CAUSES AND MECHANISMS OF SERVICE FAILURE OF TURBINE BLADES

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Abstract
The blade of the third turbine wheel (3TW) placed on the third low-pressure part (3LP) of the TG 1000 MW turbine broke during the start of turbine in October 2008. The low-pressure part blades of the third wheels are made from modified 12 % Cr martensitic steel AK1 TD.9, and the blades of the fourth wheels are made from X2CrNiMo13-4 steel. The study of causes and fracture mechanisms and also an analysis of the microstructure were performed. The main goal of these analyses was the description of microstructure influence on the crack initiation and propagation. Service loading history combined with fractographic findings offered information for a reconstruction of the blade failure history. Obtained results are summarised in presented article.

Keywords: fatigue, fracture morphology, beach marks, striation, microstructure

1 Introduction
In October 2008 the blade of the third turbine wheel (3TW) placed on the third low-pressure part (3LP) of the TG1 failed during the turbine start. Consequently, the broken blade damaged the turbine wheels number 3 and 4 on the LP3, see Fig. 1. The blade fractured in the connection part, respectively the rest of blade in the third wheel is shown in Fig. 2.

Following non-destructive inspection proved occurrence of cracks also in other blades of the third wheel as well. The blades with cracks were removed from the wheel and were sent for a detailed evaluation at the Czech Technical University in Prague. Following analyses of failed blades were oriented towards two basic areas of interest:

- evaluation of material characteristics (chemical composition, microstructure and mechanical properties),
- fractographic analysis (identification of initiation and crack growth mechanisms, reconstruction of blades failure history).

Obtained results are summarised and discussed in presented article.

2 Experimental material and methods
Three failed blades (No. 152, 156, 106) of the third wheel from the third low-pressure part were sent for the evaluation – two of them (156 and 106) were failed in laboratory (see Figs. 3,4,5).
The analysis of chemical composition was performed with two analysers the ARL 34600 OE quantimeter, and the Belec Vario Lab spectrometer. Samples cut out from different parts of failed blades were used for examination of blade material microstructure. Microstructure was evaluated in planes parallel (PO) and perpendicular (PN) to the blade axis. Metallographically polished samples were etched in a water solution with 2.5 ml of HNO$_3$ and observed through Zeiss-Neophot 32 light microscope.

Fig. 1 Damage of the third low-pressure part LP3 after one blade fracture.

Fig. 2 The fracture of the blade (No. 152) in the third wheel from LP3.

Fig. 3 Blade 152 - failed during the service of turbine.

Fig. 4 Blade 156 failed in laboratory.

Fig. 5 Blade 106 failed in laboratory.
The mechanical properties were determined with tensile test, Charpy impact test, and Brinell hardness tests. Two different types of samples with respect to the turbine blade orientation were prepared. The first set of samples was extracted from the connection part perpendicular (PN) to the blade axis; the second set was extracted from the blade base in a parallel orientation (PO) to the blade axis. Tensile tests were carried out on an INSTRON 100kN Series IX Automated Materials Testing System (according to the standard ČSN EN 10002-1) and 300 J Charpy hammer was used for the impact tests (according to the standard ČSN EN 10045-1). The Brinell hardness was determined with an EMCOTEST M4C universal hardness tester (according to the standard ČSN EN 6506-1).

Fractographic analysis was carried out on the scanning electron microscope Jeol JSM 840A. Fractographic observation revealed that fracture surfaces were covered with a thick layer of corrosion products that complicated the investigation of the fracture micromorphology. These layers were removed with ultrasonic clearing in a special solution. Fractographic reconstruction of blades failure history required information about the service loading of turbine. For this purpose detailed records of operating conditions were analysed. It was found that speed of the turbine (number of revolution per minute) and namely the changes of speed during the service can be used for fractographic reconstruction of blade failure history.

3 Results and discussion
3.1 Material characteristics

The results of the chemical analysis and the measurements of the mechanical properties (yield strength, ultimate strength, ductility, reduction of cross-section area, Charpy impact strength and hardness) are summarized in Table 1, Table 2 and Table 3 [1,2]. It is evident that the requirements of the standards for steel AK1 TD.9 are fulfilled. Only the measured Charpy impact strength was lower than the standard for the material of the blades 152, 156, 106. This could be due to the long-time operation of the components and/or the non-standard operating conditions.

Table 1 Chemical composition (weight %) of investigated blades and material requirements [1,2].

<table>
<thead>
<tr>
<th>Sample specification AK1 TD.9</th>
<th>% C</th>
<th>% Si</th>
<th>% Mn</th>
<th>% P</th>
<th>% S</th>
<th>% Cr</th>
<th>% Ni</th>
<th>% Mo</th>
<th>% V</th>
<th>% W</th>
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</thead>
<tbody>
<tr>
<td>152</td>
<td>0,14</td>
<td>0,37</td>
<td>0,46</td>
<td>0,022</td>
<td>0,01</td>
<td>11,7</td>
<td>1,85</td>
<td>0,45</td>
<td>0,30</td>
<td>1,77</td>
</tr>
<tr>
<td>156</td>
<td>0,14</td>
<td>0,37</td>
<td>0,46</td>
<td>0,021</td>
<td>0,011</td>
<td>11,6</td>
<td>1,84</td>
<td>0,45</td>
<td>0,30</td>
<td>1,77</td>
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<tr>
<td>106</td>
<td>0,16</td>
<td>0,31</td>
<td>0,41</td>
<td>0,0244</td>
<td>0,010</td>
<td>11,44</td>
<td>1,90</td>
<td>0,44</td>
<td>0,29</td>
<td>1,59</td>
</tr>
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</table>

Table 2 Results of tensile test and material requirements [1,2].

<table>
<thead>
<tr>
<th>Sample (blade No.)</th>
<th>Yield Strength R_{0,2} [MPa]</th>
<th>Ultimate strength R_{m} [MPa]</th>
<th>Ductility A [%]</th>
<th>Contraction Z [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>152/1 PN</td>
<td>845</td>
<td>957</td>
<td>20,0</td>
<td>55,4</td>
</tr>
<tr>
<td>152/2 PN</td>
<td>860</td>
<td>969</td>
<td>20,0</td>
<td>55,4</td>
</tr>
<tr>
<td>156/1 PO</td>
<td>830</td>
<td>948</td>
<td>18,3</td>
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<td>156/2 PO</td>
<td>835</td>
<td>966</td>
<td>16,7</td>
<td>55,4</td>
</tr>
<tr>
<td>156/3 PN</td>
<td>820</td>
<td>962</td>
<td>16,7</td>
<td>55,4</td>
</tr>
<tr>
<td>106/1 PO</td>
<td>860</td>
<td>965</td>
<td>16,7</td>
<td>50,9</td>
</tr>
<tr>
<td>106/2 PO</td>
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<td>957</td>
<td>17,3</td>
<td>55,4</td>
</tr>
<tr>
<td>106/3 PN</td>
<td>865</td>
<td>976</td>
<td>16,7</td>
<td>50,9</td>
</tr>
<tr>
<td>Specification AK1 TD.9</td>
<td>min. 700</td>
<td>850 - 1000</td>
<td>min. 14</td>
<td>min. 40</td>
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</table>

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The microstructure of the base material was typical for modified 12% Cr martensitic steel. The microstructure of the heat-treated (quenched and annealed) steel is shown in Figs. 6 and 7. A large amount of δ-ferrite present in the microstructure was aligned in rows, oriented parallel with the crack growth and it may have greatly influenced the propagation of the fatigue cracks.

<table>
<thead>
<tr>
<th></th>
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</thead>
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<td>152</td>
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<tr>
<td>156</td>
<td>1PO-2PO-3PN</td>
<td>41</td>
<td>40</td>
<td>50</td>
<td>255</td>
</tr>
<tr>
<td>106</td>
<td>1PO-2PO-3PN</td>
<td>36</td>
<td>41</td>
<td></td>
<td>264</td>
</tr>
</tbody>
</table>

3.2 Fractographic analysis

The fractographic analysis was carried out for all three blades (see Figs. 3, 4 and 5). Based on a detailed observation and analysis of microfractographic features we can postulate following conclusions about failure processes taking place in blades.

1. Investigated blades failed in consequence of fatigue-cracks initiation and growth.
2. Fatigue cracks initiated on surface of the upper groove of the connection part of the blades (see e.g. Figs. 3, 5 and 8). Multiple initiations were found in the blades No. 152 and 106, while in blade No. 156 was only one initiation site.
3. Surface defects and/or microstructure inhomogeneities were found in initiation sites only sporadically (e.g. Fig. 9).
4. Fractographic findings proved striation mechanism of fatigue cracks propagation (Fig. 10).
5. Many more or less distinguishable beach marks were found on fracture surfaces (Fig. 11), their occurrence indicates that the loading amplitude was not constant.
6. The detailed analysis of service conditions record (namely changes of turbine speed) allowed us to match individual beach marks with the time of relevant change of turbine speed (e.g. to the switch on, respectively switch off and/or to the other changes of speed – see Fig. 12).
7. Fractographic reconstruction of fatigue cracks growth history in blades 152 and 156 could be carried out (Figs. 13 and 14).
**Fig. 8** Blade 152 – fatigue crack initiation on groove surface.

**Fig. 9** Blade 106 – occurrence of δ-ferrite particle in initiation area.

**Fig. 10** Blade 152 – striation patch on fracture surface.

**Fig. 11** Blade 156 – occurrence of beach marks on fracture surface.

**Fig. 12** Blade 156 – matching individual beach marks with corresponding changes of turbine speed (number of revolutions per minute).
Fig. 13 Blade 156 – fractographic reconstruction of fatigue failure history.

Fig. 14 Blade 156 – fractographic reconstruction of fatigue history.

4 Conclusions
Presented paper summarised the main results obtained in the course of fractographic analysis of failed turbine blades. It was proved that the main cause of fatigue cracks initiation is low fatigue resistance of used steel AK1.TD to the service loading. Fracture micromorphology of investigated blades proved partly striation mechanisms of fatigue cracks propagation, partly presence of overload cycles in service loading spectrum. This service loading is caused primarily by centrifugal force and steam pressure, nevertheless influence of various vibrations and also technological stresses has to be taken into account as well.

It was shown that combination of fractographic findings and analysis of service conditions, respectively their changes can offer very useful information for reconstruction of service failure history. Fractographic reconstruction proved that fatigue cracks in blades initiated very early after the beginning of turbine service.

Following precautions were proposed based on obtained results:
- New material 1.4939, with minimal content of δ-ferrite will be used for the manufacture of the new blades.
- Regular non-destructive inspections of connecting parts of blades have to be realised, e.g. [16]. These inspections will be a part of the regular annual shut down of turbines.

References
Acknowledgements

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