Failure Analysis in Lacing Wire Of Last Stage Low Pressure Steam Turbine Blade

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Abstract. The present paper studies a root cause of failure analysis of lacing wire used in the last stage blade of low pressure (LP) steam turbine. The lacing wire is made of Stainless Steel Grade 17-4 PH with a diameter of 1.4 mm. The failure occurred after the unit had been operated for 4 years. The fault occurred several times during the operation periods. The failure location is near the tack weld which has functions as a stopper between the lacing wire and the stub. Macro fractography, light optical microscope and scanning electron microscope were used to examine the fracture surface and microstructure closed to the failures. The cyclic stress was evaluate using harmonic analysis simulation using FEA (finite element analysis) Ansys 2019 R2. The benchmark that is indication of fatigue failure was clearly visible. It is concluded that the failure mechanism is fatigue failure with crack initiation. Improper maintenance procedures especially welding procedures trigger an initial crack and then the initial crack gets a concentrated cyclic load causing lacing wire broken.

1. Introduction
In the current era, with demands for greater power generation capacity and good efficiency, the last stage blades of low pressure Steam Turbines are needed to be longer. To save on manufacturing costs, technology for the last stage LP Steam Turbine blade tends to use an integral shroud blade (ISB) with lacing wire on the center, so that the blade can be made thinner, but stability due to vibration and deformation can still be achieved [1]. A number of vulnerable failures occur at the last stage LP turbine blade, namely fracture on lacing wire, fretting on shroud, crack on roots, damaged on tenon and shroud [2,3,4,5,6]. The material commonly used for lacing wire is Cr17Ni4Cu4Nb, which is steel with martensitic precipitation and hardening. This material has good mechanical properties, good
corrosion resistance and good wear resistance \[7\]. Table 1. shows the specifications of LP steam turbine and the last stage blade of a power plant, where in the LP steam turbine the type is tandem compound and each has 7 stages. Last stage blade has a length of 900 mm and the material for blade and lacing wire is Cr17Ni4Cu4Nb. The working conditions of Low pressure steam turbine are 358 °C at the inlet and 47 °C at the outlet, 1.06 MPa inlet pressure and 0.0063 MPa outlet pressure.

**Table 1.** Last Blade LP steam turbine specifications

| No | Parameter                  | Unit | Value                  |
|----|----------------------------|------|------------------------|
| 1  | Type                       | Sub-critical, single-reheat, tandem compound, multi-cylinder type steam turbine. |
| 2  | Speed                      | rpm  | 3000                   |
| 3  | Number of extractions      | mm   | 7 (3+1+4)              |
| 4  | Length of last stage blade | m    | 900                    |
| 5  | Annulus area of last blade | m²   | 7.35                   |

**Material**

C = 0.07, Mn = 1, Si = 1, Cr = 15.5 - 17.5, Ni = 3-5, P = 0.04, S = 0.03, Cu = 3-5.

Tensile yield Strength = 1275 MPa
Tensile ultimate strength = 1379 MPa

On 30 November 2018 found an increase in conductivity from the online analyzer measurement in the condenser that very quickly, at 4600 µs / cm and PH <5.76, the unit was decided to be shut down and found that the condenser pipe was leaking due to being hit by the impact of a broken lacing wire from LP steam turbine blade. Further investigation on the turbine side found that lacing wire stub on the blade was broke. Several tests were carried out to find out the fracture mechanism of the lacing wire. There are two installation types of lacing wire on the blade, the first is with a tack weld that functions as a stopper between the lacing wire and the stub and the second is by welding directly into the blade. According to Lijie Qiao et all, the break of the lacing wire was driven by the continued impact of the tack weld lacing wire and stub \[7\]. While the type of lacing wire that is welded directly to the blade, high stress concentration occurs at that point which also triggers crack initiation. E. Poused et al \[8\]. Both sources of failure references conclude that the failure mechanism is from the mechanism of fatigue. In the present work a root cause failure analysis study was performed on a lacing wire of low-pressure turbine blade. The aim was to get understanding on failure mechanism and to prevent future event to occur.

2. Methodology

Table 2 shows the complete examination and methods to obtain the data. The samples were prepared based on the type of test performed. To obtain a good fracture surface, the fracture surface was cleaned with 1% HCL in acetone. The fracture surface image was captured with camera having macro
To examine details fracture surface and possible chemical present in the surface, a Hitachi Flexsem 100 scanning electron microscopes (SEM) equipped with Energy-dispersive X-ray spectroscopy (EDS) was used, and hardness mechanical properties to determine the mechanism of failure of lacing wire to support the activities of RCFA (root cause failure analysis). For microstructure testing, the specimens are grinded and polishing [9] to a minimum of 2000 grids before etching with Vilella Reagent according to the standard [10]. To observe the faulting, a macro photo was taken with a camera that has super-macro capability. Then it is done by testing with SEM. SEM samples can be tested as it is as long as the size of the test specimen can enter the chamber. The cyclic stress evaluated using harmonic analysis simulation using FEA (finite element analysis) Ansys 2019 R2.

Table 2. List of tests, data obtained and analysis

| No | Type of Testing                                      | Data obtained                                                                 | Analysis                                                                 |
|----|-----------------------------------------------------|-------------------------------------------------------------------------------|-------------------------------------------------------------------------|
| 1  | Maintenance history and visual inspection           | Maintenance data                                                             | Surface fractures, maintenance procedures                              |
| 2  | OES(Optical Emission Spectroscopy) testing with a Thermo ARL spectrometer | Chemical composition                                                         | Verification of the chemical composition of steel                       |
| 3  | Optical microscope testing with the OLYMPUS brand microscope | Microstructure image                                                         | Determine the microstructure                                            |
| 4  | SEM-EDS Scanning Electron Microscope-Energy Dispersive Testing With Microscope Electrons | microstructure image, microstructure topography, and chemical elements of steel and deposits in the sample | Determine the micro structure, fracture pattern, and chemical composition of the deposit |
| 5  | Micro hardness testing with Shimadzu test equipment  | Average hardness and distribution values                                      | Determine the degradation of hardness mechanical properties            |

3. Results and Discussion

3.1. Maintenance History

In Figure 1 show incident in November 30 2018, found several lacing wires and stubs broke, the stub rupture was caused by a continuous collision between tack weld and stub. The red line arrow indicates the position of the lacing wire fracture found in the condenser tubing. In May 2019 maintenance was carried out in a manner perform a full weld to replacing the tack weld at the ends of the lacing wire as shown in Figure 2. The GTAW (gas tungsten arc welding) method was used with ER 410 filler without pre heat and post weld treatment.
In December 2019 during inspection period, found full weld on the lacing wire have broken, especially in the heat affected zone (HAZ) area as shown in Figure 3 a, found four broken lacing wire. 3 samples are then taken and labeled A, B, C as shown in Figure 3b. From the maintenance history, it can be said that the material has a fracture in the area around the HAZ, both of that occurs in tack weld and in full weld, indicating the possibility that the welding process triggers failure. Figure 3a shows that lacing wire and stub that are not welded, both tack weld and full welding, do not fail.

Figure 1. Lacing wire fracture in LP turbine (a) condenser pipe hit by broken lacing wire, (b) position of lacing wire fracture, (c) stub rupture hit tack weld, (d) broken wire lacing position on the LP turbine stage blade.

Figure 2. Full weld and tack weld on lacing wire
3.2 Visual Inspection

The macrography image of the fracture surface is shown in Figures 4. It can be seen three fractures that a typical fault sample is fatigue fault, where the benchmark pattern is clearly visible, especially for sample A (Figure 4a) and Sample C (Figure 4c).

Figure 3. (a) Lacing wire fracture on LP turbine, (b) broken lacing wire samples

The faults in the image are quite varied but some of the most commonly recognized are the fractures starting with, initiation cracks starting from the area near the weld (HAZ) then very wide crack growth, and final fractures. The three steps of failure indicate that the lacing wire has broken due to fatigue. It is seen that the beginning of the crack is only one and starts from the same position (HAZ) marked by the arrow in Figure 4a, b, c. The second important phenomenon is that the area of the final fracture is very small (about 10-20%) of the total area as shown with dash line by Figure 4b., which indicates that the stress is quite small compared to the material strength of the steel.

Figure 4. (a) fracture sample A, (b) fracture sample B, (c) fracture sample C.

3.3 Chemical Composition (OES)

Chemical composition testing is carried out using optical emission spectrometry and the test results in Table 3 show that the chemical composition matches within the range in ASTM A564 grade 630 commonly known as Martensitic Stainless PH 17-4 or equivalent to steel on the GB / T standard 1220-2007 [11]. According to ASTM the strength of this steel both yield and maximum tensile strength depend on the final annealing treatment generally above 800 MPa [12].
Table 3. Chemical composition of OES test results

| Sample      | C   | Si  | Mn  | P   | S   | Cr   | Mo  | Cu  | Ni  | V   |
|-------------|-----|-----|-----|-----|-----|------|-----|-----|-----|-----|
| Lacing wire | 0.008 | 0.39 | 0.21 | 0.026 | 0.009 | 17.04 | 0.15 | 2.06 | 5.02 | -   |

3.4 SEM-EDS

Scanning Electron Microscope uses electrons instead of light to obtain microstructural images. Inside the chamber is also equipped with an X-ray sensor to record the X-ray characteristics of the sample so that in addition to getting an SEM tool to record the X-ray characteristics of the sample, this method is known as EDS. As long as the dimensions of the sample are smaller than the chamber volume, the sample can be directly inserted in an SEM microscope, as shown in Figure 5.

![Figure 5](image)

Figure 5. A sample of a lacing wire fracture mounted on the sample holder in a SEM machine

3.4.1 EDS results

At first glance, the macro photograph shows that the surface of the sample is not really clean, the sample tends to be slightly corroded, rather black in color, which could be the color of iron oxide. The EDS results show that oxygen is a product of the corrosion process after the sample is broken.

![Figure 6](image)

Figure 6. EDS test results for polished sample B (a) the location of the EDS signal picker, (b) spectrum produced, (c) spectrum quantification showing chemical composition.
It appears that this sample has a composition close to the composition of OES results, but oxygen and silicon were also found. This indicates that the sample has a little contamination and oxidation after it has broken. Basically the EDS spectrum shows the same phenomenon both the weld area and the fracture area as shown in Figure 6.

3.4.2 SEM results

The results of morphological observations of fractures using SEM can be seen in Figure 7. Figure 7 a. shows the SEM fracture with a slight magnification (40X) on the fracture surface of sample C, it can be seen clearly crack initiation which then propagates as shown by arrow. Figure 7 b. shows clearly the beachmark pattern, as shown by arrow mark that arises as a result of fatigue in the area of crack propagation. The higher magnification shows transgranular fault patterns both in weld metal (Figure 7 c), and in based metal (Figure 7 d).

![Figure 7. SEM fracture with a slight magnification (40X) on the fracture surface of sample C, (a) crack initiation, (b) beachmark pattern, (c). Faults in the weld metal region showing transgranular fracture, (d). Transgranular fracture appearance in a metal-based sample.](image)

3.5 Microstructure

To find out the possibility of variations in the microstructure, microstructure testing was carried out using an optical microscope. Table 4 shows the microstructure of all the samples tested which can be seen as a whole in the base-metal region are tempered martensite as shown in A2, B2 and C2. type of stainless steel PH 17-4 is tempered martensite with precipitate Cu compound distributed in the microstructure, this shows that the microstructure is appropriate on based metal. Microstructure on the weld is martensitic / ferritic as shown in B3. This is microstructure standard of SS 410 used as filler.
Material for welding. Microstructure shape of the Lacing Wire base material around the HAZ is smoother or there is a change in the shape of the granules as shown in Figure A1, B1 and C1. This indicates that the Lacing Wire material around the HAZ area is softer (there is a decrease in the hardness of the material).

**Table 4. List of microstructure based on the sample A, B, C**

| A | B | C |
|---|---|---|
| ![A microstructure](image) | ![B microstructure](image) | ![C microstructure](image) |
| 1000X microstructure | 1000X microstructure | 1000X microstructure |

**3.6 Hardness**

The hardness test is carried out in accordance with the test map presented in Figure 8. The test is carried out at a certain distance in the X-axis direction, for sample A and C. While sample B is tested in the X-axis and Y-axis direction. The test results are displayed from point 1 to point 5 as listed in
Table 5. It can be seen that the average hardness of the sample is almost the same in the range of 300 HV which falls within the standard material range according to ASTM standards. The lowest hardness is found in the area around the weld metal. Based on the results of the hardness test on the fracture surface shows the non-uniformity of material hardness and a very significant change in the shape of the granules for Lacing Wire material around the HAZ area, this shows that the Lacing Wire material on the fracture surface has a decrease in hardness (softening occurs) due to welding, and this shows that after post welding there is no post weld heat treatment. especially in the HAZ zone shows that post welding heat treatment is not carried out (treat post-welding heat according to AWS A5.9 A8.40 ER 410.), so that the hardness of the material around the fracture becomes more soft and cracked.

![Direction and point of hardness testing in samples A, B, and C](image)

### Table 5. Microhardness test results according to the sample and test direction, as well as the indentation number

| Sample    | Direction | 1   | 2   | 3   | 4   | 5   | Average |
|-----------|-----------|-----|-----|-----|-----|-----|---------|
| Sample A  | X         | 330 | 325 | 325 | 338 | 366 | 337     |
| Sample B  | X         | 321 | 325 | 335 | 326 | 316 | 325     |
| Sample C  | Y         | 315 | 320 | 306 | 299 | 261 | 300     |
| Sample C  | X         | 323 | 312 | 285 | 295 | 295 | 302     |

#### 3.7 Cyclic Stress In Lacing Wire

The harmonic analysis used comes from the CFX model shown in Figure 9 (a), where the 5 blade LP turbine model is used to save resources. The operating data inputted are the ambient air pressure, the direction and magnitude of the gravitational acceleration, and the density of water. For this case, the data input in the operating conditions is in accordance with Table 1. The turbulence model used is the k-ε scalable wall. Figure 9 (b) shows the result of the pressure contour from the CFX simulation. The results of the pressure contour are then imported for harmonic analysis as shown in Figure 9 (c). The validation used in this study is a comparison between the calculation of the power generated by LP steam turbine with the CFX model and the thermodynamic calculation based on actual operating data. Can be seen in Table 6 the calculation of the power turbine LP power from the CFX model is 152 MW. The separate calculation of turbine power from the actual operating data is 146 MW, so the difference is 4.1%.
Table 6. Calculation of Torque and Power CFD Model.

| No | Domain | Multiplier | Torque 1 Segment (Nm) | Total Torque 360° (Nm) |
|----|--------|------------|-----------------------|------------------------|
| 1  | Rotor 1| 38.4       | 304.03                | 11674.752              |
| 2  | Rotor 2| 38         | 954.463               | 36269.594              |
| 3  | Rotor 3| 38         | 943.856               | 35866.528              |
| 4  | Rotor 4| 44         | 615.213               | 27069.372              |
| 5  | Rotor 5| 39.333     | 1259.92               | 49556.853              |
| 6  | Rotor 6| 34.333     | 1141.49               | 39191.157              |
| 7  | Rotor 7| 30         | 1421.41               | 42642.3                |

Total All Stage 360° 242270.56 Nm
Rotational Speed 3000 rpm
LP Turbine Power 1 Side 76.11 MW
LP Turbine Total Power 152.22 MW

Because the normal operation of LP Turbine is at 3000 rpm or 50 Hz, and the intersection between the excitation frequency line and the vibration mode curve occurs at a ratio of 3x and 5x from the modal analysis, the amount of deformation and stress at a frequency of 50 Hz, 50 Hz x 3 = 150 Hz, and 50 Hz x 5 = 250 Hz then simulated the result showed in Table 7.

Table 7. Total Deformation and Max Principal Stress of Lace Wire Against Frequency

| Parameter                  | 50 Hz   | 150 Hz  | 250 Hz  |
|----------------------------|---------|---------|---------|
| Total Deformation (mm)     | 0.052336| 0.15088 | 0.124   |
| Principal Stress Maximum (MPa) | 11.785  | 22.435  | 40.68   |

From the deformation value it is found that the maximum stress is 40.68 occurring at a vibration frequency of 250 Hz. However, at a frequency of 150 Hz, the location of the maximum stress occurs
right around the weld area, that is, where the lace wire failure occurs. The cyclic stress that occurs in the lacing wire detail are shown in Figure 10, it can be see that the highest stress is 22.43 MPa and from Table 8 it can be see that the highest stress amplitude position are close to the actual lacing wire failure position, where actual failure is 35 mm from edge and stress concentration is 24.66 mm from edge. However the position weld from edge is 24.5 mm and welding width around 10 mm.

![Figure 10. Cyclic Stress on Lacing Wire](image)

| Type   | Value | Note | Unit  | Location X (mm) | Location Y (mm) | Location Z (mm) |
|--------|-------|------|-------|-----------------|-----------------|-----------------|
| Stress Max | 22.435 | MPa  | 125.8734 | -1655.9394 | -1438.0950 |
| Edge   | 0.5007 | MPa  | 150.4366 | -1656.4752 | -1435.9486 |

Table 8. Comparison of failure location of FEA and actual specimen

| Point Location | Stress Amplitude (MPa) | X Location (mm) | Y Location (mm) | Z Location (mm) |
|----------------|------------------------|-----------------|-----------------|-----------------|
| Stress Max     | 22.435                 | 125.8734        | -1655.9394      | -1438.0950      |
| Edge           | 0.5007                 | 150.4366        | -1656.4752      | -1435.9486      |

Distance from edge (mm): 24.663

**Actual Specimen Data**

| Documentation | Distance from edge to failure (mm) | Distance from edge to weld (mm) |
|---------------|-----------------------------------|---------------------------------|
|               | 35                                | 24.5                            |

Due to the nature of the crack propagation in the lace wire, which most of the time occurs in the embedded crack (inside the HAZ area), it is highly recommended not to carry out any procedures that can initiate cracks in the lace wire. Because, if there is a crack initiation in the lace wire, it is almost certain that the lace wire will fail without having time to inspect the crack. Inspect the presence of crack
initiation by the appropriate method on the result of welding on the lace wire. To avoid cold crack it is necessary to do preheat and post weld heat treatment.

4. Conclusions
Fractography and macro-observations show that the lacing wire is broken by the mechanism of fatigue failure where the failure begins with the initiation of a crack in the area around the weld. Clearly visible a benchmark pattern in the crack propagation area. The percentage of the area of the final fracture shows that the dynamic stress is quite small compared to the strength of the material. Improper maintenance procedures especially welding procedures trigger an initial crack then the initial crack gets a concentrated cyclic load causing lacing wire broken.

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