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Modelling of corrosion fatigue for steam turbines by probabilistic Kitagawa-Takahashi diagram

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Abstract. Probabilistic Kitagawa-Takahashi diagram is proposed for corrosion fatigue modelling of steel alloy in steam turbines.

Introduction

A probabilistic modelling is proposed for corrosion fatigue of steel alloy in steam turbines. Kitagawa-Takahashi diagram represents two distinct fatigue damage mechanisms: one associated with crack initiation (or microstructurally small cracks) and the other with crack propagation (or long cracks). These two fatigue criteria can be combined in order to simultaneously model both damage mechanisms and the transition between them. It results in a probabilistic Kitagawa-Takahashi type diagram [1], which can be used for pitting corrosion fatigue.

Probabilistic Kitagawa-Takahashi type diagram.

Corrosion (pitting) leading to fatigue crack nucleation and crack growth is considered to be among the most significant degradation mechanisms in aging structures [2]. The corrosion pits in steel alloy for steam turbines can be considered as surface (short) microcracks for determining threshold limits for fatigue cracking. The threshold for long crack fatigue can be defined using linear elastic fracture mechanics (LEFM). Then the stress intensity factor should be used for evaluating the influence of corrosion pits on fatigue such materials [3]. Speed of short cracks (surface microcracks) depends not only on the level of stress, but on the *microstructure of material*. The higher the level of stress in critical place, the greater the plastic deformation in the surface grain material and the greater the speed of crack in this grain. An initial gradual decrease in speed is due to the interaction of fatigue crack with the first sub-surface grain border. The surface speed of microcracks is minimal if its length a is equal to the dimension of grains d.

At lower levels of stress, the crack can also stop at the grain border. In this case, the local stress in the grain boundary is not big enough to re-initiation of fatigue cracks in the grain. If, on the other hand, stress is relatively high, the crack depends on the border characteristics of the grain, orientation of microcrack, etc. The crack grows through the grains to further sub-surface grains and starts gradually to behave as a long crack.

It has been observed, that most corroded pits have roughly a semi-elliptical shape with the width at the surface, $2c$, and the pit depth a. Further, investigations show that the pits can be treated as semi-circular surface short cracks.

This choice then makes it possible to define the *probability* of *crack initiation* within a grain. Equation 1 shows the probability density function used to define the threshold stress.

$$f_{01}(\sigma_{th}) = \frac{m_1}{\sigma_{th01}} \left(\frac{\sigma_{th}}{\sigma_{th01}} \right)^{m_1 - 1} \exp\left[-\left(\frac{\sigma_{th}}{\sigma_{th01}} \right)^{m_1} \right] \tag{1}$$

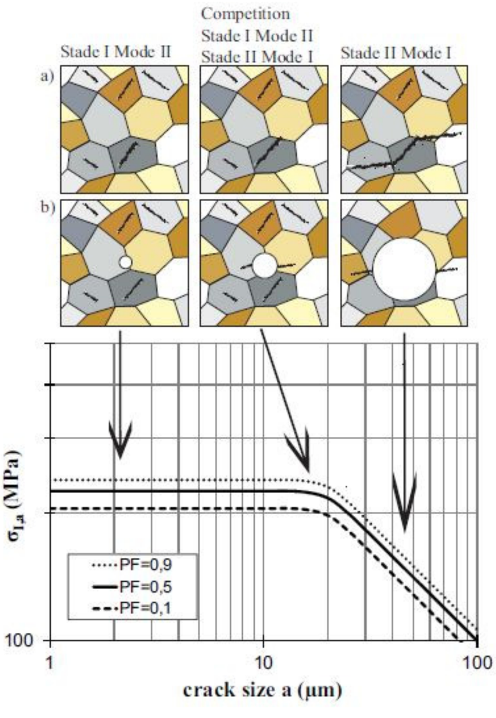
where σ_{th01} is the scale parameter and m_1 is the shape parameter (the Weibull exponent). A crack will not propagate in cyclic loading if the stress intensity factor ΔK is less than the *crack propagation* threshold ΔK_{th} ,

$$f_{02}(\Delta K_{th}) = \frac{m_2}{\Delta K_{th02}} \left(\frac{\Delta K_{th}}{\Delta K_{th02}} \right)^{m_2 - 1} \exp\left[-\left(\frac{\Delta K_{th}}{\Delta K_{th02}} \right)^{m_2} \right] \tag{2}$$

After combination of both mechanisms we get the expression for the fatigue strength as a function of the probability of failure, and the crack length, as follows:

$$\sigma_{1,a}(P_F, a) = \left[\frac{\ln\left(\frac{1}{1 - P_F} \right)}{\left(\frac{1}{\sigma'_{th01}} \right)^m + \left(\frac{Y 2\sqrt{\pi a}}{\Delta K'_{th02}} \right)^m} \right]^{\frac{1}{m}} \tag{3}$$

Equation (3), plotted as a function of the crack size, *a*, for a given probability of failure P_f , results in a probabilistic Kitagawa-Takahashi diagram. After correlation of a half pit width *c* with a crack size *a* (Fig.2) we get a corrosion fatigue strength of a material (Fig.1).



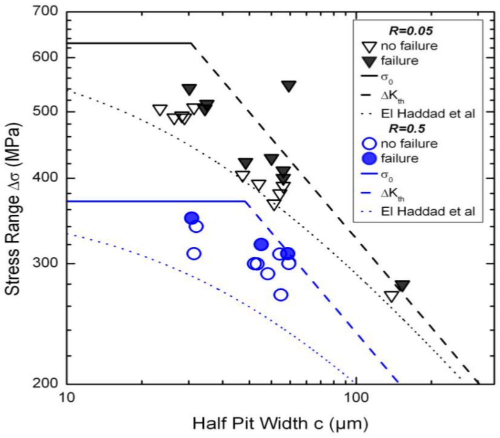


Fig. 1: Kitagawa-Takahashi diagram (Eq.1) for different failure probabilities showing the fatigue damage mechanisms a) without and b) with initial defects ($m = 20, \sigma'_{th01} = 234 MPa$, $Y = 2/\pi$, $\_K'_{th02} = 2.3 MPa.m^{1/2}$)

Fig. 2: Kitagawa-Takahashi diagram for corroded steel alloy 403/410, c is correlated with crack size a

True pit geometry

The description of true pit geometry has been published by author earlier [2]. The max. and min. depths of pits and their densities have been found. In [3] are shown the mentioned characteristics and Table 1 in [3] comprises the parameters of corrosion evaluated for part of steam turbine at power plant ETU (alloy X22CrMoV12-1, exposed 677 hr in 650°C steam).

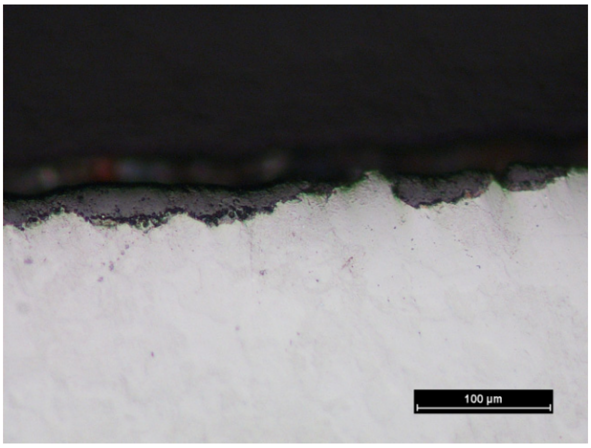


Fig.3 True geometry of corrosion

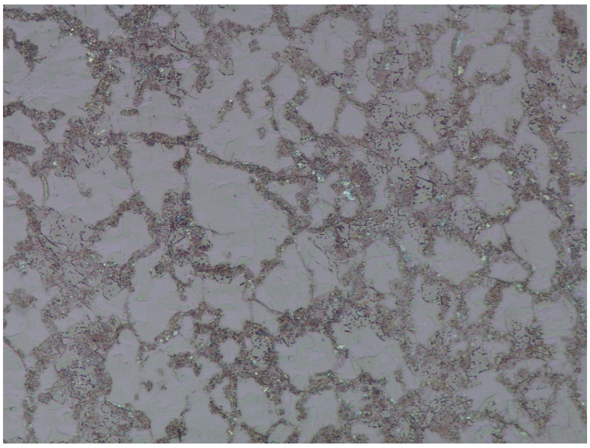


Fig.4 Alloy steel grains after corrosion

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Conclusions

A probabilistic modelling is proposed for corrosion fatigue of steel alloy in steam turbines. Crack size *a* in Kitagawa-Takahashi diagram is correlated with corroded half pit *c*.

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