of a turbine of a thermal power plant was found, and an inspection found that the blade of the 26th stage of the low-pressure rotor was all broken. The unit operated for about 40000 hours; the material of blades was martensitic heat-resistant steel 2Cr13. The blade made of this material has relatively high strength, high thermal stability, good vibration damping performance, high toughness and high cold deformation ability at the operating temperature below 700°C [2, 11]. It is a common used material of low-pressure rotor for 135MW units in China. In order to find out the cause of blade fracture, experimental analysis is carried out.

2. Experiment and analysis

2.1. Macro observation of fracture
Through the inspection of 161 blade root fractures, it is found that the fractures of the blade are all located at the blade root, and there are many damages on the blade body, which are caused by the collision after the blade falls. Figure 1 shows the overall morphology of the fractured blade.

Figure 1. Macro morphology of the blade.
Further observation of the blade fracture shows that all (161) fractures have the same morphology with typical fatigue fracture characteristics.

As shown in Figure 2, the fracture is composed of two parts: the fatigue area and the instantaneous fault area. There are two fatigue sources on the fracture, both at the R corner. The main source is at the intake side, showing as a line source, and the sub source is at the exhaust side. After the fatigue crack of main source is formed at the intake side, it propagates to the exhaust side. Due to the change of load or frequency, there are parallel shell lines on the fracture surface. This part of the main crack growth area accounts for about 2/3 of the fracture area, which is relatively flat and smooth, indicating that the crack growth is relatively slow. Another fatigue source (sub source) is formed at the exhaust side, and the crack propagates towards the intake side, also leaving shell lines. The fracture in this area is rougher than that in the main source area, indicating that the crack propagates faster and the load is larger. It can be concluded that the formation time of fatigue crack at the exhaust side is later than that of main crack source (intake side). The remaining effective area is getting smaller and smaller because the two cracks propagate towards each other. The load is increasing, and they are in a state of instability, which eventually leads to blade fracture. The rough area in the middle of the fracture is the instantaneous fault area. Therefore, the blade experiences a fatigue fracture process from crack formation, steady crack growth, unstable crack growth to final fracture.

2.2. Micro observation of fracture

Put the cleaned fracture into SEM for observation. Figure 3 shows the morphology of fatigue curve (shell line) on the fracture. Due to the light oxidation of the fracture, the fatigue curve is relatively clear. Figure 4 shows the morphology near the main crack source, and the fatigue striation can be seen locally, which is the feature of fatigue crack growth, and the secondary crack appears at the same time, indicating that the blade is under great stress. Figure 5 is a picture of the sub fatigue source area, which shows a large fluctuation of the fracture and a secondary crack, indicating that the crack propagates rapidly. Figure 6 shows the morphology of the instantaneous fault zone, and the fracture surface shows an isometric dimple. Macro inspection shows that blade fracture occurs at R corner, and fatigue crack first occurs at R corner. Figure 7 is a scanning photo of blade at R corner. It is found that there is obvious machining tool mark in R corner, which is easy to produce stress concentration, resulting in the generation of fatigue crack and fatigue fracture.
As the blade fracture is oxidized and the degree of oxidation is different, the oxygen content in different areas of the fracture is measured by X-ray energy spectrometer. From the intake side to the exhaust side, it is divided into seven zones, as shown in Figure 8. See Table 1 for the measurement results. The results show that the oxygen content is the highest in the 1, 2, 3 and 4 zones near the intake side, followed by the 7 and 5 zones, and the lowest in the 6 zones, which indicates that the intake side cracks first, the exhaust side cracks later, and the 6 zone nears the last instantaneous fault area, with the lowest oxygen content.
2.3. Chemical composition analysis

X-ray fluorescence spectrometer is used to analyze the chemical composition of three blades. The analysis results are shown in Table 2, and the specified values of relevant standards [3] are listed in the table at the same time. After comparison, the composition of blades meets the specified values of the standards.

| Element content (wt%) | C   | Si  | Mn  | P   | S   | Cr  |
|-----------------------|-----|-----|-----|-----|-----|-----|
| sample 1              | 0.20| 0.32| 0.15| 0.018| 0.008| 12.95|
| sample 2              | 0.19| 0.34| 0.15| 0.016| 0.010| 12.80|
| sample 3              | 0.19| 0.35| 0.15| 0.016| 0.008| 12.77|
| GB/T1220-92           | 0.16-0.25| ≤1.00| ≤1.00| ≤0.040| ≤0.030| 12.00-14.00|

2.4. Metallographic structure

The blade material is 2Cr13 martensitic stainless steel. The samples are cut from the blade and prepared into metallographic samples, which are observed under metallographic microscope. Figure 9 is the inspection photo of inclusions in the sample before erosion. The inclusions are tiny with small amount, and the inclusion level is less than level 2. Figure 10 and Figure 11 show the metallographic structure of the blade under 100 and 500 times magnification respectively, which is tempered sorbite with martensite orientation. The blades have been treated by thermal refining, with a quenching temperature of 950-1020 °C and the tempering temperature of 660-770 °C [4], and the metallographic structure is normal.
2.5. Hardness test

Table 3 shows the Brinell hardness test results of three blades, with test load of 29400N, holding time of 15s and indenter diameter of 10 mm. The test data is within the qualified range specified in the standard [5].

| Sample   | 1  | 2  | 3  | 4  |
|----------|----|----|----|----|
| Sample 1 | 222| 226| 226| 228|
| Sample 2 | 240| 236| 240| 245|
| Sample 3 | 246| 252| 250| 249|

3. Analysis and discussion

It is found that the chemical composition and Brinell hardness of the blade material meet the requirements of the relevant standards, and the metallographic structure of the blade is normal. The fracture analysis results show that the blade failure belongs to fatigue fracture, and the fatigue crack originates from the transition rounded corner (R corner) between the blade root and the tenon, and propagates from the intake side to the exhaust side. After the main crack source is formed and propagates for a certain distance at the intake side of some blades, a sub crack source is formed at the exhaust side, which propagates to the intake side at the same time, forming the dual source fatigue.

The process of fatigue fracture consists of three stages: crack formation, crack propagation, and the sudden fracture of the remaining section. Therefore, the fatigue fracture will go through a process and take a certain time. The three stages of fatigue process are fully reflected in this blade accident. Before the accident, the blade has experienced the process of crack formation and crack propagation, and the fatigue area has reached 2/3. It can be concluded that this process has lasted for quite a long time. The
low-pressure rotor blades of steam turbine have complex stress conditions. Firstly, they are affected by the centrifugal force and steam flow generated by themselves during the rotation of blades; secondly, they are also affected by the alternating vibration stress, centrifugal force and torsional stress caused by alternating steam flow; in addition, they are also affected by the bending stress caused by the pressure difference between the front and back of blades and the thermal stress caused by uneven heating \[6, 11\]. If the periodic variation of the blade can produce enough peak stress, the blade will fracture due to fatigue. Based on the understanding of the fracture causes of the blades of the same kind of units or materials, it is concluded that the fatigue fracture is the main failure type of the blades, which is specifically manifested in overload, high temperature, stress, corrosion and contact friction fatigue fracture. The main causes of the fatigue fracture may be the blades themselves, the operation or maintenance \[7-10\]. The reason for this blade fracture is that there are deep machining marks at the transition rounded corner (R corner) between the blade root and the tenon, which belongs to machining defects. The stress concentration is formed at the defects, and the cracks lead to blade fracture.

4. Conclusion
1. The fracture property of blade is fatigue fracture.
2. The stress concentration is caused by machining marks at the transition rounded corner (R corner) between the blade root and the tenon, which is the direct cause of cracks.

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