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Research Paper

Numerical investigations of crack initiation in impulse steam turbine rotors subject to thermo-mechanical fatigue

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HIGHLIGHTS

- Elastic and elastic-plastic finite element analyses done to study rotors cracking.
- Heat grooves are the most critical areas from the viewpoint of thermal fatigue.
- Predicted crack areas and number of cycles well correspond with inspections results.
- Stress-strain correction rules provide lower and upper bound limits of fatigue life.

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ABSTRACT

The study presents the analysis of non-stationary stresses and fatigue cracking in impulse steam turbine rotors. Field experience with cracking of rotors is reviewed, and the most frequent crack locations are identified based on the same. Mathematical models of heat transfer and material constitutive behaviour used in numerical calculations of an intermediate pressure rotor are discussed. Calculations were performed with the help of finite element method for typical transient events including cold, warm, and hot start-ups and a shutdown. The highest stress and strain amplitudes were obtained in the heat grooves of a balance piston in which cracks were often observed during non-destructive testing. The number of cycles to crack initiation calculated based on the strain amplitudes correspond well with the operating experience of this type of rotors.

1. Introduction

Steam turbine rotors are among the most critical components of power plant units and experience failures due to various damage mechanisms [1]. High-temperature rotors fail due to cracking under creep or fatigue conditions while at low temperatures, stress corrosion cracking and corrosion fatigue are the main life-limiting damage mechanisms [2]. Over the past few decades, numerous examples of cracks owing to these mechanisms were reported for steam turbine rotors operating at high [3–5] and low [6–13] temperatures. In all the cases, high stationary or cyclic stresses in combination with temperature were involved in crack initiation leading to rotor failure.

Low-cycle fatigue cracking of turbine rotors is well known for at least 50 years, and it is mainly related to high transient thermal stresses that occur during turbine start-ups and shutdowns [14]. High stresses exceeding the material yield stress at the stress concentration areas generate cyclic thermal strains, and their repetitive occurrence may lead to fatigue crack initiation after c.a. 1000 cycles. For machines operated at the base load with a low number of starts per year, the time required to reach the number of cycles is high, whereas the number of start-ups is attained in few years for units in the cyclic operation regime.

Modern energy markets place a requirement of high operational flexibility of power plant units owing to the increased share of renewables [15]. Thus, newly designed steam turbines must fulfil a series of requirements with respect to the number and duration time of start-ups from different thermal conditions and the rate of load change. To a certain extent, these requirements additionally affect old machines that switch from the base load to cyclic operation. Faster and more frequent start-ups generate excessive low-cycle fatigue damage leading to crack initiation. The problem of fatigue crack initiation is still of high practical importance as confirmed by recent findings related to cracks on impulse steam turbine rotors [16,17], necessitating crack removal by light-surface machining or costly weld repair to extend the useful life of the rotor. Additionally, transient operation affects the fatigue life of turbine casings [18,19], turbine casing distortions [20], and turbine thermal elongations [21].

Fatigue life estimations of high-temperature steam turbine rotors are most frequently based on elastic stress analyses and employ the Neuber rule for notch stress–strain correction in the elastic–plastic

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condition [14,15,17]. Previous studies did not investigate the accuracy of the approach and compare lifetime predictions with those based on non-linear elastic–plastic material models. The main objectives of the study include proposing a finite element model for impulse rotors based on an elastic–plastic material model, validating the model by using the available experience with rotor cracking, and determining the accuracy of fatigue life predictions by employing analytical stress–strain correction methods.

The study examines the problem of numerical modelling of fatigue crack initiation in steam turbine rotors with impulse blading. Numerical stress and strain analyses are performed to determine the low-cycle fatigue life of the intermediate pressure rotor of a high-power output steam turbine. The calculations were performed by using a finite element model and different material models with the aim of evaluating their usefulness to fatigue life predictions. The results of numerical calculations were compared with those of crack locations and operating experience, and good agreement was observed between predictions and tests.

2. Crack findings in impulse rotors

Non-uniform loading in conjunction with frequent start-ups and shutdowns of steam turbines leads to crack initiation in their components owing to material thermal fatigue [18]. Impulse steam turbine rotors are prone to thermal fatigue cracking because of their specific design features and non-uniform thermal loading. A typical design of a high-pressure impulse steam turbine rotor is shown in Fig. 1. The rotor includes a thick control stage disc with the highest outer diameter operating at the highest temperature and pressure. The remaining discs are thinner and exhibit lower diameters albeit longer blades. The transition radii between discs and shaft are stress raisers in which cracks may initiate and grow. The rotor ends include areas with changing diameters in which additional heat grooves are machined to reduce the negative influence of non-uniform temperature on rotor shape [23]. Similar grooves are present in the inter-stage glands, and all these regions correspond to the locations of potential cracking due to thermal fatigue.

Numerous examples of impulse rotor fatigue cracking were reported in extant studies [16,17,22–25]. The areas in which cracks are most frequently observed are schematically shown in Fig. 2. Circumferential cracks due to transient thermal stresses were typically observed in three areas as follows [23]:

(a) Heat grooves in the front glands
(b) Transition of diameters in the zones of maximum temperature
(c) Control stage disc to shaft transition radius

An example of thermal fatigue cracks in the front gland heat grooves is shown in Fig. 3. According to Mamontov and Pugaczieva [25], this type of cracking occurs after long-term operation with metal temperatures above 450 °C. Cracks reaching a depth of 1.8 mm were observed in six heat grooves of the front-end gland of a 200 MW intermediate pressure turbine rotor after 126 000 operating hours and 507 start-stop

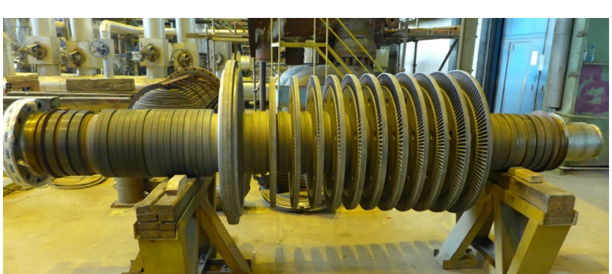

Fig. 1. High-pressure rotor of a steam turbine.

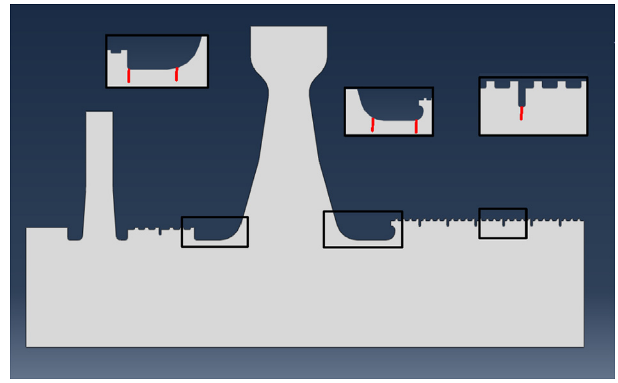

Fig. 2. Typical locations of fatigue cracking in impulse turbine rotors.

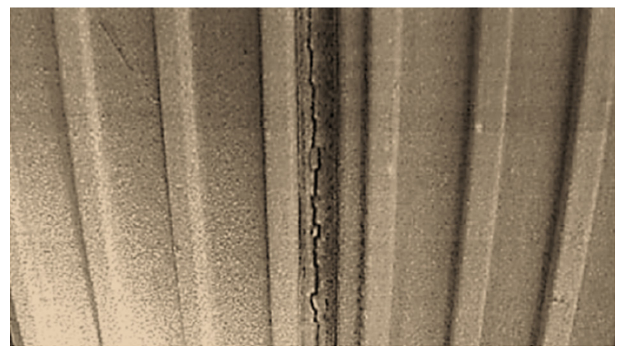

Fig. 3. Fatigue crack in the front gland heat groove.

cycles. This was attributed to the deterioration in the mechanical properties of the rotor material. Generally, for rotor materials with reduced long-term ductility, on the level of 4–10%, cracking in the heat grooves is expected after 1250 start-ups [25]. In 125 MW turbine rotors heat grooves cracking was observed after c.a. 100,000 h and 800 start-ups [23]. The crack depth did not exceed 7 mm although it exceeded the typical heat groove depth of 6 mm. Significantly higher crack lengths corresponding to a maximum of 15 mm were observed in 50 MW turbine rotors that required repair by turning and applying shrunk-on sleeves. In 200 MW turbine rotors, short cracks not exceeding 4 mm were observed after 80 000 h and 500 start-ups.

The second area of potential cracking corresponds to transitions of diameters in the zones of maximum temperature. Typical crack depth in this location was approximately 5 mm and cracking in 120 MW turbines occurred after 70–120 thousands of hours and 300–600 starts. It is necessary to remove these cracks by turning. Thus, the shape of transition between two diameters changed and led to a significant reduction in the stress concentration factor.

Circumferential cracks of similar length were observed in the control stage disc to the shaft transition radius of 55 MW turbines. In this area, longer operation time and higher number of starts are required to initiate cracking. The machines were in operation for 100–200 thousands of hours and experienced up to 2900 start-ups. A similar example described in [17] indicated that thermal fatigue cracking of a monoblock impulse rotor occurred after c.a. 200,000 h and 2000 start-ups.

The examples clearly indicate that thermal fatigue cracks may be initiated in various areas of impulse rotors after significant differences in the number of starts ranging from 300 to 3000. It indicates that crack initiation life is sensitive to thermal stresses generated during start-ups and shutdowns, and its numerical predictions require the detailed modelling of rotor thermal behaviour.