Fatigue performance of blade steel T552 in a corrosive environment

J Janoušek¹,², S Hřeben³, Z Špirit¹,², J Strejcius¹ and J Kasl⁴
¹Research Centre Rez, Hlavní 130, 250 68 Husinec-Řež, Czech Republic
²University of West Bohemia, Faculty of Mechanical Engineering, Department of Material Science and Technology, Univerzitní 22, 306 14 Plzeň, Czech Republic
³Doosan Škoda Power, Tylova 1/57, 301 28 Plzeň, Czech Republic
⁴Research and Testing Institute Plzen, Tylova 1581/46, 301 00 Plzeň, Czech Republic

jas@cvrez.cz

Abstract. This contribution is based on an experimental programme which deals with the issue of blade steel T552 corrosion fatigue damage. The specimens were taken from a reference material delivered for blade production and tested in a corrosion cell under pre-stress of 300 MPa. A chloride solution of 35 ppm was chosen as the environment at a temperature of 80 °C. Such an environment can be considered as the limit state that should not occur during the operating regime. The results are summarized and compared with experiments conducted at another workplace.

1 Introduction
Fatigue failure of steam turbine blades caused by pitting corrosion is one of the most dangerous issues of power plants. It occurs preferentially on blades in the low pressure (LP) rotors (especially on the last L-1 and L-0 stages) where early condensate develops [1, 2]. It is often reported that damage in LP steam turbines rotors initiates in highly localized areas, most commonly at corrosion pits that act as stress raisers [3, 4]. The corrosion events develop and pass through distinct stages; namely, initiation of metastable pits, the survival of few metastable pits to form stable pits, the growth of stable pits, the transition of pits into cracks, the growth of subcritical cracks, and finally unstable fracture [3]. It is possible to keep the total amount of impurities in steam below concentrations of 50 ppb; 2 ppb for chlorides, and oxygen below a threshold of 10 ppb during standard operational conditions [5]. Thermodynamic calculations predict that the concentration of nonvolatile substances (such as chlorides, sulfates and carbonates) in a liquid phase might be up to 100 times higher than in steam. [6] The concentration might be up to several ppm, especially in the transitional operational state during putting the block in and out of operation, or due to condenser leakage, etc. [7]. An environment with a chloride solution of 35 ppm can be considered as the limit state that should not occur during the operating regime [8].

The most applied materials are 12 % of chromium modified martensitic steels, then 12-15 % chromium precipitation hardened steels and, in sporadic cases, titanium alloys [9]. In terms of static
loading, the blade is exposed to centrifugal force as well as the pressure force of medium. The effect of the flow medium which flows around the blades is one of the sources of dynamic excitation. An unequal pressure field and rotor shaking could also result in excitation [10, 11]. The dynamic stresses are low compared to centrifugal forces of rotation, and the acting stress ratios can exceed values of $R = 0.9$ [1]. The number of cycles corresponds with very high cycle fatigue (VHCF), therefore the value of $10^8$ cycles is established for the fatigue limit in accordance with standards [12].

Linear elastic fracture mechanics is used for evaluating the influence of corrosion pits on fatigue. Investigations show that the pits can be treated as semicircular surface cracks with the width at the surface $2c$ and the pit depth $a$ [13]. The results are summarized in the Fatigue Crack Growth Rate (FCGR) diagram and Kitagawa-Takahashi (K-T) diagram. As an output, K-T diagrams can be used for assessment of the fatigue limit and life-time of corroded parts of steam turbines [13].

2 Description of similar tests for the same material

In the framework [1] the test environments were air and two aqueous solutions at 90 °C. De-aerated 300 ppb Cl\textsuperscript{-} solution - in such an oxygen-free environment, corrosion pits repassivate and stop growing even after exposure to more corrosive conditions such as an aerated 6 ppm Cl\textsuperscript{-} solution. The specimens were smooth with an hourglass shape and a cylindrical gauge length and they were prepared from dual certified 404/410 12% Cr martensitic steel. The specimens were ground and polished after machining. They were stress-relief annealed in high vacuum at $10^6$ Pa (heating from room temperature to 600 °C for 1 h, holding for 2 h, cooling from 600 °C to 400 °C for 2 h and to room temperature in approximately 12 h) to eliminate residual stresses. The material was hardened at 913 °C and tempered. The mean grain size was 6 µm and 44 µm (2 batches). The number of inclusions per observed area was higher by a factor of 2.7 between batches. Mainly Al\textsubscript{2}O\textsubscript{3}, MnO, Cr\textsubscript{2}O\textsubscript{3} and MnS inclusions were found. The probability of crack initiation is enhanced with an increased number of inclusions that act as stress raisers [1]. Enhanced fatigue strength of the material is, among other things, related to the lower number of inclusions. The specimens were pre-pitted in a droplet cell for studying pit-to-crack transition. Pit depths were 50 µm, 100 µm and 250 µm. The tests were conducted on ultrasonic fatigue testing equipment (dynamic component up to 20 kHz) in combination with a servo-hydraulic machine (static component). The fatigue limit was defined as the stress range where two specimens survived at least $1 \times 10^8$ cycles without failure.

In [1] a 35 l reservoir with flow rate 3 l/h was used for creating the environment. Most contact parts were made of 316 stainless steel. The corrosion potential was measured using an Ag/AgCl reference electrode, but the potentials quoted refer to the saturated calomel electrode (SCE) at 25 °C. Immersion pre-tests showed that corrosion pits can form in aerated 6 ppm Cl\textsuperscript{-} solution but the pit growth rate is low, therefore it does not compete with the artificially generated pit. The maximum depth of such formed pits was 20 µm after an immersion time of 14 hours which was the time taken to reach 109 cycles. The pH of the solutions was between 5.2 and 7.2. Ultrapure water with an initial conductivity of 0.06 µS/cm and AR grade NaCl was used. The solution was exchanged when their conductivity increased by 10 % of the initial value.

Although environmental effects are usually less significant at high loading frequency, it is known that close to threshold, and for small cracks, dissolution of microstructural barriers can lead to a reduced threshold. This was not observed in [1] due to crack closure by oxide debris and enhanced roughness. A closure-free situation was confirmed for stress ratios $R \geq 0.72$ for tests in air, $R \geq 0.76$ for de-aerated solution and $R \geq 0.72$ for aerated solution. Specimens tested in air and de-aerated 300 ppb Cl\textsuperscript{-} solution at $R = 0.8$ near fatigue crack growth threshold $\Delta K_{th}$ show no evidence of fretting in contrast to aerated 6 ppm Cl\textsuperscript{-} solution. No satisfactory explanation can be given for lower crack growth rates, and a higher near $\Delta K_{th}$ was found in de-aerated 300 ppb Cl\textsuperscript{-} than in aerated 6 ppm Cl\textsuperscript{-} solution.

In [1] for S-N tests on smooth specimens, a decrease of the fatigue limit for increasing R and corrosiveness of environment was found. For high R = 0.8 was observed only a slight decrease of the stress range by 5 MPa compared to air. The reason for this is a change in the failure mechanism.
Characteristic fatigue fracture surfaces with crack initiation at inclusions or small defects were found for small $R = 0.05$ and for $R = 0.5$ in aerated 6 ppm Cl- solution. In contrast, a cup-and-cone like fracture typical for tensile-testing was observed for $R = 0.5$ and 0.8 although fatigue lives above 108 cycles were achieved. Pre-pitted specimens with a pit depth of 100 µm did not cause final failure at $R = 0.8$ in air because it occurred elsewhere.

3 Experimental programme
The martensitic steel X12CrNiMoV12-3 Böhler T552 (also known as 403/410 12% Cr steel designated 1.4938 or 1.4939) was used as the reference material. The chemical composition is given in Tab. 1. The hardness of the material was between 309-323 HB (confirmed 325 - 339 HV0.5), yield strength $R_{p02}$ between 954 MPa and 961 MPa and ultimate (tensile) strength $R_m$ between 1058 MPa and 1061 MPa. The following processes were used for heat treatment: hardening 1040 °C/1 h/oil, tempering 620 °C/5 h/air and stress annealing 580 °C/4 h/air.

| Cr     | Ni | Mo  | Mn  | V   | Si   | C   | N2  | P   | S   |
|--------|----|-----|-----|-----|------|-----|-----|-----|-----|
| 11.70  | 2.71| 1.70| 0.75| 0.30| 0.21 | 0.12| 0.038| 0.016| 0.002|

Pre-stress was chosen for all subsequent tests up to 300 MPa. The resonant testing machine TESTRONIC 250 made by the Swiss firm RUMUL was used for all the following experiments. It is a dynamic testing machine, which works in full resonance for loads up to 250 kN. The maximum oscillating stroke extension available is up to 4 mm. The resonant operating frequency is given in a range from 40 Hz up to 250 Hz by the oscillating masses and also by the stiffness of the specimen. The corrosion measuring cell was designed, engineered and manufactured for tests in a corrosive environment. The cell has a flow volume of 1 litre, the entire electrolyte solution is about 1 000 litres per hour and the electrolyte is tempered to the required temperature with an accuracy of 1 °C. The bubbling inert gas enables control of the content of the dissolved oxygen in the electrolyte. It is also possible to adjust the pH. The control of electrical conductivity is performed continuously. During the test of corrosion fatigue the electrode potential of the specimen is also recorded. Specimens 240 mm long with a straight working part and a diameter of 8 mm were tested in the flow cell. (see dimensions in Fig. 2). The NaCl solution with a concentration of 35 ppm of chlorides was chosen for testing in a corrosive environment at a temperature of 80 °C. The content of oxygen was not controlled.

Figure 1. Corrosion cell with testing equipment.
4 Evaluation and comparison of results
A considerable scatter of results was found for tests in air (see Fig. 4). This behaviour is related to the globular inclusion (oxides) content with a size of about 10 \( \mu \text{m} \) (see Fig. 3), and many inner initiations in particular were proved on inclusions with a size of up to 40 \( \mu \text{m} \). The microstructure of the heat treatment state must be composed of fine-grained tempered martensite without hard lines or a coarse carbide network with a maximum grain size of 5.0 according to DIN EN ISO 643. In our case, the mean grain size was G4 i.e. 88.4 \( \mu \text{m} \).

The tests were performed for pre-stress 300 MPa. The slanted branch of selected points of the S-N curve was fitted by Fletcher’s version of the Levenberg-Marquardt algorithm for the minimization of the sum of the squares of the equation residuals. The program was created in a numerical computing environment and the programming language MATLAB. This regression line curve is defined by an equation that was found by a probabilistic approach as

\[
\log N = 23.4 - 6.9 \log \sigma
\]  

(1)
The S-N curve is depicted in Fig. 4. The red points are valid, (i.e. sample failed) and green arrows indicate points without rupture (or a fracture in the threaded attachment) and they were not included in the linear regression. The frequency was chosen intentionally low, approximately 66 Hz, to prevent heating of the specimen. The fatigue limit was determined on the basis of two undamaged specimens to a value 360 MPa.

![S-N curve for material T552, $\sigma_m = 300$ MPa](image)

**Figure 4.** S-N curve for pre-stress in normal component $\sigma_m = 300$ MPa tested in air.

The NaCl solution with a concentration of 35 ppm chlorides was chosen for testing in a corrosive environment at a temperature of 80 °C. The content of oxygen was not controlled. The S-N curve is depicted in Fig. 5. The fatigue limit was determined on the basis of four undamaged specimens to a value of 160 MPa. The formula for the slanted branch of the S-N curve for a corrosive environment was determined by the linear regression in the form:

$$\log N_a = 15.6 - 4.1 \log \sigma_a$$  \hspace{1cm} (2)

![S-N curve T552, solution 35 ppm Cl$^-$, $\sigma_m = 300$ MPa](image)

**Figure 5.** S-N curve for pre-stress in normal component $\sigma_m = 300$ MPa tested in a corrosion cell for an aggressive environment (solution of 35 ppm chlorides) at a temperature of 80°C.
5 Conclusions

The results of high cycle fatigue tests on blade steel Böhler T552 are summarized. The tests were performed in air and in a corrosive environment of a solution with a concentration of 35 ppm chlorides at a temperature of 80 °C. The results can be compared with experiments published by another workplace in [1] where a fatigue limit of 315 MPa was obtained for pre-stress 348 MPa. This is a very similar result because newly published experiments showed a fatigue limit of 360 MPa for pre-stress 300 MPa.

A fatigue limit of 265 MPa was obtained in [1] for pre-stress 292 MPa for tests in aerated 6 ppm Cl-solution at 90 °C. In this article the fatigue limit is about 100 MPa lower for almost the same pre-stress. The more aggressive solution is obviously the reason. To sum it up, the solution of 35 ppm chlorides decreased the fatigue limit by about 200 MPa compared to the air condition.

Another experimental programme for this steel includes corrosion fatigue tests on specimens with improved surface corrosion resistance.

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References

[1] Schönbauer B M, Stanzl-Tschegg S E, Perlega A, Salzman R N, Rieger N F, Zhou S, Turnbull A, Gandy D, Fatigue life estimation of pitted 12% Cr steam turbine blade steel in different environments and at different stress ratios, International Journal of Fatigue 65 (2014) 33-43.
[2] Steam, Chemistry, and Corrosion in the Phase Transition Zone of Steam Turbines, EPRI, Palo Alto, CA: 1999.
[3] Černý M, Alloy Corrosion in Steam Turbines, Experimental Stress Analysis 2014.
[4] Černý M, Alloy Localized Corrosion in Steam Turbines, Experimental Stress Analysis 2015.
[5] Strejcius J, Folková E, Kasl J, Řehořek J, Špirit Z, Corrosion fatigue strength of precipitation hardened martensitic steels MLX17 & T671 in a chloride ions - contaminated steam condensate, Increase of Lifetime for Components of Energy Equipment in Power Plants, Srní, Czech Republic, 2015, (in Czech).
[6] Janoušek J, Strejcius J, Hřeben S, The Environment Influence On Bladed Steel During Operational Conditions, Applied Mechanics and Materials Vol. 827 (2016) pp 185-188.
[7] Low-Pressure Steam Turbine Corrosion Mechanisms and Interactions: State of Knowledge 2010, Report, EPRI.
[8] Janoušek J, Hřeben S, Špirit Z, Strejcius J, Kasl J, Fatigue performance of blade steel T671 for different kinds of loading, Baltic X, Finland, 2016.
[9] Development of a Corrosion-Fatigue Prediction Methodology for Steam Turbine Blades: AISI 403/410 (12% Cr) and 17-4PH Blade Steels, EPRI, Palo Alto, CA: 2015.
[10] Mišek T, Dynamic Analysis of Bladed Disks of Axial Turbomachinery, doctor thesis, UWB Pilsen, 2011, (in Czech).
[11] Balda M, Červená O, Monitoring Residual Fatigue Lives of Steam Turbines Blades, Experimental Stress Analysis 2015.
[12] ČSN 420363 – Fatigue Testing of Metals – Methods of fatigue testing of metals.
[13] Černý M J, Allowed Stress Range Prediction of Fatigue Loading for Steel Alloy for Steam Turbines, Experimental Stress Analysis 2016.
[14] Atest – Inspection Certifikacate of producer and provider METAL RAVNE (Slovenia).