Determination of mechanical properties of steam turbine rotor materials

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Abstract. Increasing share of renewable energy sources in the electricity production results in a pressure on the thermal power plants to cover the power fluctuation very frequently. The increasing number of the start-ups and shutdowns as well as requirements for prompt ramping and for higher operation temperature has cardinal influence on the lifetime of the steam turbine. This all brings new challenges in to the designing process of the new steam turbines and lifetime analysis of currently operated ones. This paper aims to present experimental work, basic material parameters such as tensile test properties and FATT are determined here. Additionally, advanced material properties are probed by fracture toughness tests, fatigue crack growth tests and stress intensity factor threshold tests under various temperature ranges and cycle asymmetries. The study is carried out for several steels used for the turbine shafts design.

1 Introduction

Increasing share of renewable energy sources in the electricity production results in a pressure on the thermal power plants to cover the power fluctuation [1]. The increasing number of turbine start-ups and shutdowns as well as requirements for prompt ramping and for higher operation temperature has cardinal influence on the lifetime of the steam turbine [2],[3]. This all brings new challenges in to the design process of the new steam turbines and lifetime analysis of currently operated ones. Experimental data are a key aspect. Their influence on the accuracy of the resulting analysis is crucial. In order to provide useful and realistic input data for the FEM based design, a close relationship between the testing laboratory and the simulation team is always necessary. Testing condition must be clearly specified, and in many cases must correspond with the operation conditions of given component, like temperature, load rates, testing frequency etc. [4][5]. Any deviation can then lead to over-conservative results, or even worse, to too optimistic ones.

In the case of this project there was requirement to describe transition properties of given rotor steels and to characterize fracture behaviour during operation conditions of the rotor materials. Critical for each mechanically loaded component is to avoid operation in temperatures at which the material exhibits brittle or ductile-to-brittle transition characteristics. Therefore, the so-called fracture appearance transition temperature (FATT) was determined by means of standard Charpy impact tests.
as the first parameter on which testing temperatures for subsequent tests were based. Subsequently, tensile tests were performed for temperature range from 20 to 600°C for basic characterization providing also necessary input data for further tests and simulations.

The Fatigue crack growth tests (FCG) were subsequently performed at temperatures FATT-30°C, FATT, FATT+30°C and operating temperature for considered materials. These tests were subsequently supplemented by measurements of stress intensity factor (SIF) threshold range $\Delta K_{th}$ in the same temperature interval. It is assumed that during the start-stop cycles, the rotor is loaded by a superposed high-frequency load, therefore, in order to get relevant data, testing at various load asymmetries $R$ was carried out. Another important material parameter for numerical simulations, which represents the relationship between the toughness, stress and flaw size is fracture toughness $K_{IC}$, which was measured and evaluated for above mentioned temperature intervals.

The experiments described above were carried out on four materials typically applied in steam turbine design.

2 Experiments - overview

Four different steam turbine (ST) materials were investigated in this project. The detailed parameters of individual above-mentioned tests are given in individual chapters below.

Description and justification of applied different temperature ranges is presented in Figure 1.

![Figure 1. Justification of the temperature test ranges for testing of material fracture mechanics properties.](image)

2.1 Tensile tests

Tensile tests were carried out according to the standard CSN EN ISO 6892-1 and CSN EN ISO 6892-2 in temperature range 20, 200, 400 and 600 °C. Geometry of the specimen is presented in Figure 2.
2.2 Determination of the FATT
Tests were performed in accordance with the standard ČSN EN ISO 148-1 and ČSN EN ISO 14556 on impact pendulum with the energy capacity of 300 J. Standard Charpy geometry with V-notch and dimensions of 10x10x55 mm was used. The temperature interval of the tests corresponded to the needs of individual materials for the full determination of FATT.

2.3 Fatigue Crack Growth tests (FCG) and identification of ΔKth
Test procedure for measurement of FCG rates (i.e. Paris’ curves) and ΔKth are given in the ASTM E645-15 standard. Tests were performed using magneto-resonance testing machine Rumul with adapted split furnace or cooling chamber. Crack growth was monitored indirectly by means of measurement of the specimen’s compliance using the Crack Opening Displacement (COD) extensometer. Geometry of the specimens is shown in Figure 3a.

In all cases the specimens were precracked up to a/W = 0.3 with resulting SIF range 16 MPa√m. Tests were carried out at temperatures FATT-30°C, FATT, FATT+30°C, 20 and 600 °C and asymmetry ratios R applied here are 0.1 and 0.7. Temperature of individual tests and coefficient of the asymmetry are presented in Table 1 and Table 2.

2.4 Fracture toughness measurement - KIC
In the transition temperature range the fracture toughness was measured according to the standard for Master curve evaluation ASTM E1921-16. In the ductile region the J-R curve concept according to the
ASTM E1820-11 was followed. In all cases the CT specimen geometry was used (Figure 3b). Specimens were precracked up to a/W = 0.5 and the final SIF range was 16 MPa√m. Before testing, side grooves were machined with total depth of 2 mm from each side to ensure mode I crack growth throughout the entire specimen cross section. Tests were carried out in the temperature range FATT ± 30°C. 10% Cr ferritic rotor steel was tested at temperature 20 and 600 °C. Test conditions are summarized in Table 3.

| Test parameters    | low alloy heat resistant rotor steel | low alloy high strength rotor steel | alternative low alloy heat resistant rotor steel | 10% Cr ferritic rotor steel |
|--------------------|-------------------------------------|-----------------------------------|-----------------------------------------------|-----------------------------|
| T=FATT - 30°C, R=0,1 | X                                   | X                                 | X                                             | X                           |
| T=20°C, R=0,1      |                                     |                                   | X                                             |                             |
| T=FATT-30, R=0,7   | X                                   |                                   | X                                             |                             |
| T=20°C, R=0,7      | X                                   |                                   | X                                             |                             |
| T=100°C, R=0,1     | X                                   | X                                 | X                                             |                             |
| T=600°C, R=0,1     |                                     |                                   |                                               | X                           |

| Test parameters    | low alloy heat resistant rotor steel | low alloy high strength rotor steel | alternative low alloy heat resistant rotor steel | 10% Cr ferritic rotor steel |
|--------------------|-------------------------------------|-----------------------------------|-----------------------------------------------|-----------------------------|
| T=FATT – 30°C, R=0,1 | X                                   | X                                 | X                                             |                             |
| T=20°C, R=0,1      |                                     |                                   | X                                             |                             |
| T=FATT-30°C, R=0,7 | X                                   |                                   | X                                             |                             |
| T=20°C, R=0,7      | X                                   |                                   | X                                             |                             |
| T=100°C, R=0,1     | X                                   | X                                 | X                                             |                             |
| T=200°C            |                                     |                                   |                                               | X                           |
| T=600°C, R=01      |                                     |                                   |                                               |                             |

| Test parameters    | low alloy heat resistant rotor steel | low alloy high strength rotor steel | alternative low alloy heat resistant rotor steel | 10% Cr ferritic rotor steel |
|--------------------|-------------------------------------|-----------------------------------|-----------------------------------------------|-----------------------------|
| T=FATT             | X                                   | X                                 | X                                             |                             |
| T=FATT - 30°C      | X                                   | X                                 | X                                             |                             |
| T=FATT + 30°C      | X                                   | X                                 | X                                             |                             |
| T=20°C             | X                                   | X                                 | X                                             |                             |
| T=600°C            |                                     |                                   |                                               | X                           |


3 Results and discussion
In Figure 4, the comparison of the static material properties in relation to the temperature is depicted. Highest values of \( R_m \) and \( R_{p0.2} \) exhibit material \textit{Alternative Low alloy heat resistant steel}. As expected, material \(textit{Low alloy heat resistant steel} has the lowest \( R_m \) and \( R_{p0.2} \) in the temperature range 20 – 400 °C.

FATT results are summarized in Table 4. Except the \textit{Low alloy high strength steel}, all materials exhibit ductile-to-brittle transition temperature at approx. room temperature. Great emphasis must be placed on handling the LP part of the rotors at this temperature, not only during the installation process, but even more at the operating temperatures where may approach the transition region and where the roots of the blades are stressed mechanically, due to centrifugal force and vibrations. In the HP and IP part of the steam turbine the operating temperature is above the transition region. The domain loading is due to the thermal stress, which are caused be start-ups, shot-downs and load changes.

Results obtained from the fracture toughness measurement are presented in Table 4. The \textit{Low alloy high strength steel} and \textit{10% Cr ferritic rotor steel} only exhibit the value of fracture toughness higher than 200 MPa√m at FATT temperature.

SIF threshold value \( \Delta K_{th} \) is ranging from 7.3 to 10.3 MPa√m at temperature FATT-30°C and R = 0.1 (Figure 5). It was observed that \( \Delta K_{th} \) drops by approx. 40% at R = 0.7 and at the same temperature level. The similar effect of R was observed on FCG rates, i.e. with increasing R the crack exhibits a higher crack growth rate.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure4.png}
\caption{Comparison of the average tensile tests results for four investigated materials}
\end{figure}

\begin{table}[h]
\centering
\caption{Summarization of transition temperature FATT and fracture toughness tests \( K_{IC} \)}
\begin{tabular}{|c|c|c|c|c|c|c|c|}
\hline
Designation of the steel & FATT temperature (°C) & Fracture toughness (MPa√m) at given temperature & \multicolumn{3}{c|}{Fracture toughness (MPa√m) at given temperature} \\
 & Centre & Circumference & FATT-30 & FATT & FATT+30 & 20 & 600 (°C) \\
\hline
low alloy heat resistant & 27.0 & 32.0 & 94.2 & 129.2 & 262.0 & & \\
low alloy high strength & -114.0 & -152.0 & 153.0 & 248.2 & 508.6 & 292.2 & \\
rotor steel & & & & & & & \\
alternative low alloy heat & 26.0 & 2.0 & 103.3 & 174.6 & 178.6 & & \\
resistant rotor steel & & & & & & & \\
10% Cr ferritic rotor steel & 3.6 & & & & & & 246.0 & 211.8 \\
\hline
\end{tabular}
\end{table}
Figure 5. Summarization of the test results from FCG and ΔKth measurements

4 Conclusion
This paper aim is to summarize the test campaign performed in order to provide material input data for numerical simulations of FCG rates in ST rotors. The tests prove that the test conditions must not be underestimated, especially the effect of other parameters such as R and temperature. Especially, increasing R has negative influence on the resulted FCG parameters as well as on ΔKth. At the same time it was proven, it is very useful to support tests with tensile and FATT tests, which are not time or money consuming and whose benefits are undeniable.

Tests results will be used as input parameters for FEA simulations of residual service life of in service steam turbine rotors.

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