CAUSES AND PROPAGATION OF FATIGUE CRACKS IN TURBINE BLADES

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Abstract

The paper assesses the impact of structural factors in the initiation and development of fatigue cracks in martensitic chromium steels used in the long blades of low pressure steam turbine units. There are compared the original steel AK1 TD.9 and newly used steel X12CrNiMoV12 -3. Results of microstructural analysis and mechanical tests are completed by fractographical analysis.

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Key words: sturcture, low pressure turbine, steel AK1 TD.9, steel X12CrNiMoV12-3

1. INTRODUCTION

After 8 years of operation, the blade of the third impeller of low pressure turbine part of 1,000 MW turbine was damaged and the subsequent "Schaufelsalat" led to damage of adjacent blade runner wheels No. 3 and 4 (Fig. 1) [1]. The crack initiation and subsequent fracture of turbine blade occurred always in the area of tree hanging (Fig. 2). Mostly, cracks initiated on the back of the blade in the middle part. Scarcely the initiation occurred in the blade corner or in the region of the blade bed.

These blades are subject to testing at higher speeds (3180 rpm) and operating temperatures range from about 60 to 80 °C. Cracks in the region of the blade hinge were found during the subsequent control crack detection within other levels of TG1 and TG2.
Blades of 3rd impellers with cracks, which were found at low levels, were subjected to the following tests - fractographical analysis of the damaged blades, estimation of the defect distribution timing, metallurgical analysis, chemical composition control, control of mechanical properties.

Original blades of the third impellers were made by die forging of steel AK1 TD.9 and heat treated (1010-1030 °C/ oil + 650 - 750 °C/ water) to meet the requirements of the 750 MPa yield strength, ultimate strength of 850 - 1 000 MPa, elongation 14%, 40% contraction and notch toughness of 50 J/cm².

2. EXPERIMENTAL

2.1 Control of chemical and microchemical composition of blade material

Chemical composition of the blades was due to the number of melts checked by three different devices: quantometers ARL 34600 OE spectrometer Běleč Vario Lab. and electron microanalyzer Camebax MICRO CAMECA with energy-dispersion analyzer KAVEX.

Blades made of five of the melts met the requirements of the declared chemical composition of steel; even though sometimes the content of phosphorus reached the limit values (see Table 1). The results did not show any significant differences from the standard [2].

Table 1 Chemical composition

<table>
<thead>
<tr>
<th>Melt</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Ni</th>
<th>V</th>
<th>Mo</th>
<th>W</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard</td>
<td>0.10-0.16</td>
<td>max.</td>
<td>0.60</td>
<td>0.025</td>
<td>max.</td>
<td>10.50-12.00</td>
<td>1.50-1.80</td>
<td>0.18-0.30</td>
<td>0.35-0.50</td>
<td>1.60-2.00</td>
</tr>
<tr>
<td>96682</td>
<td>0.13</td>
<td>0.44</td>
<td>0.40</td>
<td>0.024</td>
<td>0.010</td>
<td>11.81</td>
<td>1.64</td>
<td>0.27</td>
<td>0.44</td>
<td>1.85</td>
</tr>
<tr>
<td>97310</td>
<td>0.13</td>
<td>0.41</td>
<td>0.34</td>
<td>0.025</td>
<td>0.004</td>
<td>11.23</td>
<td>1.66</td>
<td>0.25</td>
<td>0.38</td>
<td>1.80</td>
</tr>
<tr>
<td>96100</td>
<td>0.13</td>
<td>0.38</td>
<td>0.34</td>
<td>0.020</td>
<td>0.012</td>
<td>11.12</td>
<td>1.59</td>
<td>0.25</td>
<td>0.41</td>
<td>1.82</td>
</tr>
<tr>
<td>73782</td>
<td>0.14</td>
<td>0.42</td>
<td>0.33</td>
<td>0.019</td>
<td>0.010</td>
<td>11.70</td>
<td>1.75</td>
<td>0.25</td>
<td>0.46</td>
<td>1.82</td>
</tr>
<tr>
<td>85570</td>
<td>0.13</td>
<td>0.50</td>
<td>0.25</td>
<td>0.020</td>
<td>0.009</td>
<td>11.90</td>
<td>1.70</td>
<td>0.25</td>
<td>0.45</td>
<td>1.86</td>
</tr>
</tbody>
</table>

2.2 Control of mechanical properties of the blades

The mechanical properties of blades have been inspected by a tensile test, impact test according to Charpy and Brinell hardness. Samples were taken from the tree hanging, which had a transverse orientation (TO), and from the blade root (blade-lock transition region) which had a longitudinal orientation (LO).

The requirement for the 750 MPa yield strength, ultimate strength 850-1 000 MPa, elongation 14% and 40% contraction were met within all measurements. Measured impact values of two blades were less than the 50 J/cm² required. Hardness values and their deviations lay within the expected results. Hardness of blades with cracks was about 5% lower than hardness of blade without crack [3].

2.3 Light microscopy – metallography analysis

Microstructure of blade base materials and areas of fracture surfaces was carried out on samples of longitudinal (LO) and transverse (TO) sections of blades. Samples were taken from the tree hanging of blade and also from the middle part of blade leafs. Samples were evaluated on a light microscope Zeiss Neophot-32 with 100x, 200x and 500x magnification in the etched condition (Vilella-Bain).

The microstructure of the material was typical for Cr martensitic steel - tempered martensite of heat treated steel in the state after heat treatment (quenched and tempered) (Fig. 3). Within the structure a significant proportion of δ-ferrite, which showed line-like arrangement was also found.
δ-ferrite lines were oriented in parallel to the direction of initial crack growth and subsequent analysis shown that these longitudinal ferrite systems had great effect on the initiation of fatigue cracks acceleration (Fig. 4).

To determine the percentage of δ-ferrite in the structure only metallographic methods could be used. NIS Elements software, mathematical grid method with 132 points developed by Škoda Výzkum and assessment of the portion of δ-ferrite only in areas of fracture surfaces were applied. When analyzed with the assistance of NIS Elements software, six fields of vision images of microstructure of 100x and 200x magnification were used (Fig. 5), the δ-ferrite regions were highlighted by threshold in colour.

Grid mathematical method having 132 nodal points was performed using conventional metallography on six randomly selected fields of vision of the basic material (Fig. 6) and the fracture surfaces, where the presence of δ-ferrite was highest.

Microstructural analysis of δ-ferrite was carried in etchant Beraha I (24 g NH₄FHF, 200ml of HCl, 1000 ml distilled water, 1g K₂S₂O₅). From Figure 7 it is clear that the lines of δ-ferrite are formed by individual grains, on whose borders dispersion particles are visible at higher magnification.
Microstructural composition of the matrix and δ-ferrite was observed in the transmission electron microscope JEOL JEM2000FX at accelerating voltage 200 kV and energy dispersive X-ray microanalyzer LINK AN10000 was used for quantitative analysis of the chemical composition of the sample.

In the basic martensitic structure (Fig. 8) proportion of δ-ferrite of globular shape (Fig. 9) was observed. On its interface with the martensitic phase a distinct high density of carbide and intermetallic phases was visible.

The diffraction pattern of martensite matrix revealed not only the diffraction traces of martensite, but also diffraction traces of the corresponding carbide $M_{23}C_6$ type [3]. Due to the small accuracy of interlamellar distances identification of magnetic samples, the presence of isolated particles of other carbides (hexagonal type carbides $\text{Cr}_7\text{C}_3$, $\text{Mo}_2\text{C}$, $\text{W}_2\text{C}$, or carbonitrides, possibly $\text{Fe}_2\text{W}$) cannot be omitted.

In the dark field using a carbide reflection (Fig. 10) a thick occupancy of grain boundaries and the boundaries of martensite laths by carbide particles and precipitates with dimensions in the range of about 100-100 nm was visible. It is obvious that these initiation sources of brittle failure are in case of border areas δ-ferrite more numerous than those in the areas of martensitic inter-laths regions.

2.4 Fractographic analysis

Fractographical analysis was performed not only on a broken blade, but also on the other 12 blades of 3rd runner wheel, where during NDT inspections the presence of cracks in the first lock groove was detected. The analysis was focused both on a qualitative description of the mechanism of initiation and development of fatigue cracks, and on the fractographical reconstruction of the history of violations of individual blades [4] and [5]. The results of fractographical analysis revealed the following findings on the process of the third wheel blades of low pressure levels:

a) In virtually all cases it was found out that fatigue cracks initiate at the surface of the upper lock groove of the back or side channel of the blade. The initiation occurred either as a single initiation (Fig. 11), in many cases, however, a multiple initiation was also found. Fractographical analysis did not show the presence of any structural defects or inhomogeneities that might be causing fatigue crack initiation.

b) Fatigue crack propagation was performed in all cases mainly by striation mechanism.

In respect to the proven series of more or less significant progressive lines (Fig. 12) it can be stated that the process of the blade damage occurs substantially during loading with time varying amplitude with the occurrence of overload cycles. These lines define the position and shape of the crack fronts at the moment of overload cycles corresponding to start and shut down of the turbine, or the over speed test. If there are sufficient details about the operation of the turbine available, it is possible to reconstruct the time process of the blade damage (Fig. 13).
c) To determine the size of the increase in crack length in each campaign not only spacing of these lines should be measured, but it is necessary to measure the size of the fracture surfaces between adjacent lines. Line spacing along the front of cracks changes quite significantly (Fig. 13), which suggests a change of stress at the crack tip, both in time and in space.

**Fig. 11** Crack initiation on lock slot surface  
**Fig. 12** Lines process on fracture surface

**Fig. 13** Fractographic reconstruction development disorder that led to breaking blades

The summary of the analysis and generalization of the results obtained in our work and their comparison with results of other work revealed that violation of third impellers of low pressure levels is achieved by two different mechanisms:

* Mechanism A

Cracks initiate at the surface of the upper lock groove of the back or side of the channel. In many cases, these initiations are multiple. In the first stage the crack is spread in almost radial direction (to the wheel axis). In the next phase of violations the crack begins to spread very asymmetrically, yet there is both a significant acceleration of crack growth along the groove, also the plane gradually spreads to the circumferential direction, i.e. in a plane almost perpendicular to the longitudinal axis of the blade. In both stages the crack propagates practically only by striation mechanism. More or less distinct processual lines appear on the fracture surface. These lines define the position and shape of the fatigue crack front at the time of overload cycles, corresponding to the start and shut down of the turbine, or to the over speed test. Based on the identification of the processual lines in relation to the turbine operation the time reconstruction of violation process was performed for crashed blade and for another 6 blades. The obtained results lead to the conclusion that the mechanism of blade violations and occur relatively soon after the launch. This method has been found within violation of a total of 17 blades.
• Mechanism B
Cracks initiate on the bezel between the top groove of lock and the front blade leading edge. In the first stage the crack spreads by striation mechanism, and by intergranular decohesion. On the corresponding areas no processual lines corresponding to overloading and switching off the turbine were found and therefore it can be assumed that these areas were created during a single campaign. It shows that crack propagation in this stage is relatively fast. In the second stage the crack propagates by striation mechanism only and fracture surfaces reveal progressive lines, defining the position and shape of fatigue crack front at the moment of overload cycles corresponding to start and shut down the turbine, or the over speed test. Based on the identification of the processual lines in relation to the course of turbine the time reconstruction of process violations for three turbine blades was made. The obtained results lead to the conclusion that the initiation of this type of failure occurred at different times (time to initiation differed by several years - [5]). This method has been found within violation of a total of 4 blades.

3. CONCLUSION

The results of analysis of monitored blades suggest the following findings on fatigue violation of 3rd runner wheel of low-pressure turbine components.

The fatigue cracks in the blades of third runners of low pressure parts are caused due to the increased activity of cyclic stress conditions. To the issue of the original material properties of steel AK1 TD.9 and newly used steel Böhler T552 a great attention was paid during the years 2009-2010. Also an extensive set of experiments on a number of departments in the Czech Republic was performed.

For all observed cracks the first stage of fatigue crack propagation occurred by combination of striation mechanism and intergranular decohesion. Suspect that the intergranular cracks on the blades in the initial stage are cause due to stress corrosion cracking has not been confirmed. Elevated levels of corrosion-active elements of chlorine and sulphur were not confirmed.

It turns out that the presence of δ-ferrite - its shape, orientation and layout - has a negative impact on material resistance against the initiation and further development of fatigue cracks.

The reason is cracking of carbide and intermetallic phases at the interface with the martensitic matrix. A similar mechanism is also pronounced by distinctive line-like structure of carbonitride particles. The fractographical reconstruction revealed that the initiation of fatigue cracks within observed blades occurred relatively soon after the launch of the turbine, but the process slowed down during the operation.

LITERATURE


