Failure analysis of the low-pressure blade lacing wire in steam turbine

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Abstract. The failure analysis of the low-pressure last stage blade lacing wire in steam turbine made of 0Cr17Ni4Cu4Nb(S17400) is presented. The failure of the low-pressure last stage blade occurred at 7 operating years. Several examinations were carried out to identify the blade lacing wire failure’s root cause: macroscopic inspection, chemical composition analysis, hardness test, metallographic analysis, microscopic examination and inspection of maintenance records. It is found that there is local displacement of the roots of the low-pressure rotor, and the collision between the lacing and the lacing holes is the direct cause and external mechanical incentive of the lacing fracture. The high content of P element and the high hardness reduce the plasticity and toughness of the material which is the intrinsic factor of this tensile fracture. Without obvious plastic deformation, the low-pressure last stage blade lacing wire breaks rapidly. It is suggested to find out the local displacement of blade root and fix it in a reliable way, check the strength after eliminating the harmful defects such as cracks, and replace the blade if necessary, strictly according to DL/T438-2016 and the manufacturer's standard requirements for the inspection of the lacing wire before use.

Keywords: Turbine blade; lacing wire; fracture; failure analysis.

1. Introduction
Steam turbine blades are critical components in power plants, which convert the linear motion of high temperature and high pressure steam flowing down a pressure gradient into a rotary motion of the turbine shaft. The low pressure turbine blades, designed to extract the final remnant of energy from the passing steam flow, are relatively large scale rotating airfoils due to the significant centrifugal forces experienced during normal operation. Four blades are grouped together by a lacing wire. Low pressure (LP) blades of a steam turbine are generally found to be more susceptible to failure than intermediate pressure (IP) and high pressure (HP) blades. [1-4]

0Cr17Ni4Cu4Nb (S17400) steel is a martensitic precipitation hardening stainless steel. The steel has high corrosion resistance, good attenuation performance, easy adjustment of strength level, simple welding process, especially corrosion resistance and water drop resistance than 12% Cr steel, and has good comprehensive mechanical properties. It can be used for turbine low pressure final stage moving blades and structural parts with working temperature below 300℃ in corrosive environment. [5-8]
The gas turbine, steam turbine and generator are rigidly connected in series on a long axis, the steam turbine model is HTC158# (D10 optimized type), three-pressure, intermediate reheat, single-shaft, impulsive non-extraction pure solidification unit. The high-pressure cylinder of the steam turbine is arranged in reverse flow. At the final stage of the medium-pressure cylinder, there is intake steam from the waste heat boiler low-pressure superheated steam. The medium pressure cylinders are mixed with the steam and flow into the low pressure cylinder. The low pressure cylinder is a double-flow down-flow type with 6 pressure stages for a total of 12 stages. The parameters of low pressure steam are shown in Table 1.

| Table 1. The parameters of low pressure steam. |
|-----------------------------------------------|
| Extraction condition | Pure coagulation condition |
| Steam inlet pressure (MPa) | 0.37 | 0.40 |
| Steam inlet temperature (°C) | 305.05 | 304.54 |
| Steam flow (t/h) | 38.28 | 44.24 |
| Exhaust steam pressure (KPa) | 3.67 | 4.90 |
| Exhaust steam temperature (°C) | 27.51 | 32.54 |
| Exhaust flow (t/h) | 211.16 | 362.42 |

During the No.7 steam turbine set overhaul in April 2019, it was found that there were lacing wire fracture and leaf blade hole damage of the last stage low-pressure blade, and the material was 0Cr17Ni4Cu4Nb(S17400) with 13 mm diameter. A series of tests were carried out to analyze the cause of failure.

2. Experimental procedure
The objects to investigate into were lacing wire fracture and leaf blade hole damage (8.090 h service exposed) obtained from the plant. After an extensive visual examination, chemical analysis of the lacing wire material was carried out by spectral analysis method. A portion of the failed lacing wire fractured surface was cut for metallography. The metallographic samples were prepared by using standard metallographic techniques and etched with reagent Ferric chloride and hydrochloric acid during 15s at room temperature. The brinell hardness test and vickers hardness test were carried out on the cross section of the lacing wire. Brinell Hardness Testing Machine with bearing of 2.5mm in diameter under a load of 1840 N. Microhardness Vickers tests were performed with a 200 g load and an indentation time of 15 s. Micro-indentation tests were also carried out on defined areas of the sample. The applied load was 1960 mN. The microstructure of the lacing wire material was analyzed using an optical microscope and a TESCAN VEGA3 LM scanning electron microscope (SEM).

3. Results

3.1. Visual inspection
Low pressure blade lacing wire and brace hole site inspection situation as shown in fig.1. There is a gap between lacing wire with brace hole, accidental abnormal factors may lead to the collision of lacing wire and brace hole in operation, local defects were first produced on the outer surface or the inner surface of the pull rib hole, local defects subsequently develop into microcracks in high-speed rotation or re-collision, macroscopic defects caused by microcrack growth are related to collision energy, frequency and contact area, etc. local defects can form Local crack of blade hole (b), gap of blade hole (c), severe crack of blade hole (c). In addition, it can be seen from (b) that the collision at different locations can form multiple cracks at different locations (9 o’clock and 12 o’clock), extending along the inner wall to the outer wall. (e) visible fracture in overall level, no obvious plastic deformation, the characteristics of brittle fracture, fracture surface local oxidation corrosion, show the maintenance when the brace has broken the oxidation, fracture surface smooth metallic parts, may be associated with cracking section between local touch after grinding, according to the fracture extended morphology, visible inspection...
blade fracture source of brace in the A1 and A2 position, extension area located at the position B, instantaneous fault zone located at the position C.

(a) Fit between lacing wire and blade hole  (b) Local crack of blade hole
(c) Gap of blade hole  (d) severe crack of blade hole
(e) Fracture of lacing wire

Figure 1. Morphology of failed low-pressure blade

3.2. Chemical analysis
Thermo ARL8860 spectrometer was used for spectral analysis, and the analysis results were the average of the three test results, as shown in table.2. It can be seen that the content of P exceeds the requirements of manufacturer's standard, and the content of other major elements meets the requirements. Generally, P element is considered as the harmful element in steel, which can reduce the plasticity and toughness of steel, and increase the brittle transition temperature of steel, leading to the cold brittleness of steel.
Table 2. Spectral analysis results (wt%).

| Elements | C  | Si | Mn | P  | S  | Cr | Ni | Cu | Nb+Ta |
|----------|----|----|----|----|----|----|----|----|-------|
| Result   | 0.040 | 0.38 | 0.23 | 0.035 | 0.004 | 15.84 | 4.41 | 3.37 | 0.28   |
| Manufacturer's standard | ≤0.055 | ≤1.00 | ≤0.50 | ≤0.030 | ≤0.020 | 15.00~ | 3.80~ | 3.00~ | 0.15~ |

3.3. Hardness test

Brinell hardness test and vickers hardness test were carried out on the cross section of the lacing wire. The hardness test location was shown in fig.2, and the results of brinell hardness test were shown in table.3, and vickers hardness test results were shown in fig.3. It can be seen that the detected brinell hardness value exceeds the manufacturer's standard requirements, and the distribution trend of vickers hardness of the tensile rib cross-section of the blade shows an upward trend from the central part to the edge part. The measured minimum value is 308HV, and the measured maximum value is 326HV, both of which exceed the manufacturer's standard requirements.

![Location of hardness measuring point](image)

(a) Brinell hardness test  (b) Vickers hardness test

**Figure 2.** Location of hardness measuring point

Table 3. Brinell hardness test results (HBW)

| Measuring point | 1  | 2  | 3  | 4  | manufacturer's standard |
|-----------------|----|----|----|----|-------------------------|
| Result          | 320| 314| 315| 318| 262-302                 |

![Vickers hardness test results](image)

**Figure 3.** Vickers hardness test results

3.4. Microscopical investigation

The metallographic structure of the outer edge and the central part is martensite without obvious abnormality, which was shown in fig.4.
The source area, extension area and transient fracture area of lacing wire were analyzed by SEM respectively, and the results are shown in fig. 5. Visible fracture source (A1) local pit, for external surface of the lacing wire after the collision, the follow-up development in high speed rotating or collision again as the crack, and gradually expand to the central part, micro has the obvious river pattern, spreading area and transient breaking cleavage fracture morphology, found no toughening nest morphology, as a typical brittle fracture. There are smooth grinding surface and directional grinding mark in the fracture, which may be related to the friction between the sections after lacing wire fracture. The local pore morphology of the fracture may be the original defect of the material.
4. Conclusion
In summary, local displacement exists in the blade root of the last stage of low-pressure rotor, and the collision between the lacing wire and brace hole during operation is the direct cause and external mechanical inducement of the failure. The high content P element and hardness of lacing wire reduce the plasticity and toughness of the material, which are the internal factors of this lacing wire fracture. Brittle fracture occurs rapidly without obvious plastic deformation of the steel.

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