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EFFECT OF STRAIN RANGE AND HOLD TIME ON HIGH TEMPERATURE FATIGUE LIFE OF G17CrMoV5-10 CAST ALLOY STEEL

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Abstract

In this work, cast steel G17CrMoV5-10 was investigated. The material subject to investigation as part of this study is commonly used to manufacture steam turbine casings. Modern steam turbines operate under elevated temperature and complex oscillated loads. Thus, the focus of this study was to investigate material under behavior during low cycle fatigue (LCF) test performance at 500°C with and without hold time in tension. During all types of test, cyclic softening of cast steel was noticed. Increasing of total strain rate and applying hold time significantly reduce fatigue life. During hold time, due to temperature and tension the material creep what is confirmed by increasing inelastic stain accommodation.

Keywords: fatigue, LCF, hold time, strain, steam turbine
Article category: research article

Introduction

A steadily increasing demand for energy is noticed these days, and since it is reasonable to expect the same trend to continue in the near future, a need is felt for a mechanism that would ensure continuous improvement in the lifetime and safety of energy systems (Golaski, 2019). Conventional power electricity energy production requires diversification with other sources due to depletion of natural resources and ecological aspects such as CO_2 emission. Current turbomachinery components need to be redesigned to meet new requirements that have arisen as a result of challenging market conditions, which have emerged in the recent past. Hence, the materials constituting the components of the turbines should be carefully assessed. It is necessary to check their capacity for new applications in renewable energy, particularly in concentrated solar power plants. The number of turbine start–stop cycles depends on the time of day and night and is more frequent than in conventional turbine applications in a coal power plant. (Holdsworth, 2001; El May, Saintier, Devos, & Rozinoer, 2015; Millien, 2020)

In this work, the characterization of cast steel G17CrMoV5-10 has been performed. This material is commonly used to manufacture turbine casing (Golaski, 2019). However, for new applications in renewable energy generation, despite there being an insufficiency in the design data, the material characterization has still been carried out. Performing fatigue tests under load allows us to obtain an introduction to the analysis of material behavior under complex states of stress, especially under scenarios in which new machine applications that involve frequent start–stop cycles are simultaneously considered. The mechanical test of main attention is low cycle fatigue (LCF). The tests were performed at an elevated temperature of 500°C. Trials were carried out on large-diameter cylindrical samples with and without hold time. Then analysis and visualization were carried out of all recorded data to demonstrate the material behavior during ongoing cycles, as well as to ascertain the response of the material during tension and compression that would enable the assumed total strain to be realized with and without hold time.

Material

G17CrMoV5-10 cast steel complying with EN 10213 (Steel Castings for Pressure Purposes, 2016) was tested. Chemical composition was measured using an optical emission spectrometer (OES) and a carbon and sulfur analyzer (quantitative technique), and the measurements are shown in Table 1. The test material was manufactured by sand casting in cylinders of 30-mm diameter. The material was subject to heat treatment as follows:

- hardening at 960°C/5 h/AC; and
- tempering 736°C/5 h/AC.

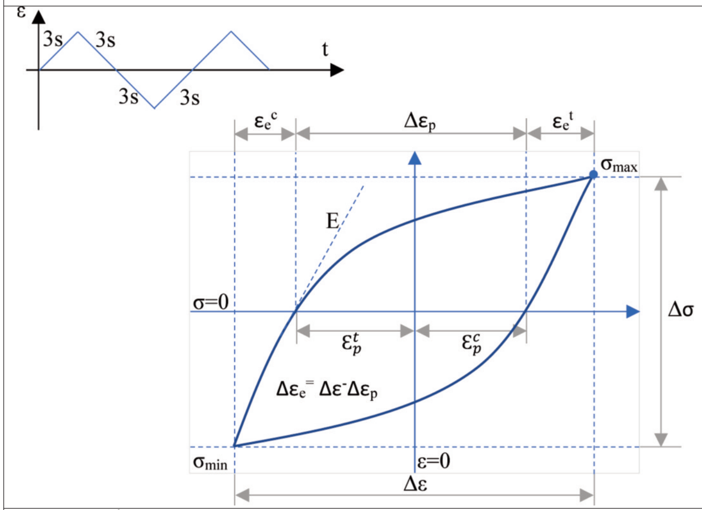
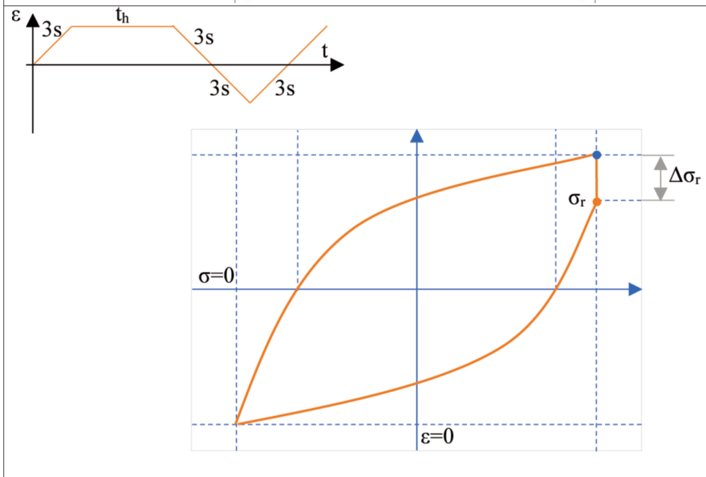
Table 1. Steel G17CrMoV5-10 chemical composition for cast.

Element	**C**	**Si**	**Mn**	**P**	**S**	**Ni**	**Cr**	**Mo**	**V**	**Cu**	**Sn**
wt.%	0.19	0.4	0.9	0.014	0.011	0.08	1.44	1.04	0.2	0.30	0.001

Experimental Procedure

A full reverse stain-controlled fatigue test according to ASTM E606 (Standard Test Method for Strain-Controlled Fatigue Testing, 2008) was prepared. The test settings matrix used is presented in Table 2. Cylindrical samples with 8-mm diameter in the gauge section have been used. The tests were performed at 500°C for a total of two strains — 0.4% and 0.6%. Constant triangular waveform of the load cycle was applied when no hold time was introduced, while trapezoidal waveform was applied with imposed hold times of 120 s.

Table 2. LCF fatigue test matrix.

<table>
<tr><td>Temperature, T (°C)</td><td>500</td><td rowspan="3">Hold time, t_h (s)</td><td rowspan="3">Frequency, (Hz)</td><td rowspan="3">Total strain, $\Delta\varepsilon$ (%)</td></tr>
<tr><td>Strain ratio, $R=\frac{\varepsilon_{max}}{\varepsilon_{min}}$</td><td>-1</td></tr>
<tr><td colspan="2">Cycle scheme</td></tr>
<tr><td colspan="2" rowspan="2">
</td><td rowspan="2">0</td><td rowspan="2">0.08</td><td>0.4</td></tr>
<tr><td>0.6</td></tr>
<tr><td colspan="2" rowspan="2">
</td><td rowspan="2">120</td><td rowspan="2">0.008</td><td>0.4</td></tr>
<tr><td>0.6</td></tr>
</table>

LCF, low cycle fatigue.

Results and Discussion

Due to the large amount of test data, recorded throughout all LCF tests, three hysteresis loops for each case were analyzed, as shown in Figure 1. The curves show the stress–strain responses for selected cycles: beginning of life (100%), middle-life (50%), and end-of-life (0%). The envelope field of the loop is proportional to the energy irreversibly dispersed in the material (Kocańda, 1985; Carroll & Carroll, 2011; Alsmadi, Alomari, Kumar & Murty, 2020). For total strain 0.6%, the greater energy share is visible, observed with respect to the loops obtained for 0.4% of total strain. For added hold time 120 s, the behavior is similar: the area of the hysteresis loop field is increasing compared to loops without hold time. Introduction of hold time at tension causes a decline of maximum stresses during the lifetime of the cycle. The distribution of maximum stresses is presented in Figure 2. Cyclic softening of the material is noticed for all types of tests. Material softening is higher for curves with hold time.

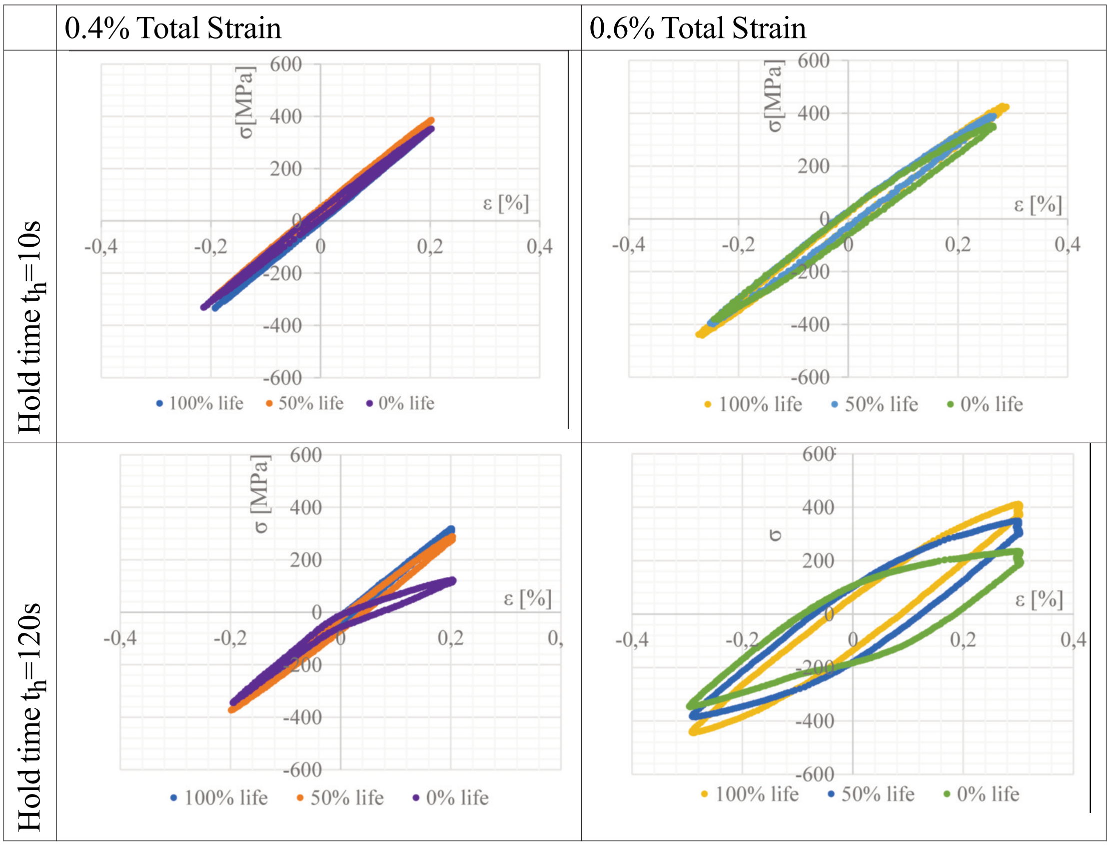


Figure 1. Hysteresis loop of the LCF test shown for 100%, 50%, and 0% of life. LCF, low cycle fatigue.

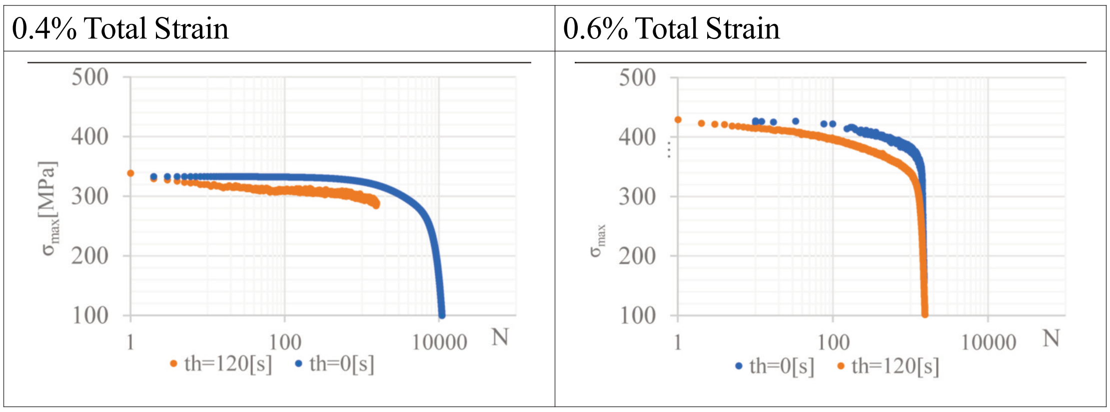


Figure 2. Maximum stresses.

The fatigue life — number of cycles to failure N_f — is shown in Figure 3. Both total strain range and hold time contribute to significant reduction of fatigue life. Increasing total strain range from 0.4% to 0.6% without hold time causes a drop of fatigue life to 85%, and with added hold, to 58%. Hold time reduces 70% of fatigue life for total stain 0.4% and 17% for 0.6%.

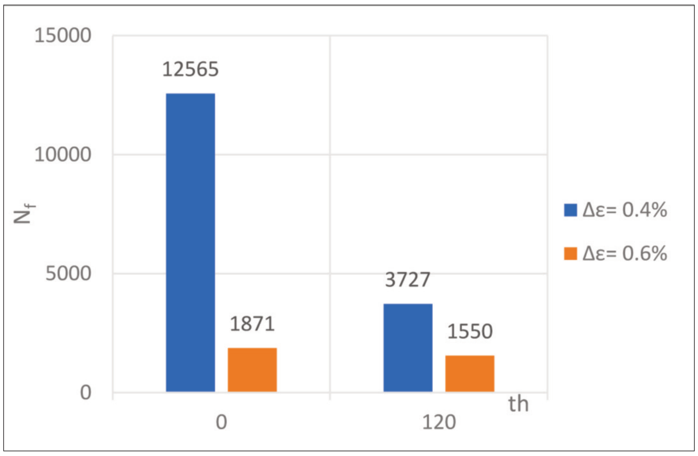


Figure 3. Fatigue life for 0.4% and 0.6% $\Delta\varepsilon$ total stain.

No impact of test condition on modulus of elasticity E was noticed. The average value was 169 GPa. Stress relaxation occurs during the tensile hold time presented in Figure 4. A similar drop 60% was observed for both test conditions.

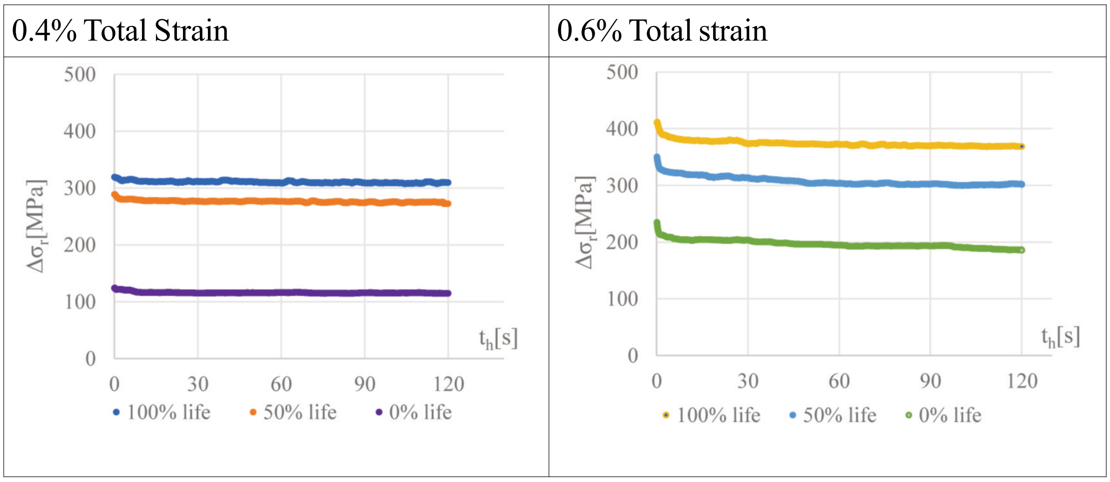


Figure 4. Stress relaxation during hold time, t_h = 120 s.

The contribution of total inelastic strain $\Delta\mathcal{E}_p$ and elastic $\Delta\mathcal{E}_e$ (Kuhn & Medlin, 2000) has been calculated, as indicated in Figure 5. The value of $\Delta\mathcal{E}_p$ increases during material fatigue life, higher of 0.6% of total strain and with added hold time. This behavior suggests the occurrence of creep damage at test temperatures under relaxation stress on tension. Stresses were relaxed during the hold time under strain-controlled creep-fatigue tests, as presented in Figure 4, from σ_{max} to σ_r. Creep damage occurs, which is indicated by stress reduction. A similar observation is recorded in the literature (Takahashi, 2008; Carroll & Carroll, 2011; Alsmadi et al., 2020)

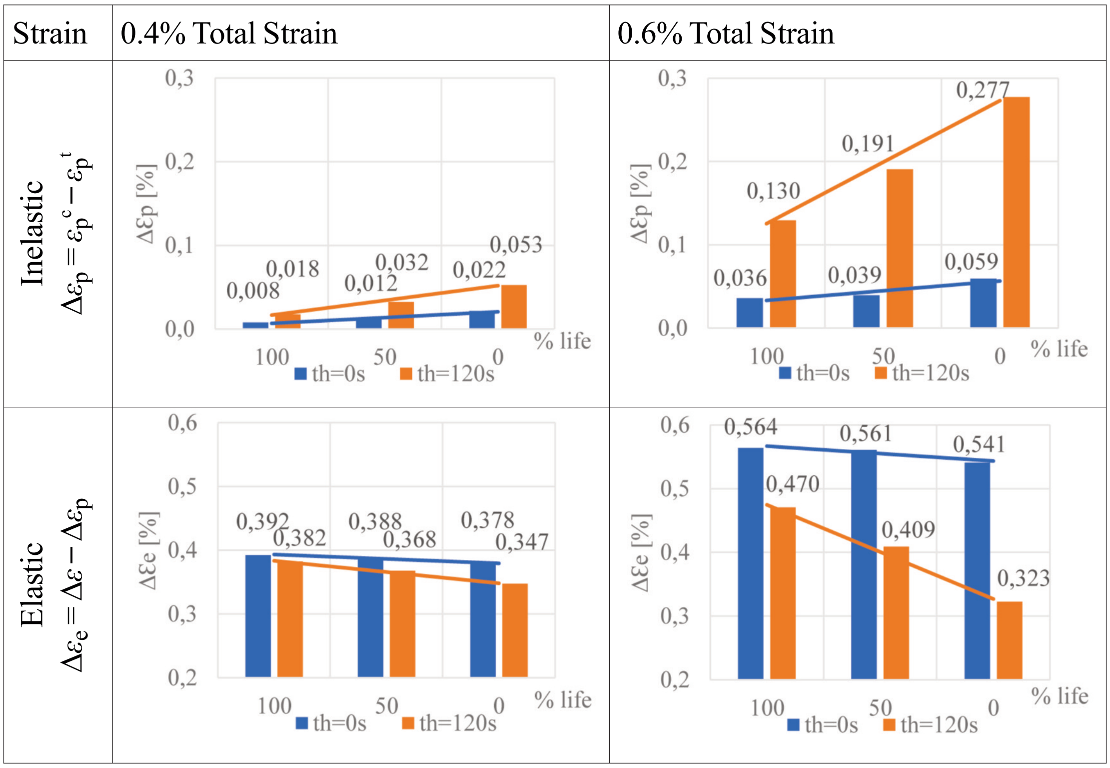


Figure 5. Strain during tests for 0.4% and 0.6% of total strain.

Additionally, as is shown in Figure 6, hold time causes increasing of the mean stress—it becomes compressive for the material (Takahashi, 2008). Compressive stresses can be considered as recovery of creep caused by tensile (Swindeman & Ren, 2018). Higher levels of compressive stresses were observed for 0.4% of total strain, which is another factor that explains the longer life in comparison with 0.6% of total strain.

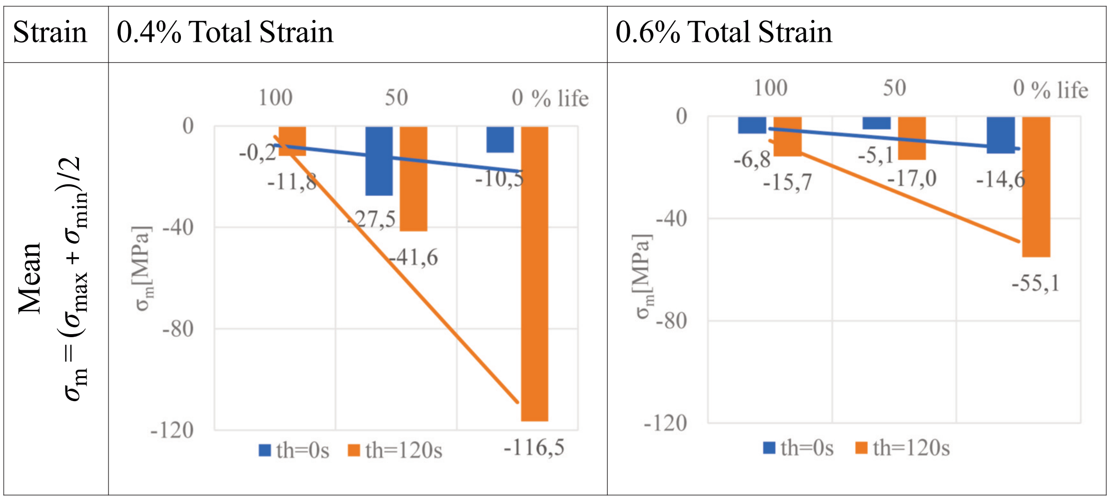


Figure 6. Alternating and mean stresses for 0.4% and 0.6% of total strain.

Conclusions

This study has led to the following conclusions:

1. Increasing total strain with application of hold time during tension resulted in a decrease of fatigue life of G17CrMoV5-10 cast steel.
2. Cyclic material softening behavior was noticed for all types of test conditions.
3. Fatigue tests with hold time showed occurrence of permanent deformations in the material during the life cycle, caused by cyclic creep.

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