Phenomenological models for lifetime prediction under low-cycle fatigue and thermo-mechanical fatigue loading conditions

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Doctoral study programme: Mechanical Engineering, Study field: Mechanics of Rigid and Deformable Bodies and Environment

1. Introduction

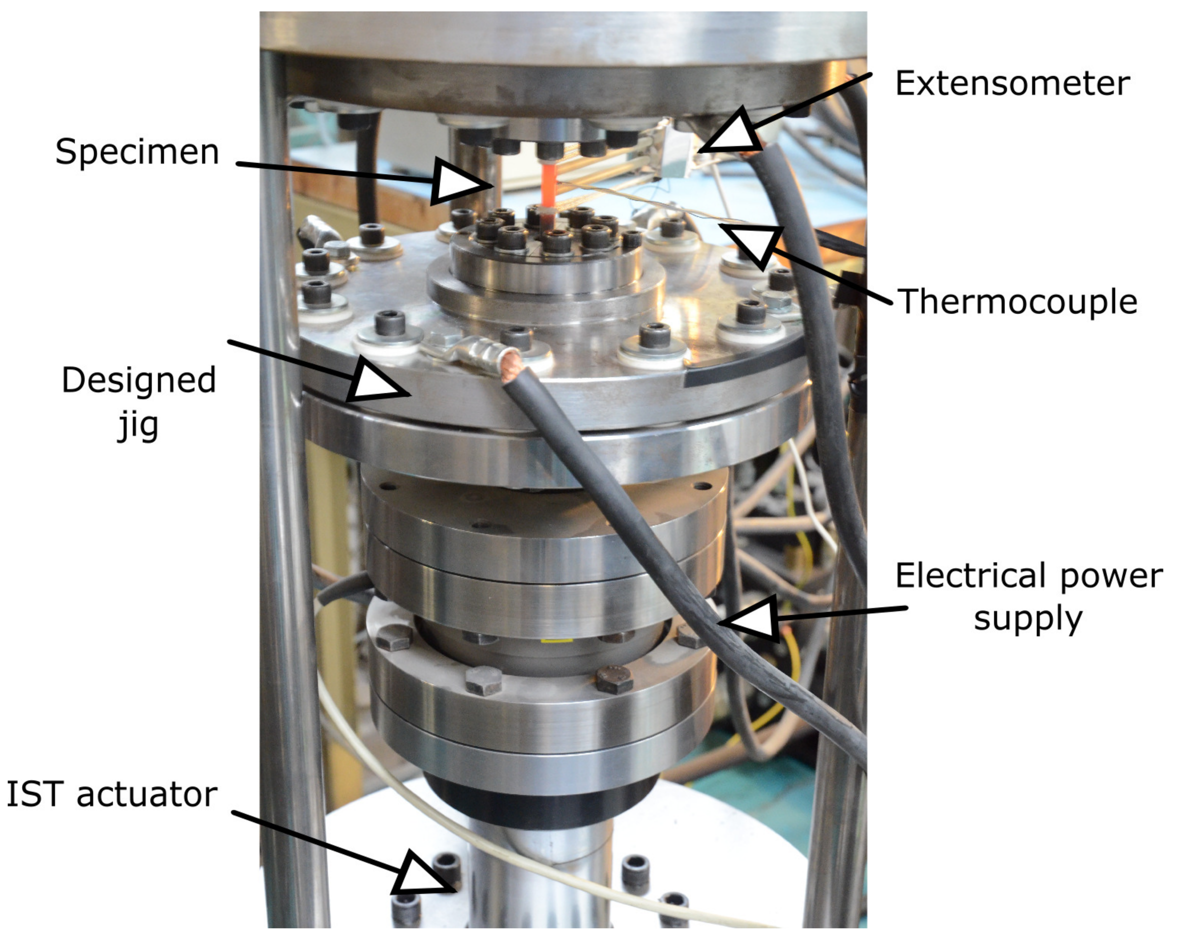
- Low-Cycle Fatigue (LCF) and Thermo-Mechanical Fatigue (TMF) are usually caused by the start-up and stop phases during the service life of a high-temperature component
- LCF can be used for loading cycles with constant temperature, whereas TMF should be considered, if the temperature changes significantly during a loading cycle
- TMF is caused primarily by cyclic thermal loading and additional mechanical loading; TMF can result in considerably shorter life in comparison with LCF, therefore reliable life prediction method is necessary
- High temperature LCF and TMF are important consideration in design phases of components in the course of variable service conditions, such as turbine housing of a turbocharger, turbines, exhaust manifold, aircraft engine parts or fossil power-plant components

2. Aims of the doctoral thesis

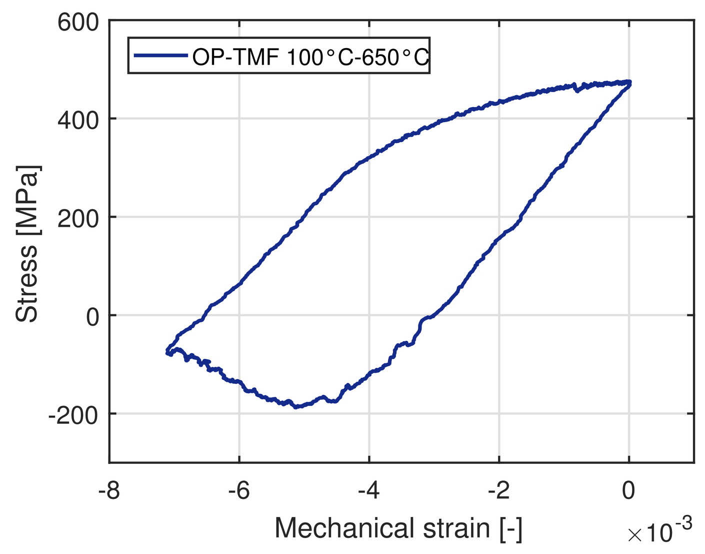
1. Proposal of a novel energy based fatigue criterion that can be used for lifetime predictions of complex engineering components under LCF and TMF loading.
2. Development of the control algorithms for the newly in-house designed test stand that can be used for uniaxial strain controlled LCF and TMF tests.
3. Experimental research of mechanical behaviour of SiMo cast iron under TMF and LCF loading conditions. Acquirement of experimental data in order to calibrate a viscoplastic material model and a novel fatigue criterion.
4. Implementation and numerical integration of a unified viscoplastic material model as user material subroutine for Abaqus finite element software.
5. Development of the calibration tool for the material model. Proposal of a novel method for calibration of temperature dependent material parameters.

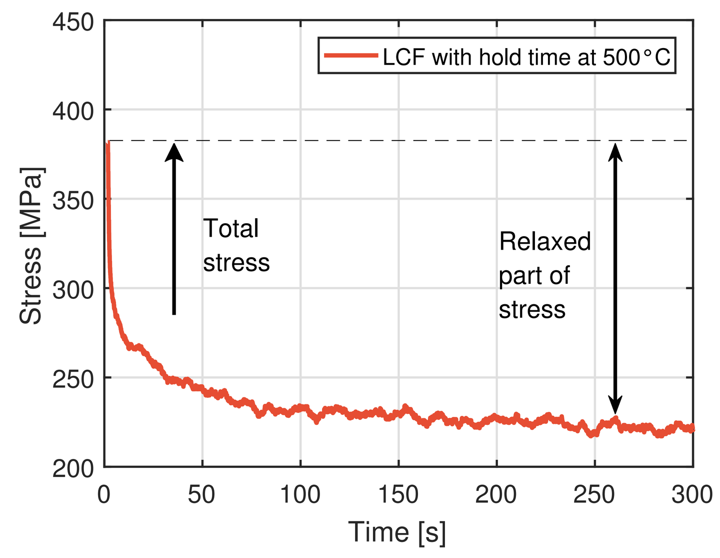
3. Experiments

- Tests were performed for SiMo 4.06 cast iron for temperatures between 20°C and 750°C; SiMo is used in automotive industry for production of exhaust manifolds and turbine housings
- In-house designed test stand for uniaxial LCF/TMF testing:

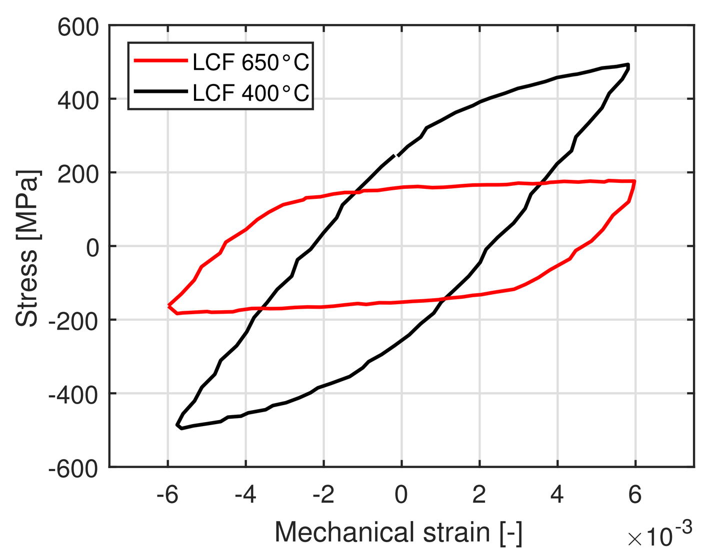


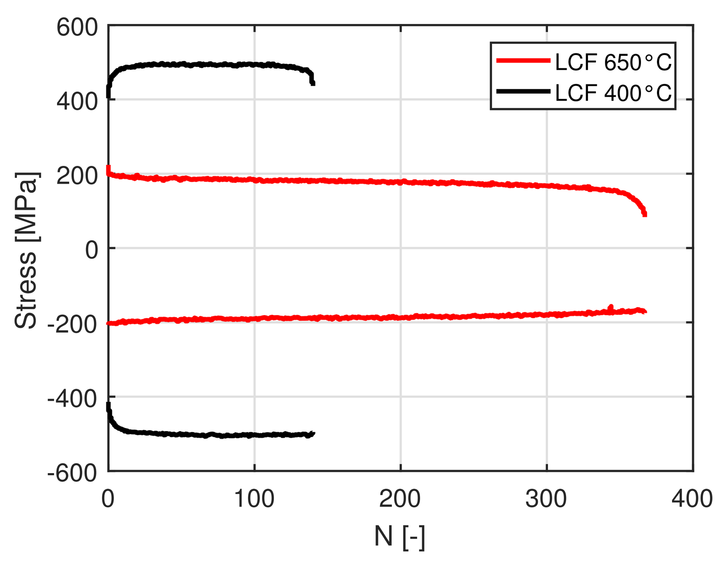
- Following material tests were carried out on in-house designed test stand:
  1. Triangular LCF tests
  2. Out-of-phase TMF (OP-TMF) tests
  3. LCF tests with hold time in tension, i.e. creep-fatigue tests
- OP-TMF test between 100°C and 650°C (left) and creep-fatigue test at 500°C (right):





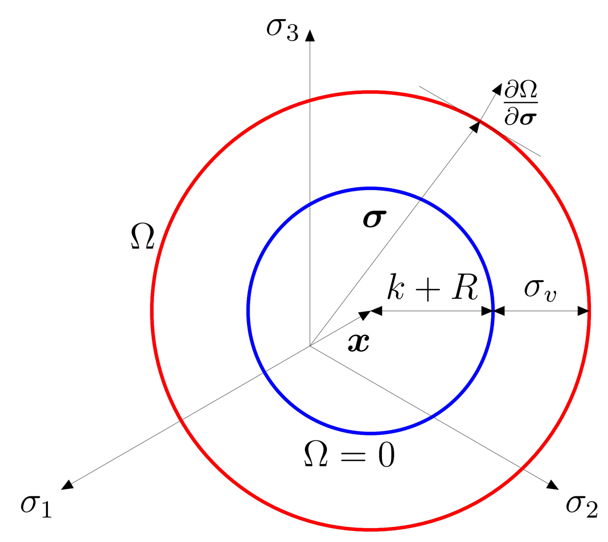
- Isothermal LCF test results at 400°C and 650°C:





4. A unified viscoplastic material model

- A unified viscoplastic material model with non-linear kinematic hardening, isotropic hardening and hyperbolic sine flow rule:



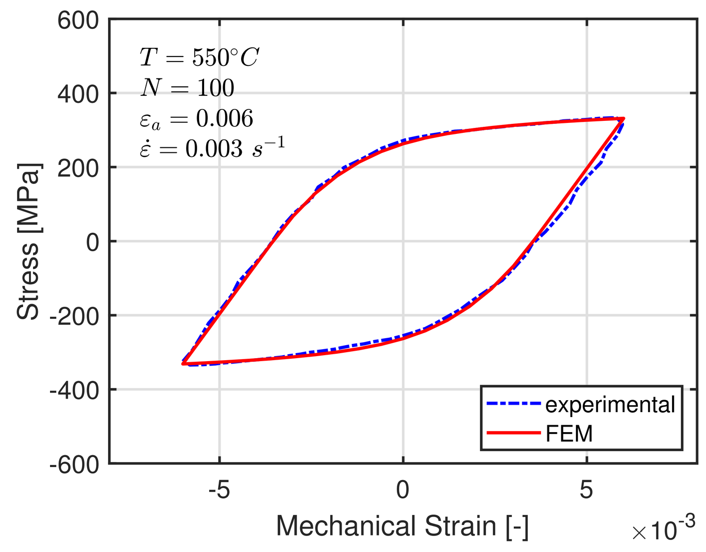
$$\dot{p} = \frac{\partial \Omega}{\partial f} = \alpha \sinh \langle \beta f \rangle ,$$

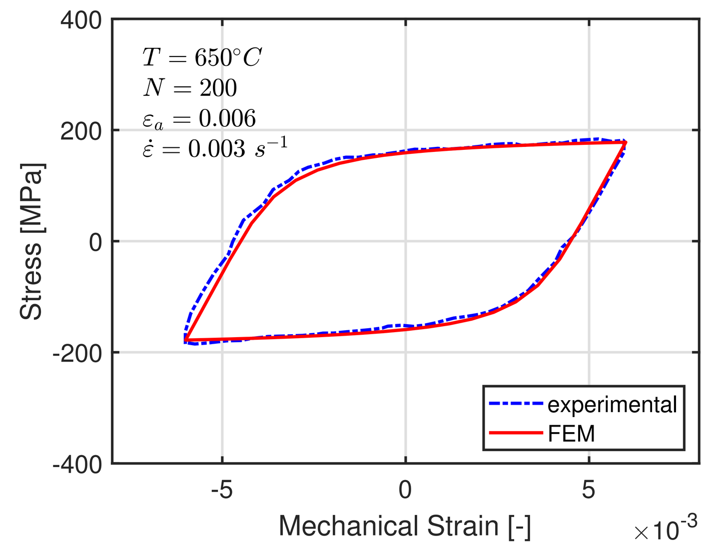
$$\dot{\varepsilon}^{pl} = \frac{\partial \Omega}{\partial \boldsymbol{\sigma}} = \frac{\partial \Omega}{\partial f}\frac{\partial f}{\partial \boldsymbol{\sigma}} = \dot{p}\boldsymbol{n}$$

$$f = J(\boldsymbol{\sigma} - \boldsymbol{x}) - k - R$$

$$\dot{\boldsymbol{x}}_i = \frac{2}{3} C_i \dot{\varepsilon}^{pl} - \gamma_i \boldsymbol{x}_i \dot{p} + \frac{1}{C_i}\frac{\partial C_i}{\partial T}\boldsymbol{x}_i \dot{T}$$

- The material model is implemented as user material subroutine for Abaqus finite element software
- Simulated and experimental hysteresis loops:





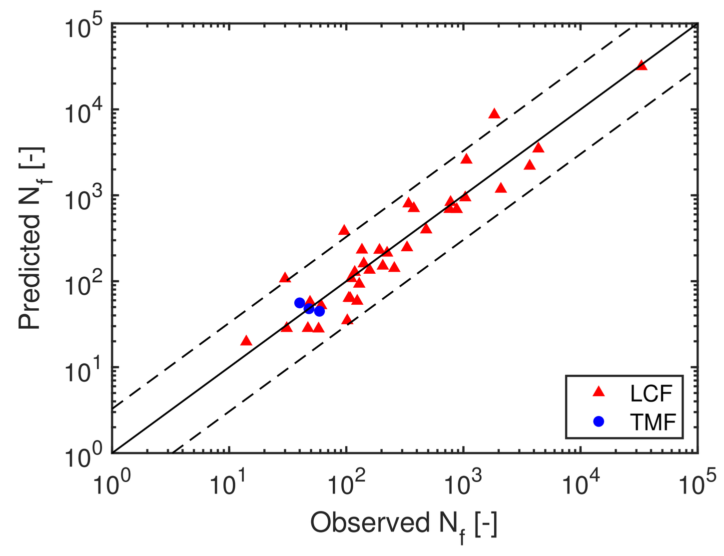
5. A novel fatigue criterion

- The modified dissipated energy per cycle criterion is suggested as follows:

$$w + \alpha \left(-1 - R_\sigma\right)^{-1} = A N_f^B ,$$

$$w = \int_{cycle} \boldsymbol{\sigma} : \dot{\varepsilon} \, dt, \quad R_\sigma = \frac{\sigma_{min}}{\sigma_{max}}$$

- Mean stress term is added in order to improve fatigue predictions for TMF tests
- Observed and predicted lifetime for specimens:



6. Conclusions

1. A novel energy based fatigue criterion was proposed in order to predict LCF/TMF lifetime for specimens and for complex engineering structures. A reasonable correlation was achieved between the observed results and the predicted results.
2. The proposed control and control algorithms for the new in-house designed test stand enable strain-controlled high temperature uniaxial LCF and TMF tests on specimens.
3. Large amount of new experimental data was generated for SiMo for temperatures between 20°C and 750°C. This can be used for calibration of constitutive material models and for fatigue analysis.
4. A unified viscoplastic material model was implemented as UMAT for Abaqus. The consistent tangent stiffness was derived on the basis of numerical integration scheme.
5. The temperature dependent unified viscoplastic material model was calibrated from the obtained experimental data. The non-linear kinematic hardening model parameters, C_{1-3} and γ_{1-2}, were calibrated systematically with temperature, mathematically represented as a Boltzmann function.

7. Selected author's publications

[1] Bartošák, M., Novotný, C., Španiel, M., Doubrava K. Life assessment of SiMo 4.06 cast iron under LCF and TMF loading conditions. *Materials at High Temperatures* (2018), doi: 10.1080/09603409.2018.1542825, Article in Press.
[2] Bartošák, M., Španiel, M., Doubrava K. FEM Implementation of a unified viscoplastic model and its application to modelling cyclic mechanical behaviour of ductile cast iron under LCF and TMF loading conditions. Under review in journal *Materials at High Temperatures*.
[3] Bartošák, M., Španiel, M., Doubrava K. Thermo-Mechanical Fatigue of SiMo 4.06 Turbocharger Turbine Housing: Damage Operator Approach. Under review in journal *Engineering Failure Analysis*.

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