

EFFECT OF STRESS RELAXATION ON CREEP OF STEAM PIPE SYSTEMS

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FUEL-BASED ELECTRICITY
AND HEAT PRODUCTION



Effect of stress relaxation on creep of steam pipe systems

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Förord

Denna rapport är slutrapportering av projekt M 39197 Inverkan av spänningsrelaxation på krypning av ångledningssystem (Energimyndighetens projektnummer P 39197) som faller under teknikområde material- och kemiteknik inom SEBRA, samverkansprogrammet för bränslebaserad el- och värmeproduktion.

Tommy Larsson på E.ON har granskat projektet ur teknisk och måluppfyllande synvinkel.

SEBRA, samverkansprogrammet för bränslebaserad el- och värmeproduktion, är efterföljaren till Värmeforsks Basprogram och startade som ett samarbetsprogram mellan Värmeforsk och Energimyndigheten 2013. All forskningsverksamhet som bedrevs inom Värmeforsk ingår sedan den 1 januari 2015 i Energiforsk. Därför ges denna rapport ut som en Energiforskrapport.

Programmets övergripande mål är att bidra till långsiktig utveckling av effektiva miljövänliga energisystemlösningar. Syftet är att medverka till framtagning av flexibla bränslebaserade anläggningar som kan anpassas till framtida behov och krav.

Programmet är indelat i fyra teknikområden: anläggnings- och förbränningsteknik, processtyrning, material- och kemiteknik samt systemteknik.

Stockholm april 2016

Helena Sellerholm

Områdesansvarig

Bränslebaserad el- och värmeproduktion, Energiforsk AB

Sammanfattning

Kraftvärmeverk med ångturbin består av en panna med ett ång-vatten-system för värme och elproduktion. För att uppnå hög elverkningsgrad för anläggningen krävs hög ångtemperatur och högt ångtryck. Det innebär att krypning blir livslängdsbegränsande för de delar som utsätts för de högsta temperaturerna. Noggrann bestämning av återstående livslängd kräver simulering av krypbeteendet i ångledningssystemet och det bör företrädesvis inkludera hela systemet. Det har visats tidigare att spänningsrelaxation är viktigt att beakta vid simuleringen.

I detta arbete har spänningsrelaxationsprovning utförts vid tre olika töjningsnivåer för två vanliga rörmaterial, P22 med alternativ beteckning 10CrMo9-10 tidigare även benämnt SS 2218 (2.25Cr-1Mo) och P91 med alternativ beteckning X10CrMoVNb9-1 (9Cr-1Mo). Det har även utförts sekventiell provning där material genomgått spänningsrelaxation vid tre olika töjningsnivåer på ett sätt som i någon mening efterliknar förhållandena vid tre på varandra följande uppstartsperioder för en riktig panna. För att jämföra resultaten och demonstrera betydelsen av de erhållna materialdatana och valet av lämplig materialmodell, så genomfördes analyser med finita elementmetoden (FEM) av de utförda sekventiella försöken.

Följande slutsatser drogs:

- Relaxationsbeteendet hos P22 är oberoende av den initial plastiska töjningen, eftersom det inte föreligger någon signifikant effekt av hårdnande eller mjuknande.
- Nortonmodellen är otillräcklig för att simulera tidiga förlopp hos relaxationen, då dessa inkluderar effekten av primärt kryp.
- Modellen "combined time hardening" medger rimligt noggrann modellering av resulterande spänning under relaxation av material som inte tidigare utsatts för spänningsrelaxation.
- Modellen "combined time hardening" medger rimligt noggrann modellering av resulterande spänning under relaxation av P22 material även om det tidigare utsatts för spänningsrelaxation.
- För noggrann modellering av spänningsrelaxation av P91 material utsatt för tidigare cykler av spänningsrelaxation, så skulle det krävas att en hårdnandemodell inkluderas.
- Det observerade hårdnandet hos P91 är skäl för oro, eftersom det medför långsammare spänningsrelaxation och därmed förhöjda spänningar under signifikanta driftsperioder, vilket är troligt kommer att ge lokalt reducerad kryplivslängd.

Summary

A combined heat and power (CHP) plant with a steam turbine consists of a boiler with a steam-water system for heat and electricity production. To achieve high electrical efficiency for the plant high steam temperature and pressure is required. This involves that the service lifetime will be limited by creep in the parts of the plant that are exposed to the highest temperatures. Precise remaining lifetime assessment requires simulation of the creep behaviour of the steam pipe system and should preferably include the entire system. It has been shown previously that it is important to consider stress relaxation in the simulation.

In the present study stress relaxation testing was performed at three different strain levels for two common pipe materials, P22 also denominated 10CrMo9-10 and earlier SS 2218 (2.25Cr-1Mo) and P91 also denominated X10CrMoVNb9-1 (9Cr-1Mo). Also sequential testing was made where the materials underwent stress relaxation at three strain levels after each other in a way that to some extent resembled the conditions of three consecutive start-up periods of a real plant. To compare the results and to demonstrate the importance of the acquired material data and the appropriate choice of material model Finite Element Method (FEM) analyses of the performed sequential tests were made.

The following conclusions were drawn:

- The relaxation behaviour of P22 is independent on the initial plastic strain, since there is no significant hardening and softening effects.
- The Norton model is insufficient for simulating early stages of relaxation, since these include effect of primary creep.
- The combined time hardening model allows reasonably accurate modelling of the resulting stress during relaxation of material not previously exposed to stress relaxation.
- The combined time hardening model allows reasonably accurate modelling of the resulting stress during relaxation of P22 material even when exposed to previous stress relaxation cycles.
- For accurate modelling of stress relaxation of P91 material exposed to previous stress relaxation cycles, it would be required to include a work hardening model.
- The observed work hardening effect of P91 is a reason for concern, since it results in slower stress relaxation and thus elevated stresses for significant periods in service which is likely to cause reduced creep life, locally.

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1 Introduction

A combined heat and power (CHP) plant with a steam turbine consists of a boiler with a steam-water system for heat and electricity production. To achieve high electrical efficiency for the plant high steam temperature and pressure is required. The limits are typically set by the properties of the used materials. This may be corrosion properties and mechanical properties depending on fuel, position in the plant and operation conditions. As a consequence, the choice of material, its properties and how components are designed with respect to them are of high importance for safe, reliable and economic operation of a plant with high electrical efficiency.

The properties of interest for steam pipe systems located outside the furnace and flue gas path of a boiler are primarily related to creep. Hence, creep is considered in the design of such pipe systems involving a design life time, e.g. 200 000 hours of operation. Proper life assessment of the system also requires attention to the creep stresses that it is subjected to and the creep behavior of the materials that it is constructed in. In a recent Energiforsk project M12-218 [1] the system stresses of a complex steam system was numerically simulated with respect to the effects of starts and stops. That project showed that after each start-up there was a period of stress redistribution within the system caused by stress relaxation.

Creep and stress relaxation are closely connected material behaviours. At idealised conditions creep refers to the elongation (or compression) of a material over time, when it is subject to a constant stress. That means that the strain increases with time. For most engineering metals, such as steel, this requires elevated temperature. Stress relaxation is slightly more difficult to envision. It refers to a piece of material that has been elongated (or compressed) and then been fixated so that it is constrained and cannot change its length over time. At temperatures where creep could occur the stress in the material will then be lowered over time. More precisely the stress will decrease with time under constant strain conditions until it asymptotically approaches a final stress level.

The mechanism behind stress relaxation could be imagined as creep occurring inside the material without being visibly noticeable from the outside. If the constraints of the piece of material are released so that it becomes unloaded, the elongated (or compressed) material reverts towards the original length of the piece. However, the longer the period of stress relaxation the smaller the springback. That means that the permanent elongation (or compression) present after unloading the piece becomes bigger with time. This is very much similar to creep. Hence, stress relaxation is occasionally referred to as creep relaxation. The process can also be expressed as the stress relaxation occurs by the constant total strain being transformed from originally consisting of primarily elastic strain to finally consisting primarily of plastic strain (permanent creep deformation).

In a complex steam pipe system the stress distribution is due to internal pressure, dead weight of the constituting components and the overall thermal expansion. Thus, the stresses in one pipe or component depend on the stresses in more or less all the other parts. As the system is subjected to high temperature and stress it will undergo creep. This will affect the stress and strain distribution over time in the entire system. Hence, modelling and simulation of the creep behaviour in a live steam pipe system should preferably include the entire system. The before mentioned report of Energiforsk

project M12-218 [1] showed that stress relaxation after start-up needs to be included in the analysis for high accuracy. It is primarily the stresses that develop at the thermal expansion of the system that are relaxed by creep. It was also shown that the amount of additional stress due to thermal expansion at a certain position typically decreased during the first two or three cycles to the level of stress that is caused by internal pressure and dead weight.

The purpose of a steam pipe system simulation could be to assess the creep life of the components, but also to determine positions where particularly high creep strain would occur. The latter information could be used for replica testing, i.e. metallographic analysis with respect to creep damage development, followed by a recommended service time to next re-inspection or planning for component replacement if required. To find the correct positions for taking such samples the simulation needs to be accurate. Otherwise places with high creep damage could be missed.

Modelling creep in a steam pipe system with precision requires access to relevant material data. Today modelling is usually done based on data from traditional creep testing at constant stress (performed according to standardised methods [2, 3]), whether the process to be modelled is creep or stress relaxation. Thereby the results will be approximations. Data from more accurate stress relaxation tests (performed according to standardised methods [4, 5]) are rarely used and they are not easily found, if even existing. The lack of relevant material data results in that modelling often has to be done with the relatively simple Norton creep model, instead of for example the more advanced combined time hardening model, see section 2.2.

In the present study stress relaxation testing was performed at three different strain levels for two common pipe materials, P22 also denominated 10CrMo9-10 and earlier SS 2218 (2.25Cr-1Mo) and P91 also denominated X10CrMoVNb9-1 (9Cr-1Mo). Also sequential testing was made where the materials underwent stress relaxation at three strain levels after each other in a way that to some extent resembled the conditions of three consecutive start-up periods of a real plant. To compare the results and to demonstrate the importance of the acquired material data and the appropriate choice of material model Finite Element Method (FEM) analyses of the performed sequential tests were made.

It has been shown that the low alloy steel 2.25Cr-1Mo will stress relax at 510°C (950°F) and above, while the effect is small at 482°C (900°F) and below [6]. The same study also demonstrated that during repeated loading followed by stress relaxation the material behaviour is not easily predicted. Other studies have shown that alloy P22 may both harden and soften during repeated loading and stress relaxation testing [7] and that the remaining creep life may decrease rapidly through the same testing [8].

Only limited information is published on stress relaxation behaviour of P91 and especially regarding repeated loading and stress relaxation. Some work has been published on stress relaxation-fatigue. However, such experiments are typically been performed with several thousands of loading cycles and relaxation times as short as a few hours. This makes comparison to this work difficult. Nevertheless, it has shown that relaxation-fatigue testing of P91 is detrimental to fatigue life [9]. It is therefore reasonable to expect that it is also detrimental to remaining creep life, similar to what has been shown for P22 [8].

The long term overarching goal of the project is to create good possibilities for safe and reliable operation of complex steam pipe systems throughout their entire life. This shall be achieved by allowing the behaviour of the complete system under creep load to be simulated with respect to shutdown periods based on real test data for repeated loading and stress relaxation. This will enable a refined determination of the creep strain at the most affected positions, which makes it possible to specify the control interval more accurately and consequently also the possible need of component replacements. This is expected to result in more reliable operation and the possibility for higher plant availability through shorter revision stops.

Specific goals are to obtain data for stress relaxation of two commonly used materials and to study their behaviour during repeated loading and stress relaxation similar to a number of operation cycles for a CHP plant. Further recommendations are to be given for how to refine creep modelling of steam pipe system through the use of data from the performed relaxation tests.

2 Experimental

2.1 STRESS RELAXATION TESTING

2.1.1 Test rig and sample design

The stress relaxation tests were performed in specially adapted creep test rigs shown in Figure 1. The sample is mounted inside the furnace. The temperature of the sample is measured by thermocouples and the temperature is automatically regulated through a control unit. The force is applied on the sample by a stepper motor through a gear drive. The load is measured by a load cell and the sample elongation by a pair of extensometers.

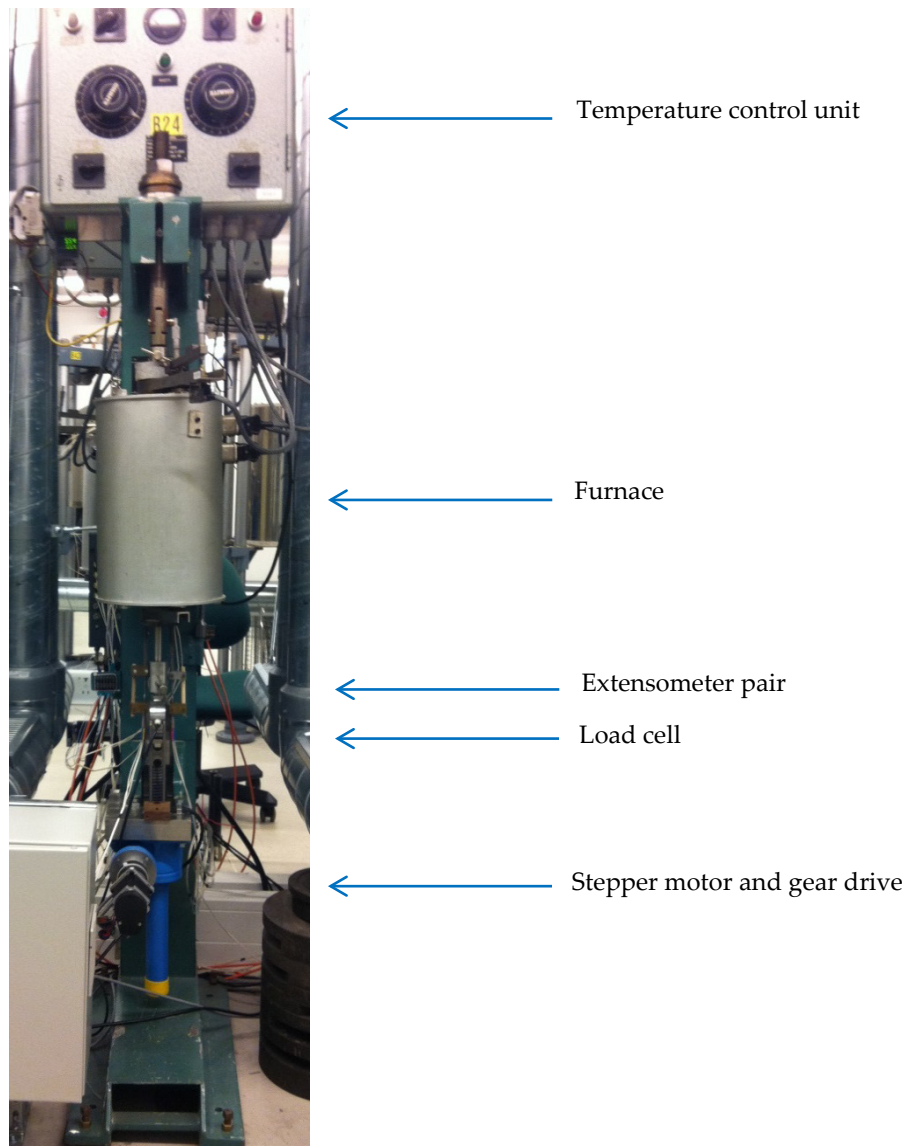


Figure 1. Test rig for stress relaxation with a sample mounted inside the furnace.

When performing regular creep testing the machine is operated in force control. The load is then electronically regulated to a pre-set value and the sample elongation with time is recorded. When performing stress relaxation testing the sample elongation is fixed, while the decrease in stress with time is recorded. If the test rig stiffness would approach infinity it would not be necessary to operate the stepper motor during the test once the sample has been loaded to the pre-set load or strain level. However, as the stress decreases the machine responds with some springback related to its compliance. There is a need to compensate for this machine compliance during testing; otherwise the sample will not maintain constant strain. This is done electronically by manoeuvring the stepper motor according to a pre-determined load dependent calibration scheme.

The design of the test samples is shown in Figure 2. The central parallel length is 75 mm and the diameter of that section is 5 mm. The ridges of either side of the parallel length are used for attaching the extensometers. The ridge-ridge length is 85 mm and constitutes the extensometer gauge length.

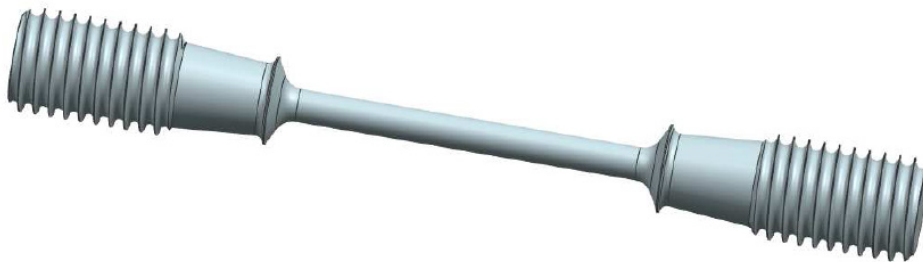


Figure 2. Test sample for stress relaxation.

2.1.2 Materials and test conditions

Two materials were included in the tests, P22 (2.25Cr-1Mo) and P91 (9Cr-1Mo). The typical operation temperatures differ slightly between these alloys. Based on this the test temperatures were set to 530°C for P22 and 560°C for P91. The P22 material is from the same pipe as was used in the Energiforsk project M12-218 [1]. Based on literature data the elastic modulus of the materials was assumed to be 165 GPa.

The test were carried out with a loading sequence of 6 min up to the target initial stress, a hold time with constant stress until a target strain value was obtained, which was followed by a stress relaxation period. The target initial stress was 140 MPa for P22 and 200 MPa for P91. The levels were chosen to be able to reach the target strain value within a reasonable time of some hours, without exceeding the yield strength at the test temperature. The target plastic strain values were 0.25 %, 0.15 % and 0.10 %. Since the extensometers measure the actual sample elongations corresponding to the total strains, the elastic strains, 0.085 % for P22 and 0.121 % for P91, were added to the plastic strains to obtain the target total strains. When the target total strain was reached by creep deformation the operator changed the control mode of the test rig from force

controlled to constant strain control to start the stress relaxation. During the period of stress relaxation the change in stress was monitored.

For each test material one sequential test was made in addition to the before mentioned stress relaxation tests. The sequential test was performed so that the sample was exposed to three consecutive stress relaxation tests with the target plastic strain for the first sequence of stress relaxation being 0.25 %. Then the sample was unloaded. This was followed by a new sequence of stress relaxation with the additional target plastic strain being 0.15 %. Then the sample was unloaded once more followed by the last sequence of stress relaxation with the additional target plastic strain being 0.10 %.

2.2 STRESS RELAXATION SIMULATION

The simulations of stress relaxation are performed according to the same procedure and with the same loading times as the relaxation tests, i.e. relaxation sequences where each sequence include loading to a fixed value, a period of constant load and finally a period of fixed displacement where the load is allowed to relaxed by creep. First, each one of three sequences is simulated individually. Then, the three sequences are applied successively.

The simulations are carried out by use of the FE-program Ansys 16.2 [10]. Since the test specimen is both symmetric and axisymmetric the FE-model is a 2D-axisymmetric half model of the specimen. Figure 3 shows the FE-model with the element discretization.

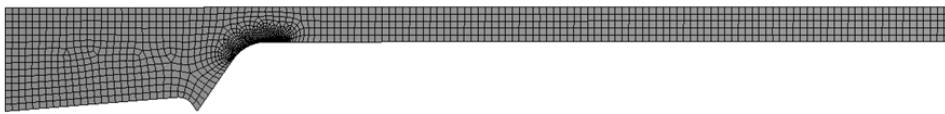


Figure 3. The finite element model of the test specimen.

2.2.1 P22 and material model

The simulation of P22 is performed at the temperature 530°C, which is the same as the test. The load is increased during the first 6 minutes to finally reach 140 MPa at the gauge section of the specimen. The load is then kept constant during the second phase and finally the displacement is kept constant in the third phase. The times for the phases are different for the three sequences and listed in Table 1.

Table 1. Duration of each phase for the three sequences.

	Increasing load phase	Constant load phase	Constant displacement phase
Sequence 1	6 min	3.4 h	318.5 h
Sequence 2	6 min	5.6 h	185.4 h
Sequence 3	6 min	3.3 h	246.4 h

Two material models have been used during the simulations of P22; Norton's creep law, see Equation 1, and a combined time hardening model, see Equation 2. The Norton model considers only secondary creep whilst the combined time hardening model addresses both secondary and primary creep. The equations for the two models are:

Norton:
$$\frac{d\varepsilon_{cr}}{dt} = B \cdot \sigma^n \quad (\text{Eq. 1})$$

Combined time hardening:
$$\varepsilon_{cr} = C_1 \sigma^{C_2} t^{C_3+1} / (C_3 + 1) + C_4 \sigma^{C_5} t \quad (\text{Eq. 2})$$

where ε_{cr} is creep strain, σ is stress, t is time and $B, n, C_1, C_2, C_3, C_4, C_5$ are material parameters. The P22 material has been creep tested before in the Energiforsk project M12-218 [1] and the test results were evaluated to fit a Norton creep model with the following values of the material constants B and n : $B = 2.40 \cdot 10^{-77} [\text{Pa}^{-n}/\text{s}]$ and $n = 8.4$ [1]. These test data is also the source for the evaluation of the material constants in the combined time hardening model. The model is fitted by the least square method. The data and the fitted model are shown in Figure 4. The fitted parameters are listed in Table 2.

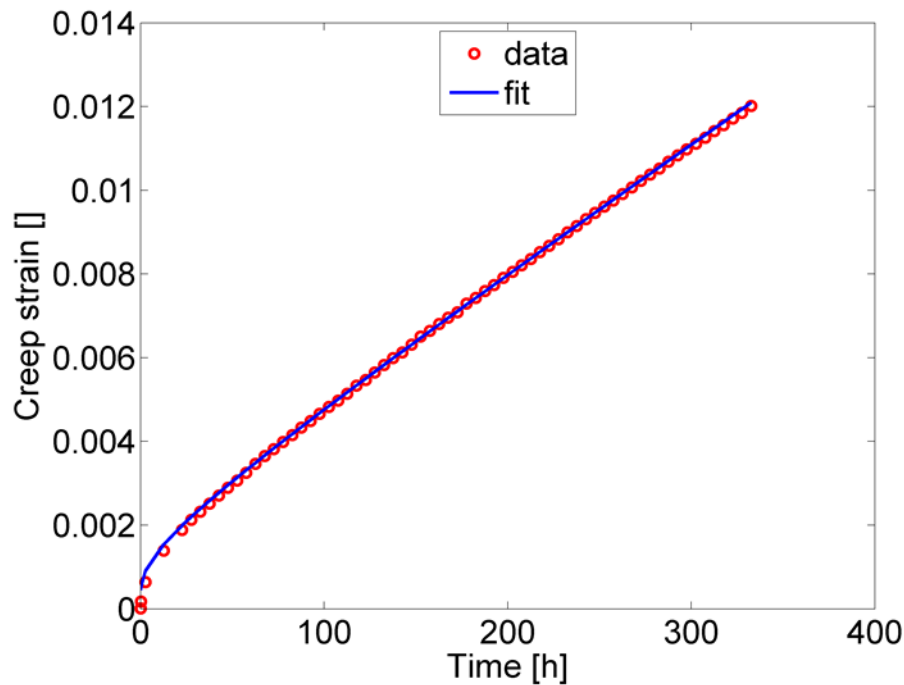


Figure 4. Data from creep test on P22 [11] and the fitted combined time hardening model.

Table 2. Fitted parameters for the combined time hardening model.

Fitted parameter	value
C_1	$1.9232 \cdot 10^{-36} [\text{Pa}^{-C_2}]$
C_2	3.7538
C_3	-0.6345
C_4	$2.7518 \cdot 10^{-77} [\text{Pa}^{-C_5}]$
C_5	8.3992

2.2.2 P91 and material model

The simulations of P91 were carried out at the same temperature as in the relaxation tests, 560°C. The load is increased during the first 6 minutes to finally reach 200 MPa in

the gauge section of the specimen. The load is then kept constant during the second phase and finally the displacement is kept constant in the third phase. The times for the phases are different for the three sequences and listed in Table 3.

Table 3. Duration of each phase for the three sequences.

	Increasing load phase	Constant load phase	Constant displacement phase
Sequence 1	6 min	1.8 h	335.6 h
Sequence 2	6 min	1.4 h	425.5 h
Sequence 3	6 min	1.4 h	262.5 h

Experience from the simulations of P22 shows that the results from the combined time hardening model are more realistic, hence only the combined time hardening model are used in the simulation of P91, see Equation 2. There were no suitable creep test results available on the same batch of material as was used for the relaxation testing. Creep data for other batches of P91 can be found in the literature. Creep data that includes strain-time curves, which is needed for the material model, is rare. Nothing was found at the test temperature, 560°C, since this is not a typical temperature for creep testing. However, data from tests at 550°C was found [12]. Shown in Figure 5 is creep strain versus time for 4 different loads. A model is fitted to the data of 180 MPa and 200 MPa, see Figure 6. The figure shows that the fit is not perfect at the curve corresponding to 180 MPa. This deviation is probable due to the latter part of the 200 MPa strain curve in Figure 6, which shows a tendency to tertiary creep. The fitted parameters are listed in Table 4.

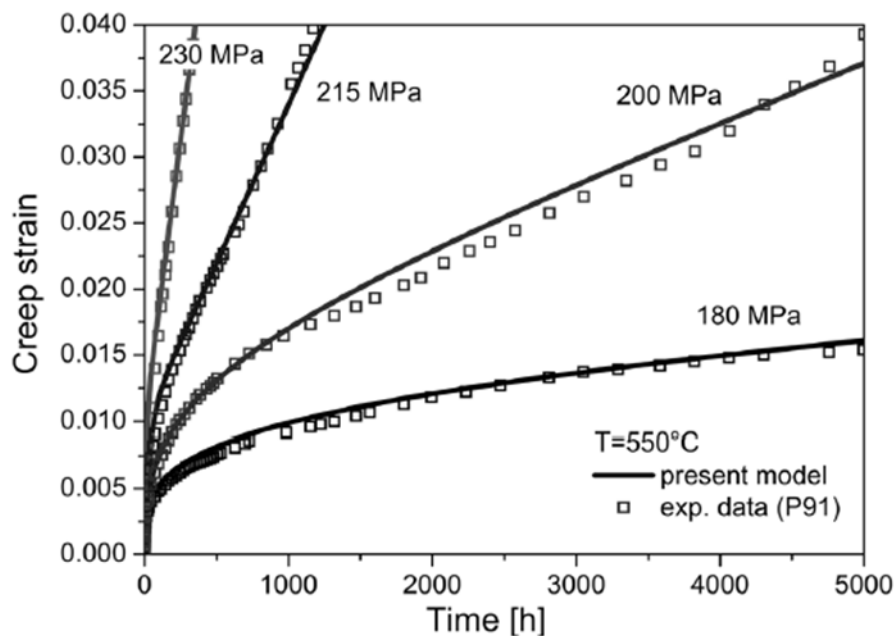


Figure 5. Creep test results for P91 [12].

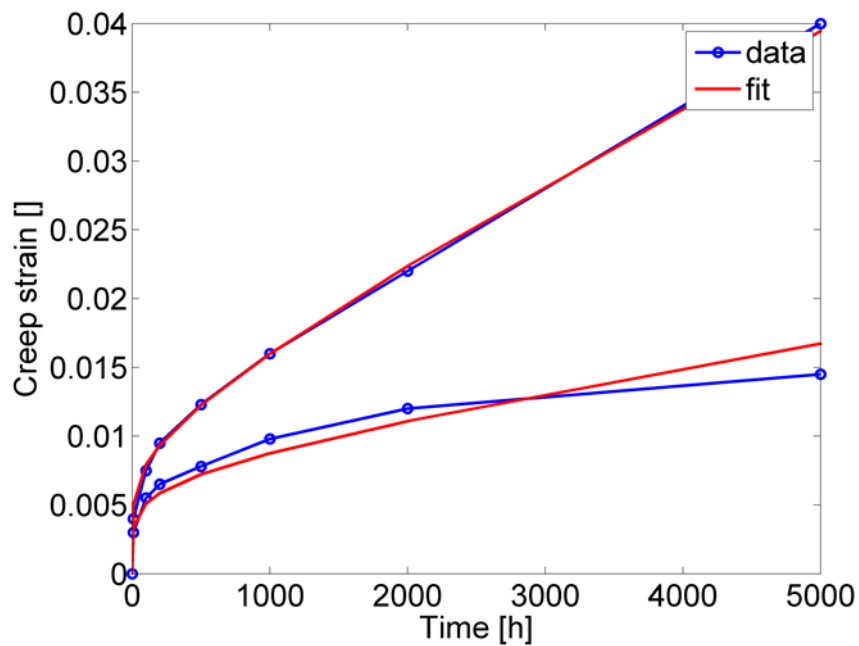


Figure 6. Creep test results for P91 [12] and fitted combined time hardening model.

Table 4. Fitted parameters for the combined time hardening model.

Fitted parameter	value
C_1	$1.9232 \cdot 10^{-36} [\text{Pa}^{-C_2}]$
C_2	3.7538
C_3	-0.6345
C_4	$2.7518 \cdot 10^{-77} [\text{Pa}^{-C_5}]$
C_5	8.3992

To adjust this fitted model to the right temperature 560°C another work [13] is used. In this article the minimum creep strain for P91 at different temperatures and loads are measured, see Figure 7. For simplicity it is assumed that the minimum creep strain is located at a linearly distributed position between the two temperatures 823 K (550°C) and 848 K (575°C) at 200 MPa. This assumption gives a value of the minimum creep strain at 560°C. Listed in Table 5 are the minimum creep strains at 200 MPa for 550°C and 575°C together with the estimated creep strain for 560°C. The minimum creep strain at 560°C is 3.46 times larger than the minimum creep strain at 550°C. Finally, the second creep factor in the fitted combined time hardening model is multiplied by this factor, 3.46.

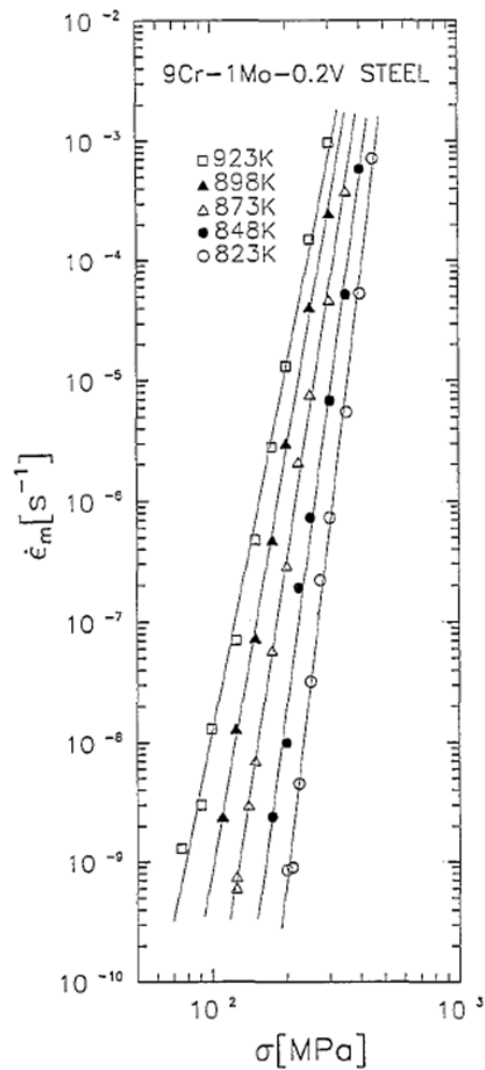


Figure 7. Creep test results for P91 from 5 different temperatures [13].

Table 5. Fitted parameters for the combined time hardening model.

Temperature	Minimum creep strain velocity
550 °C	$9 \cdot 10^{-10}$ [1/s]
575 °C	$2 \cdot 10^{-8}$ [1/s]
560 °C	$3 \cdot 10^{-9}$ [1/s] estimated

3 Results

3.1 RESULTS OF STRESS RELAXATION TESTING

3.1.1 Alloy P22

Single loading relaxation testing

The test results for P22 from traditional stress relaxation tests consisting of only a single loading and relaxation step are shown in Figure 8. There is substantial scatter in the recorded curves caused by test rig issues. Nevertheless, it can be concluded that the curves at least approximately follow each other irrespective of the strain levels.

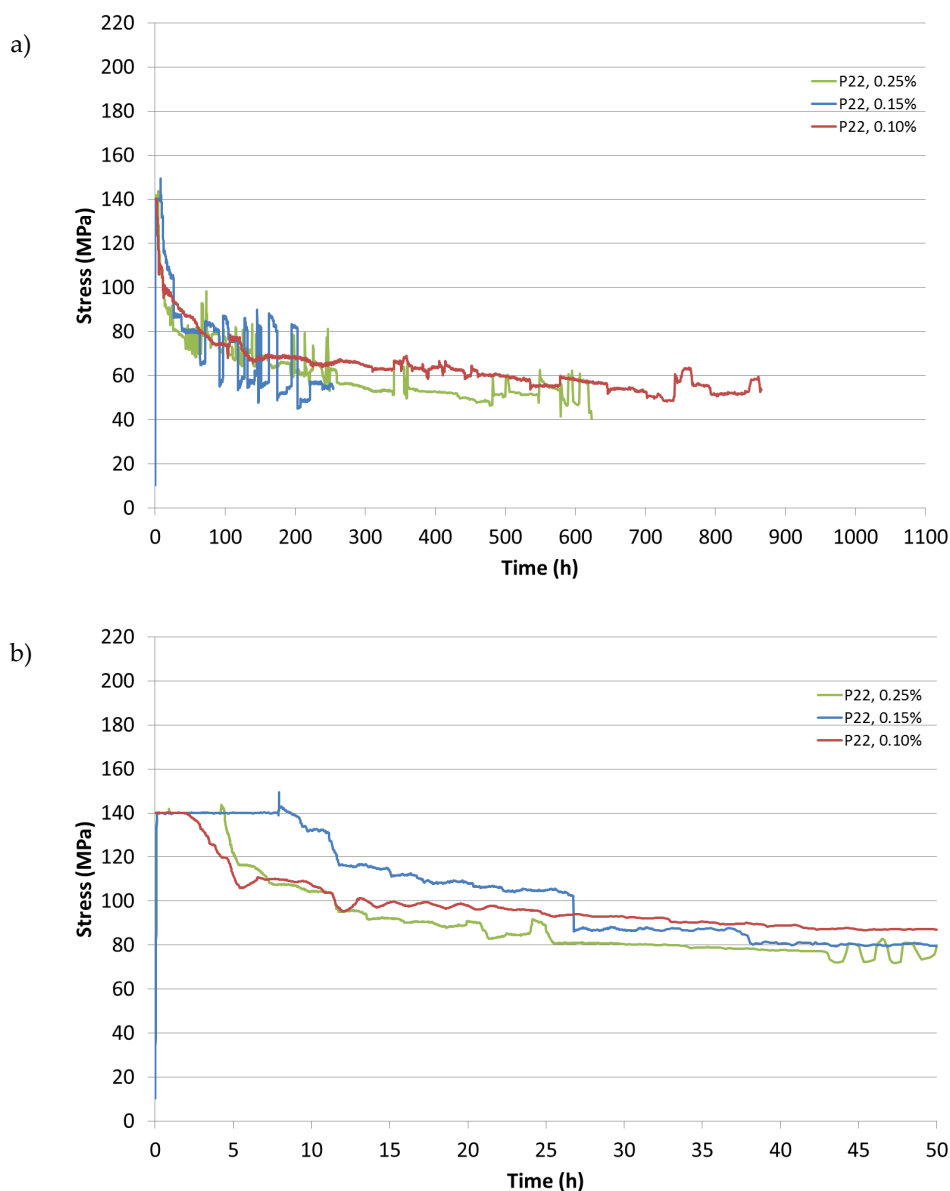


Figure 8. Stress relaxation test results for P22 at 530°C from three independent tests at different strain levels, a) entire test periods and b) close-up of initial test periods.

Repeated loading relaxation testing

The test results for P22 from sequential stress relaxation tests consisting of three steps with loading and relaxation at different strain levels are shown in Figure 9. There are a few clear jumps in the curves of Figure 9a. These are caused by technical issues with the test rigs that could not be resolved within the course of the project. The jumps are caused by small errors in the control of the strain levels. The data can be approximately corrected by adjusting the curves by vertical translation of them to remove the jumps and make them appear continuous. The error adjusted curves are shown in Figure 9b.

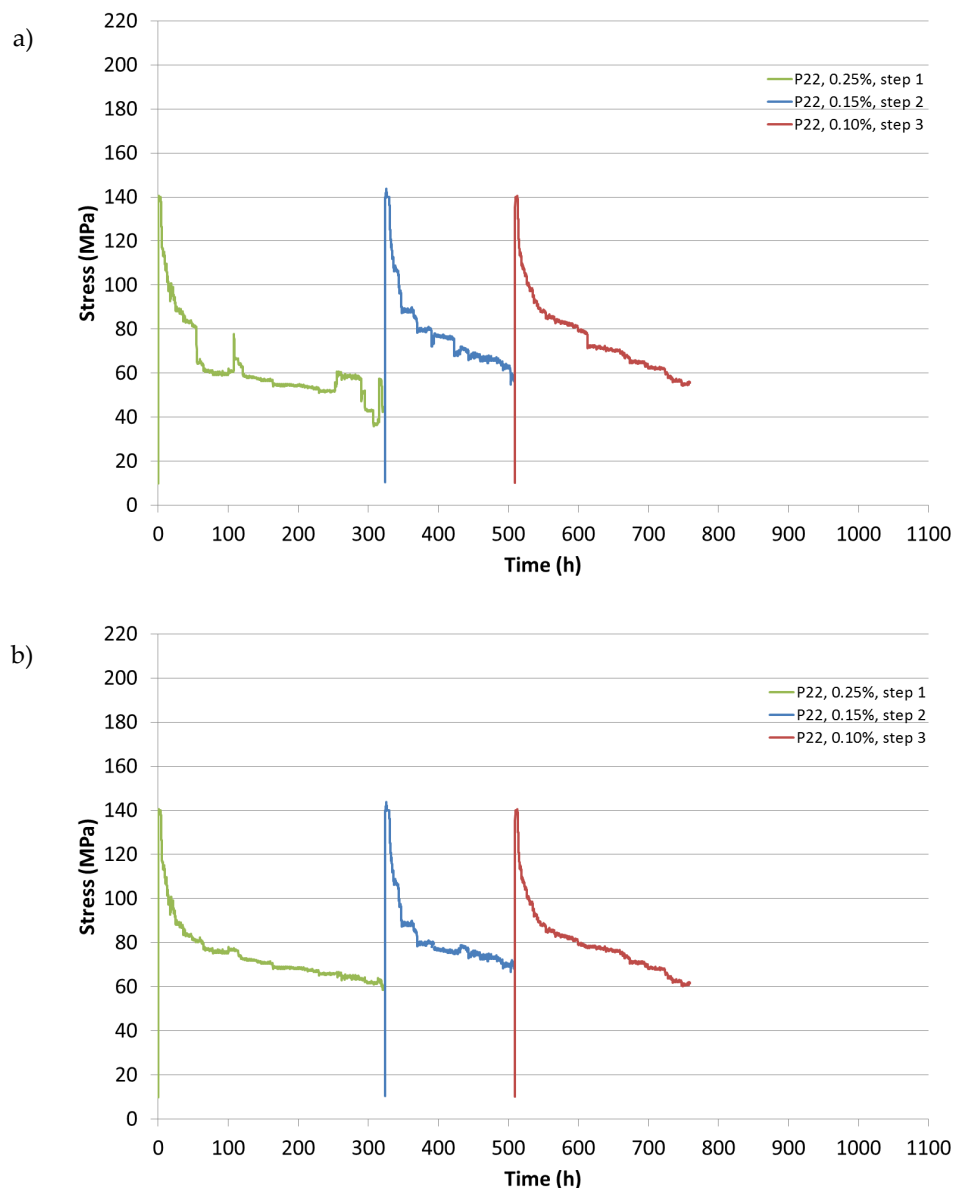


Figure 9. Stress relaxation test results for P22 at 530°C from sequential testing consisting of three steps with loading and relaxation at different strain levels, a) recorded data and b) error adjusted data.

The test results for P22 from sequential stress relaxation tests consisting of three steps with loading and relaxation at different strain levels are shown in Figure 10 with the results from the different steps being superimposed on each other. This facilitates comparison of the curves. It is seen that there is little difference in the curves, despite that they are run in sequence and at different strain levels. The tests being made in sequence results in step 2 and 3 being made on a sample which is not virgin. This is in contrast to the results of Figure 8, which are from three different virgin samples.

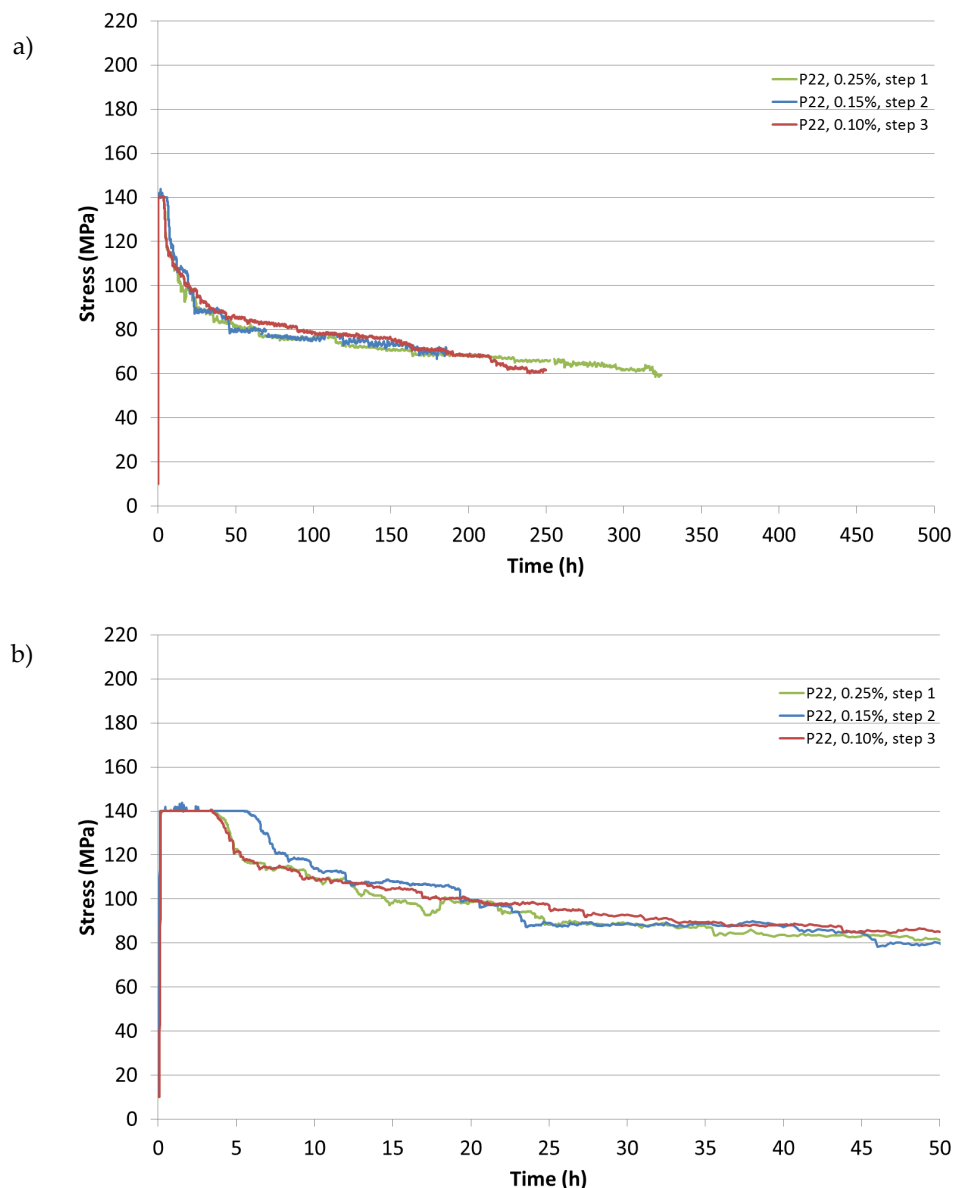


Figure 10. Stress relaxation test results (error adjusted data) for P22 at 530°C from sequential testing consisting of three steps with loading and relaxation at different strain levels, a) entire test periods and b) close-up of initial test periods for each step.

3.1.2 Alloy P91

Single loading relaxation testing

The test results for P91 from traditional stress relaxation tests consisting of only a single loading and relaxation step are shown in Figure 11. There is substantial scatter in the recorded curves caused by test rig issues. Because of this it is not possible to conclude much regarding differences in behaviour depending on strain level, except that they approximately appear to approach about the same asymptotic level after long time.

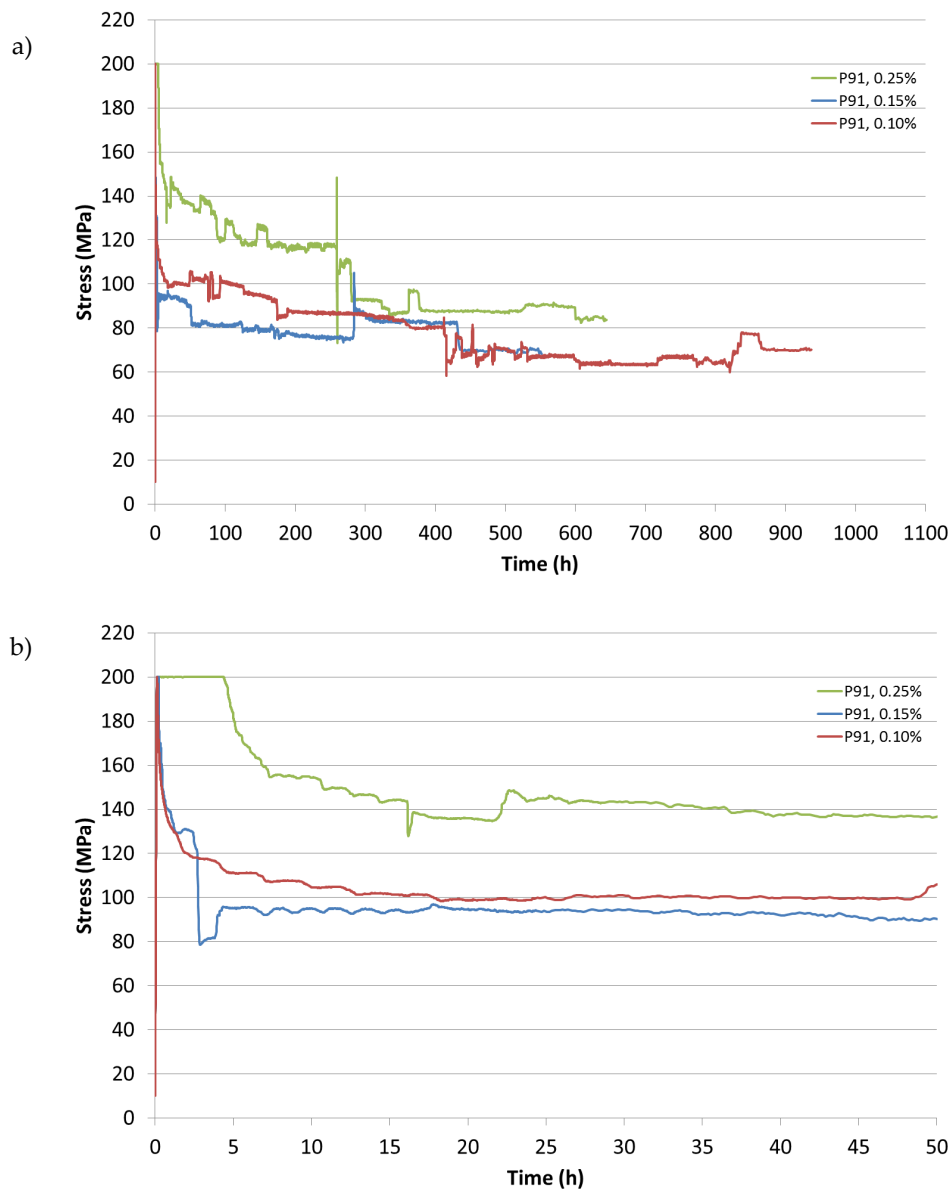


Figure 11. Stress relaxation test results for P91 at 560°C from three independent tests at different strain levels, a) entire test periods and b) close-up of initial test periods.

Repeated loading relaxation testing

The test results for P91 from sequential stress relaxation tests consisting of three steps with loading and relaxation at different strain levels are shown in Figure 12. A single erroneous jump is visible, for which adjustment had to be made the same way as for P22. It is observed that the curves become positioned at higher stress levels for each step. This means that there is less or slower stress relaxation for each step in the sequential testing.

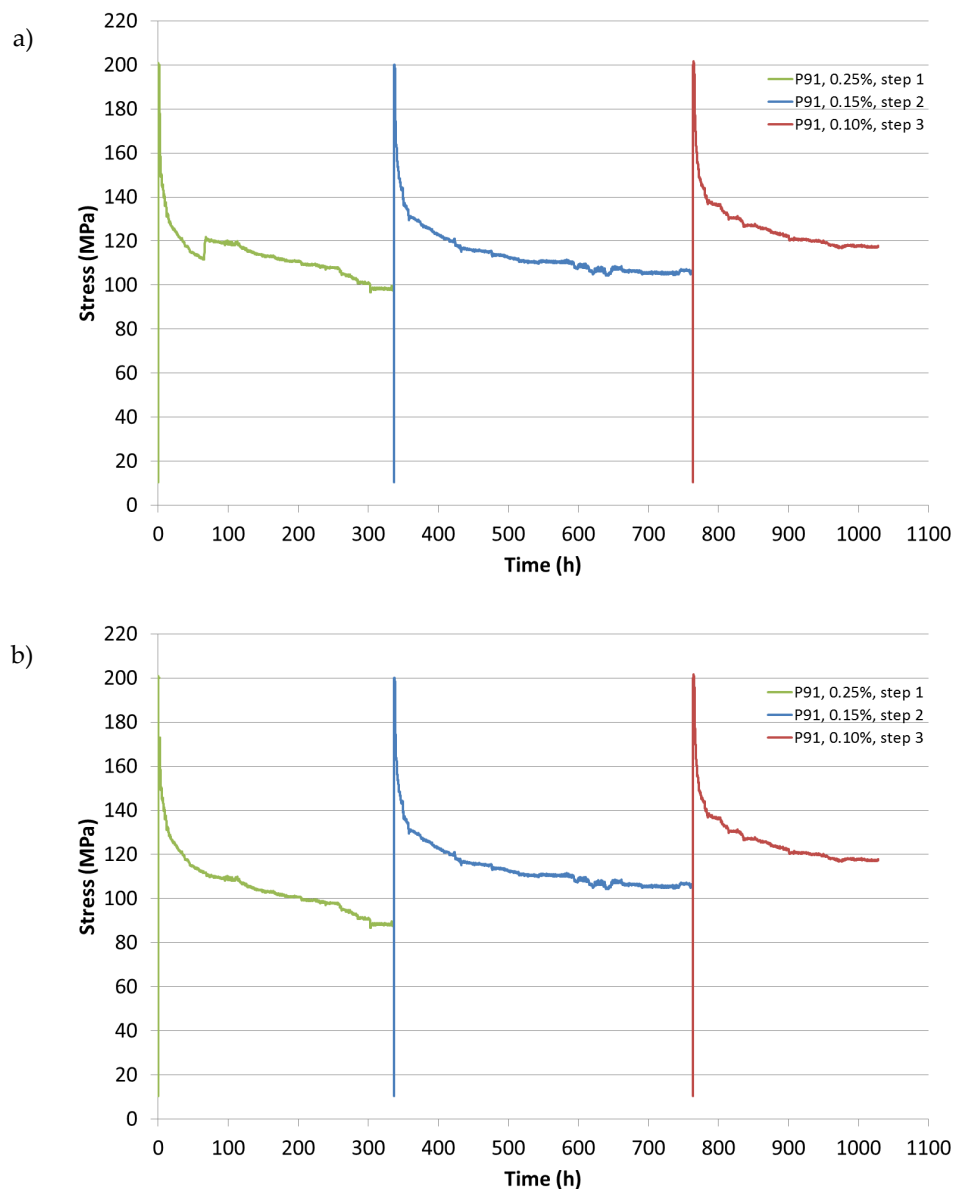


Figure 12. Stress relaxation test results for P91 at 560°C from sequential testing consisting of three steps with loading and relaxation at different strain levels, a) recorded data and b) error adjusted data.

The test results for P91 from sequential stress relaxation tests consisting of three steps with loading and relaxation at different strain levels are shown in Figure 13 with the results from the different steps being superimposed on each other. This facilitates comparison of the curves. It is seen that the relaxation process becomes slower for each step. It also appears as the curves for each step would approach a higher asymptotic level after long time, if that step was not terminated.

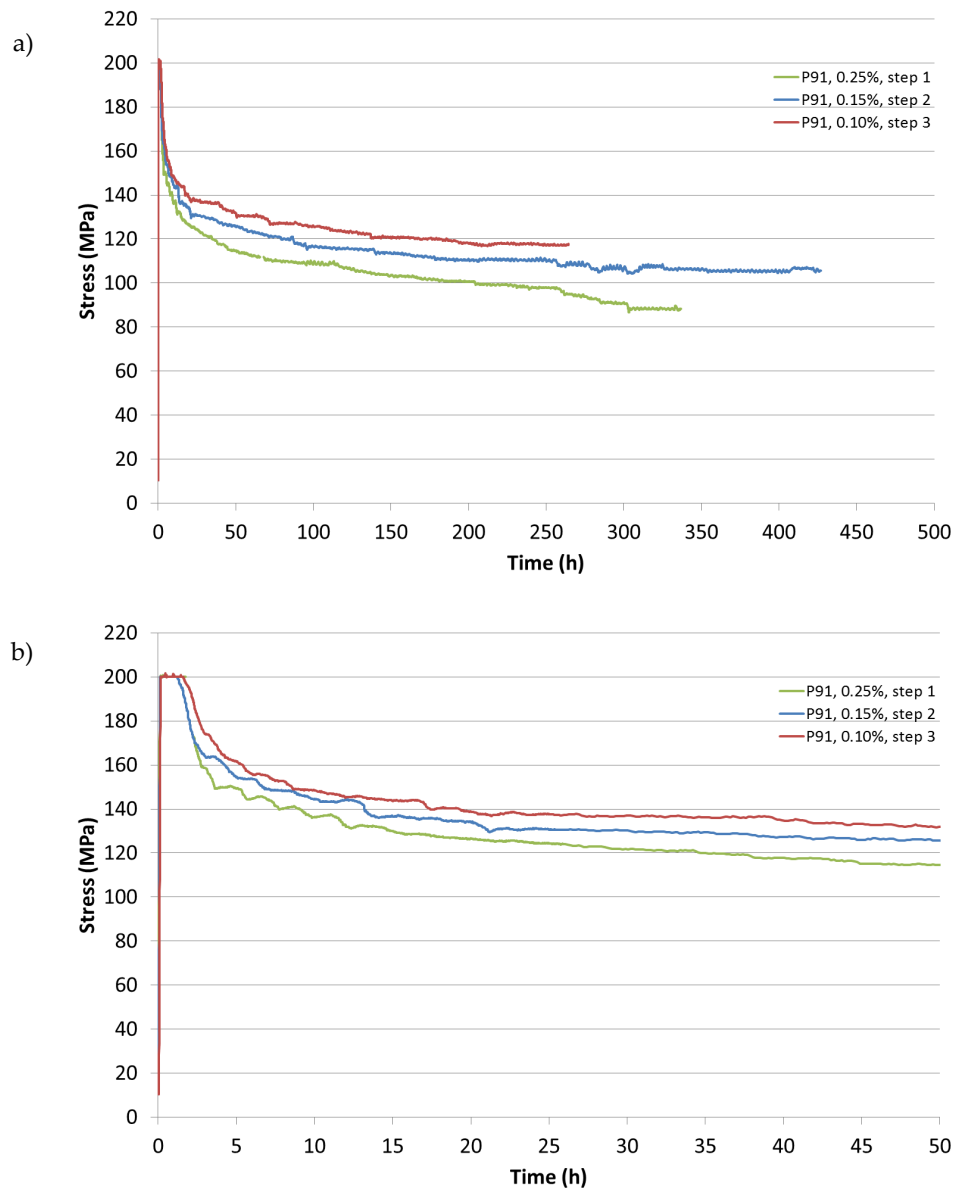


Figure 13. Stress relaxation test results (error adjusted data) for P91 at 560°C from sequential testing consisting of three steps with loading and relaxation at different strain levels, a) entire test periods and b) close-up of initial test periods for each step.

3.2 RESULTS OF STRESS RELAXATION SIMULATION

3.2.1 Alloy P22

Norton creep model

The Norton creep model is first simulated for the first step of sequential testing of P22. Figure 14 shows the normal stress during the constant load phase and at the end of the relaxation phase. The stress has decreased from 140 MPa to 78.6 MPa in the central parallel (cylindrical) part of the specimen during the relaxation. Figure 15 shows the final creep strain after the first sequence. Finally the normal stress in the specimen is plotted versus time in Figure 16. Just as expected the stress relaxes more rapidly at the beginning.

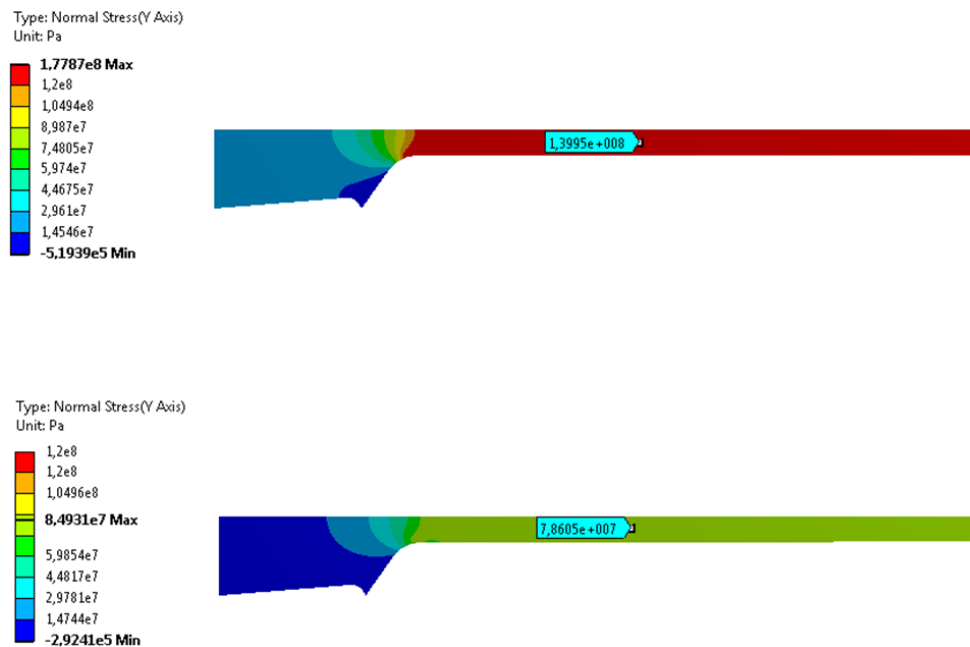


Figure 14. Normal stress in the specimen axial direction, on top: during the constant load phase, bottom: at the end of the first step of sequential testing of P22.

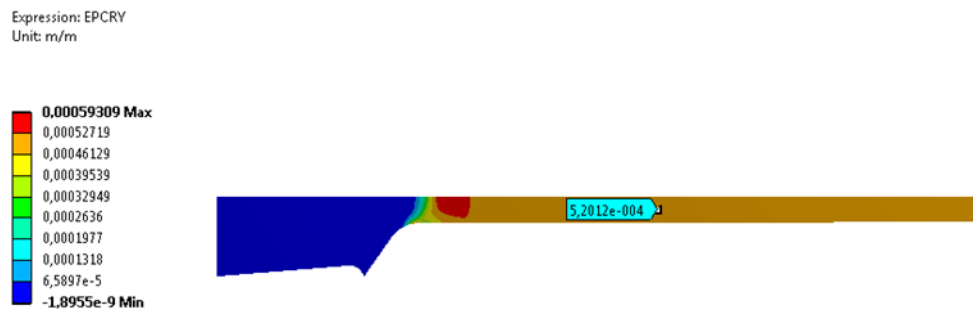


Figure 15. Resulting creep strain after the first step of sequential testing of P22.

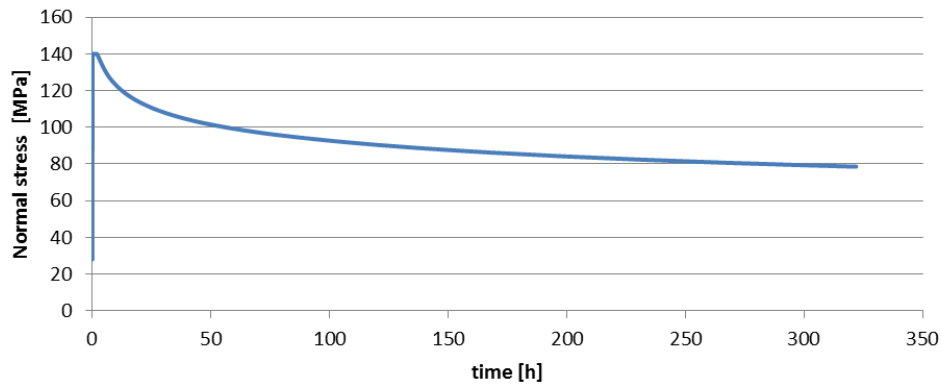


Figure 16. Resulting normal stress during the first step of sequential testing of P22. Norton model.

Combined time hardening creep model

The combined time hardening creep model is simulated for the first step of sequential testing of P22. Figure 17 shows the normal stress in the axial direction plotted versus time. Here the relaxation is even more rapid in the beginning, compared to the Norton simulation. This is also expected since the primary creep effect is present in the combined time hardening model.

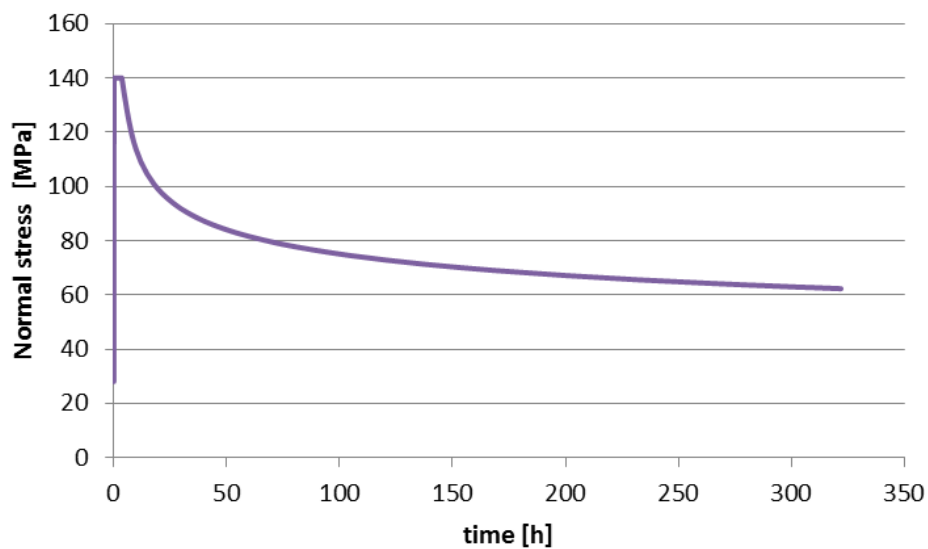


Figure 17. Resulting normal stress during the first step of sequential testing of P22. Combined time hardening model.

The simulation of the second and third step of the sequential testing of P22 is done in two ways. The reason for this is that looking at Equation 2 it is seen that the primary creep behaviour is only present during the beginning of time t . Hence, the second and third step lacks primary creep effects if they are simulated successively. This is done in the first simulation. Shown in Figure 18 is the normal stress versus time for all three steps when they are simulated successively in time.

In the second simulation of the sequential testing of P22 the three steps are simulated independently. Shown in Figure 19, Figure 20 and Figure 21 is the normal stress versus time when each sequence is simulated separately. The disadvantage with the separated simulation is that no permanent strains from the preceding sequence are transferred to the present one. In other words, no permanent creep strains from the first sequence are transferred to the second sequence. In Figure 22 the three sequences are plotted after each other in the same graph. Comparing Figure 18 and Figure 22 it can be seen that the normal stress relaxes more rapidly for step two and three in the graph in Figure 22, since the primary creep effect is included.

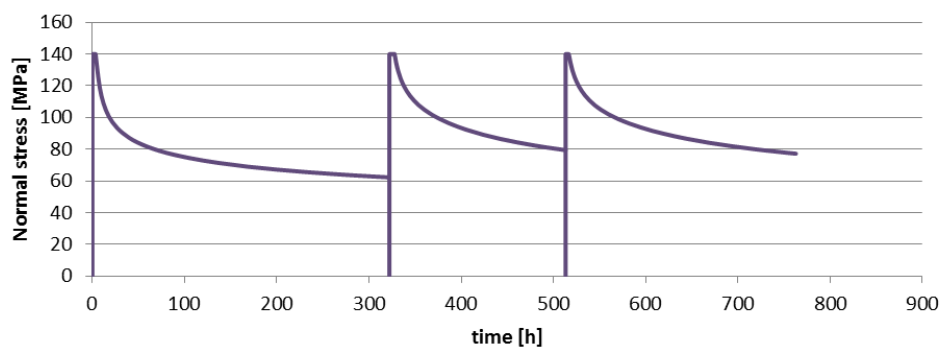


Figure 18. Resulting normal stress during all three steps of sequential testing of P22, when simulated successively. Combined time hardening model.

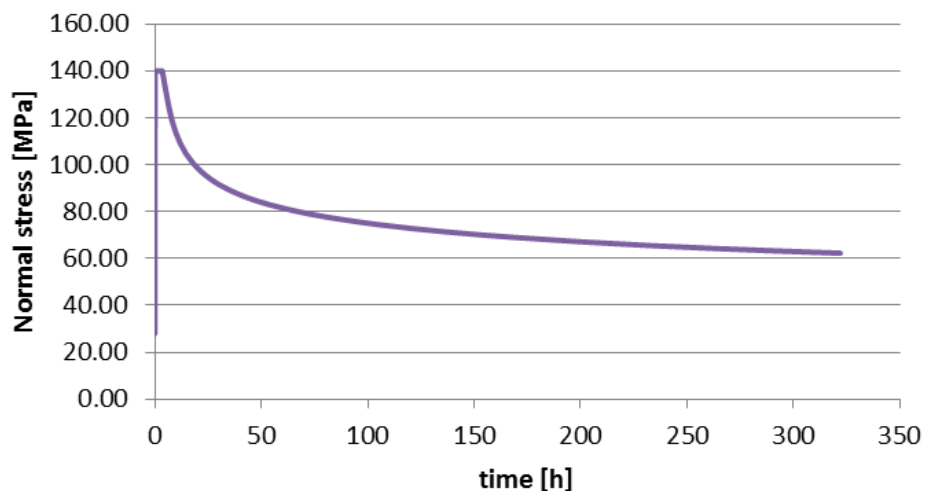


Figure 19. Resulting normal stress during the first step of sequential testing of P22, when simulated successively. Combined time hardening model.

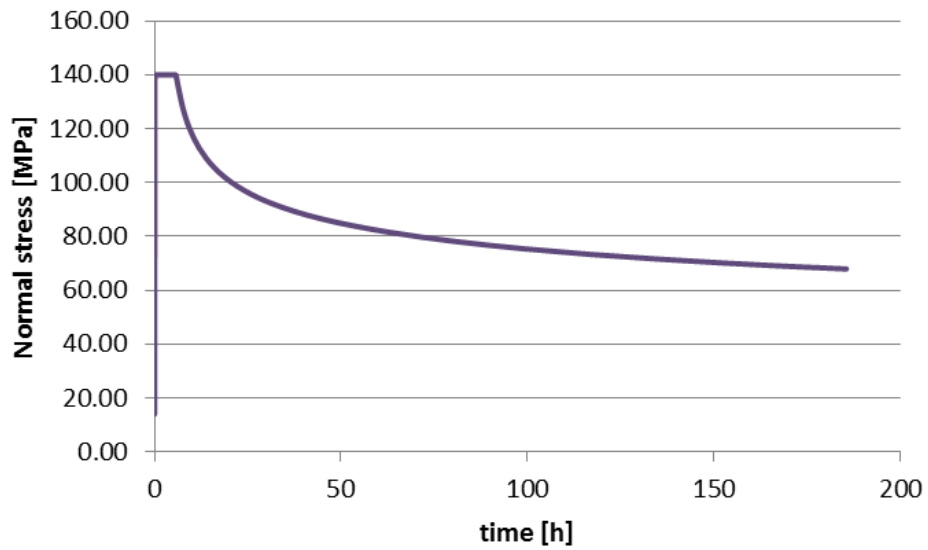


Figure 20. Resulting normal stress during the second step of sequential testing of P22, when simulated separately. Combined time hardening model.

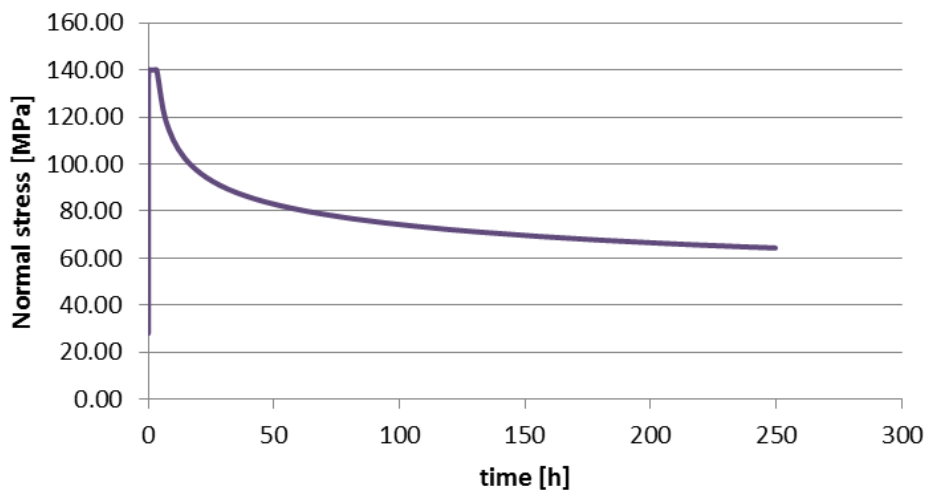


Figure 21. Resulting normal stress during the third step of sequential testing of P22, when simulated separately. Combined time hardening model.

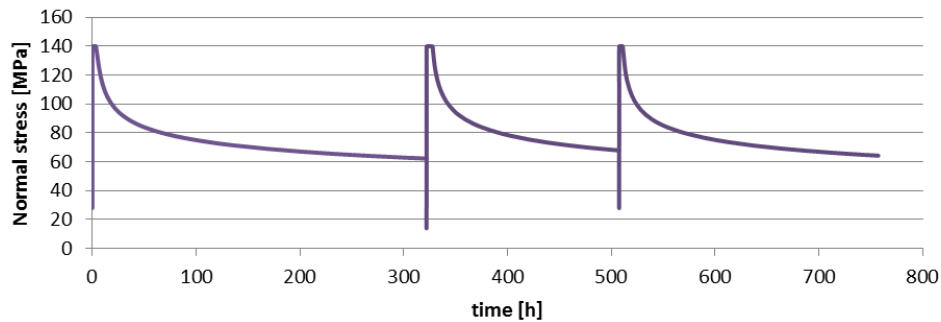


Figure 22. Resulting normal stress during all three steps of sequential testing of P22, when simulated separately and plotted after each other along the time-axis. Combined time hardening model.

3.2.2 Alloy P91

Combined time hardening creep model

The stress relaxation simulation of P91 is made only with the combined hardening model and with the different steps modelled separately. This was chosen to include primary creep in all steps of the sequential testing as was discussed in Section 3.2.1 for P22. Figure 23 shows the normal stress for the first step. Figure 24 and Figure 25 show the resulting normal stress for step two and three, respectively.

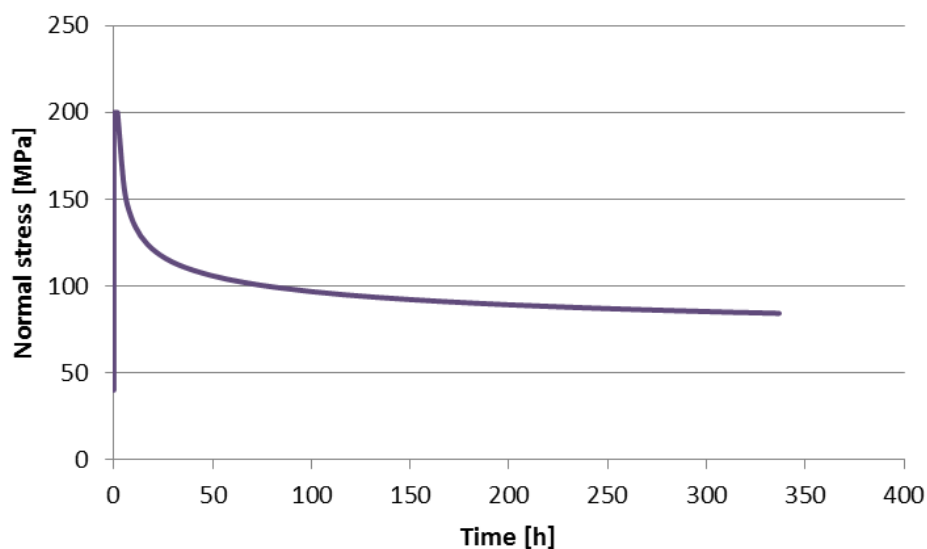


Figure 23. Resulting normal stress during the first step of sequential testing of P91, when simulated successively. Combined time hardening model.

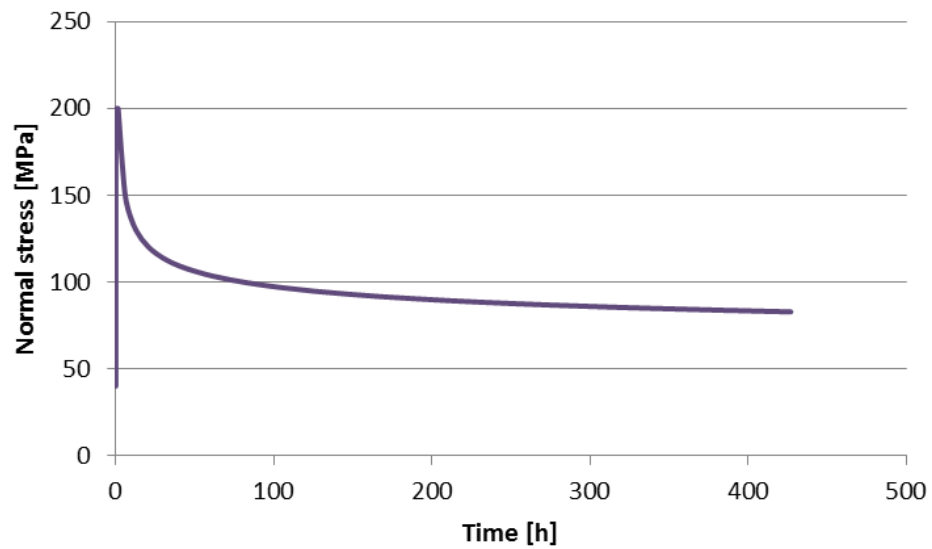


Figure 24. Resulting normal stress during the second step of sequential testing of P91, when simulated separately. Combined time hardening model.

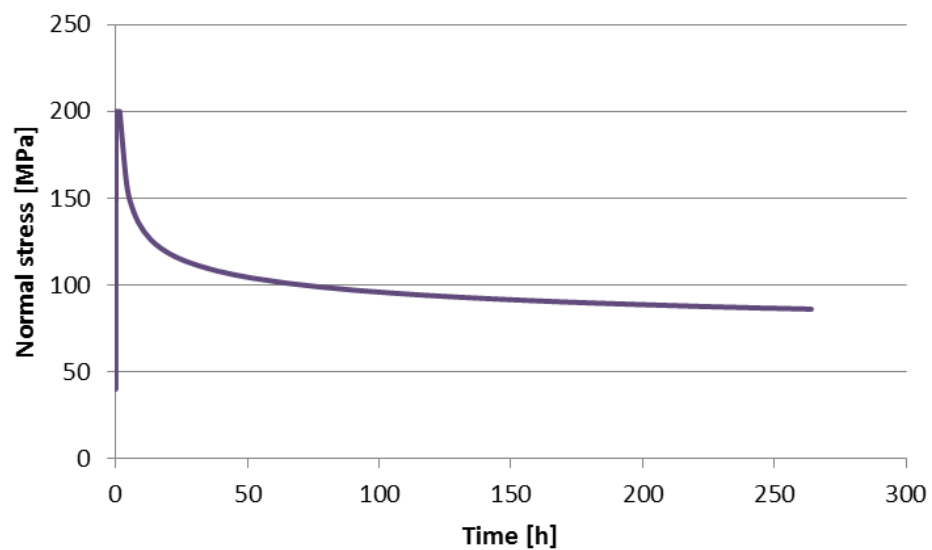


Figure 25. Resulting normal stress during the third step of sequential testing of P91, when simulated separately. Combined time hardening model.

4 Comparison of results from stress relaxation testing and simulation

4.1 ALLOY P22

Norton creep model

The results from the first step of the sequential testing of P22 and from the corresponding simulation with the Norton creep model are compared in Figure 26. At the beginning the relaxation according to the simulation is slower than according to the testing. The simulated normal stress becomes about 20 MPa higher than the stress recorded during the testing from about the twentieth hour until the end. To accurately simulate the normal stress relaxation it is clear from the graph that primary creep must be considered.

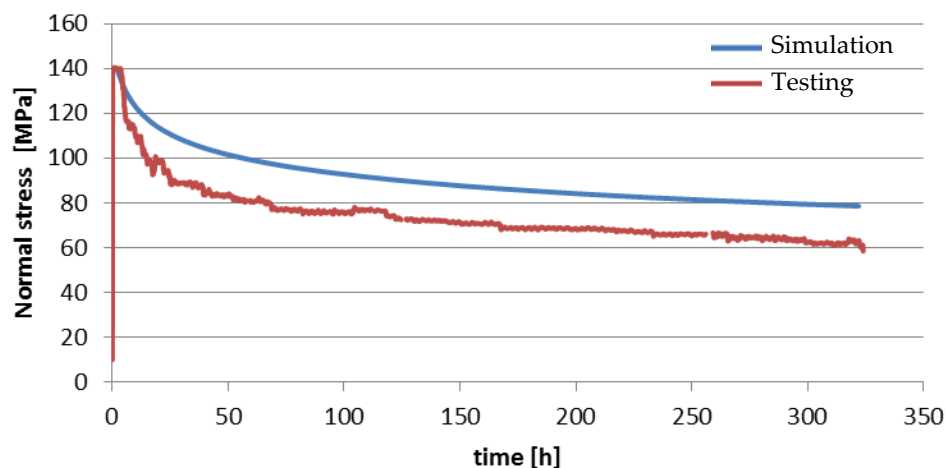


Figure 26. Results from stress relaxation testing of the first step of sequential testing of P22 and from the corresponding simulation with Norton model.

Combined time hardening creep model

The results from the first step of the sequential testing of P22 and from the corresponding simulation with the combined time hardening creep model are compared in Figure 27. The results from the testing and simulation are very similar. Looking closer at the first 20 hours a difference can be noticed just after the constant load phase, see Figure 27b. Here the relaxation according to the simulation is somewhat slower than according to the testing, but eventually the stress reaches the same level.

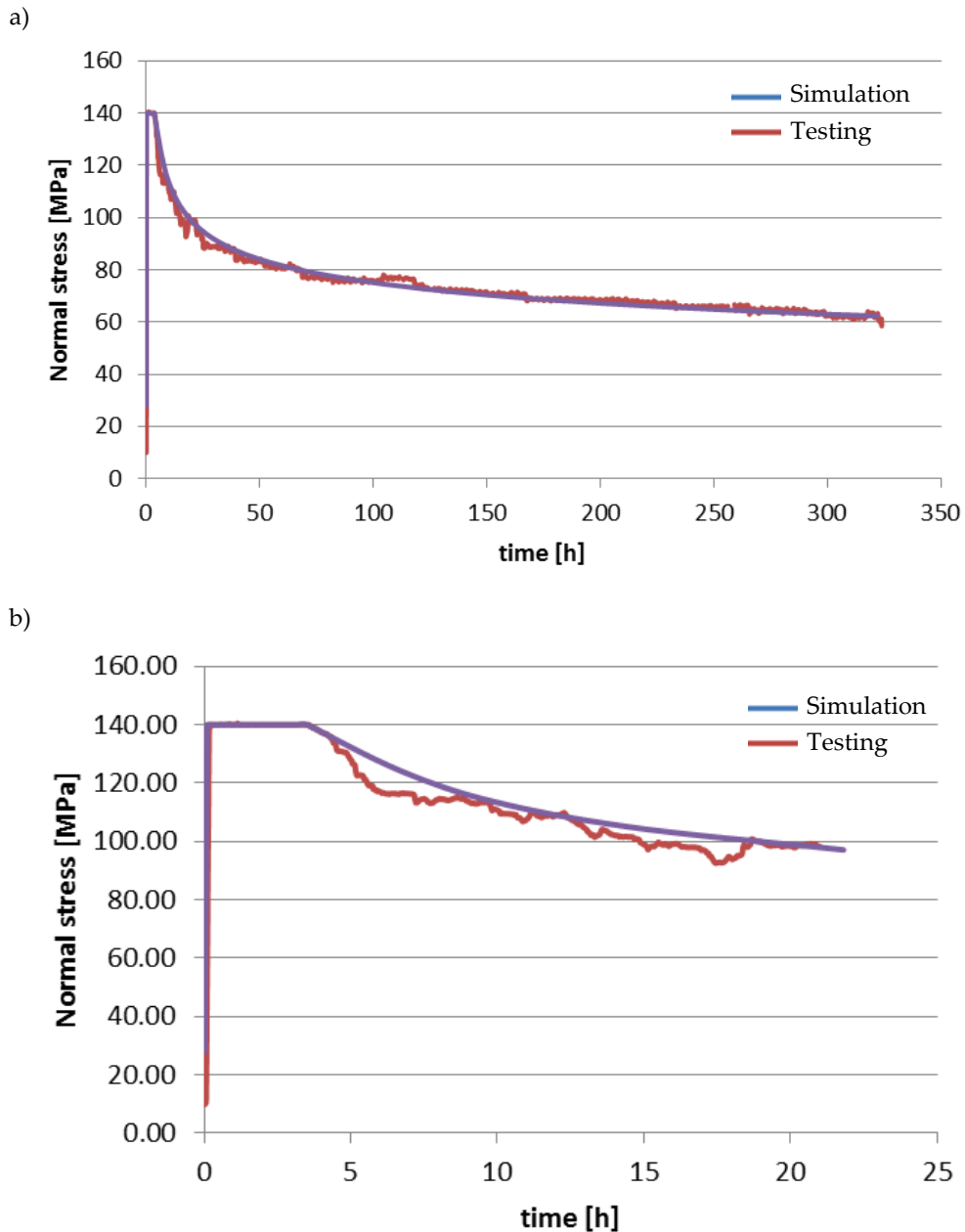


Figure 27. Results from stress relaxation testing of the first step of sequential testing of P22 and from the corresponding simulation with combined time hardening model, a) entire test period and b) close-up of initial test period.

The results from all steps of the sequential testing of P22 and from the corresponding simulation with the combined time hardening creep model, when simulated successively, are compared in Figure 28. The relaxation according to the testing is faster than according to the simulation at the beginning of step two and three. This suggests that some primary creep occur also during these steps. In Figure 29 the results from all steps of the sequential testing are compared again, but with the simulation results when each simulation is done separately, i.e. with primary creep effect at the beginning of each step. The results from the testing and simulation are now more similar.

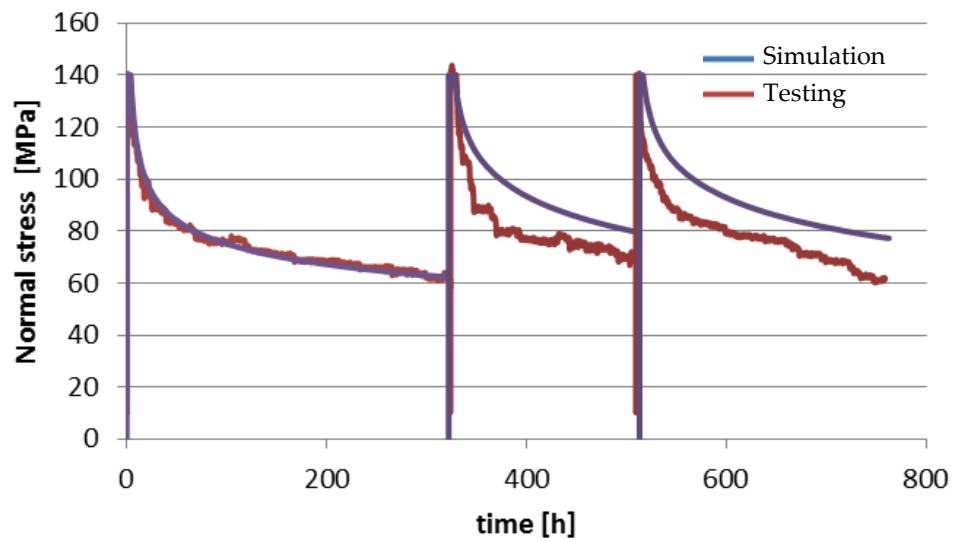


Figure 28. Results from stress relaxation testing of all three steps of sequential testing of P22 and from the corresponding simulation with combined time hardening model, when simulated successively.

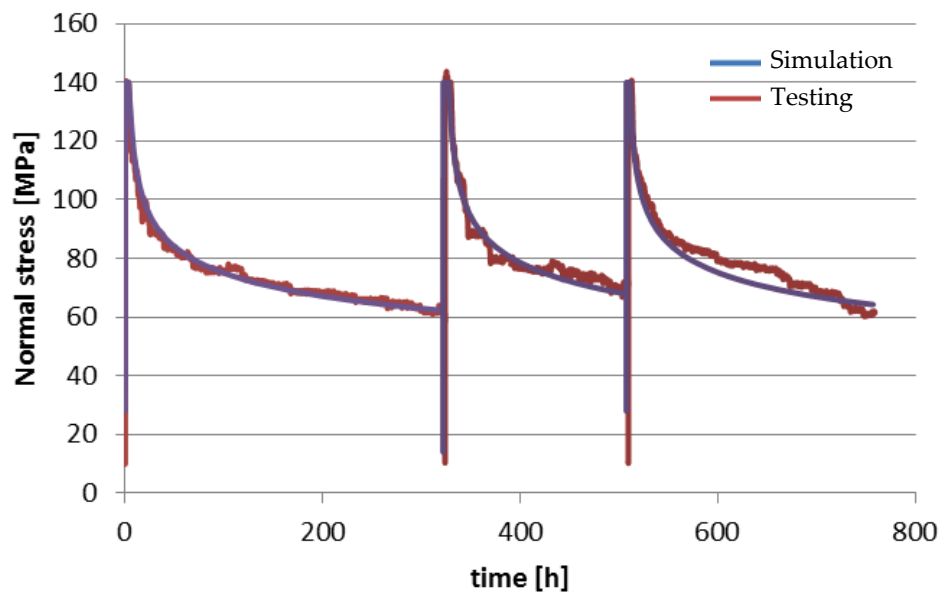


Figure 29. Results from stress relaxation testing of all three steps of sequential testing of P22 and from the corresponding simulation with combined time hardening model, when simulated separately and plotted after each other along the time-axis.

4.2 ALLOY P91

Combined time hardening creep model

The results from the first step of the sequential testing of P91 and from the corresponding simulation with the combined time hardening creep model are compared in Figure 30. The results are not identical but similar. Looking closer at the first 20 hours it is clear that the relaxation according to the testing is faster than according to the simulation during the first hours after the constant load phase. The final stress is about 85 MPa for both the testing and simulation.

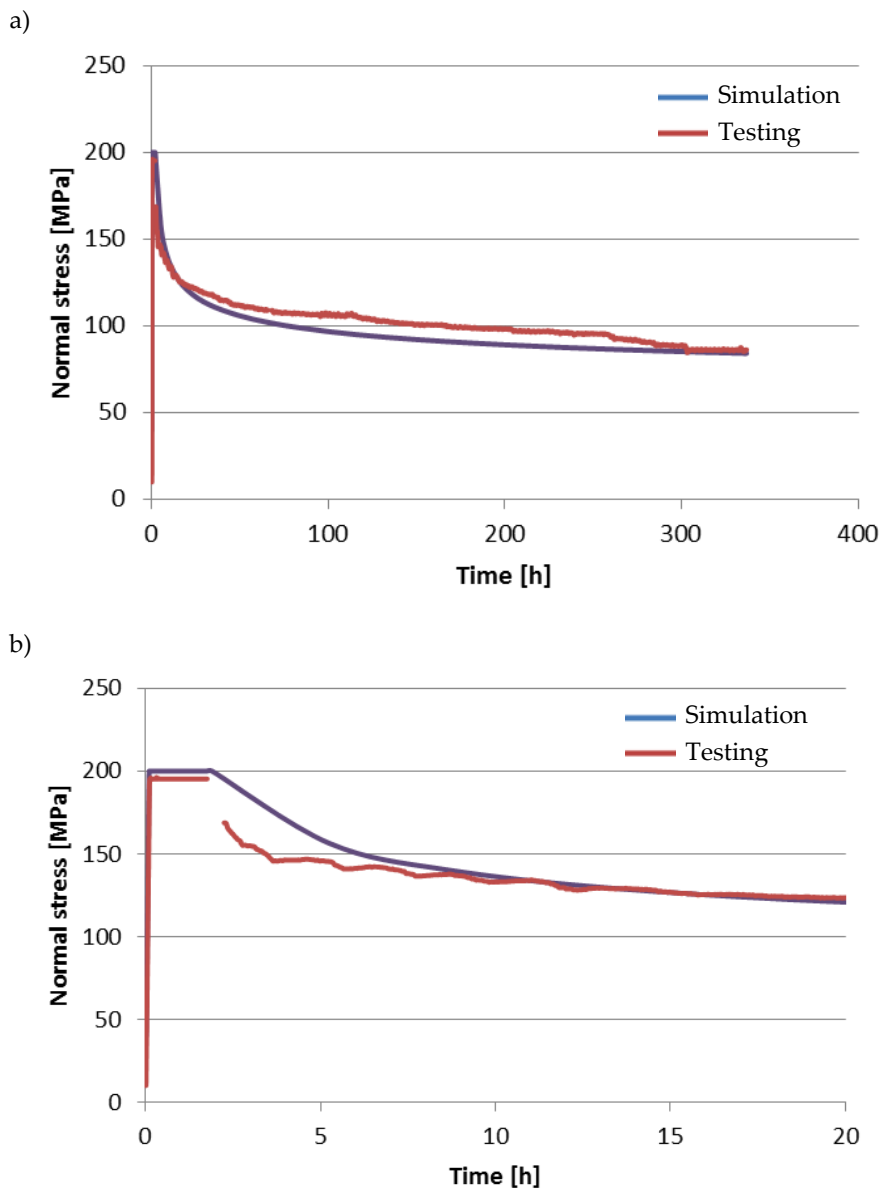


Figure 30. Results from stress relaxation testing of the first step of sequential testing of P91 and from the corresponding simulation with combined time hardening model, a) entire test period and b) close-up of initial test period.

The results from the second step of the sequential testing of P91 and from the corresponding simulation with the combined time hardening creep model, when simulated separately, are compared in Figure 31. The results are not the same for the testing and the simulation. The final stress for the testing is larger here compare to the first step, about 100 MPa, whilst the simulation final stress is again about 85 MPa. It is likely that the material relaxes less the second time it experience the load cycle. However, in the simulation the material is new at the beginning of step two and without any permanent strains from the first step. Hence, the simulation results in almost the same final stress. The holding times for the constant load phase are somewhat different between step one and two so the results are not exactly the same.

This pattern repeats for the final third step. The results are compared in Figure 32. The final value of the stress in the test is 115 MPa, whilst it is again about 85 MPa for the simulation. All three sequences are plotted after each other in Figure 33 for easy comparison.

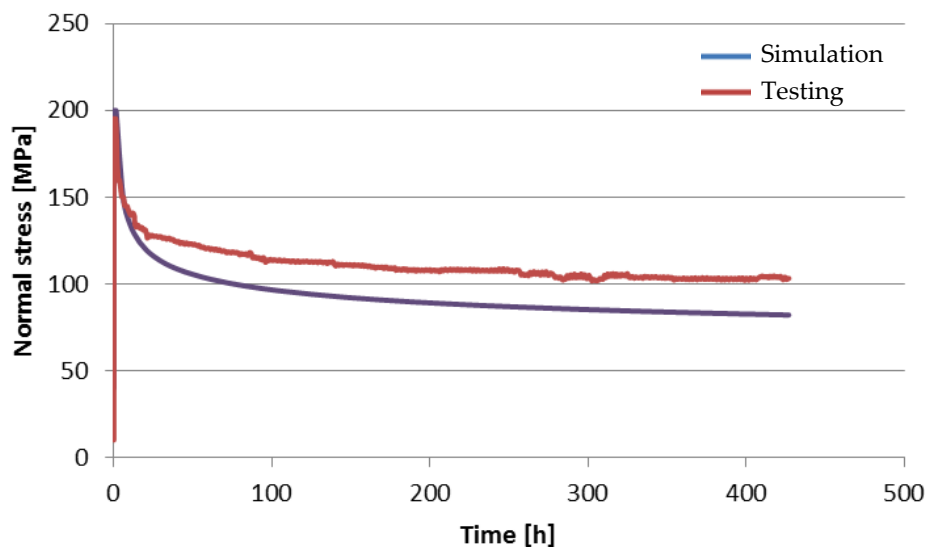


Figure 31. Results from stress relaxation testing of the second step of sequential testing of P91 and from the corresponding simulation with combined time hardening model, when simulated separately.

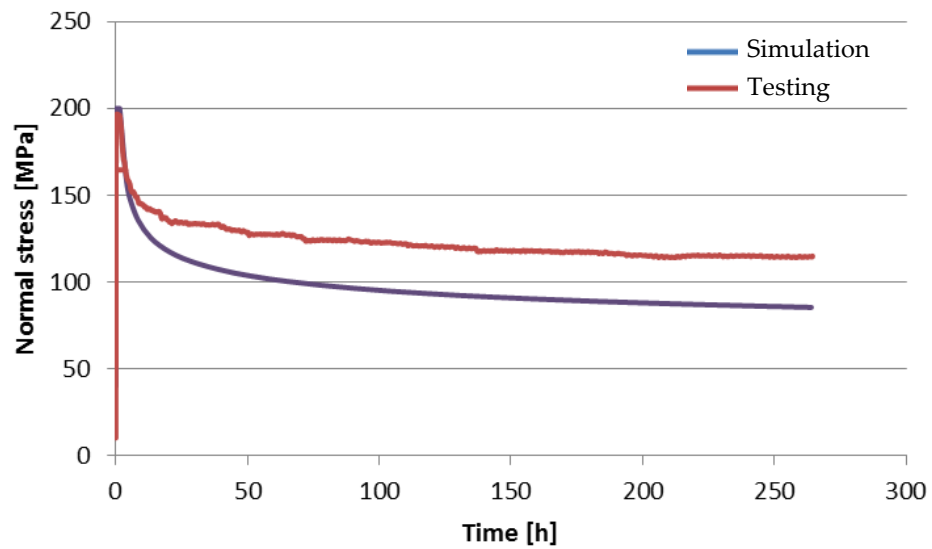


Figure 32. Results from stress relaxation testing of the third step of sequential testing of P91 and from the corresponding simulation with combined time hardening model, when simulated separately.

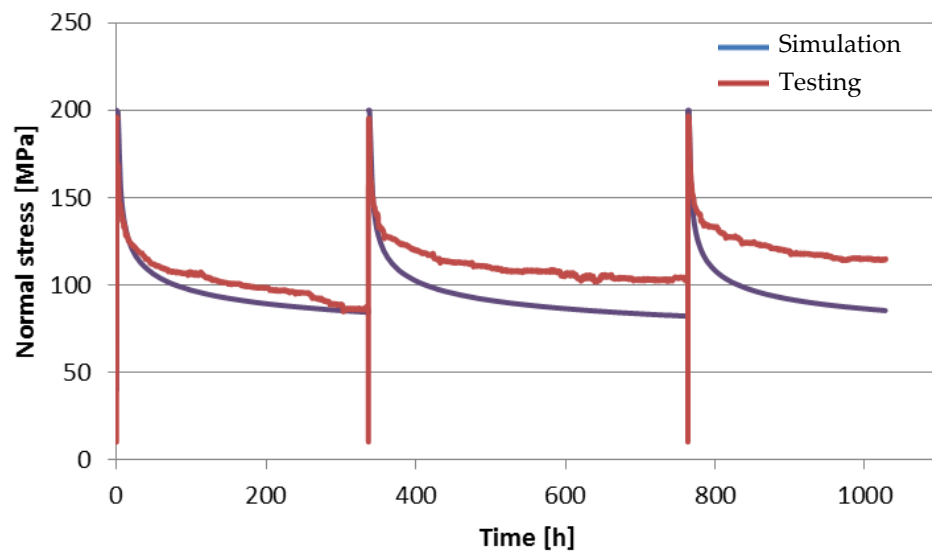


Figure 33. Results from stress relaxation testing of all three steps of sequential testing of P91 and from the corresponding simulation with combined time hardening model, when simulated separately and plotted after each other along the time-axis.

5 Discussion

5.1 STRESS RELAXATION AND CREEP STRAIN IN TESTS AND SIMULATIONS OF P22

Figure 33 and Figure 33 show that the combined hardening model that include both primary and secondary creep stages fits better with the experiments than the Norton model (secondary creep only). Consequently and as also can be seen in these figures, a larger amount of stress relaxation is also predicted for the combined hardening model than for the Norton model.

The stress relaxation plots in section 3 and 4 are all taken from the plain and undisturbed part of gauge well away from the radius between the gauge and the ridge, see Figure 33. In Figure 33 it can be seen that there is a red area which involves an enhancement of the creep strain that is due to the stress relaxation at the end of the test. Also the amount of stress relaxation is higher in this area although it is not indicated by the curvatures in Figure 33 and Figure 33. This is an effect of biaxiality since there are also stresses in the radial direction of the specimen at the radius. These radial stresses will influence the axial strain as shown in Figure 33.

However, the plot in Figure 33 is a result of the simulation by use of the Norton model. The corresponding plot when the combined hardening model is used is seen in Figure 33. The creep strain due to the relaxation, i.e. the elastic strain in the specimen that has been transformed to permanent creep strain, is considerably higher with this model. The creep strain at the gauge is $\sim 0.10955\%$ at the end of the simulation. Although the maximum strain, $\sim 0.11982\%$, is not indicated by colours in this plot it is in the same area as shown in Figure 33.

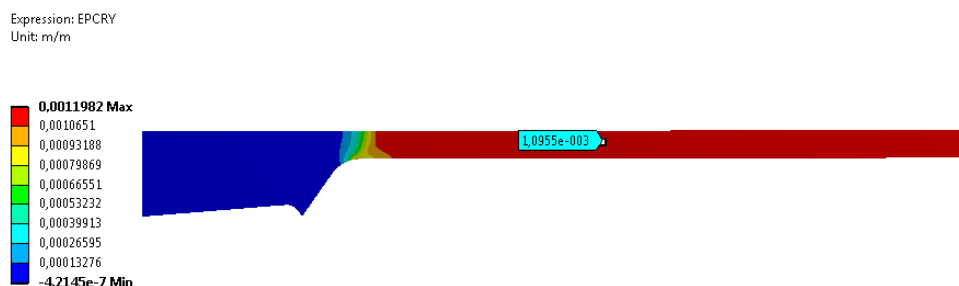


Figure 34. Resulting creep strain after the first step of sequential testing of P22.

Since the sequential test and the sequential simulation of P22 show good agreement to each other it can be concluded that there are no significant softening or hardening mechanisms involved by the testing with these three cycles. Further, the good agreement is a strong indication that the required error adjustment of the data in Figure 9 is adequate.

5.2 STRESS RELAXATION AND CREEP STRAIN IN TESTS AND SIMULATIONS OF P91

The differences between simulated and tested creep relaxation in the last two sequences of P91 can be explained by work hardening. The microstructure in P91 is complex, particularly during creep. By metallographic investigations of the test specimens it could be possible to investigate the relation between changes in the microstructure during the straining before relaxation and the hardening effects. These hardening effects could then be modelled and incorporated to an enhanced and more advanced creep relaxation model.

5.3 COMPARISONS TO MAIN STEAM PIPE OPERATION

For P22 all the three relaxation cycles gave approximately the same result although the plastic strains before the relaxation were different for each individual test. So were also the results for the sequential test. The explanation for this is that, as previously concluded, there is no significant hardening and softening effects. In such case it does not matter if the initial plastic strain is 0.25 %, 0.15 % or 0.10 % since it is only the elastic part of the strain that relaxes by creep.

In a main steam pipe system there may be thermal expansions that may introduce local plastic strains. However, since an elastic stress analysis is performed in the design review phase of a new or a reconstructed pipe system such high stresses in most cases would be detected and reduced before the start of the operation.

In operation the internal pressure and possibly also dead weight contribute significantly to the total stress. Thus, the thermal stresses relax asymptotically toward a stress level due to these two load components. Results of simulations of the main steam pipe system of P22 in Heleneholmsverket in Energiforsk project M12-218 showed that the elastic strains due to thermal expansion relaxed to a level that corresponded to the internal pressure in a few cold start cycles.

In pipe systems of P91, however, it is more detrimental if plastic strains would appear in the system as a result of thermal expansion. This is because the hardening effect results in slower stress relaxation and thus elevated stresses for significant periods in service which would involve reduced creep life, locally.

5.4 PROJECT GOAL FULFILMENT

The long term overarching goal of the project of creating good possibilities for safe and reliable operation of complex steam pipe systems throughout their entire life has been achieved through enabling the possibility of simulating the behaviour of the complete system under creep load with respect to shutdown periods based on real test data for repeated loading and stress relaxation. This allows a refined determination of the creep strain at the most affected positions, which makes it possible to specify the control interval more accurately and consequently also the possible need of component replacements.

The specific goals of obtaining data for stress relaxation of two commonly used materials and to study their behaviour during repeated loading and stress relaxation similar to a number of operation cycles for a CHP plant has been fulfilled through the performed testing. The obtained test data has been thoroughly evaluated through the comparisons to the FEM analyses. Recommendations are given in Section 7 for how to refine creep modelling of steam pipe systems through the use of the data.

6 Conclusions

From the performed tests and simulations the following conclusions are drawn that are considered general for comparable cases:

- The relaxation behaviour of P22 is independent on the initial plastic strain, since there is no significant hardening and softening effects.
- The Norton model is insufficient for simulating early stages of relaxation, since these include effect of primary creep. This results in rather large errors in the calculated stress levels even after long time, when primary creep is negligible.
- The combined time hardening model allows reasonably accurate modelling of the resulting stress during relaxation of material not previously exposed to stress relaxation, with the exception of the vary initial stages of relaxation.
- The combined time hardening model allows reasonably accurate modelling of the resulting stress during relaxation of P22 material even when exposed to previous stress relaxation cycles, since it did not show any hardening and softening effects.
- The way the combined time hardening model typically is implemented in FEM programs makes it require special attention to the time dependence of the creep and relaxation process, when used of for simulating cyclic events, such as repeated start-stops. Otherwise the primary creep effect may become inaccurate for all cycles but the initial.
- For accurate modelling of stress relaxation of P91 material exposed to previous stress relaxation cycles, it would be required to include a work hardening model.
- The observed work hardening effect of P91 is a reason for concern, since it results in slower stress relaxation and thus elevated stresses for significant periods in service which is likely to cause reduced creep life, locally.

7 Recommendations and exploitation

To accurately assess for a live steam system the important positions for replica testing and the time intervals for when to do this it is recommended to model the entire steam system with respect to creep. To ensure the accuracy of the results the effect of stress relaxation due to thermal expansion needs to be modelled adequately during the simulation. It is recommended that this shall be made by a combined time hardening model that considers both primary and secondary creep.

It is further recommended that the effect of at least three consecutive start-stop cycles shall be included in the assessment. It is stressed that the combined time hardening model requires special attention to be paid to the proper handling of the time dependence of the creep. During this work it was made by modelling the different cycles independently, which basically made the time variable to be reset for each cycle, resulting in the primary creep being calculated as for virgin material during every cycle.

This is a feasible method for simulation of stress relaxations where only elastic strains are involved in the thermal expansion. In case of a plastic strain component in the thermal expansion this is also a feasible method for the simulation of materials such as carbon and low alloy steels that do not harden or soften significantly at repeated cycling. However, for steels with a martensitic microstructure there is a deformation hardening mechanism that has to be analysed and considered in the simulation to obtain the correct effect of stress relaxation.

For the materials and temperatures used in this work, it is recommended to use the same material parameters as here. For other materials or temperatures these parameters need to be fitted to existing creep data according to the same method used in this work.

8 Future work

To further increase the accuracy of creep simulation of steam systems where stress relaxation contributes to the stress and strain distribution it is suggested that future work may include:

- Improving the quality of the simulation of the first hours of stress relaxation. This requires improving the simulation of early stages of primary creep. It is anticipated that this will require testing of primary creep and stress relaxation testing to give material data input for work involving improvements of the actual modelling.
 - Work related to primary creep simulation preferably should address not only the topic of stress evolution during stress relaxation, but the strain evolution during the preceding loading stage as well. This since refined strain determination would be valuable for assessment of the creep strain within the simulated components, which is a critical parameter for remaining creep life.
- Implementing the effect of work hardening of P91 into simulation models for steam systems made of this alloy. It is anticipated that this will require testing of primary creep and/or stress relaxation testing combined with metallographic analysis of the microstructure evolution during the testing to give material data input for work involving improvements of the actual modelling.
 - To properly implement the the effect of work hardening and other possible similar effects not identified during this work a broader investigation of these are required. This implies testing other loading cycles, with the first obvious choice being loading to the same strain during three consecutive stress relaxation cycles at constant temperature.
 - There could be a temperature influence on the effect of work hardening. As a first approach to investigate this, tests should be performed at different, but constant, temperatures. This should preferably be followed by a test scheme investigating what would be the effect of work hardening at one temperature and relaxation during another. This may better resemble the conditions of a boiler that frequently change between operation under full and partial load.
- Starts and stops influence the evolution of stresses and strains in a steam system as a result of creep due to stress relaxation. As a first approach life assessment is based on the developed creep strains over a number of cycles. It is recommended as a future work to investigate if there are additional negative effects on the remaining creep life originating from for example creep-fatigue or relaxation-fatigue interactions caused by the loading cycles.

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EFFECT OF STRESS RELAXATION ON CREEP OF STEAM PIPE SYSTEMS

Kryp är livslängdsbegränsande för delar i kraftvärmeverk utsatta för höga temperaturer. Noggrann bestämning av återstående livslängd kräver simulering av krypbeteendet i ångledningssystemet, varvid det är viktigt att beakta spänningsrelaxation.

Provning av spänningsrelaxation har utförts vid olika töjningsnivåer för rörmaterialen P22 och P91. Det har även utförts sekventiell provning där material genomgått spänningsrelaxation vid olika töjningsnivåer på ett sätt som efterliknar flera på varandra följande uppstartsperioder för en panna. För jämförelse har analyser med FEM av de sekventiella försöken genomförts.

Det påvisades att den ofta använda Nortonmodellen är otillräcklig för att simulera spänningsrelaxation, medan modellen "combined time hardening" ger rimlig noggrannhet vid modellering av nytt material. För noggrann modellering av spänningsrelaxation av P91 material utsatt för flera cykler av spänningsrelaxation, så krävs vidare arbete för att inkludera en hårdnandemodell.

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