Investigation of hold period influence on residual fatigue live in steam turbine shaft design

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Abstract. Growth of share renewables in the field of electric power supplier and a lack of mechanism to cover shortage, force standard supplier of energy to stabilize the electrical grid. This situation is then demonstrated by increase of hot-start and cold-starts. But there is a lack for robust tool for qualitative assessment of residual life of the turbine shaft and for design of such a component. The goal of this paper is to present influence of the holding period on low-cycle fatigue (LCF), thermo-mechanical fatigue (TMF) and the so called Damage Operator Approach (DOA) by Nagode, which were used as a new approach for design of turbine shaft in Doosan Škoda Power.

1 Introduction

The energy industry is nowadays subjected to greater demands. One of them is growing share of renewables in gross final energy. In comparison, in 2004 was the share of renewable in gross final energy consumption 8.5%, compared with 17.0% in 2016 [1]. Goal from EU is to have a 20% share in 2020. In Czech republic the share of renewables was 10.3% in the beginning of the year 2018 [1]. However, the fluctuating nature of the renewables creates instability in the energy systems. Because a lack of system, which would cover “energy fluctuations”, these energy instabilities has to be in large measure compensated by thermal power sources. As results of this, the operating conditions are changing, particularly in number of startups and shutdowns, and at the same time, is here demand on acceleration the whole process of startups and shutdowns.

Turbine shaft are designed according to the number of required cold-start cycles and hot-start cycles. Usual number of cold-start is 50-250 cycles and 6000-8000 cycles of hot-starts, respectively. Where the cold-start is defined as a start from almost zero speed and cooled state, in comparison to the hot-start, where starts begin from warmed state, these cycles are mostly related to the fluctuation of the power supply.
Above mentioned, this brings questions about residual life of several decades running turbine shaft and needs for new attitudes in turbine shaft design.

The standard attitudes for derivations of material criterion are based usually on low cycle fatigue (LCF). Limitations of LCF is because of isothermal nature of LCF and because the damage mechanism in turbine shaft is thermo-mechanical (TMF). In literature is therefore possible to find new attitudes in LCF testing [3][4][5].

The life accessing for such a complexly loaded component is not possible without finite element method (FEM), which is very challenging task, because of combination damage process, where the most significant are fatigue, creep and oxidation [6][7]. Nagode et al. [8] suggested new the so-called Damage Operator Approach (DOA) which proposed computation process for estimating fatigue damage of component subjected to thermal and mechanical loading. Aim of this paper is to introduce experimental work and partial results carried out within the FLEXTURBINE project. Namely, experimental work dealing with comparison of Young’s modulus measured by standard tensile test and dynamic modulus attitude. Subsequently, problem of the hold period on LCF tests results is discussed. TMF test experiment used for verification of the DOA model is outlined.

2 Experimental work

For estimation of the basis material proprieties the tensile tests at room and elevated temperature were carried out. From the nature of tensile tests it is not in all cases appropriate to take the results of the Young’s modulus. The Young’s modulus is fundamental element used for deriving other parameters, whose underestimation can lead in mismatch in results. Therefore, the dynamic modulus was measured and evaluated according to ASTM E1876-09, where the modulus is obtained based on the impulse excitation technique analyzing the vibration of a test sample or component after it was impulse excited.

The material subjected to testing was a chrome-molybdenum creep resistant steel applicable to steam turbine shafts. Comparison of Young’s modulus resulted from tensile tests and dynamic modulus is presented in Figure 1.

![Figure 1. Temperature dependence on Young’s modulus](image)

As was presented above, the standard attitude for life prediction is based on standard LCF test. Low cycle fatigue is covered by standard e.g. ASTM E606. But loading of the turbine shaft is rather out of description listed in the standard, from the view of velocity/frequency of loading. In a fact, in a real shaft loading regimens with long hold period between the individual loading cycles can be found. Effect of the hold period on LCF results wasn’t know and therefore investigation of this effect were investigated.
2.1 Low-cycle fatigue

Fatigue damage and life time prediction under LCF is described by Manson-Coffin and Basquin curve, see equation (1).

\[
\varepsilon_a = \left( \frac{\sigma_f}{E_{\text{eff}}} \right) \left( 2N_f \right)^b + \varepsilon_f \left( 2N_f \right)^c
\]

(1)

Where \( \varepsilon_a \) is a strain amplitude, \( N \) is number of cycles to failure, \( \sigma_f \) and \( b \) are the fatigue strength coefficient and exponent, \( \varepsilon_f \) is fatigue ductility coefficient and \( c \) is the fatigue ductility exponent.

Standard LCF tests were carried out according to the standard ASTM E606 in temperature range 20-600°C.

Firstly, the specimen size was designed in that manner to avoid buckling during cyclic compressive load increases. In Figure 2 is presented the final specimen size which was used for all tests and results from simulation of the buckling at 600°C. LCF tests were carried out on servo-hydraulic testing machine MTS 810 with load capacity 250kN at room and elevated temperatures. In the second case, the split three-zone tube furnace Mellen was employed for heating samples up to 600°C.

![Figure 2. LEFT Geometry of the specimen; RIGHT Simulation of the Buckling, F=50kN, E=170GPa, T=600°C](image)

One of the key parameters of LCF tests is number of cycles to initiation. One of the attitude to evaluate this, which comes from the standard, is to evaluate the cycles to initiation as intersection of the envelope Force-Count and a horizontal line which lie in the thirty percent of the maximal force. According to our investigation, this attitude lead to underestimating of the results. Therefore new methodology for evaluation of the cycles to initiation was proposed. This methodology is based on finding of the saturated part of the Force-Count curve, middle of the interval is evaluated as cycles to saturation (\( C_{\text{SAT}} \)), cycles to initiation (\( C_{\text{IN}} \)) are evaluated to the intersection point of parallel line to the saturated part of the Force-count curve which lie below the saturated part in distance of five percent, and Force-count curve.

2.2 Low-cycle fatigue with hold period 10 min

For investigation of the hold period effect the LCF test were carried out, but 10 minutes delay between individual cycles. During the holding period constant value of deformation was hold. Test were carried out on servo-hydraulic testing machine Inova, deformation of the specimens were measured by means of High temperature extensometer Epsilon model 3549.

Demonstration of the Force – Deformation course is shown in Figure 3. All tests were carried out with asymmetry coefficient \( R = 0 \) and strain amplitude 0.7%. This test takes roughly 7 days to reach a rupture. In comparison, LFC test with the same parameters takes 20 minutes. The longer-term exposure will give preference to further degradation process, oxidation. Metallographic
analysis reveal, that the hold period effect cause growth of radial crack in the specimen with sharper manner, than in standard LCF. Influence of the atmosphere and temperature on the oxidation process will be done within the future work.

Comparison of metallographic evaluation from specimens after LFC and LCF with hold period is in **Figure 4**. The hold period effect cause a decrease of the number of the cycles to initiation because of above mentioned reason. Comparison LCF and LCF with hold period results in **Figure 5**.

**Figure 3**. Demonstration of the course of the force and deformation during LCF with hold period at 550°C and strain amplitude 0.7%, R=0

**Figure 4.** LEFT radial crack length in specimen after LCF test; **RIGHT** radial crack length in specimen after LCF with hold period
Figure 5. Relation between cycles to initiation and temperature for LCF and LCF with hold period; R0, deformation amplitude 0.7%

2.3 Thermo-mechanical fatigue

Design of the tests and specimens was derived from ASTM E2207 standard. Tests are carried out on servo-hydraulic axial-torsional testing machine. DIC system Mercury provides the control signal for the machine in axial and torsional direction. Heating of the specimens realized by resistive heating system. Infrared camera was used for evaluation of temperature distribution field. It was found that only 5mm is possible to consider as temperature homogeneity area. Therefore, $L_o$ of the virtual extensometer was set to be 4 mm. Experimental setup is presented in Figure 6.

Figure 6. Setup for TMF experiment, 1- Servo-hydraulic axial torsional machine; 2- Infrared camera; 3 – resistive heating grips; 4 - DIC system; 5 – detail of the specimen from DIC; 6 – detail of the specimen from infrared camera

TMF experiments were carried out under strain and temperature control. Whereas the temperature was in- or out-off-phase, respectively. The cycle asymmetry coefficient R-1 was used for new fatigue tests, where the maximum axial strain $\varepsilon_a$ 0.005 and maximum temperature T 600 °C was in phase (0°) or out-off phase (180°), as document Figure 7.
3 Conclusion
This paper briefly presents the experimental program carried out in the scope of FLEXTURBINE project. Influence of measurement technique on results of Young’s modulus was presented. It was found that hold period effect significantly LFC test results. The long term exposure lead to involvement of other damage mechanism such as oxidation. Simultaneously attitude for verification of the DOA by means of TMF experiment was preformed.

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