THE EFFECT OF STRENGTH DIFFERENTIAL ON MATERIAL EFFORT OF STEAM TURBINE ROTORS UNDER THERMO-MECHANICAL LOAD

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1. Introduction

A bulk of mechanical integrity analyses of machinery components employ the classical Huber-Mises-Hencky plasticity theory to define the equivalent stress and describe the plastic response of materials [1]. This theory assumes that the mean stress has no effect on plastic flow and the material is incompressible in the plastic regime. The classical definition of equivalent stress based on the second invariant of the deviatoric stress tensor J_2 neglects the strength differential effect, i.e. the difference of yield stresses in tension and compression, which was experimentally found in many materials [2]. For materials exhibiting this effect, a better match of theoretical predictions with experimental stress-strain curves was found when Burzyński yield condition was applied. According to the Burzyński hypothesis, the measure of material effort defining the limit of elastic range is a sum of the density of distortion elastic energy and a part of density of dilation elastic energy [3]. The first contribution is related with the Huber-Mises-Hencky (HMH) equivalent stress, while the second part is mean stress dependent. The resulting definition of equivalent stress σ_B explicitly includes the yield stress in compression σ_y^C and tension σ_y^T by their ratio $k = \sigma_y^C / \sigma_y^T$ and reads [4]

(1) $$\sigma_B = \frac{1}{2k}\left[3(k-1)\sigma_m + \sqrt{9(k-1)^2\sigma_m^2 + 4k\sigma_e^2}\right],$$

where σ_m is the mean stress and σ_e is the Huber-Mises-Hencky equivalent stress.

2. Experimental investigations of 2CrMoV steel

High-temperature rotors operating at temperature below 540°C are usually made of 2CrMoV creep-resistant steel of martensitic microstructure. Round specimens made from this steel were used in uniaxial tensile and compression tests conducted at room temperature. Tensile tests were performed on 6 specimens having gauge length L_0 = 35 mm and diameter d_0 = 7 mm. For compression tests also 6 specimens of gauge height h_0 = 18 mm and diameter d_0 = 12 mm were prepared. Average stress-strain curves at tension and compression obtained from the tests are presented in Fig. 1 which clearly shows significant differences between the two curves in plastic conditions. The measured yield stress at tension was $\sigma_y^T = 727$ MPa, while at compression reached $\sigma_y^C = 798$ MPa, which results in their ratio k = 1.1.

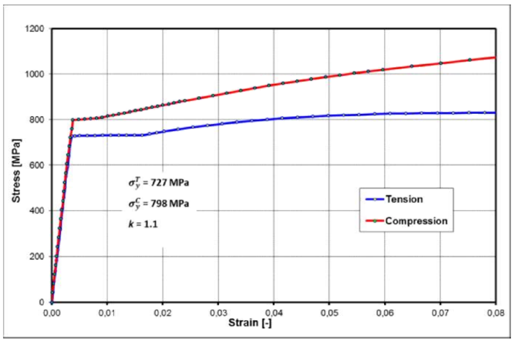

Fig. 1. Stress-strain curves of 2CrMoV steel at tension and compression.

3. Numerical analysis of steam turbine rotor

The material effort of a steam turbine rotor subject to thermo-mechanical loading was investigated by performing transient finite element analysis. Linear elastic material model was adopted together with temperature-dependent material properties and nonlinear thermal boundary conditions. Variations in time of the mean stress and the equivalent stresses evaluated at the circumferential U-groove using both hypotheses are shown in Fig. 2. The Burzyński stress was calculated assuming constant yield stress ratio k = 1.1. For most of the time, the Huber-Mises-Hencky stress is visibly higher than that obtained with Burzyński hypothesis and their ratio attains 1.16. In this phase, the mean stress is negative and lower than $1/3\sigma_e$, but when it exceeds this limit, the Burzyński stress becomes slightly higher and the stress ratio does not drop below 0.97. The operation phase when the mean stresses are negative corresponds to the rotor heating-up, while the positive mean stresses are present in steady-state and during cooling down phase. Thus, high compressive stress states reduce the material effort and due to the strength differential effect allow for higher HMH stresses during heating-up without adversly affecting the rotor material effort and damage. This is of high practical importance as the rotor heating-up takes place during turbine start-up and more accurate determination of the equivalent stress can allow for better utilization of material strength and result in a reduction of start-up time.

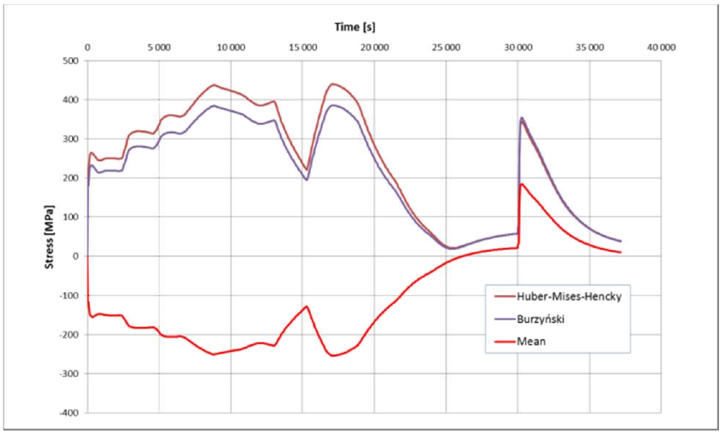

Fig. 2. Variations of equivalent stress evaluated using Huber-Mises-Hencky and Burzyński hypotheses.

5. Summary

The existence of strength differential effect in 2CrMoV rotor steel was prooved experimentaly and its positive effect on the material effort was shown by numerical simulations of the rotor during transient operating conditions. The measured magnitude of strength differential k = 1.1 results in the equivalent stress ratio reaching a maximum of 1.16 at the circumferential U-groove during the compressive phase of the cycle. Thus, the use of Burzyński hypothesis allows for better utilization of material strength provided that the strength differential effect is experimentally confirmed.

References

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