Very high cycle fatigue behavior in crankshaft steel

M. C. Teixeira[1*], P. R. Costa[2], M. V. Pereira[1], M. Freitas[3], L. Reis[3]

[1]*Pontifícia Universidade Católica do Rio de Janeiro, Rua Marques de São Vicente, 225, 22451-000 Rio de Janeiro, Brasil*
[2]*Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1, 1049-001 Lisbon, Portugal*
[3]*IDMEC, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1, 1049-001 Lisbon, Portugal*

E-mail address: mclaract@gmail.com

Abstract Components of systems subjected to dynamic loading can be prone to failure by fatigue damage in some stage of their life. Being the most common and the most unpredictable type of failure it is vital that the fatigue study and projection of the applied material for all the components under dynamic loadings is made for its maintenance, thus ensuring the safety and reliability of the system. In this paper the fatigue results obtained from a crankshaft that failed in service are presented, concerning its behavior in the Very High Cycle Fatigue (VHCF) regime. For this purpose, an ultrasonic fatigue test was conducted using a piezoelectric transducer. Different stresses levels were applied using a stress ratio -1 and corresponding S-N curve was plotted. All fracture surfaces of the tested specimens which achieved failure were analyzed via an optical microscope for preliminary comprehension of the crack initiation site.

***Keywords**:* Very High Cycle Fatigue (VHCF); Ultrasonic fatigue; S-N curve; fracture surface; crankshaft steel.

1. Introduction

Several components and engineering structures are subject to fatigue failures. In a more current approach, various materials, especially those of high strength steel have presented fatigue life beyond 10^7 cycles. The accomplishment of tests aiming to understand the behavior of materials in the very high cycle fatigue (VHCF) region in a much shorter time interval was only made possible by the high frequency used (usually at 20kHz), differently from conventional tests. Thus, evaluation of VHCF behavior has become extremely important for component and structural designs that reach 10^7-10^{12} cycles. Such tests are called ultrasonic fatigue tests and many analyses for different materials were already made applying only tension compression [1-2], torsion [3] and even multiaxial bending [4]. In addition to the advancement related to the test duration, many researchers have observed different characteristics in the mechanism of fatigue crack initiation. In general, fatigue cracks start at the surface of the material. However, in the VHCF regime, some fracture surfaces show the fatigue crack initiation at subsurface or internally due to internal defects of the material such as inclusions and pores. It is important to point out that many studies report the appearance of a strain around the internal defect which gives origin to crack initiation, called fish-eye. Therefore, the propagation of the crack fatigue occurs in two distinct areas, propagating the fatigue crack inside the fish-eye and propagating the fatigue crack outside the fish-eye [5-6].

The purpose of this study is to evaluate the behavior of the steel used in crankshaft of a thermal electric power plant in VHCF, aiming at the implementation of an economically viable procedure that allows actions to evaluate and quantify the accumulated damage and to extend useful life, according to current requirements of the areas of generation and transmission of energy in thermal plants.

The specimens used in this study were machined from crankshaft, made of a high strength steel (DIN 34CrNiMo6), which had suffered fatigue failure. These specimens were tested at high frequency, 20 kHz and loading ratio -1, and S-N curve was obtained in the VHCF region and the fracture surfaces were analyzed, with the aim of an identifying the site of fatigue crack initiation.

2. Experimental Methodology

As it has been mentioned the material in study is a DIN 34CrNiMo6 used in a thermal energy plant crankshaft. All the specimens were machined directly from the same part of the failed crankshaft.

Initial dimensions of the ultrasonic fatigue specimens were calculated based on Bathias geometry and equations [7] making use of the steel's, Young's modulus and density. Afterwards, the obtained dimensions were introduced in the Abaqus finite element software for readjustment, where modal analysis was performed until a final geometry close to 20 kHz first longitudinal resonance mode was obtained.

The chosen final geometry and a meshed image of the specimen are presented in Figure 1 which also shows a representation of the excited resonance mode displacement of the designed specimen.

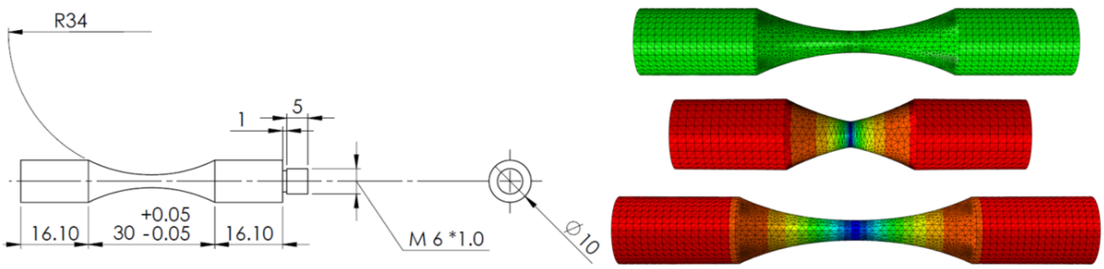

Figure 1: Ultrasonic fatigue specimen.

After machining all the specimens, the ultrasonic fatigue tests were then started. For the first specimen tested a strain gauge was attached and the specimen was tested both in a conventional hydraulic fatigue machine and in the ultrasonic fatigue machine built in the Instituto Superior Técnico laboratories [8].

The analysis in the conventional machine was made with the purpose of comprehending the strain gauge response for a given deformation, thus knowing the corresponding strain for each volt of response. Afterwards the same specimen was introduced in the ultrasonic machine where several tests with different power settings were conducted.

All the tests were performed within a power control setting, meaning that the machine will maintain the same applied power throughout the entire fatigue test. The strain analysis of several power settings gives a function of the induced stress for each power setting.

A Polytec laser is used for cycle counting during all fatigue tests. The laser is directly pointed to the free base of the specimen. Along with the strain analysis, mentioned before, the displacement at the free base is also measured using the laser. Using the equations presented by Bathias in [7] a corresponding stress is calculated, with the use of the displacement and specimen's dimensions, and compared with that obtained via the strain gauge measurement. The results from the power/stress calibration using the strain gauge and the laser are shown in Figure 2.

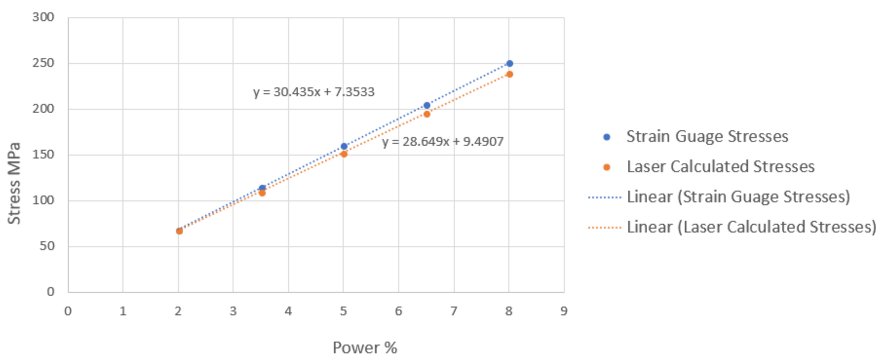

Figure 2: Linear results of strain gauge stresses and laser calculated stresses.

Both functions obtained are linear and show similar results with a small deviation that increases with higher power settings.

Knowing the applied stresses for each power setting of the piezoelectric transducer, the fatigue analysis in the VHCF region can be started. Temperature is controlled so as to ensure the same conditions for all the tests. The specimens are painted in black and frequency analysis of the setup, with the specimen attached, is made before any fatigue test. This frequency analysis is performed with the transducer software where a frequency scan is made in whole frequency range of the transducer. The black paint applied serves to help the sensor temperature measurements.

In every test the specimen was kept under cyclic resonance loading until there was enough damage for it to make the component's set lose the resonance frequency within the range of work of the transducer. The specimen was withdrawn from the ultrasonic machine and total failure is made by applying continuously higher tensile force. The specimen's breakage gives the possibility to observe the fatigue crack created for analysis.

The applied powers were chosen in accordance with the specimen's results obtained throughout the study. If in a certain power a specimen would not break within 10^9 cycles then a higher power was applied in the subsequent specimen and if failure occurred with a low number of cycles a lower power was chosen afterwards.

3. Results

All the cyclic stress / number of cycles were plotted in a logarithmic scale graph as shown in Figure 3. The run out specimens are distinguished using triangular indicator.

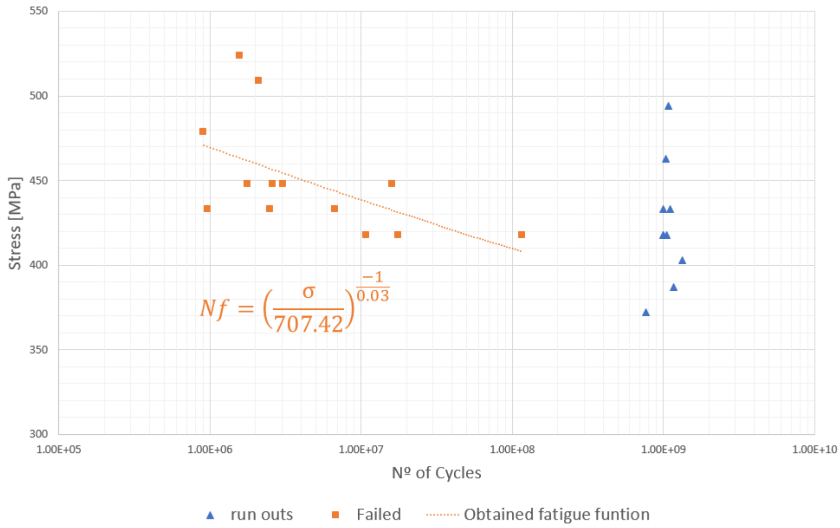

Figure 3: Crankshaft steel S-N curve in VHCF.

Even though there is a variation in the results for each applied stress, the material still shows a fatigue tendency of having higher life for lower stresses in the VHCF regime. The stresses applied that showed fatigue failure in the VHCF regime showed to be higher than expected since it is almost half of the rupture stress of the material under study. High cycle fatigue test is needed to understand if the performed ultrasonic test alters in some way the material's response and somehow making the necessary applied stresses be higher than expected.

All the tested specimens that came to fail were analysed in the microscope in order to have a preliminary idea of where the fatigue crack initiated. Some specimens shown to have crack initiation on the surface, some indicated clear subsurface initiation and others showed internal initiation. Some of the fatigue crack results for all the three cases are shown in Figure 4. All the specimens that clearly exhibited surface crack initiation are the ones with a higher applied stress. Some of the subsurface and internal crack initiation sites show a circular greyer area which is believe to correspond to fish-eye region [5], as can be observed in Figure 4B and 4C.

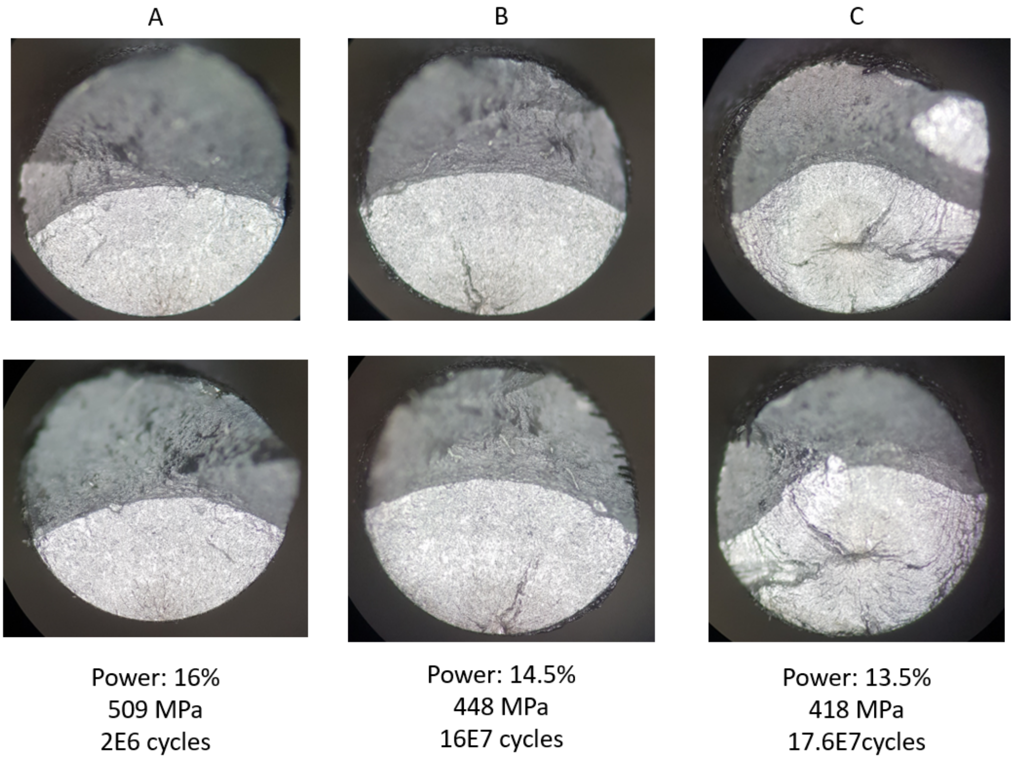

Figure 4: Fracture surfaces: A - surface initiation, B - subsurface initiation, C – internal initiation.

A SEM analysis is needed in order to fully understand where crack initiation does, in fact, occurred, i.e, whether it is subsurface or internal with a possible fish-eye formation and also to follow crack evolution along cross section of the specimen.

Acknowledgements

This work was developed within the scope of the Research and Technological Development of the Brazilian Electric Energy Sector Program regulated by ANEEL, with the support of the Eneva Companies - Pecém II Energy Generation S.A., Itaqui Energy Generation S.A. and Paranaíba I, II and III Energy Generation S.A.

References

[1] Marines, I., Dominguez, G., Baudry, G., Vittori, J., F., Rathery, S., Doucet, J., P., Bathias, C., 2003. Ultrasonic fatigue tests on bearing steel AISI-SAE 52100 at frequency of 20 and 30 kHz. International journal of fatigue, 25, 1037-1046.
[2] Stanzl-Tschegg, S., E., 2017. Influence of material properties and testing frequency on VHCF and HCF lives of polycrystalline copper. International journal of fatigue, 105, 86-96.
[3] Marines-Garcia, I., Doucet J., Bathias, C., 2007. Development of a new device to perform torsional ultrasonic fatigue testing, international journal of fatigue, 29, 2094-2101.
[4] Brugger, C., Palin-Luc, T., Osmond, P., Blanc, M., 2016. Gigacycle fatigue behaviour of a cast aluminium alloy under biaxial bending experiments with a new piezoelectric fatigue testing device. Procedia Structural Integrity 2, 1173-1180.
[5] Kazymyrovych, V., 2009. Very High Cycle Fatigue of Engineering Materials. Faculty of Tecnology and Science Materials Engineering.
[6] Bathias, C., 1999. There is no infinite fatigue life in metallic materials. Fatigue and fracture of engineering materials and structures, 22, 559-566.
[7] Bathias, C., Paris, P. C., 2005. Gigacycle Fatigue in Mechanical Practice (1st ed.). New York: Marcel Dekker.
[8] Freitas, M., Reis, L., Anes, V., Montalvão, D., Ribeiro, A. M., Fontes, M., 2011. Design and assembly of an ultrasonic fatigue testing machine. Anales de Mecánica de la Fractura, 1, 335-340.