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THERMO-MECHANICAL FATIGUE OF SI-MO 4.06 TURBINE HOUSING OF TURBOCHARGER - DAMAGE OPERATOR BASED LIFETIME PREDICTIONS

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Abstract: *The paper presents application of damage operator based lifetime calculation for cast iron turbine housing of the turbocharger. Combination of thermo-mechanical fatigue and creep is considered, oxidation effect is taken into account indirectly. Results from transient thermal and elastoplastic finite element analysis are used for fatigue and creep damage calculation. Viscoplastic approximation based on nonlinear, strain controlled Maxwell model is used. Critical zones on the turbine housing of the turbocharger have been observed. Different damage parameters including dissipated energy for continuous damage calculation will be discussed.*

Keywords: Thermo-mechanical fatigue, Kinematic hardening, Creep, Hysteresis operator, Turbine housing of the turbocharger.

1. Introduction

Turbine housing of the turbocharger provides kinetic energy, needed for charging, using remaining enthalpy of the exhaust gas. Inhomogeneous distribution of temperature and boundary conditions of the component constrains thermal expansion, resulting in inelastic strains and stresses. Operating status is nearly cyclically stable. Also, at high temperature, creep and relaxation effects cannot be neglected.

Turbine housing of the turbocharger operating under thermo-mechanical cycle is considered for damage calculation. Temperature loading results from transient thermal finite element analysis (FEA), stress-strain response is obtained from elastoplastic FEA with non-linear temperature dependent kinematic hardening. Viscoplastic approximation is done as part of the post-processing step. Fatigue and creep damage are calculated separately. Oxidation is taken into account indirectly, as material tests were performed under ambient conditions. So called damage operator for variable temperature, developed especially by Nagode et al. (2010), enabling continuous calculation for non-isothermal thermo-mechanical loading, is used for fatigue damage calculation. Equivalent cycle temperature and separate rainflow counting aren't needed.

2. Material data assessment

Elastoplastic material response has been numerically modeled in ABAQUS. Constitutive model used represents mathematically Bauschinger's effect and other effects observed for materials subjected to cyclic loading, using associated flow rule and von Mises yield criterion. Widely accepted and commonly implemented in commercial software - Chaboche nonlinear temperature dependent kinematic hardening is selected from available models of incremental plasticity, capable to describe cyclic loading scenario, both isotropic and kinematic hardening, ratcheting and other phenomena. Three term backstress Chaboche model is proposed. Rather than on current temperature, model parameters have been calibrated to follow monotonic downward trend depending on temperature, mathematically described as Boltzmann function. Only cyclically stable hysteresis loops are point of the interest for thermo-mechanical fatigue. Elastoplastic

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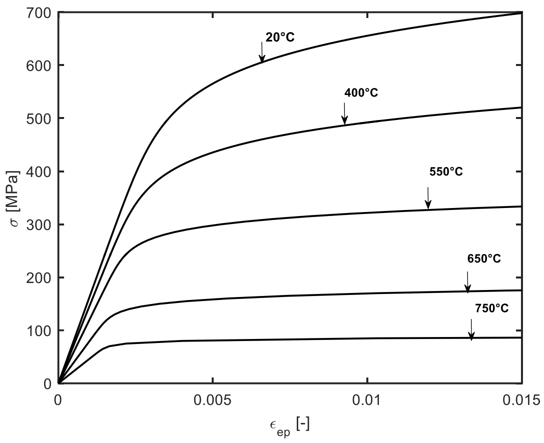
material model has been calibrated from isothermal strain controlled low-cycle fatigue tests, attained at high strain rates for a few distinct temperatures, fully covering temperature range of the investigated component.



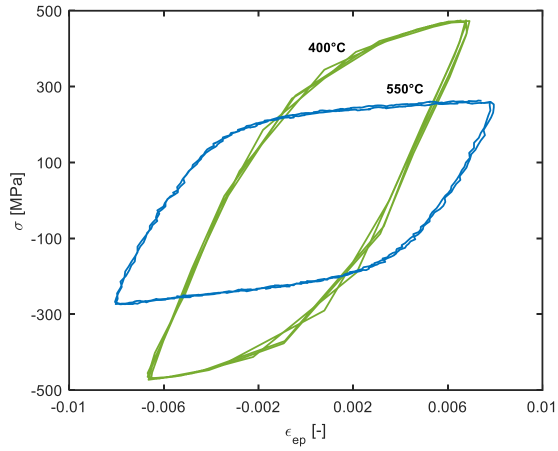


Fig. 1: Cyclically stable cyclic stress-strain curves and test hysteresis loops at mid-life.

Cyclic creep or relaxation curves are needed for time-dependent plasticity modelling. Visco-parameters have been assessed from LCF tests performed at two different strain rates at three selected temperatures. Viscoplastic approximation is proposed as a part of postprocessing step. Law of perfect viscoplasticity with the elastic domain, used for approximation, is defined as follows:

$$\dot{\varepsilon}_{vp} = \langle \frac{\sigma - k(T)}{K(T)} \rangle^{N(T)} \tag{1}$$

Where $k(T), K(t)$ and $N(T)$ are material and temperature dependent parameters.

3. Damage calculation

3.1. Fatigue damage

It has been shown, that commonly used and standardized rainflow method corresponds directly to elastoplastic material behavior and memory rules. Continuous damage calculation could be modelled using hysteresis operators.

First, nodal temperatures and equivalent stresses are transferred from elastoplastic FEA. Uniaxial total strain is assessed, expressed in the form of so-called Prandtl type operator. Subtracting viscoplastic strain from total strain using nonlinear strain controlled Maxwell model results in elastoplastic strain that contributes to fatigue damage. True stress can be expressed in the form of Prandtl type operator. For selected damage parameter, using linear damage accumulation, fatigue damage can be expressed as a total variation, representing cyclic fatigue damage evolution:

$$D_f(t_i) = \sum_{j=1}^{i} \left| \mathcal{D}(t_j) - \mathcal{D}(t_{j-1}) \right| \tag{2}$$

$$\mathcal{D}(t_i) = \sum_{j=1}^{n_p} \gamma_j(T_i) P_{\gamma j}(t_i) \tag{3}$$

The damage parameter dependent play operator with general initial value is given as follows:

$$P_{\gamma j}(t_i) = max\left\{P(t_i) - p_j, min\left\{P(t_i) + p_j, \frac{\gamma_j(T_{i-1})}{\gamma_j(T_i)} P_{\gamma j}(t_{i-1})\right\}\right\} \tag{4}$$

Where the Prandtl densities $\gamma_j(T_i)$ and fictive yield damage parameters p_j in the range $j = 1, \dots, n_p$ could be derived explicitly from available temperature dependent damage parameter – life curves (fatigue curves). Damage parameter follows kinematic hardening and Masing memory rules.

3.2. Creep and total damage calculation

For a creep damage calculation widely accepted Robinson's rule (time fraction rule) is used:

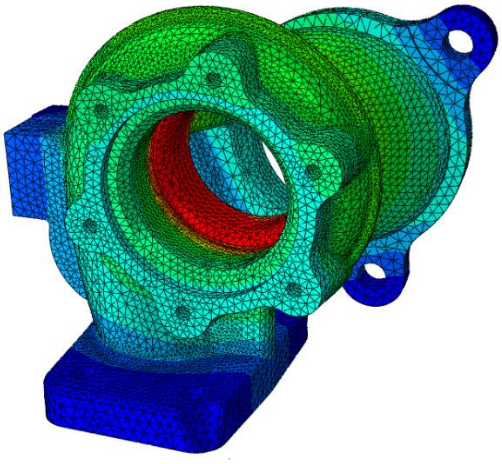
$$D_c(t) = \int_0^t \frac{dt}{t_R(\sigma(t),T(t))} \tag{5}$$

Where t_R is rupture time for current stress and temperature. Total damage including creep, fatigue and oxidation is obtained as follows:

$$D(t) = D_c(t) + D_f(t) \tag{6}$$

4. Turbocharger housing lifetime predictions

Heat transfer coefficients have been determined experimentally from known temperature history from test stand. Transient thermal and elastoplastic FEA has been performed for whole model (coarse mesh) and for submodels in ABAQUS, too. Thermal shock with maximum temperature up to 600°C is considered.



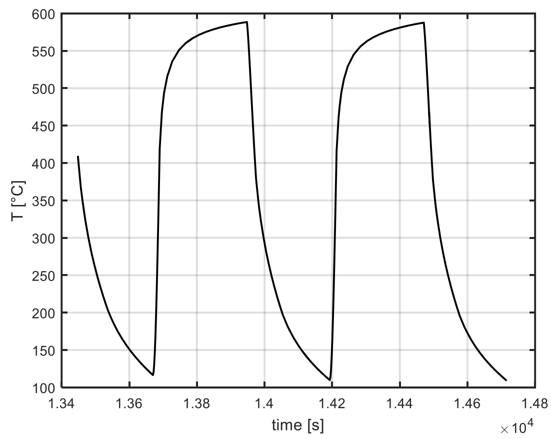


Fig. 2: Simulated thermal shock.

User C/C++ post-processing program with fast computation speed has been developed for viscoplastic approximation and damage calculation, implemented in ABAQUS. Critical zones for the turbine housing of the turbocharger subjected to thermo-mechanical fatigue and creep have been identified.

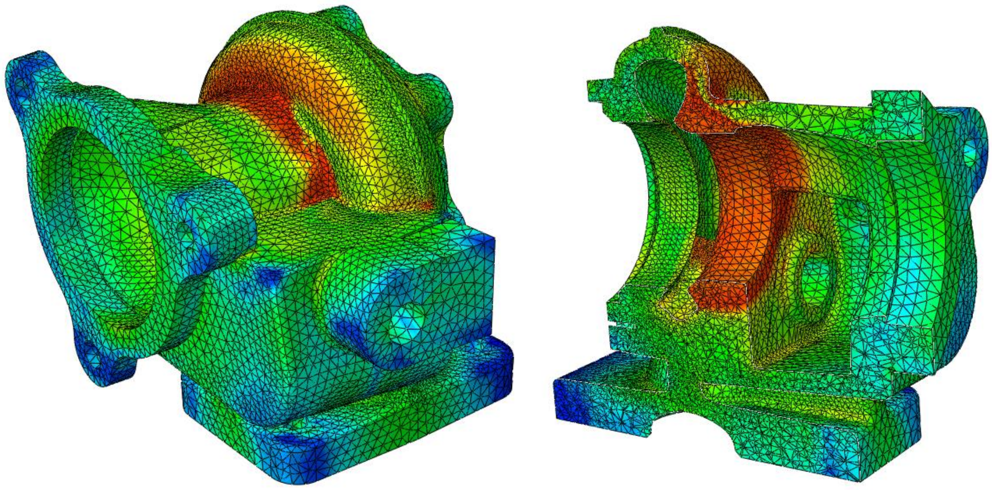


Fig. 3: Observed critical zones.

5. Conclusions

Proposed elastoplastic material model in FEA is capable of describing time independent behavior of the component. Viscoplastic approximation enables fast computation of viscous strain, using nonlinear Maxwell model. Critical zones for the turbine housing of the turbocharger have been identified according to simulated loading. Damage operator enables continuous damage calculation, which is especially suited for thermo-mechanical fatigue.

Future research will be directed especially to viscoplasticity modelling and multiaxial temperature dependent fatigue criterion. Also, other types of thermal loadings should be simulated on turbine housing of the turbocharger. Finally the results should be verified experimentally by partial destruction or total destruction of the component on the test stand.

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