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Engineering models for softening and relaxation of Gr. 91 steel in creep-fatigue conditions

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Abstract

Purpose – There are a number of different approaches for calculating creep-fatigue (CF) damage for design, such as the French nuclear code RCC-MRx, the American ASME III NH and the British R5 assessment code. To acquire estimates for the CF damage, that are not overly conservative, both the cyclic material softening/hardening and the potential changes in relaxation behavior have to be considered. The data presented here and models are an initial glimpse of the ongoing European FP7 project MATISSE effort to model the softening and relaxation behavior of Grade 91 steel under CF loading. The resulting models are used for calculating the relaxed stress at arbitrary location in the material cyclic softening curve. The initial test results show that softening of the material is not always detrimental. The initial model development and the pre-assessment of the MATISSE data show that the relaxed stress can be robustly predicted with hold time, strain range and the cyclic life fraction as the main input parameters. The paper aims to discuss these issues.
Design/methodology/approach – Engineering models have been developed for predicting cyclic softening and relaxation for Gr. 91 steel at 550 and 600°C.
Findings – A simple engineering model can adequately predict the low cycle fatigue (LCF) and CF softening rates of Gr. 91 steel. Also a simple relaxation model was successfully defined for predicting relaxed stress of both virgin and cyclically softened material.
Research limitations/implications – The data are not yet complete and the models will be updated when the complete set of data in the MATISSE project is available.
Practical implications – The models described can be used for predicting P91 material softening in an arbitrary location (n/N_{f0}) of the LCF and CF cyclic life. Also the relaxed stress in the softened material can be estimated.
Originality/value – The models are simple in nature but are able to estimate both material softening and relaxation in arbitrary location of the softening curve. This is the first time the Wilshire methodology has been applied on cyclic relaxation data.

Keywords Relaxation, Creep-fatigue, Cyclic softening, Gr. 91 steel

Paper type Research paper

Introduction

The design of the European GEN-IV reactors, i.e. ASTRID (sodium fast reactor) and MYRRHA (lead-cooled fast reactor) will rely on the French design RCC-MRx Code (2012). The operating temperatures for some of the components will be within the lower region of

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the creep regime or just below negligible creep temperatures resulting in potential creep and creep-fatigue (CF) damage accumulation. In the MATISSE project, the assessment and modeling methodologies for determining softening, relaxation and CF damage are developed for the cyclically softening P91 ferritic/martensitic steel. The interaction diagram methodology based on different approaches for creep damage in RCC-MRx, ASME III NH (ASME Boiler and Pressure Vessel Code, 2008) and R5 (2003) exhibits different challenges for the assessment of CF data. The P91 steel is still considered a key material for some of the future GEN-IV concept even though it has been replaced in ASTRD by other materials such as Alloy 800 and 316L and 316L(N) due to the challenges caused by the material softening. Thus, the P91 steel has for the time being been moved to the probationary phase rules in the RCC-MRx code.

In this paper, low cycle fatigue (LCF), CF and creep relaxation data of the ongoing European FP7 project MATISSE are assessed together with earlier data from the MATTER project (Pohja, Holmström, Nilsson, Payten, Lee and Aktaa, 2014; Pohja *et al.*, 2016; Holmström, Pohja and Payten, 2014). Some MATISSE results by KIT have recently been published in Führer and Aktaa (2016).

Both an engineering softening model and a relaxation model are constructed based on the currently available data. The impact of hold time, strain range, temperature and cyclic life fraction on softening and relaxation behavior is studied and compared with literature (Fournier *et al.*, 2008, 2009; Asayama and Tachibana, 2007; Takahashi, 2012).

Materials and methods

Materials

In the MATISSE project, two heats of Grade 91 steels are being tested. These steels were also tested in the previous FP7 project MATTER. The chemical compositions are given in Table I.

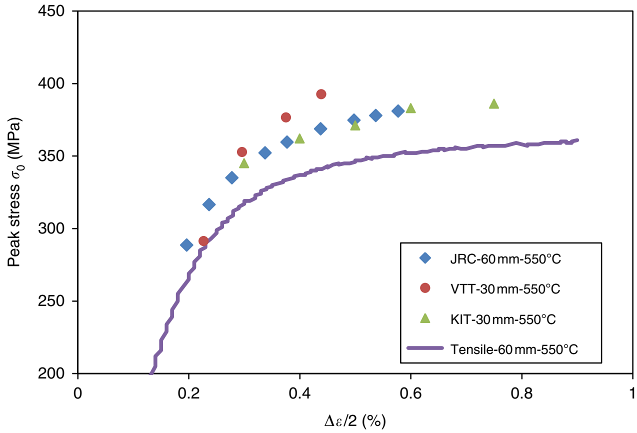
The thicker P91 heat (MATTER-I) is a 60 mm thick plate from ArcelorMittal. This heat is tested in "as received" condition, i.e. austenitization at 1,060°C for 4 h, quenching and tempered at 760°C for 3 h and 20 min. All JRC and REZ tests have been conducted on this material heat. The thinner 30 mm thick P91 sheet (MATTER-II) has undergone a heat treatment consisting of austenitization at 1,050°C during 30 min, quenched and tempered at 780°C during 1 h. All tests by KIT and VTT have been conducted with this material heat.

The 30 mm plate virgin material has a somewhat higher strength than the 60 mm plate at 550°C as can be deducted from Figure 1. The figure also shows that both P91 steel heats are

Element	MATTER-I	MATTER-II
C	0.12	0.086
Cr	8.32	8.91
Mo	1.02	0.917
V	0.235	0.198
Nb	0.084	0.08
Mn	0.41	0.365
Si	0.24	0.324
N	0.041	0.041
Al	0.006	0.018
Ni	0.1	0.149
P	0.009	0.017
S	0.001	0.001

Source: Pohja *et al.* (2016)

Table I. Chemical composition wt % of the studied MATTER P91 heats



Notes: It is to be noted that the strain rate is 0.167%/min for the KIT LCF tests (30 mm plate), 6%/min for both the JRC (60 mm plate) (de Haan, 2014a) and the VTT LCF tests (30 mm plate) (Pohja, Nurmela and Moilanen, 2014). The strain rate is 0.3%/min for the tensile tests (de Haan, 2014b)

Figure 1.
The LCF stress-strain response measured during the first one-fourth cycle (virgin) at specified strain in comparison to the tensile test curve of the thicker material

strain rate sensitive. The corresponding small differences in yield strength and strain hardening of the materials will affect the peak stresses at the specified test strain ranges and therefore also the relaxed stresses.

Testing

In MATISSE, several test types are included in the test program with the main objective of determining the softening response of P91 as a result of combined creep and fatigue.

The LCF and CF test program of MATISSE is given in Table II. The standard LCF tests in strain control, shown in Figure 2, are used as base for studying the material softening behavior. Creep relaxation periods, i.e. hold times (t_h) applied at the specified strain maximums, tension, compression or both. Both tests with hold times in every cycle (CF, as shown in Figure 3) and tests with combined LCF cycling and holds in specific locations of the softening are studied. Applying long hold times up to 72 h, in selected LCF cycles allows for studying long-term relaxation behavior of softened material. It would not be possible to reach the same level of softening in reasonable testing times if the same hold time would be applied in every cycle.

Table II.
Test laboratory-specific tests types and strain ranges for determining cyclic softening

Organization/Lab	Test type (plate)	Total strain range	Temperature	Hold time (min and h)	Hold position
KIT (Führer and Aktaa, 2016)	LCF/CF (30 mm)	0.6%, 0.8%, 1%, 1.2%, 1.5%	550°C	0, 1 min, 10 min, 1 h, and 3 h	Tension, compression, both
VTT	LCF/CF (30 mm)	0.5%, 0.7%, 0.9%	600°C	intermediate 24 and 72 h holds	Tension
JRC	LCF/CF/CF$_m$ (60 mm)	0.5%, 0.7%	550, 600°C	intermediate 72 h holds	Tension
REZ	CF (60 mm)	0.9%, 0.7%, 0.5%	600°C	1 and 12 h holds	Tension

Test results and model fitting

LCF and CF tests at 550°C

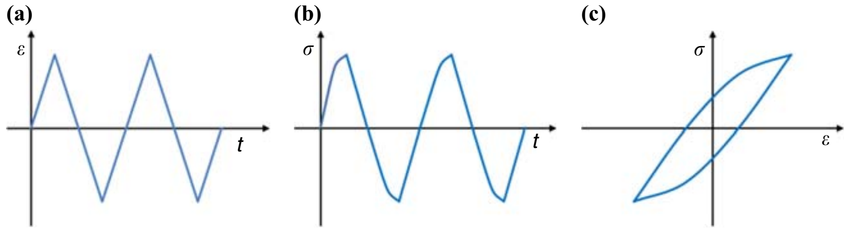
Isothermal LCF tests as well as CF tests were performed on specimen from the 30 mm plate (MATTER-II) at 550°C with strain amplitudes ranging from ±0.3 to ±0.75 percent. The strain rate applied was 10^{-3}/sec (0.167%/min). The characterization of the influence of hold time on cyclic softening was the main objective of this test series. The experimental results have been previously published and discussed in (Führer and Aktaa, 2016) and the main observations used for model development are summarized below.

In Figure 4, the peak stresses of a LCF test are compared to CF tests with a hold time. The hold times are of equal duration and performed in tension, compression and in both tension and compression. First, although softening behavior varies between different heats of P91, it is repeatable for samples of the same heat as shown by identical peak stresses for repeated LCF tests. Second, tensile peak stresses are reduced due to tensile hold time whereas compressive peak stresses are reduced due to compressive hold time. Combined hold times under tension and compression lead to lower stresses under tension as well as compression, notably further reducing the stress range compared to single sided hold times.

The influence of hold time duration on the softening rate is shown in Figure 5. For hold times up to 1 h, a longer hold time will cause a lower peak stresses. For hold times longer than 1 h, there is no additional decrease of peak stresses. Interestingly, increasing the hold time from 1 to 3 h significantly reduced number of cycles to failure (N_f) by almost a factor of 2, whereas tensile hold times up to 1 h only slightly decreased cyclic life.

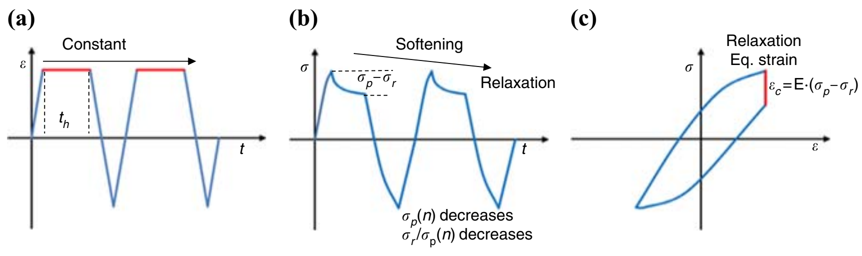
The impact of hold times on softening was investigated at different strain amplitudes. As seen in Figure 6, the softening is significantly more pronounced at smaller strain amplitudes.

Lastly, in Figure 7, the peak stresses and relaxed stresses for CF tests with a ±0.75 percent strain amplitude and a hold time of $t_h = 1$ h are presented. It is shown that



Notes: (a) Strain-time plot; (b) stress-time plot; (c) stress-strain plot

Figure 2. The strain controlled low cycle fatigue (LCF) test with $R = -1$



Notes: (a) Strain-time plot; (b) stress-time plot; (c) stress-strain plot

Figure 3. The strain controlled creep-fatigue (CF) test with $R = -1$, hold in tension

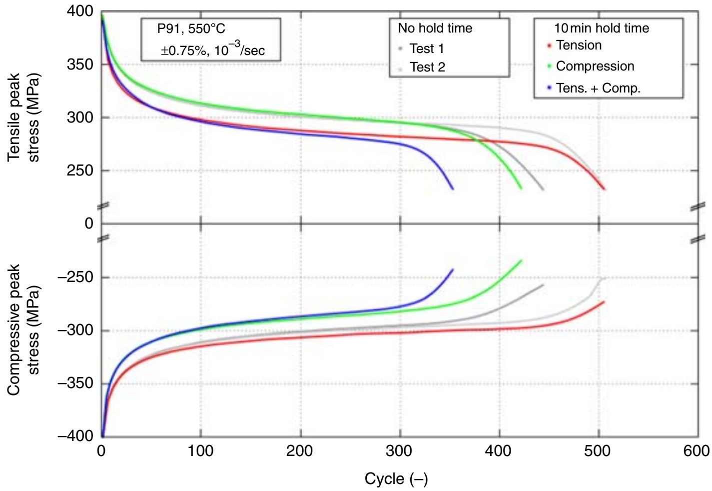


Figure 4.
Influence of hold time position on cyclic softening for ±0.75 percent strain amplitude and hold time of $t_h = 10$ min

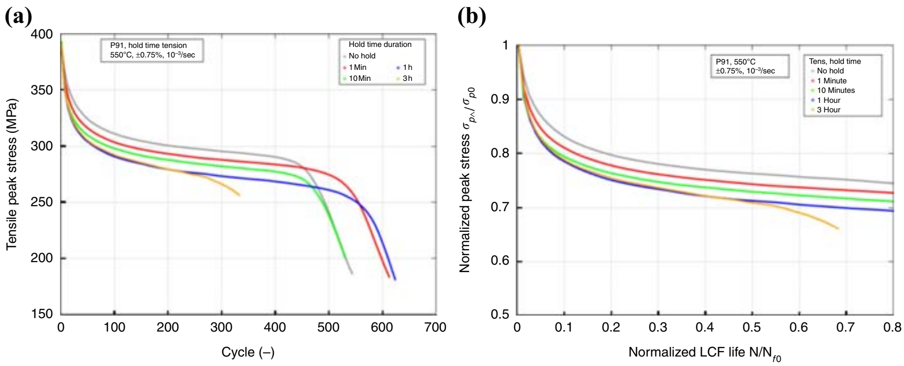


Figure 5.
CF softening in comparison LCF softening

Notes: (a) Softening curves for total strain range $\Delta\varepsilon$=1.5% for LCF and CF tests (R=–1) with hold in tension for t_h=1 min, 10 min, 1 h and 3 h (Führer and Aktaa, 2016); (b) normalized softening curves

cyclic softening not only affects peak stresses but also the amount of stress relaxation. The relaxed stress seems to drop to a nearly constant amount of relaxation after about 20 percent of the cyclic life. In absolute values, the relaxed stresses for tensile and compressive hold times are similar. On the other hand, combined hold times under tension and compression show a larger amount of stress relaxation than single sided hold times of same duration.

Based on these experimental observations, an engineering model for prediction of peak stresses and relaxation was developed.

CF tests with long relaxation periods

The current JRC data on virgin material relaxations for 0.25 and 0.35 percent strain at 550 and 600°C, with a maximum hold time of 39 days for one of the 550°C tests, are

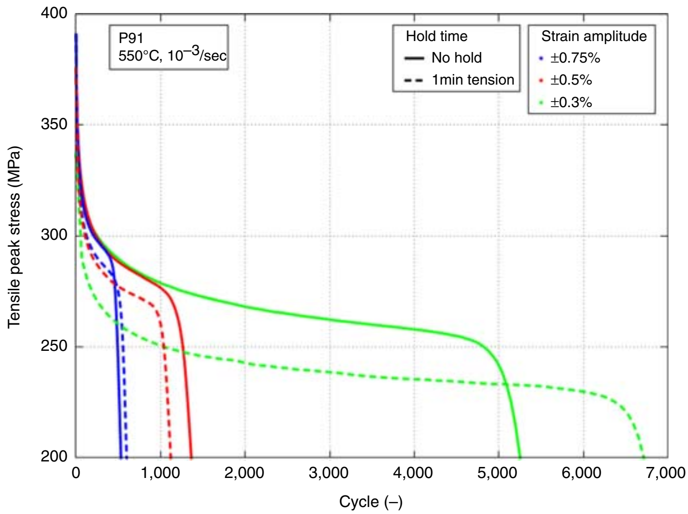


Figure 6.
LCF and CF test softening curves for tests at $\Delta\varepsilon = 0.6\text{-}1.5$ with a hold time of $t_h = 1$ min

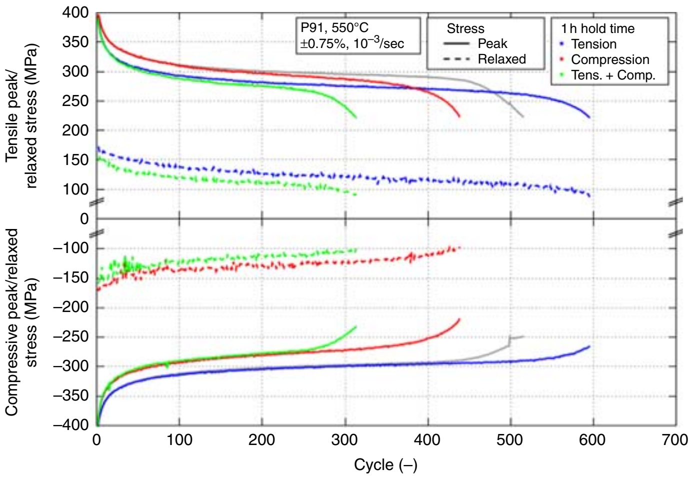


Figure 7.
Peak stresses and relaxed stresses for ±0.75 percent strain amplitude and hold time of $t_h = 1$ h

shown in Figure 8. A relaxation curve at the end of cyclic life is compared to a virgin material curve in Figure 9.

For the relaxation modeling, a simplified data set is constructed from the raw data by extracting the relaxed stress at 0.01, 0.1, 0.3, 1, 3, 12, 24 and 72 h of relaxation.

Modeling

In the model equations, the unit of stress is MPa, for time hours, stain in mm/mm and the cycles are naturally counted in whole numbers.

Models for LCF and CF softening

It can be shown that the softening rate of LCF tests as a function of normalized cycles is well presented by the following equation. The chosen softening (decay) function is inspired from

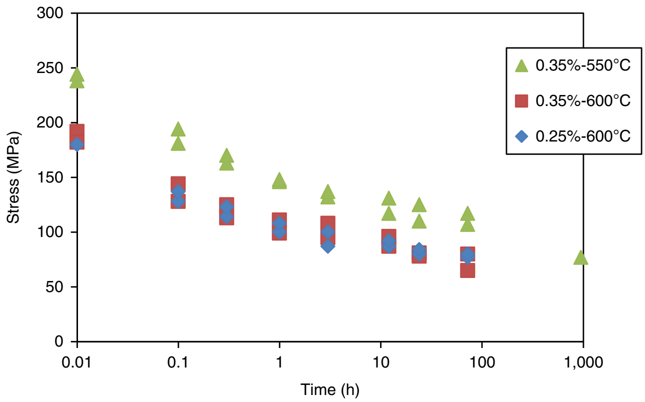


Figure 8.
Relaxation curves for 72 h hold times for virgin material tested at 0.25 and 0.35 percent tensile strain at 600 and 550°C

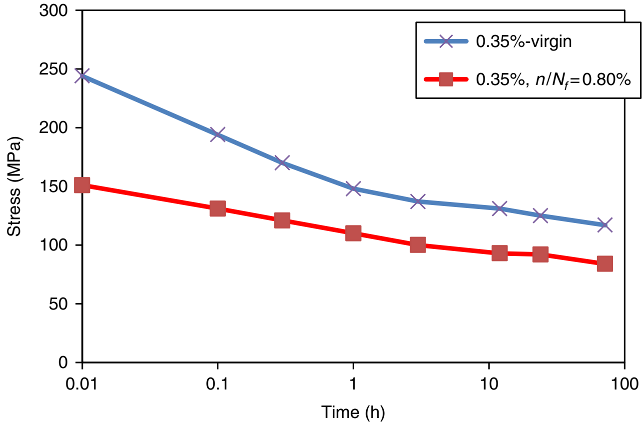


Figure 9.
Relaxation curves for softened material $\Delta\varepsilon/2 = 0.35$ percent, 550°C with tensile hold in virgin state and in end of cyclic life ($n/N_f = 80$ percent) in comparison to virgin material

the Manson-Halford equation for CF cyclic life (Manson, 1968):

$$\frac{\sigma_{pn-LCF}}{\sigma_{p0}} = A_1 + \frac{A_2}{A_3 + (N/N_{f0})} \tag{1}$$

The cyclic peak stress (MPa) at cycle n is then simply $\sigma_{pn-\mathrm{LCF}} = f(n/N_f)\cdot\sigma_{p0}(\Delta\varepsilon, T)$, where σ_{p0} is the virgin material peak stress (one-fourth cycle) at the specified strain and temperature. The parameter A_1 is describing the lower bound of softening and the parameters A_2 and A_3 influence the rate of softening. The function is optimized in the n/N_{f0} range 0-80 percent, where n is the cycle number and N_{f0} is the number of cycles to failure in a LCF test at the specified strain and temperature. The initial parameter values, acquired for the softening model using data for both the MATTER materials, are given in Table III and the fit to the measured LCF softening curves is shown in Figure 10.

It can also be shown that when hold times (t_h) are introduced, the softening rate is increased. The effect of hold time is intuitively (at least partly) explained by an increased plastic strain range caused by the relaxing stress where elastic strain is converted into plastic strain.

In the case of CF tests with hold times, the softening rate can be corrected by introducing two correction factors as given in Equation (2) where $P_1 = f(t_h)$ and $P_2 = f(\Delta\varepsilon)$. The chosen functions for the t_h and $\Delta\varepsilon$ dependence are given in Equations (3) and (4). The corresponding initial fitting parameters are given in Table IV.

The final form of the correction factors P_1 and P_2 still need to be further optimized with a wider range of strains and hold times expected to be available at the end of the MATISSE project:

$$\frac{\sigma_{pn}}{\sigma_{p0}} = P_1 \cdot P_2 \frac{\sigma_{pn-\mathrm{LCF}}}{\sigma_{p0}} \tag{2}$$

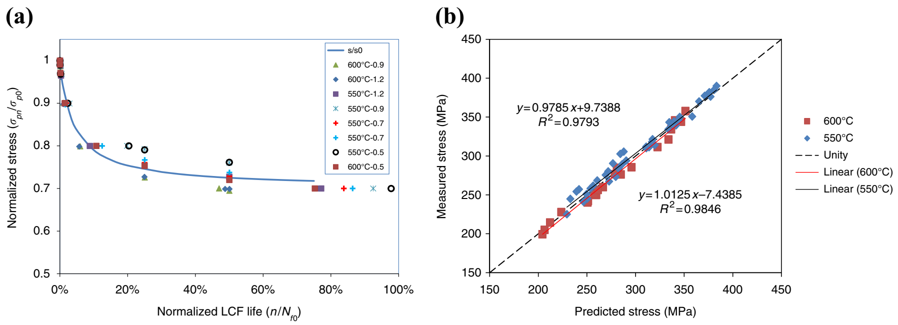
$$P_1(t_h) = B_1 + B_2 \cdot \log(t_h) \tag{3}$$

$$P_2(\Delta\varepsilon) = C_1 + C_2 \cdot \frac{1}{\Delta\varepsilon} \tag{4}$$

With these equations in placed the hold time and strain range dependent peak stress in an arbitrary location of the softening curve (0-80 percent) can now be predicted as $\sigma_{pn} = f(\Delta\varepsilon) \cdot f(t_h) \cdot f(N/N_f) \cdot \sigma_{p0}$.

Table III. Initial fitting values for the LCF softening model (Equation (1))

Parameters	LCF softening (Equation (1))
A_1	0.70170
A_2	0.01276
A_3	0.04441



Notes: (a) Model (blue line) for LCF softened material at 550 and 600°C; (b) predicted vs measured peak stresses at specified n/N_f

Figure 10. Softening curve for LCF tested material and predicted peak stresses at specified cyclic life ratio

Table IV. Initial fitting values for the CF softening model (Equations (3) and (4))

	Parameters	
CF softening t_h correction (Equation (3))	$B_1 = 0.94$	$B_2 = -0.02$
CF softening $\Delta\varepsilon$ correction (Equation (4))	$C_1 = 1.025$	$C_2 = -0.067$

To test the model on data that have not been a part of the fitting data set the model was applied on two additional tests. The predicted vs measured peak stress at the beginning and in the middle of the cyclic life is shown in Figure 1(a) for the KIT test with a hold time of 3 h and cycled at a total strain range of 1.5 percent. Note that the data are presented as a function of normalized (LCF) cyclic endurance. In Figure 11(b), the initial 70 cycles of a REZ test with a hold time of 1 h cycled at a total strain range of 0.5 percent are presented as a function of cycles. The model prediction for the high strain range test seems to be good throughout the softening curve. For the low strain range test, the measured softening rate is faster than the predicted one, especially in the initial cycles. However, even for this test the predicted rate of softening (slope) seems to match.

Model for relaxation

The relaxation curve from an arbitrary location in the softening curve can be fitted to a Wilshire model (WE) (Wilshire *et al.*, 2009) modified for use with relaxation data. The model was chosen since it has been applied successfully in a European Creep Collaborative Committee round-robin on long-term (static) relaxation modeling (Holmström, Pohja, Auerkari, Friedmann, Klenk, Leibing, Buhl, Spindler, and Riva, 2014). The WE stress-time behavior during the hold period is given in the following equation:

$$\frac{\sigma_{rn}}{\sigma_{ref}} = \exp\left(-k\left(t_{rel}\cdot\exp\left(\frac{-Q}{R\cdot T}\right)\right)^{u}\right) \tag{5}$$

where t_{rel} is the relaxed time (h), u and k are fitting factors and Q is the activation energy (J/mol) optimized on the relaxation data and R is the gas constant (8.314 J/molK). The normalizing reference stress σ_{ref} (MPa) is based on the ultimate tensile strength R_m at temperature T (Kelvin). The σ_{ref} $(\Delta\varepsilon,\, t_h) = R_m\,(T)$ for the virgin material and no hold time and a strain range of 0.7 percent. The reference stress is corrected as given in the following equation for both virgin and cyclically softened material. Note that two separate models may be needed when more data are available:

$$\sigma_{ref} = \frac{R_m(T)}{P_0\cdot P_1}\cdot P_2 \tag{6}$$

The parameter P_0 is the LCF softening ratio calculated from Equation (1) and P_1 is the parameter giving the effect of hold time as in Equation (3) and P_2 as in Equation (4).

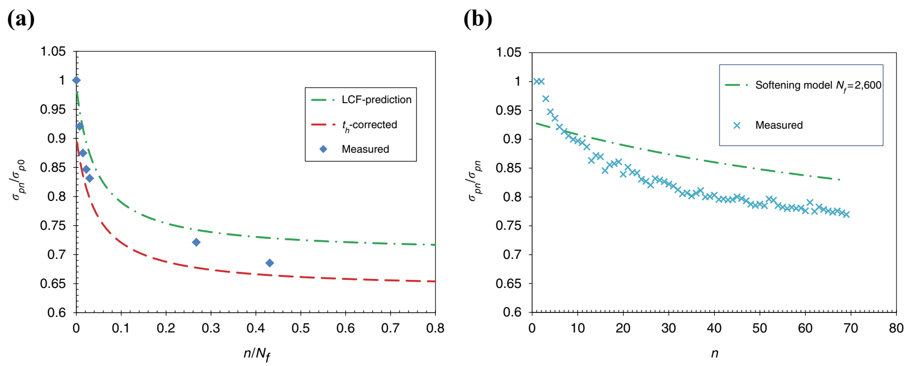


Figure 11.
Measured and predicted peak stresses for CF tests

Notes: If the normalization is done by true cyclic endurance then the hold time corrections should not be applied. (a) 3 *h* hold, D*e*=1.5 percent, 550°C; (b) 1 *h* hold, D*e*=0.5 percent, 600°C

By rearranging Equation (5), the time to acquire a specified level of relaxation can be calculated as given in Equation (7). And the relaxed stress as a function of peak stress, hold time and temperature as given in Equation (8):

$$t_{rel} = \left(\frac{\ln(\sigma_{rn}/\sigma_{ref})}{-k}\right)^{1/u} \cdot \exp\left(\frac{Q}{R \cdot T}\right) \tag{7}$$

$$\sigma_{rn} = \exp\left(\ln(\sigma_{ref}) - k\left(t_{rel} \cdot \exp\left(\frac{-Q}{R \cdot T}\right)\right)^{u}\right) \tag{8}$$

Note that since the WE relaxation model is divided into two stress regions the u and k parameters have to be chosen accordingly.

The initial fitting parameters for the relaxation model are given in Table V and the resulting predicted vs measured relaxed stresses are presented in Figure 12.

To test the relaxation model on data that have not been a part of the fitting data set the model was applied on two relaxation curves from literature. In Figure 13, the relaxation test by Takahashi (2012) is plotted against the above described model. In Figure 14, a test curve from a JAEA report (Asayama and Tachibana, 2007) is predicted. The JAEA curve fits well if the reference stress is increased by 15 percent. This difference can be directly related to differences in peak stress since the applied model is based on rather low strength material heats. The fit for the Takahashi case is matching the measured behavior if the reference stress is increased by 5 percent.

Parameters	$\sigma/\sigma_{ref} \geqslant 0.35$	$\sigma/\sigma_{ref} < 0.35$
All data		
k	55.554	0.1478
u	6.9512	0.07088
Note: $Q = 180$ kJ/mol		

Table V. Initial fitting values for the WE relaxation model (Equation (5))

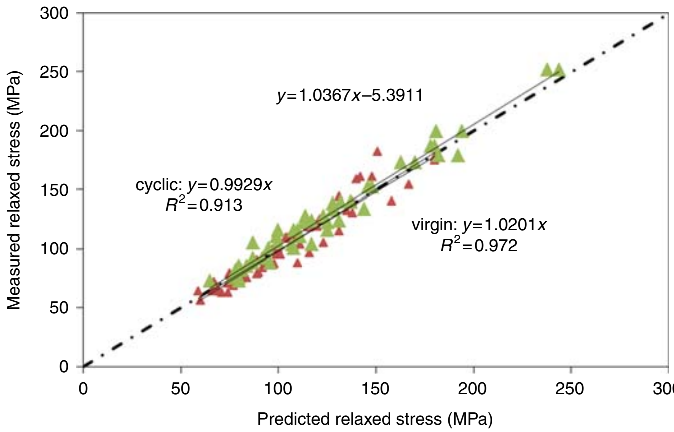


Figure 12. Modeled and measured relaxed stress at specified time for virgin and cyclically softened material

Discussion

The test data and the above presented models demonstrate the complexity and challenges related to the accurate prediction of relaxation behavior. However, with the relaxation and softening models in place it will now be possible to study the impact of strain range and hold time on different CF damage concepts such as the time life fraction and the ductility exhaustion as well as simplified models. This work is anticipated to be part of the final assessments and reporting of the MATISSE project.

Since the cyclic material characteristics, such as cyclic softening in this case, clearly have an effect on the relaxation/creep rate during strain holds, it is also clear that the virgin material or the mid-life cycle alone are not necessarily sufficient representatives of the cyclic behavior of the material.

For components in service the material softening in the form of decreased hardness could be a good indicator for detecting creep or CF damage.

The robust prediction of relaxation under conditions with wide range of temperature, strain and very long hold periods during the whole 60 years lifetime of a component may be challenging, even for the best of methods.

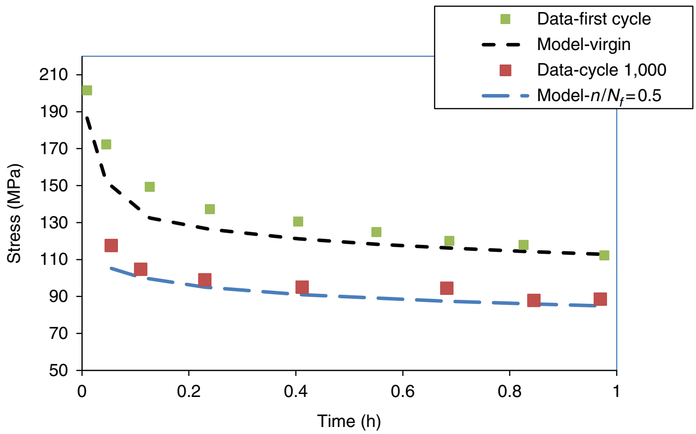


Figure 13. Measured and predicted relaxed stress of test performed by Takahashi (2012), 600°C, $\Delta\varepsilon = 0.5$ percent, virgin and $n = 1{,}000$ cycles

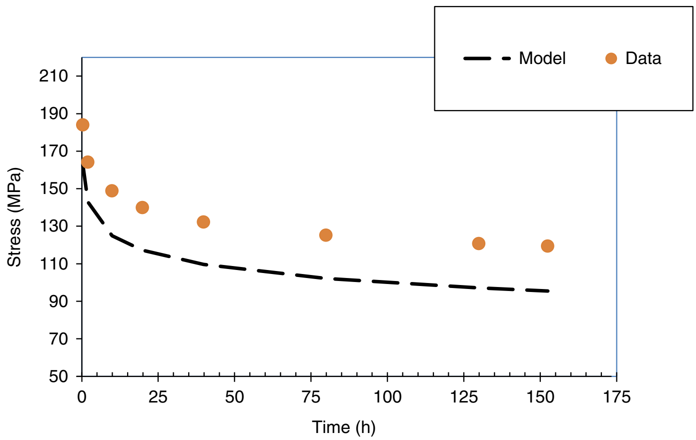


Figure 14. Measured and predicted relaxed stress of a test presented in JAEA report (Asayama and Tachibana, 2007), 550°C, $\Delta\varepsilon = 0.6$ percent, virgin material

Conclusions

The following conclusions can be made from the assessment of the LCF and CF data produced in MATISSE:

- tensile peak stresses are reduced due to tensile hold time whereas compressive peak stresses are reduced due to compressive hold time;
- combined hold times under tension and compression lead to lower stresses under tension as well as compression;
- hold times of same duration lead to significantly more pronounced softening for smaller strain amplitudes;
- a simple engineering model can adequately predict the LCF and CF softening rates of Gr. 91 steel;
- a simple relaxation model has successfully been adapted to predict relaxed stress for both virgin and softened material;
- the models are still to be improved by adding both higher and lower strain range data as well as different hold times and temperatures; and
- the applicability of the models was successfully tested against public domain data.

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