Isothermal LCF, Relaxation and Thermomechanical Fatigue Tests of Si-Mo Based Cast Iron

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Abstract: High temperature behaviour of the tested material can be influenced by various processes, such as oxidation, cyclic creep and phase transformations, according to the selected temperature and strain rate. Isothermal low cycle fatigue (LCF), cyclic relaxation and thermomechanical fatigue (TMF) tests were conducted on Si-Mo based cast iron for the wide temperature range on the constructed thermomechanical fatigue test stand.

Keywords: cast iron; low cycle fatigue; thermomechanical fatigue; relaxation; viscoplasticity; TMF test stand.

1 Introduction

Ductile cast irons are often used for turbocharged diesel engine components, e.g. turbine housing of a turbocharger. Very good castability and relatively low price makes silicon-molybnedum cast iron a good choice for these components. Turbocharger applications are characterized by operating temperature usually below 650°C, but temperature may exceed up to 800°C.

Silicon-molybdenum cast iron components are often subjected to a complex mechanical and thermal loadings during the lifetime. Inhomogenous temperature distribution, mechanical loads, restricted thermal strains and boundary conditions of the components during variable operating conditions, containing start up, load, partial load and shutdown phases, often lead to a state, that is usually termed as a thermomechanical fatigue [1, 2]. High operating temperatures pottentially induces creep and time dependent effects. The durability assesment is increasingly demanded to ensure the field reliability targets [3]. This or a similar type of loading is usually simulated at uniaxially loaded specimens on a test stand, which enables to independently control temperature and mechanical loading, e.g. [3, 4, 5, 6].

First the paper presents construction and control of the TMF test stand. In a second part, the cyclic mechanical behaviour and durability are studied for the investigated material based on the performed tests.

2 Experiments

2.1 Test Stand

All tests were carried out on Instron PL 160 K servo-hydraulic actuator. The heating of the specimen is achieved by a direct electrical resistance heating, i.e. by passing a electric current through the specimen. This is attained by the additional heating device added to the Instron servo-hydraulic actuator, Fig. 1 and Fig. 2. The cooling of the specimen is passive, under the ambient air, meanwhile. The maximum achievable load for the machine is 160 kN and the maximum allowable temperature is up to 1000°C, depending upon the diameter of the specimen.

Temperature is measured by K-type spotwelded thermocouple [7] in the center of the specimen. Strain is controlled by the axial high temperature extensometer (up to 1200°C) with ceramic bars. Force is measured by the built-in load cell of the testing machine. PC based system is accompanied by NI-DAQ measurement card to ensure the collection of data from the sensors. The card is also used for the heating control as well as strain control. Closed-loop PID control is achieved by the combination of LabView and Instron controlling software (i.e. RS Console), outlined in Fig. 3. Among others, Instron software provides the safety limits for the tests.

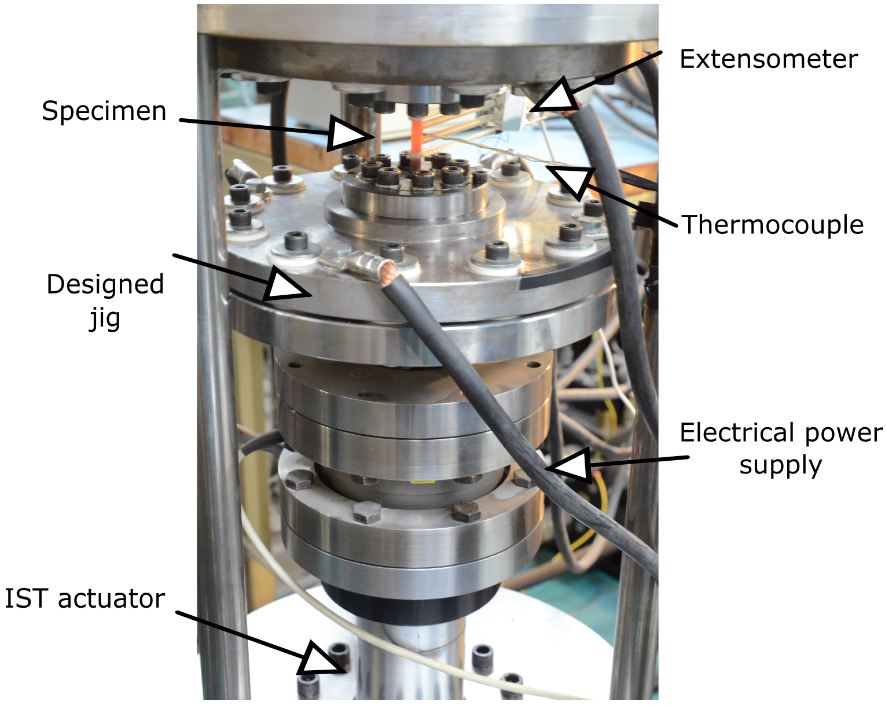


Figure 1: Test stand.

Several measurements by the infrared thermography and numerical simulations of the heated specimen temperature field preceded in order to verify the temperature uniformity in the gauge length of the specimen. The radial temperature differences are assumed to be negligible, also because of the relatively high thermal conductance of the investigated material. Further, value of the supply voltage for the heating was recorded for the selected geometry of the specimen and for the selected temperature range for a purpose of controlling the signal from the thermocouple. The thermocouple is removed and the new one is welded, if the value deviates more than approximately 5% from the known static characterictic. In the case of TMF test, the supply voltage is controlled for the maximum and minimum temperature of the cycle.

Figure 2: Heated specimen.

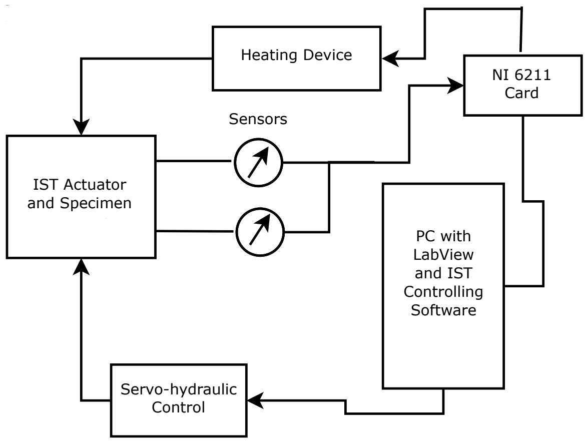


Figure 3: Outline of the proposed closed-loop control of the test rig.

2.2 Investigated Material

The material under investigation is the silicon molybdenum cast iron with a spherical graphite, annealed. The chemical composition of the material is given in Tab. 1. Size of the spherical graphite was approximately 15 µm. Tests were performed for the round solid specimens with the gauge diameter 6.5 mm and gauge length 8.9 mm. Specimens were machined for the testing.

Table 1: Chemical composition of Si-Mo cast iron.

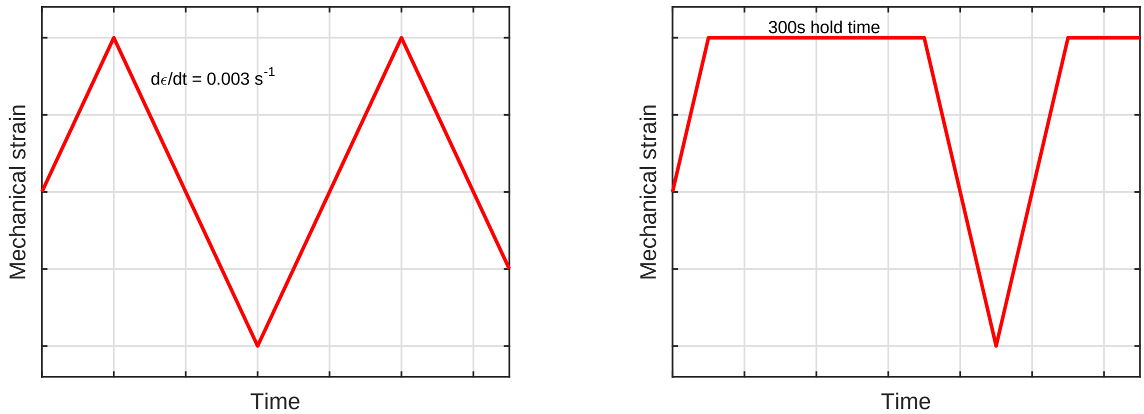
Si [%]	C [%]	Mo [%]	Mn [%]	Cr [%]	Cu [%]	Mg [%]	P [%]	Ni [%]	Al [%]
4.10	3.21	0.555	0.394	0.085	0.066	0.048	0.038	0.024	0.018

2.3 Test Conditions

Following uniaxial tests were performed on unnotched specimens

- isothermal LCF,
- (cyclic) relaxation tests,
- out of phase TMF tests.

All tests were attained as strain controlled. Isothermal LCF tests were carried out under ambient condition, extending the temperature from 20°C up to 750°C, as fully reversed (R_ϵ =-1), for the variable mechanical strain ranges $\Delta\epsilon$ from 0.005 to 0.02. Relaxation tests were performed as isothermal at 550°C, 650°C and 750°C for the strain range $\Delta\epsilon$= 0.012 with 300 s hold time in a tension, during which a creep behaviour is observed in the form of a relaxation. LCF and cyclic relaxation tests were performed with the constant strain rate, $\dot{\epsilon} = 0.003\ s^{-1}$, as a triangular and trapezoidal shape, respectively. The waveformes are presented in Fig. 4. The reason for the high strain rates, in the case of isothermal LCF, is to minimize creep effects.



(a) (b)

Figure 4: Strain-time paths for isothermal LCF (a) and relaxation tests (b).

Thermomechanical tests were performed with the minimum test temperature 100°C , maximum temperature varied from 550°C to 800°C, with no dwell periods. For the test between 100° and 650°, the heating phase lasted approximately 104 s, followed by the cooling on air, 240 s total time. The thermal strain was totally suppresed for these tests, so the total strain ϵ_t was kept constant. Total mechanical strain ϵ_m, according to the condition $\epsilon_t = \epsilon_{th} + \epsilon_m$, was then shifted against the thermal strain ϵ_{th} by 180° with amplitude equal to the thermal strain amplitude, Fig. 5. This kind of test is often called as out of phase TMF (OP-TMF).

3 Experimental Results

For the isothermal LCF tests, cyclic softening was observed for the temperatures higher than approximately 500°C, softening was more significant with the increasing temperature. On the other hand cyclic hardening was observed for the temperatures below 500°C. Specimens showed monotonically increasing durability in the high strange ranges with the increasing temperature. Decrease in the lifetime was observed with the increasing temperatures for the low strain range tests. Strain-life curves for the selected temperatures are presented in Fig. 12, where N_f are cycles to a failure, determined classically when a 10% drop in stress occured compared to the stabilized stress.

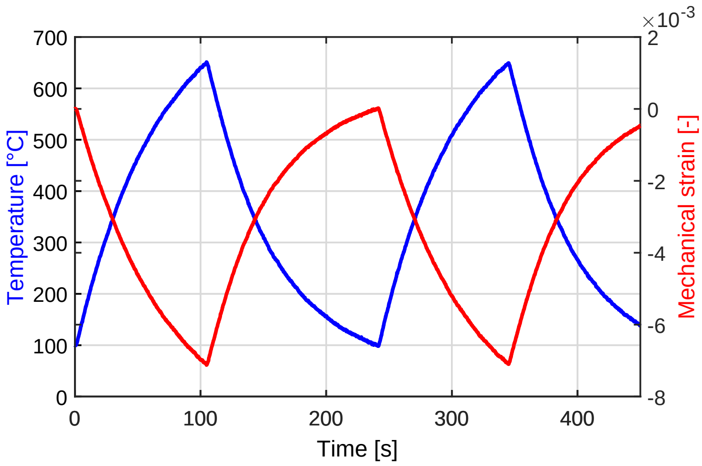


Figure 5: Temperature-, strain-time path for TMF test.

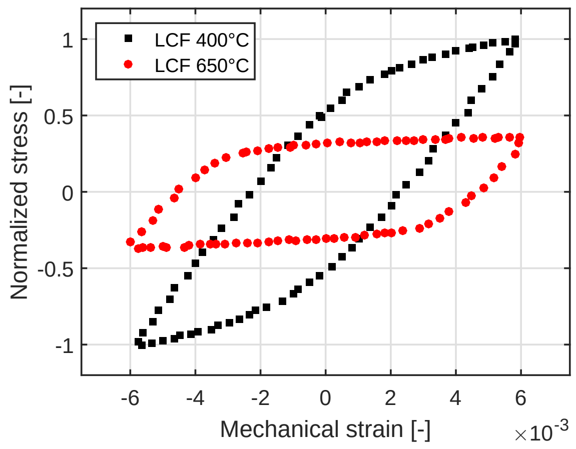


Figure 6: LCF at 400°C and 650° - stabilized hysteresis stress-strain loops.

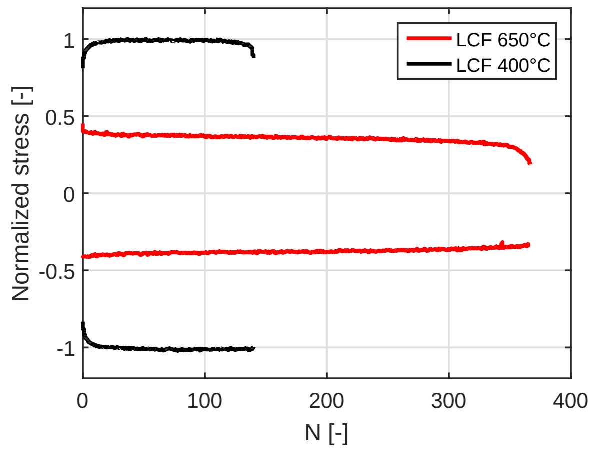


Figure 7: Maximum and minimum stress as a function of the number of cycles.

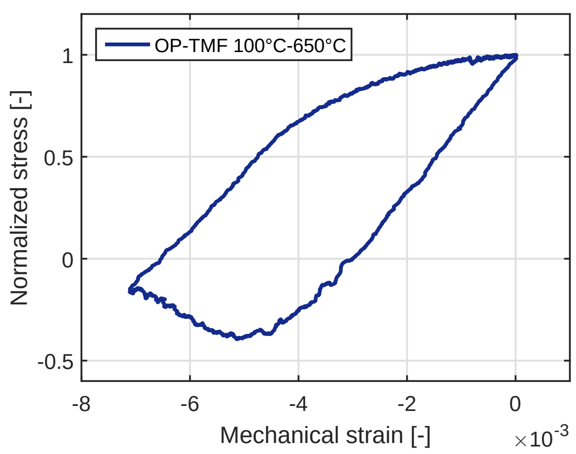


Figure 8: Out of phase TMF between 100°C and 650°C; hysteresis stress-strain loop.

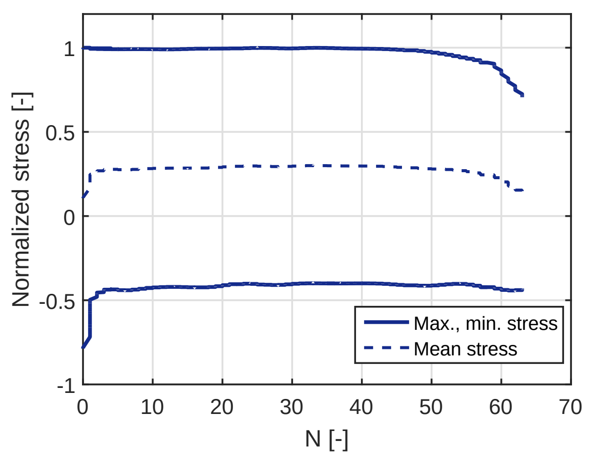


Figure 9: Maximum, minimum and mean stress as a function of the number of cycles.

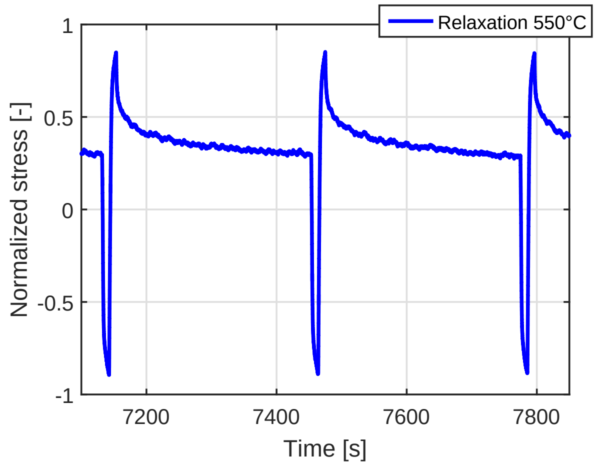


Figure 10: Cyclic relaxation test; 300s hold time in tension at 550°C.

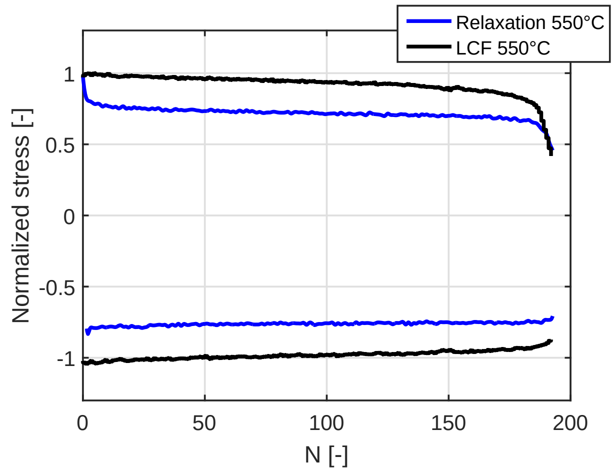


Figure 11: Maximum and minimum stress as a function of the number of cycles.

Fig. 6 presents the stabilized stress-strain hysteresis loops for the selected strain range $\Delta\epsilon$=0.012 at the temperature 400°C and 650°C, respectively. Maximum and minimum stress as a function of the number of cycles is for the selected LCF tests presented in Fig. 7. Mean stress is close to zero for the above mentioned tests.

Out of phase TMF test were conducted with the thermal strain equal to the negative total mechanical strain, this should represent extreme conditions, i.e. as a fully constrained material element during a heating and cooling down phases. Stabilized stress - strain hysteresis loop for the cycle between 100°C and 650°C is presented in Fig. 8. Maximum, mean and minimum stress as a function of cycles are shown in Fig. 9. TMF lifetime is drastically reduced compared to the isothermal LCF tests, one can note that this is due to the significant influence of the mean stress. Stabilization is achieved already after the first two cycles for the selected TMF test.

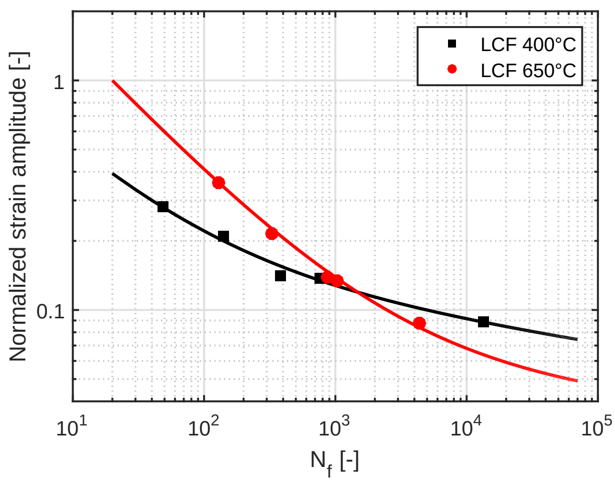


Figure 12: Manson-Coffin-Basquin curves at 400°C and 650°C.

Axial stress as a function of time for the cyclic relaxation test with 300 s hold time in a tension at 550°C is presented for the strain range $\Delta\epsilon$=0.012 in Fig. 10. One can see that more than 50% of the stress relaxes during the first tens of seconds during the hold time, this is even more significant for a higher temperature, at 750°C it is over the 70%. Fig. 11 presents the maximum and minimum stress as a function of the cycles, the test with the hold time is compared to the isothermal LCF without hold time for the same strain range and temperature. Interaction of the creep and plasticity [8, 9] is obvious, also resulting in the overall decrease in the stress amplitude for the test with the hold time compared with the LCF.

4 Conclusion

The obtained experimental data allow to calibrate and identify commonly used elastoplastic and/or viscoplastic material models [8, 9], mostly based on isothermal LCF data and verified on performed TMF tests.

The constructed TMF test stand compromises the capabilities and price. However, it's planned to install a cooling air jet to ensure the faster cooling and strain rate for TMF tests. As a contrary to the passive cooling, heating can be much faster than was shown.

For the specimens, a various life reduction has been observed depending on the selected strain range and temperature. Effect of the mean stress on the lifetime is significant for the out of phase TMF tests. Further, significant stress relaxation was shown for the specimens with the increasing temperature for the tests with the hold time in a tension. The material is experiencing a relatively strong time dependent effects above approximately 500°C. Interaction of creep and plasticity could be also observed in the form of the overall decrease in the stress amplitude for the cyclic relaxation test compared with the LCF test without hold time. More TMF tests with different temperature/mechanical strain phase and LCF tests at different strain rates are planned for the silicon-molybdenum cast iron.

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