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On the relationship between stress intensity factor and fractographic aspects of a crankshaft steel in VHCF

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ABSTRACT:
The fatigue failure in the very high cycle regime (VHCF) tends to initiate in subsurface or internally to microstructural defects. In this case, the fracture surface may present specific features such as fish-eye and fine granular area (FGA). The fatigue crack develops in four different stages: crack initiation, crack growth within the fish-eye, crack growth outside the fish-eye and final fracture. In the center of the fish-eye, an inclusion is usually observed surrounded by the FGA. In the present work, VHCF tests (frequency = 20 kHz and loading ratio = -1) were performed on a DIN 34CrNiMo6 steel specimens taken from crankshaft which failed in service in an electrical power generating plant. S-N curve were established and fractographic analysis was carried out on the fracture surface of the fatigue specimens. Fish-eye and FGA regions were observed by scanning electron microscopy (SEM) and their sizes were measured with the aid of digital image program (DIP) and then compared with estimates made by using empirical equations encountered in the literature. Stress Intensity Factor (SIF) for internal cracks was also calculated at the boundaries of these regions. Results obtained have indicated that the measured FGA size is in fair agreement with estimated values. Further, the value of maximum SIF at FGA boundary can be consider as the threshold for short crack growth. For the fish-eye boundary, on the other hand, maximum SIF value corresponds to a change in the stable crack propagation mode.

Key-words: ultrasonic fatigue testing, fish-eye, fine granular area, SIF

INTRODUCTION

Evaluation of the behavior of the VHCF region has become extremely important for designing structures that are capable of reaching 10^6 - 10^7 to 10^9 - 10^{10} cycles under high frequency dynamic loads during their in-service lifetime.

The study of fatigue in the VHCF regime has become viable due to the introduction of ultrasonic fatigue testing machines which operate at a much higher frequency than conventional fatigue testing, thus inducing a great number of cycles in short time and making it easier and more reliable to understand the behavior of materials in the VHCF region.

Bathias was one of the first researchers to perform several tests of different steels and obtain various data that led to the possibility of extending S-N curve [1].

In 1999, Bathias [2-3] confirmed that metallic materials do not possess infinite life in fatigue and in 2006, Sonsino [4] reported that fatigue strength decreases with the increase in the number of cycles. Fatigue behavior of high strength steels in VHCF regime presents different aspects compared to high cycle fatigue (HCF) regime. In conventional high cycle fatigue, crack initiation starts preferentially on the surface, while in VHCF, the site of crack initiation is often in the subsurface or at internal nonmetallic inclusion. Additionally, the fracture surface in VHCF regime can present fish-eye morphology and fine granular area (FGA) phenomenon adjacent to the initial defect [5-9].

The main objective of the study was to evaluate the VHCF behavior of on parts of a steel crankshaft that had undergone a premature fatigue failure during operation in a thermoelectric plant and also to analyze the resulting fracture surfaces. Another aspect in the present work refers to the comparison of the measured fish-eye and FGA sizes with estimates made by empirical equations available in the literature [10]. Finally, the stress intensity factor (SIF) values at the boundaries of these fractographic facets are to be calculated.

EMPIRICAL EQUATIONS

Several studies were developed in order to estimate the FGA size. Murakami [10-12], Liu [10,11,13] and Yang [10,11,14] developed expressions that relate FGA size to the applied stress amplitude and mechanical properties of the material. The FGA size in the expressions given below is considered to correspond to that of a circle and hence can be represented by $\sqrt{area_{FGA}}$.
Murakami and co-authors [10-12] proposed that FGA size is dependent on the applied stress amplitude (σ_a) and Vickers hardness (HV) as:

$$\sqrt{area_{FGA}} = \left[\frac{C\ \ (HV+120)}{\sigma_a}\right]^6 \qquad (1)$$

where C is a constant whose values vary with crack initiation site, being equal to 1.43 for superficial initiation and 1.56 for crack initiation internally.
Liu and co-authors [10,11,13] adapted Murakami's equation and proposed a single value for the constant C.

$$\sqrt{area_{FGA}} = \left[\frac{2(HV+120)}{\sigma_a}\right]^6 \qquad (2)$$

In the two equations given above, the FGA size is expressed in μm.
An expression obtained by Yang and co-authors [10,11,14] indicates that the FGA size is influenced by σa as well as the material's yield stress (σ_y). The FGA size in meters is given by

$$\sqrt{area_{FGA}} = 1240\frac{1}{{\sigma_y}^{0{,}533}}\frac{1}{{\sigma_a}^2} \qquad (3)$$

A schematic diagram of the FGA and fish-eye regions is presented in Fig. 1. Taking into account the FGA and fish-eye sizes, it is possible to calculate the stress intensity factor, ΔK, at their boundaries.

$$\Delta K_{int} = \frac{2}{\pi}\Delta\sigma\sqrt{\pi a} \qquad (4)$$

where $\Delta\sigma$ is the applied stress range, a is an interior crack radius and can be replaced by the FGA or fish-eye radius (r_{FGA}, $r_{fish\text{-}eye}$).
In fully reversed cyclic loading, the equation (4) can be rewritten to maximum SIF, K_{max} [15].

$$\Delta K_{int} = 2K_{max} = \frac{4}{\pi}\sigma_a\sqrt{\pi a} \qquad (5)$$

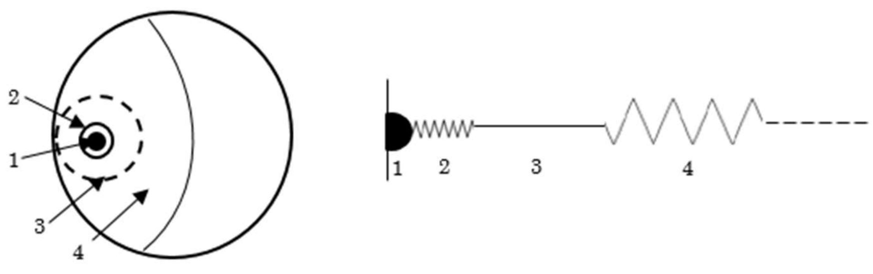

Fig.1: Schematic drawing of the fracture surface in VHCF (1- inclusion, 2- FGA, 3- fish-eye and 4 – final fracture) adapted from [7,8].

EXPERIMENTAL PROCEDURE

Material

The material used for this study was a high strength steel, DIN 34CrNiMo6, used in the fabrication of many mechanical components. The machined specimens were obtained directly from the failed crankshaft under study. The chemical composition (restricted to main elements) and mechanical properties are presented, respectively, in Tables 1 and 2. The steel has a density of 7.870 kg/cm^3 and its Vickers hardness amounts to 330 HV.

Table 1: Chemical composition with main elements.

Steel	Fe (%)	C(%)	Cr (%)	Mo (%)	Ni (%)
DIN 34CrNiMo6	95.1	0.38	1.51	0.24	1.75

Table 2: Mechanical properties.

Steel	σ_u (MPa)	σ_y (MPa)	E (GPa)
DIN 34CrNiMo6	900	760	207

Fatigue testing

For the VHCF testing, the specimen dimensions were based on the Bathias geometric principle taken from his book [1]. These dimensions depend on the density and dynamic modulus of elasticity which is slightly different from the static modulus. Using this principle, the resonance length (16.10 mm) and total length (62.2 mm) of the specimen were obtained and are shown in the Fig. 2.

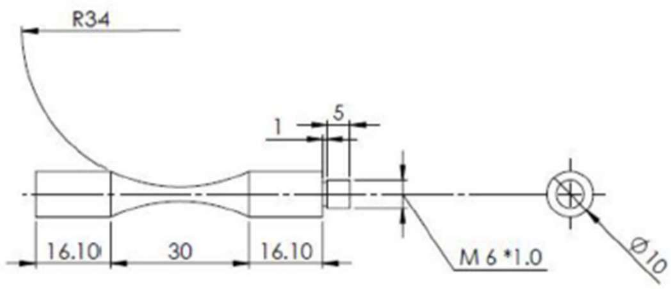

Fig.2: Shape and dimensions of fatigue specimen (units in mm).

The specimens were submitted to ultrasonic fatigue test (frequency = 20 kHz) in fully reversed condition (R = -1). All tests were performed at a constant power setting of the transducer, under temperature control. The temperature control serves to prevent any specimen from reaching high temperatures that could alter properties of the steel thus maintaining the same conditions for all the tests. These tests were carried out in Instituto Superior Técnico laboratories in Lisbon University. After the test, fracture surface was observed with the aid of SEM and optical microscopy.

RESULTS AND DISCUSSION

S-N curve

The experimentally obtained S-N curve is presented in Fig. 3, where the stress amplitude σ_a is plotted versus the number of cycles to failure N_f.

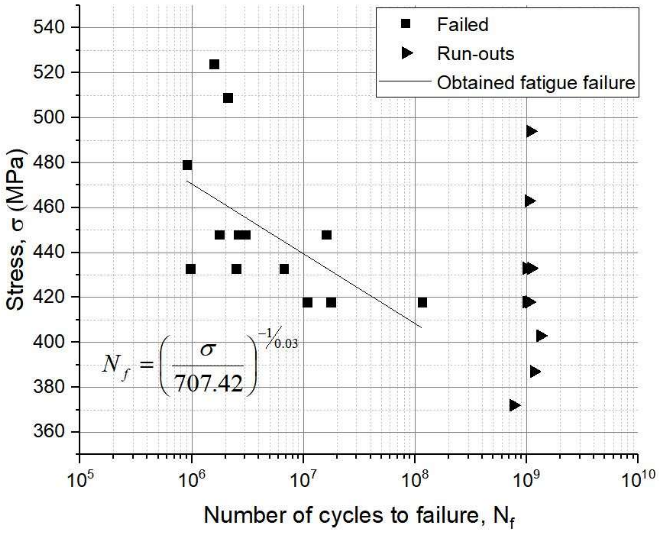

Fig.3: S-N curve for crankshaft steel in VHCF.

Even though there is a considerable scatter in the results, as can be observed from Fig.3, the material still shows a fatigue tendency of having higher life for lower stresses in the VHCF regime. The applied stresses that caused fatigue failure in the VHCF regime are shown to be higher than expected, achieving levels almost equivalent to half of ultimate tensile strength of the material under study. In fact, two of the run-out specimens did not fail under the action of stress higher than 450 MPa.

Fracture surface

In seven specimens were encountered fish-eye and FGA morphologies. Fig. 4 presents a specimen that failed after 1.6 x 10^6 under a cyclic stress of 524 MPa. The site of crack initiation is clearly identified. It is possible (Fig. 4a to 4c) to observe a circular shaped spot and smooth surface indicating the fatigue crack growth, which characterizes fish-eye morphology. Figure 4d, exhibits the fish-eye region, emphasizing the FGA area (fine grained) nearby the initial defect.

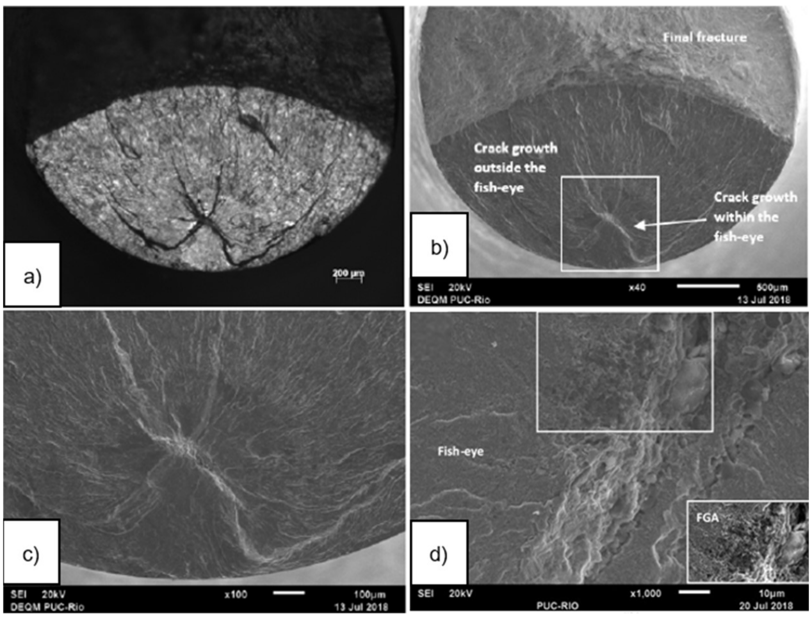

Fig.4: Fracture surfaces obtained by optical microscope and SEM.

FGA size and SIF prediction

FGA size was measured with the aid of digital image program (DIP) and compared with Murakami's [10-12], Liu's [10,11,13] and Yang's [10,11,14] expressions. These correlations were carried out on seven specimens fatigue loaded to under varying cyclic stress levels (test number). Fig.5 presents a comparison between empirical equations aforementioned (1-3) and FGA size measured.

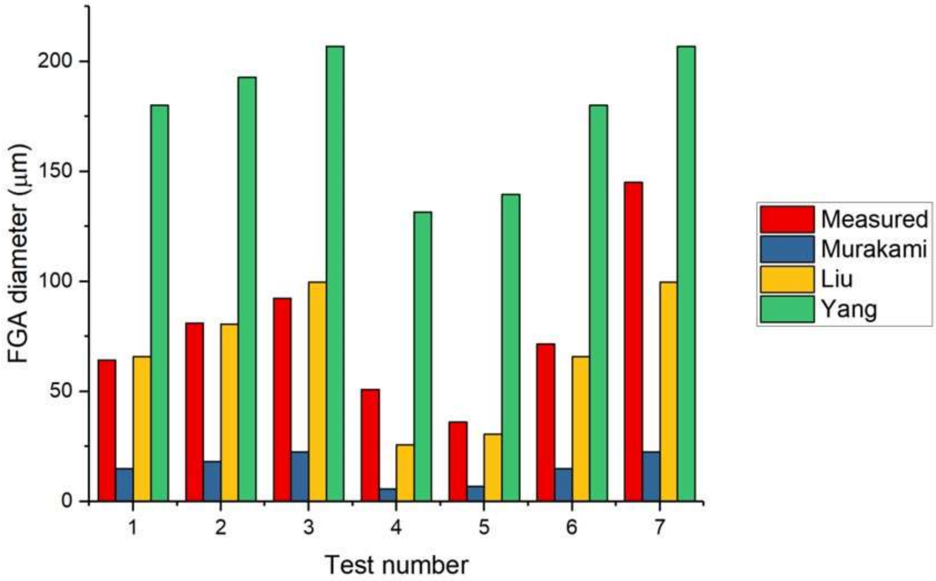

Fig.5: Comparison between FGA size measured and empirical equations [10-14].

Using equation (5) the maximum SIF (K_{max}) values were calculated at the boundaries of FGA and fish-eye region. The values obtained can be seen in Fig. 6 in terms of a number of cycles to failure. Mean values of 4 and 9.8 MPa m$^{1/2}$ were obtained for r_{FGA} and $r_{fish-eye}$ respectively. It is important to point out that, whereas the value of $K_{max,FGA}$ can be compared with the threshold value for high strength steels, $K_{max,fish-eye}$ can be interpreted as threshold for the end of circular crack growth mode.

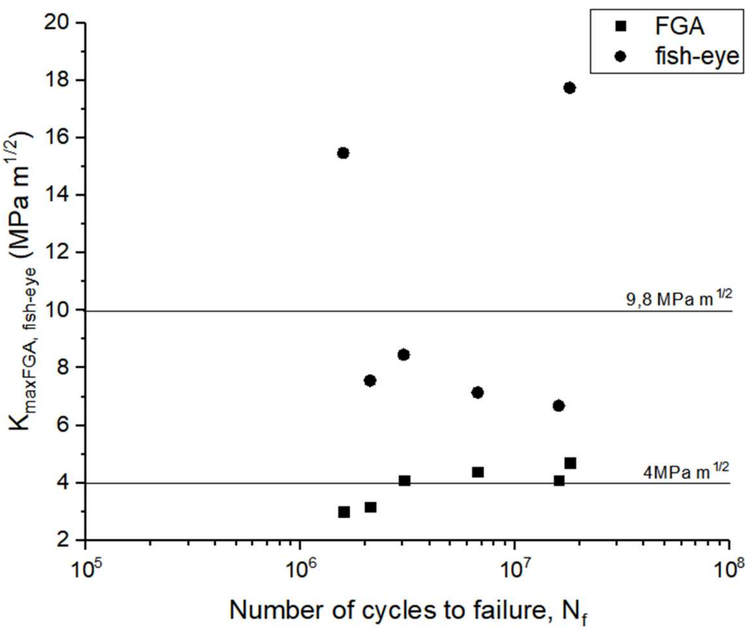

Fig.6: K_{max} of FGA and fish-eye as a function of N_f.

CONCLUSION

Based on the work developed the following conclusions can be drawn:

- Despite the scatter associated with the S-N data, DIN 34CrNiMo6 steel presents higher fatigue life for lower stresses in line with the concept of VHCF.
- The FGA sizes obtained by Liu's equation are in good agreement with the experimentally measured values.
- The value of maximum SIF at FGA boundary ($K_{max,FGA}$) can be considered as the threshold for short crack growth.
- The fish-eye boundary corresponds to a change in the stable crack propagation mode.

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