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Fatigue life estimation of pitted 12% Cr steam turbine blade steel in different environments and at different stress ratios

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ABSTRACT

The influence of corrosion pits on the endurable fatigue loading in different environments and at various stress ratios has been investigated for 12% Cr steam turbine blade steel. Very high cycle fatigue measurements were performed using ultrasonic fatigue testing technique with superimposed static load at stress ratios ranging from $R = 0.05$ to $R = 0.9$. Fatigue crack growth rate (FCGR) measurements in the near threshold regime and *S–N* tests were conducted at a temperature of 90 °C in air, de-aerated 300 ppb Cl^- solution and aerated 6 ppm Cl^- solution. The influence of corrosion pits on the fatigue limit was determined with artificially generated corrosion pits. It was found that the FCGRs in solution are lower and the threshold stress intensity factor ranges ΔK_{th} are higher than in air. Fracture surface investigation with scanning electron microscope and roughness measurement were made which suggest oxide and roughness induced crack closure as the most appropriate explanation. Data evaluation of fatigue life tests with pre-pitted specimens supports the applicability of treating pits as effective cracks. An estimation for the stress intensity factor range of pits which allows determining the endurable fatigue loading was empirically found.

1. Introduction

Fatigue failure of steam turbine blades originating from corrosion pits is a critical issue for power plant operators and may cause catastrophic damage. After decades of research with the aim of understanding the basic phenomena and predicting damage evolution [1–7], the necessity of an applicable methodology is still a contemporary issue. Fatigue failure of steam turbine blades caused by pitting corrosion occurs preferentially in low pressure blades where early condensate develops. Activation of pitting is not expected during standard operational condition because the condensate on the turbine blades is oxygen free. But unexpected occurrences – e.g. leaking of the condenser – may create corrosive environments with critical amounts of corrosives such as chloride. When combined with off-load aeration, corrosion pits can form that can act as stress raisers. If a corrosion pit exceeds a critical size, the increase of the local stresses can initiate a fatigue crack. Evaluation of endurable cyclic loading due to pitting was done in terms of linear elastic fracture mechanics (LEFM) by several authors [4–14]. It is assumed that pits can be treated as effective cracks, which allows determination of the threshold stress intensity factor range for crack growth under cyclic loading, ΔK_{th}. With this estimation, the endurable cyclic stresses can be estimated for pitted components according to the pit size. Kitagawa and Takahashi [15] provided an extension of LEFM to small cracks. By using the threshold stress intensity factor for long cracks and the fatigue limit, it is possible to determine the threshold for small crack growth. The applicability to small defects like pits allows the description of the pit-to-crack transition in terms of fracture mechanics.

Steam turbines, which were designed for a maximum operational time of 20 years, are in service since more than 40 years. High frequency fatigue loading at the last stage of low-pressure blades is induced by inhomogeneous steam flow. The stresses are low compared to centrifugal forces of the rotation and the acting stress ratios can exceed values of $R = 0.9$. The number of load cycles that accumulate over decades are in the range of very high cycle fatigue (VHCF) which can be hardly achieved with conventional testing techniques. Therefore, ultrasonic fatigue testing has become a standard method which allows testing in the VHCF regime within tolerable time.

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Table 1
Chemical composition of 403/410 SS (in weight%).

Material	C	Cr	Mn	Si	Ni	Mo	Cu	S	P
R	0.13–0.14	11.79–11.8	0.41–0.49	0.18–0.26	0.28–0.33	0.13–0.18	0.07–0.10	<0.002	<0.020
W	0.14	11.56	0.50	0.02	0.47	0.18	0.16	0.005	0.01

In the present work, fatigue crack growth rate measurements in the near threshold regime and fatigue life tests were performed using ultrasonic fatigue testing technique. Test environments were air and two aqueous solutions at 90 °C. De-aerated 300 ppb Cl^- solution was used to simulate the service condition of low pressure blades in the last stage where early condensate develops [16]. In this oxygen-free environment, corrosion pits repassivate and stop growing. When these pits are re-exposed to a more corrosive condition, they do not tend to continue growing. To simulate a more aggressive environment in which corrosion pits can form, additional tests in aerated 6 ppm Cl^- solution at 90 °C were carried out. Fractographical investigations with scanning electron microscope (SEM) were used to identify the mechanisms of fatigue crack initiation and propagation. Data obtained with pre-pitted specimens were evaluated in terms of fracture mechanics. The results are correlated with threshold stress intensity factors of long cracks and fatigue limits of smooth specimens in Kitagawa–Takahashi diagrams which allows predicting the endurable stresses of pitted components.

The geometry of corrosion pits is often simplified as semi-circular or semi-elliptical [4–14]. But in fact, the shape of pits is more complex and additional aspects as surface roughness of the pit may have a significant influence. Analytical concepts were discussed to describe the pit shape and the geometry parameters were correlated in terms of stress intensity factors. A modification according to the experimentally determined parameters was necessary to determine the relationship between geometrical parameters of pits and endurable cyclic stresses. In other words, a geometry factor Y of corrosion pits for 12% Cr steam turbine blade steel was semi-empirically determined.

Table 2
Mechanical properties of 403/410 SS at room temperature.

Material	Tensile strength (MPa)	Yield strength (MPa)	Elongation A (%)	Reduction of area (%)
R	767	596	23	68
W	723	562	22	69

2. Experimental

2.1. Material

The material tested was dual certified 403/410 12% Cr martensitic steel. Two different batches of material were used (material certificate ID starting with "*R*" and "*W*"). The material was hardened at 913 °C and tempered. The chemical compositions and the mechanical properties (provided by the supplier) are shown in Tables 1 and 2, respectively. The mean grain size was 6 μm for Material R and 44 μm for Material W. The microstructure of both materials is shown in Fig. 1.

2.2. Test specimens

The shapes of the specimens used for *S*–*N* tests and FCGR measurements are shown in Fig. 2. After machining, the specimens were ground and polished with abrasive paper (up to grade #4000). They were stress-relief annealed in high vacuum at 10^{-6} Pa (heating from room temperature to 600 °C in 1 h, holding for 2 h, cooling from 600 °C to 400 °C in 2 h and to room temperature in approximately 12 h) to eliminate residual stresses.

Hourglass shaped specimens with a cylindrical gauge length were used for *S*–*N* tests as shown in Fig. 2a. To study pit-to-crack transition, corrosion pits were generated in the gauge length of some specimens. The pre-pitting procedure was developed at NPL [17]. A droplet cell is used to produce single corrosion pits with a controlled depth repeatable to within 10%. Pit depths of 50 μm, 100 μm and 250 μm were used in this test program. Fig. 3 shows a corrosion pit with a diameter of approximately 50 μm. The maximum pit depths and the widths of the pits on the surface (perpendicular to the direction of applied load) were measured prior to fatigue testing using a travelling microscope. After fatigue failure, the fracture surface was observed with SEM and both pit depth and surface width were determined.

Tubular specimens with a starter notch were used for FCGR measurements and determination of threshold stress intensity factors (Fig. 2b). The starter notch was introduced at the centre of the specimen where the cyclic strain amplitude is a maximum by

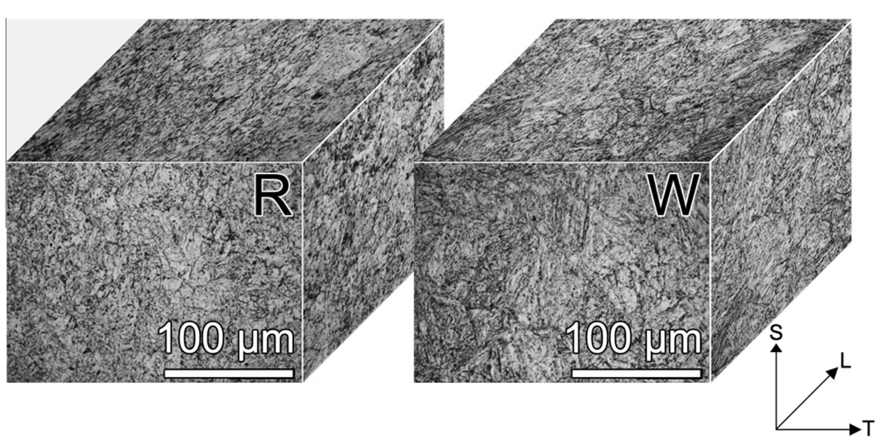

Fig. 1. Microstructure of 403/410 testing material from batches *R* and *W*.