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Simulation and Analysis of Data for Enhancing Low Cycle Fatigue Test Procedures

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Abstract

The simulation and analysis of data for enhancing low cycle fatigue test procedures is discussed in this report. The analysed materials are an austenitic stainless piping steel and an austenitic weld material. This project continues the work performed in 2003 and 2004. The fatigue test data treatment application developed within the project in 2004 for the preparation of the fatigue data has been developed further. Also, more fatigue test data has been analysed with the application than in 2004. In addition to this numerical fatigue simulations were performed with FEM code ABAQUS. With the fatigue test data treatment application one can e.g. both calculate cyclically certain relevant characteristic values, e.g. elastic range, and form a set of certain cyclical parameter values needed as a part of ABAQUS analysis input files. The hardening properties of metals were modelled with both isotropic and kinematic hardening models.

The further development of the application included trimming of the analysed data, and consequently trimming of resulting hardening parameters. The need for the trimming arose from the fact that the analysed fatigue test data presents some scatter caused by the limited accuracy of the test equipment and the sampling rate. The hardening parameters obtained from the application analysis results were used in the subsequent ABAQUS analyses, and then the fatigue test data were compared with the ABAQUS simulation results. After finding a procedure to trim result data to get smooth curves for cyclic hardening, hardening and softening could be reproduced in ABAQUS analysis with a reasonable accuracy.

The modelling of the fatigue induced initiation and growth of cracks was not considered in this study. On the other hand, a considerable part of the fatigue life of nuclear power plant (NPP) piping components is spent in the phase preceding the initiation and growth of cracks.

Key words

low cycle fatigue, steel, stainless, austenitic, material model, finite element model

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Preface

This report has been prepared under the research project INPUT VÄSYMA. The project is a part of SAFIR, which is a national nuclear energy research program. In the structure of SAFIR, this research project is a subproject of project INPUT, which is a part of a larger project system INTELI. INPUT stands for Reactor circuit piping, and INTELI stands for Integrity and lifetime of reactor circuits. The work was carried out at VTT Industrial Systems. VÄSYMA project was funded by the State Nuclear Waste Management Fund (VYR), Nordic nuclear safety research (NKS; NKS-R Framework) and the Technical Research Centre of Finland (VTT).

Espoo

Authors

Contents

1 Introduction

The simulation and analysis of data for enhancing low cycle fatigue test procedures is discussed in this report. The analysed materials are an austenitic stainless piping steel and an austenitic weld material. This project continues the work performed in 2003 and 2004, the results of which are reported in references /1,2/. The fatigue test data treatment application developed within the project in 2004 for the preparation of the fatigue data has been developed further. Also, more fatigue test data has been analysed with the application than in 2004. In addition to this numerical fatigue simulations were performed with FEM code ABAQUS. With the fatigue test data treatment application one can e.g. both calculate cyclically certain relevant characteristic values, e.g. elastic range, and form a set of certain cyclical parameter values needed as a part of ABAQUS analysis input files.

In the numerical analyses performed in this study with ABAQUS the type of considered fatigue data was low-cycle, and consequently only strain rate independent models were applied. The applied yield function was that of von Mises. The hardening properties of metals were modelled with both isotropic and kinematic hardening models.

The main emphasis in this study, however, was on the analyses performed with the fatigue test data treatment application, and further development of it. In 2004 only part of the fatigue data available to the project were analysed with the application. To obtain more accurate and representative estimates for kinematic hardening and cyclic hardening parameters needed in the ABAQUS analyses, considerably more constant amplitude fatigue test data were analysed with the application in 2005. The further development of the application included trimming of the analysed data, and consequently trimming of resulting hardening parameters. The need for the trimming arose from the fact that the analysed fatigue test data presents some scatter, which is also typical for any fatigue test data. This scatter is caused by the limited accuracy of the test equipment and by the duration of the time step between the measurement time instants (i.e. the cyclic stress-strain curves are not continuous, but are composed of a finite number of measurement points). The hardening parameters obtained from the application analysis results were used in the subsequent ABAQUS analyses, and then the fatigue test data were compared with the ABAQUS simulation results.

The modelling of the fatigue induced initiation and growth of cracks was not considered in this study. On the other hand, a considerable part of the fatigue life of nuclear power plant (NPP) piping components is spent in the phase preceding the initiation and growth of cracks.

The structure of this report is the following. After this introduction the report continues with presenting the goal of this study. A brief description of the characteristics of hardening and softening is presented then. The processing of the fatigue test data and procedures to estimate kinematic and cyclic hardening parameters are presented after that. Then the report moves on to describe the applied approaches in trimming the fatigue test data and the hardening parameters. A comparison of the ABAQUS simulation results to the fatigue test data is presented then. The report ends with conclusions and suggestions for future plans.

2 Goal

The main challenge in the project is to analyse data acquired in fatigue low cycle tests in a way to determine parameters for elastic-plastic analysis in ABAQUS FE-software. Fig. 2.1 illustrates fatigue test data as a stress-strain curve. Figs. 2.2 and 2.3 show illustrations of parameters required in FE-analysis to describe plastic behaviour of the material. Finally, Fig. 2.4 shows an example of results, i.e. the difference between test data and calculated data.

Another challenge is to develop a procedure to determine reliable parameters with an optimum amount of work. The task includes finding ways e.g. to optimise data acquisition during fatigue tests, to minimise processing of test data and to minimise validation analysis.

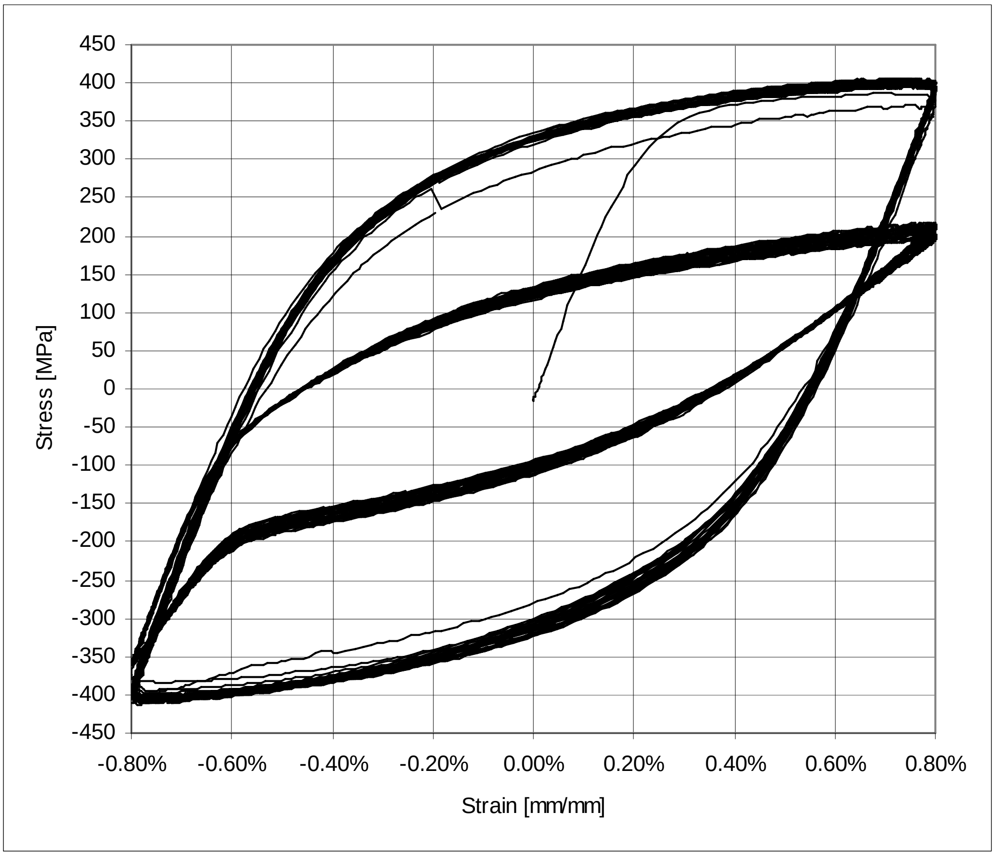


Figure 2.1 Sample stress-strain curve from fatigue test.

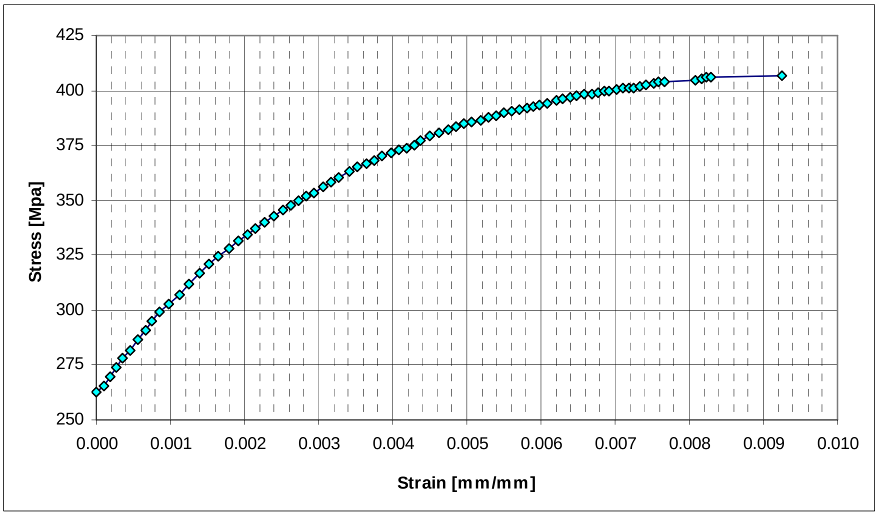


Figure 2.2 Sample kinematic hardening curve for ABAQUS analysis.

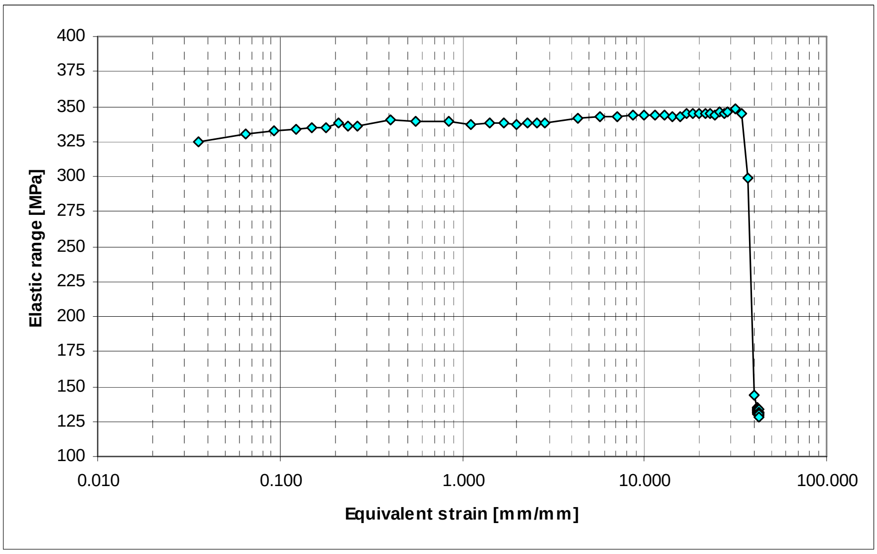


Figure 2.3 Sample cyclic hardening curve for ABAQUS analysis.

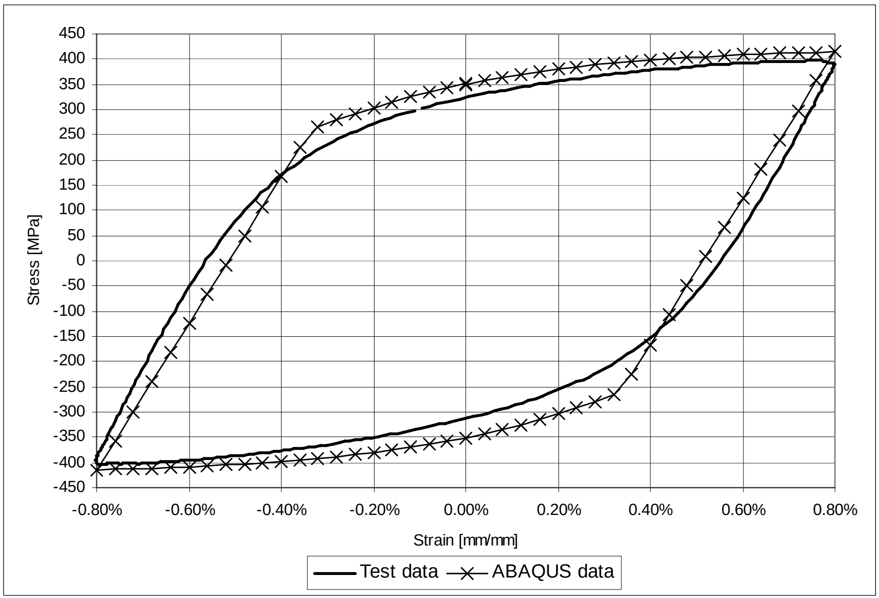


Figure 2.4 Sample comparison of test data and ABAQUS analysis data.

3 Hardening and softening during fatigue test

In commonly applied and generally accepted plasticity theory the basic concept with which material hardening and softening can be approached is the yield surface. More precisely, the yield surface is defined as the boundary of elastic range for rate-independent plastic material, in either stress or strain space. The shape of the yield surface depends on the entire history of deformation from the reference state. During plastic deformation the states of stress or strain remain on the subsequent yield surfaces. The yield surfaces for actual materials are experimentally found to be mainly smooth, although they may develop pyramidal or conical vertices, or regions of high curvature. If elasticity within the yield surface is linear and unaffected by plastic flow, the yield surfaces for metals are convex in the Cauchy stress space /3/.

In addition to stress distribution the yield surface is dependent of temperature and so called internal variables /4/.

The yield surface can change its size and shape in the stress space. When the yield surface expands it is said that material hardens, and when it contracts it is said that material softens. These two phenomena can be illustrated by looking at a case of uniaxial stress in two specimens of metal alloy analysed in this study, the stress amplitude curves of which are shown as a function of experienced load cycles in Fig. 3.1. Besides the steeply descending short end parts, during ascending curve parts the specimens harden and during descending parts they soften, i.e. during the former parts the yield limit rises, and during the latter parts it lowers. As mentioned above, both of these curves have abruptly descending, almost vertical end parts, during which macroscopic cracks first initiate, and then grow and coalesce, which finally leads to rupture of the specimens.

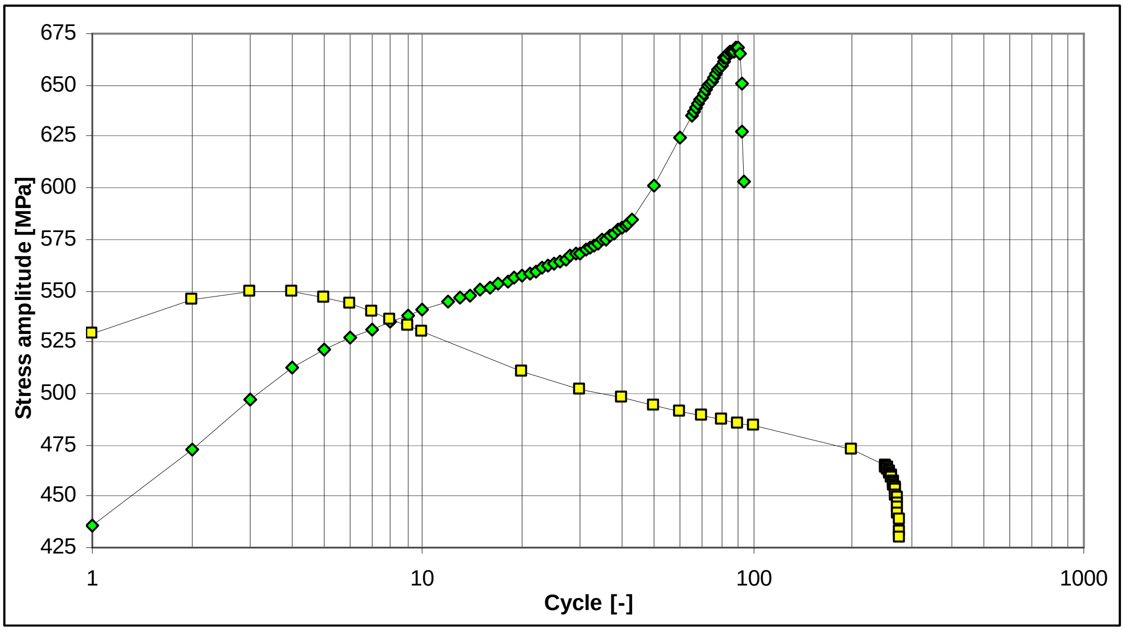


Figure 3.1. Samples of hardening and softening. Besides the steeply descending short end parts, during ascending curve parts the specimens harden, and during descending parts they soften.

Another and more detailed example of cyclic metal hardening and softening is presented in Fig. 3.2. In the enlarged detail figures of the various stages of hardening and softening the limits of accuracy of the test equipment start to show too, as most of the points forming the curve in question deviate slightly from the smooth curve path.

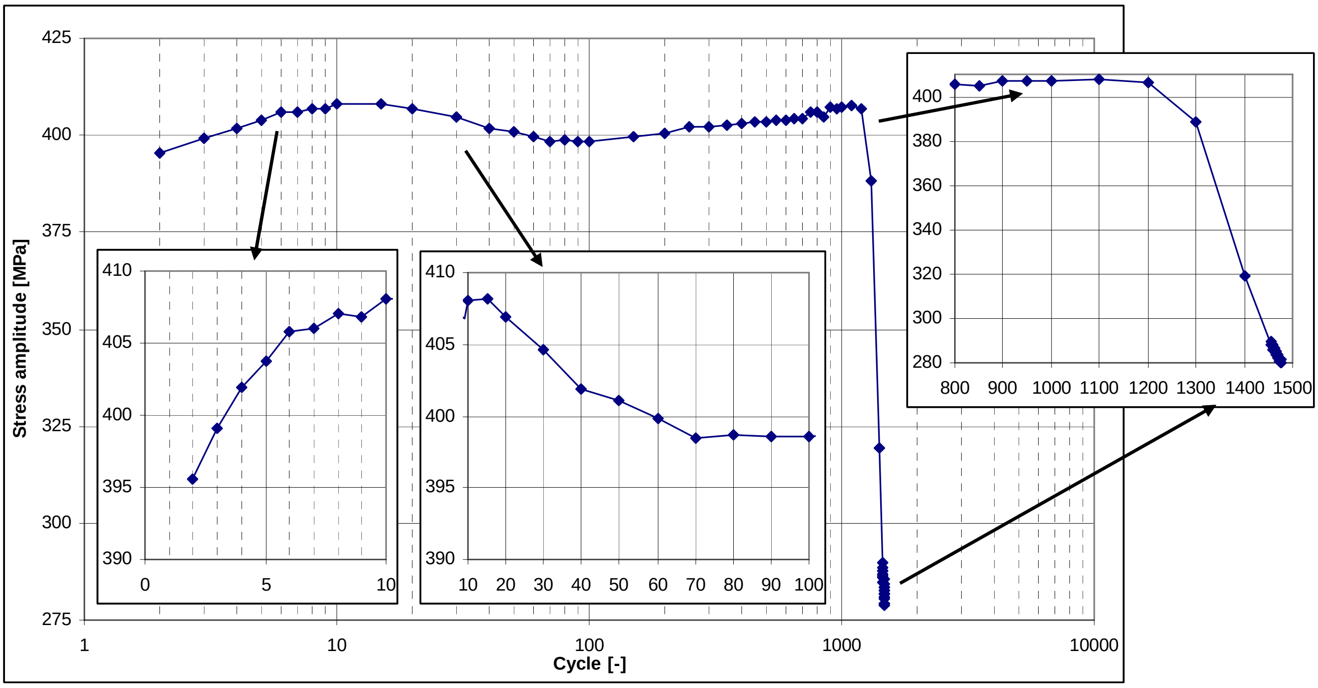


Figure 3.2 Stages of hardening and softening.

The dependence of the yield function on the internal variables describes usually the hardening/softening properties of the material /4/. In the simplest plasticity model ("perfect plasticity") the yield surface acts as a limit surface and there are no hardening parameters at all: no part of the model evolves during the deformation. However, complex plasticity models usually include a large number of hardening parameters.

Stress states that cause the yield function to have a positive value cannot occur in rate-independent plasticity models, although this is possible in a rate-dependent model.

Drucker defines a work-hardening, or “stable”, plastic material as one in which the work done during incremental loading is positive, and the work done in the loading-unloading cycle is nonnegative; this definition is generally known in the literature as Drucker’s postulate /5/.

The hardening described by the expansion of the yield surface in the stress or strain space is called isotropic, while that described by the translation is called kinematic. Many materials can show mixed behaviour, i.e. to a varying extent combined isotropic and kinematic work hardening/softening /4/.

In the following Figs. 3.3 to 3.5 are for the metal alloy analysed in this study examples of: cyclic hardening during the first load cycles, gradual softening during the consequent load cycles, and final hardening and breaking down.

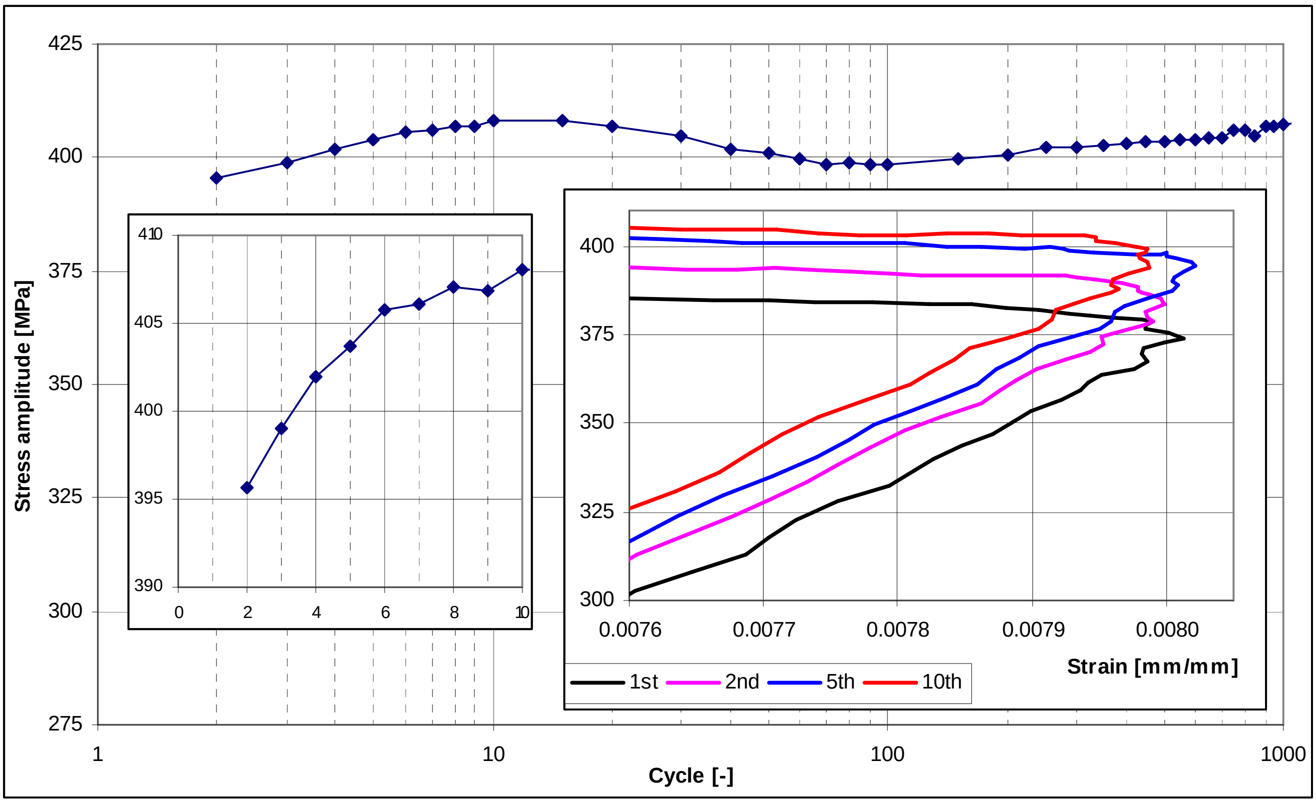


Figure 3.3. Hardening during the first load cycles.

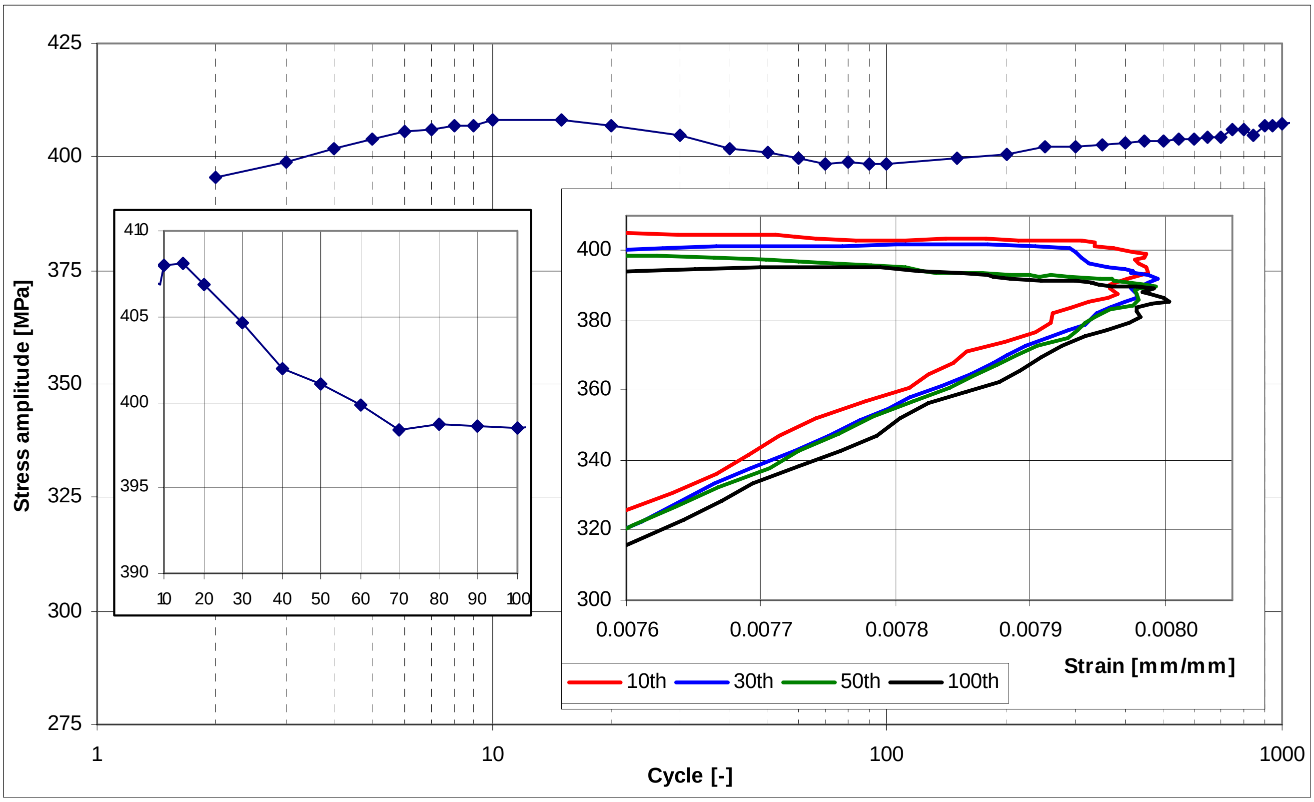


Figure 3.4. Gradual softening after the first load cycles.

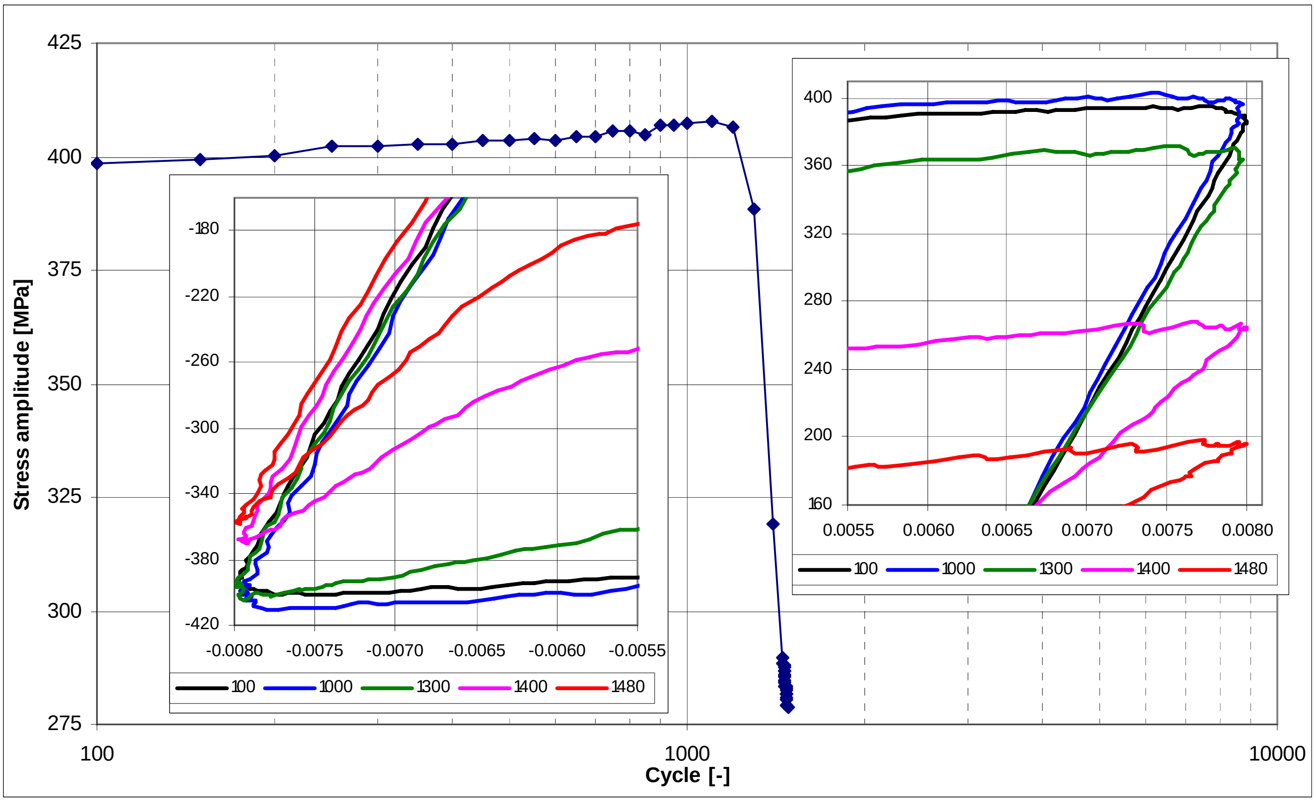


Figure 3.5 Final hardening and breaking down.

4 Definition of hardening parameters

4.1 Processing of the fatigue test data

In order to describe the behaviour of the material for ABAQUS analysis in forms of parameters illustrated in Fig. 2.2 and 2.3, the test data, i.e. stress-strain curves, have to be processed. A code to process the data all through the test duration was written as reported in reference /2/. Below (Fig. 4.1) there is a short description of the procedure. For each cycle the yield stress in compression is determined as the point where stress curve crosses a straight line corresponding the selected plastic strain (strain offset parallel to slope of the curve start). The elastic range is the difference between the peak stress and the yield stress. The yield stress in tension is the valley stress with the addition of the elastic range.

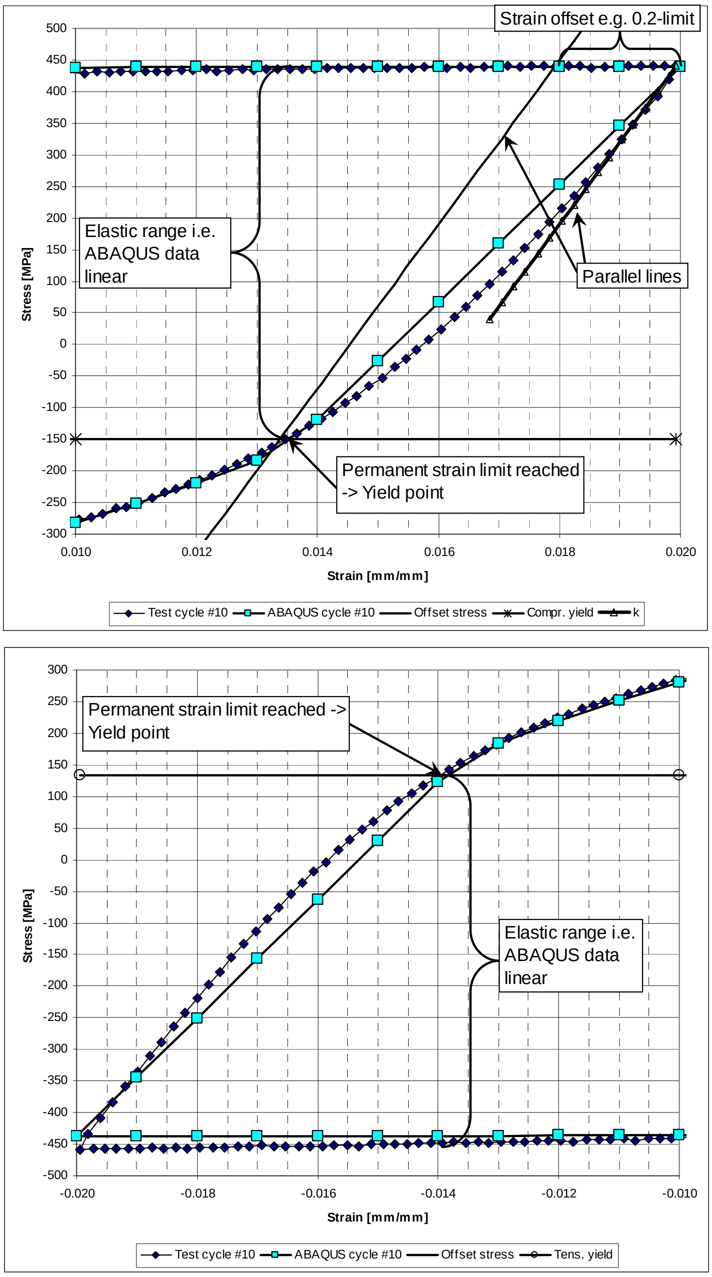


Figure 4.1 Graphical illustration of elastic range definition /2/.

4.2 Kinematic hardening

One of the parameters for ABAQUS analysis is the kinematic hardening. It describes the form of the stress-strain curve in the plastic zone. The tenth cycle is assumed to represent a stabilized cycle and is selected to describe the kinematic hardening. In reference /2/ there are a couple of results reported, but here all of the test data is considered. Fig. 4.2 shows the kinematic hardening of all the test data for austenitic base material. Tests were done with five different strain amplitudes, two of which having two or three tests. Lower strain amplitude tends to produce lower hardening, though the start point, i.e. yield stress, appears to vary so that the curves cross each other. The phenomenon is discussed later in Chap. 5.2 and Chap. 6, where test data and results from ABAQUS analyses are compared.

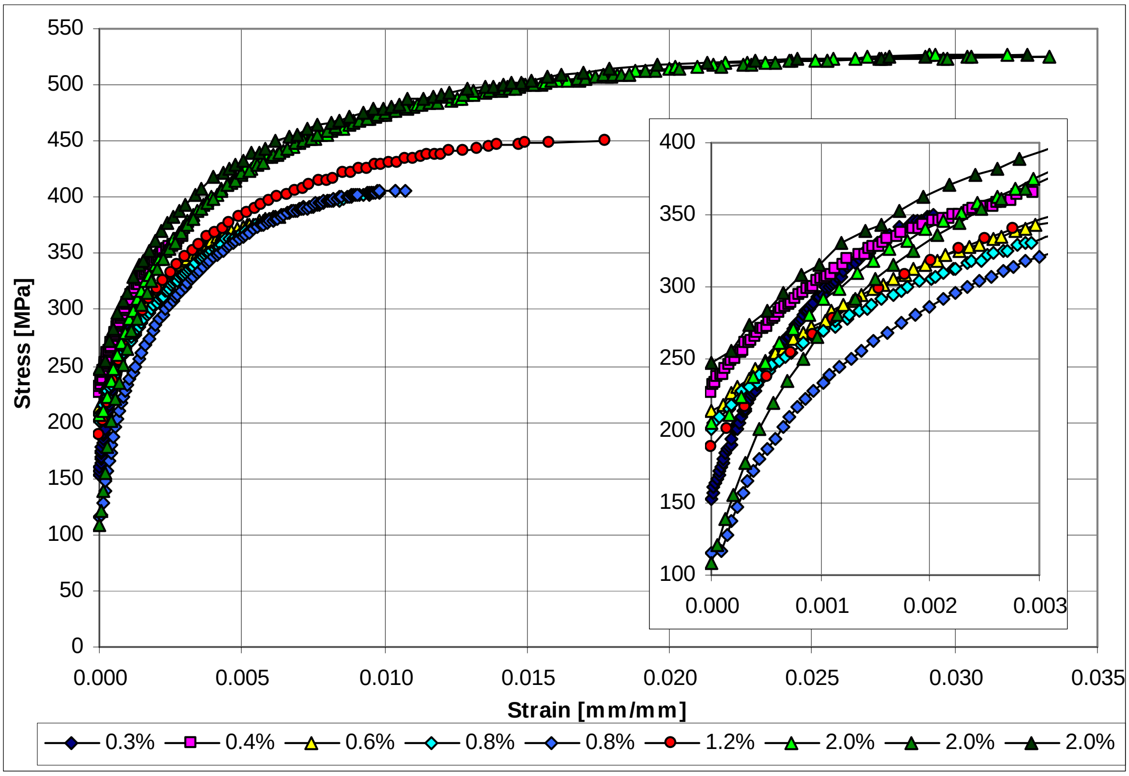


Figure 4.2 Kinematic hardening of austenitic base material with various strain amplitudes.

4.3 Cyclic hardening

Another parameter for ABAQUS analysis is the cyclic hardening. It defines the progress of the elastic range when loading is repeated. The cyclic hardening is described as the elastic range in stress units (MPa in SI units) per equivalent plastic strain in strain units (mm/mm). In reference /2/ a couple of cases are introduced. In this project all test data is gathered together. Fig. 4.3 illustrates elastic ranges per number of loading cycles and Fig. 4.4 the final cyclic hardening of an austenitic base material. As previously in Chap. 4.2, tests were done with five different strain amplitudes, two of which have two or three tests. The material has a hardening tendency, especially with high strain amplitudes. Fig. 4.5 shows the cyclic hardening of an austenitic weld metal, which tends to soften.

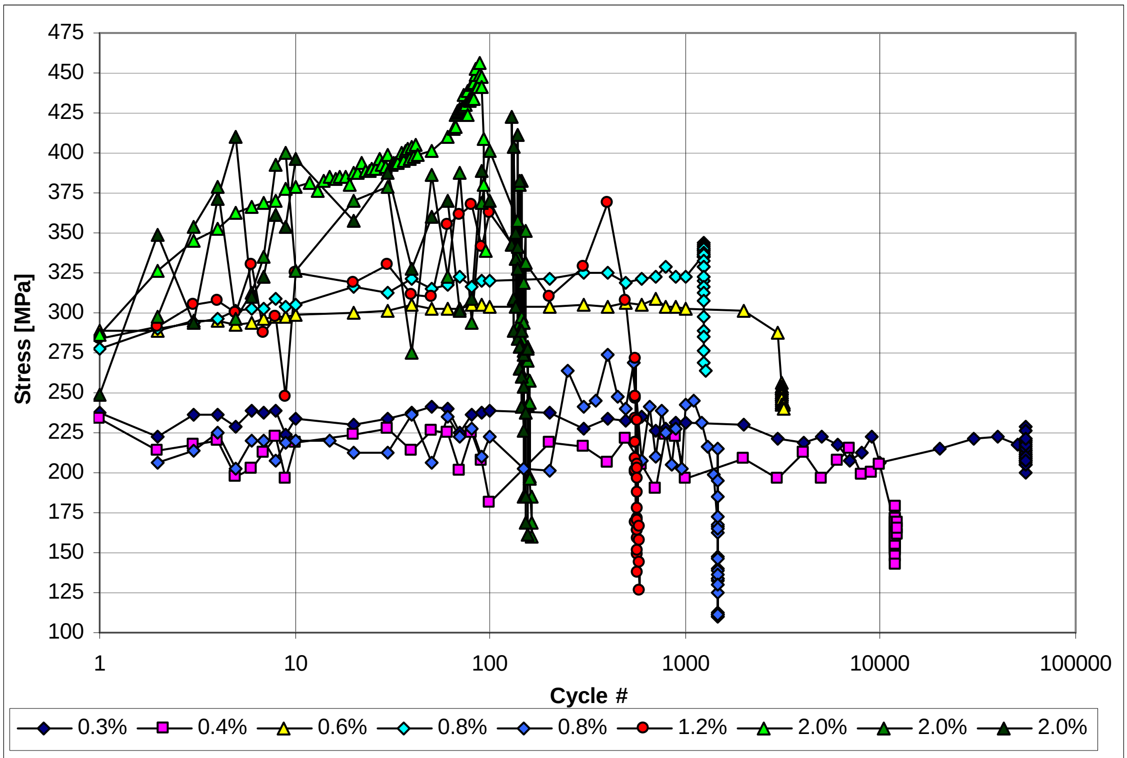


Figure 4.3 Elastic ranges of austenitic base material with various strain amplitudes.

The diagrams of cyclic hardening for both materials seem to have more or less of scattering of data. In some cases the elastic range seems to vary smoothly, whereas other diagrams are strongly fluctuating. The next chapter deals with the need of trimming data and procedures how to trim.

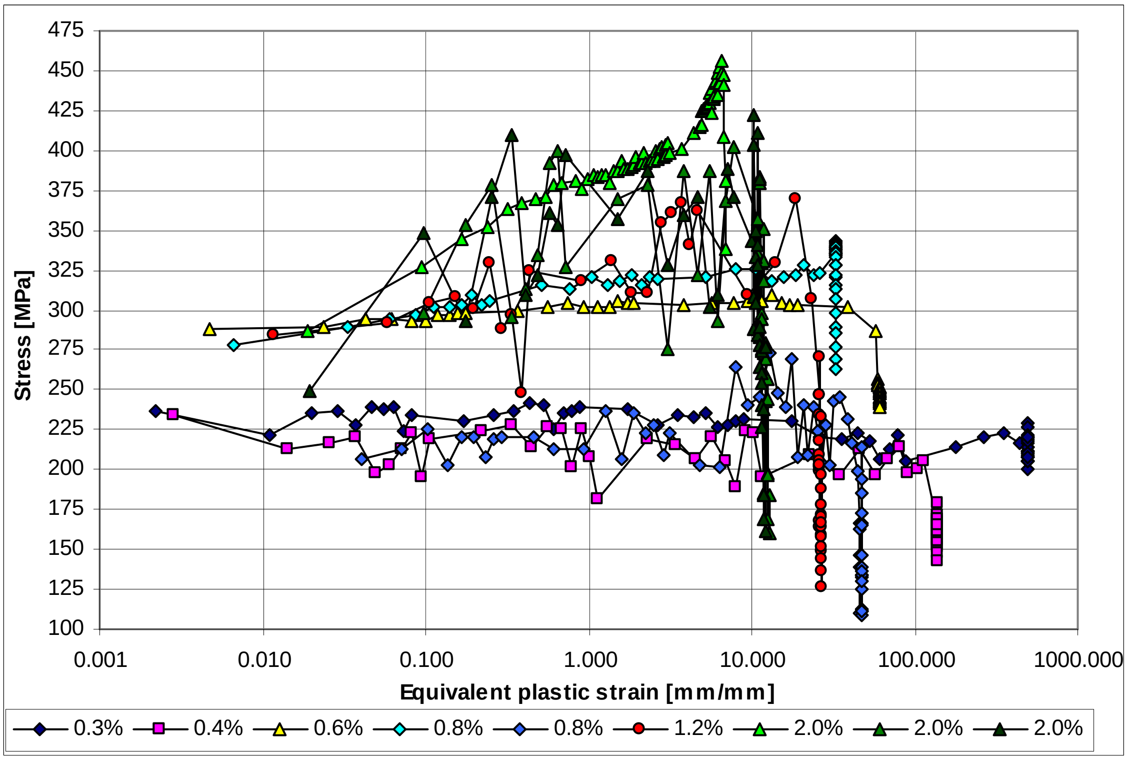


Figure 4.4 Cyclic hardening of austenitic base material (hardening tendency).

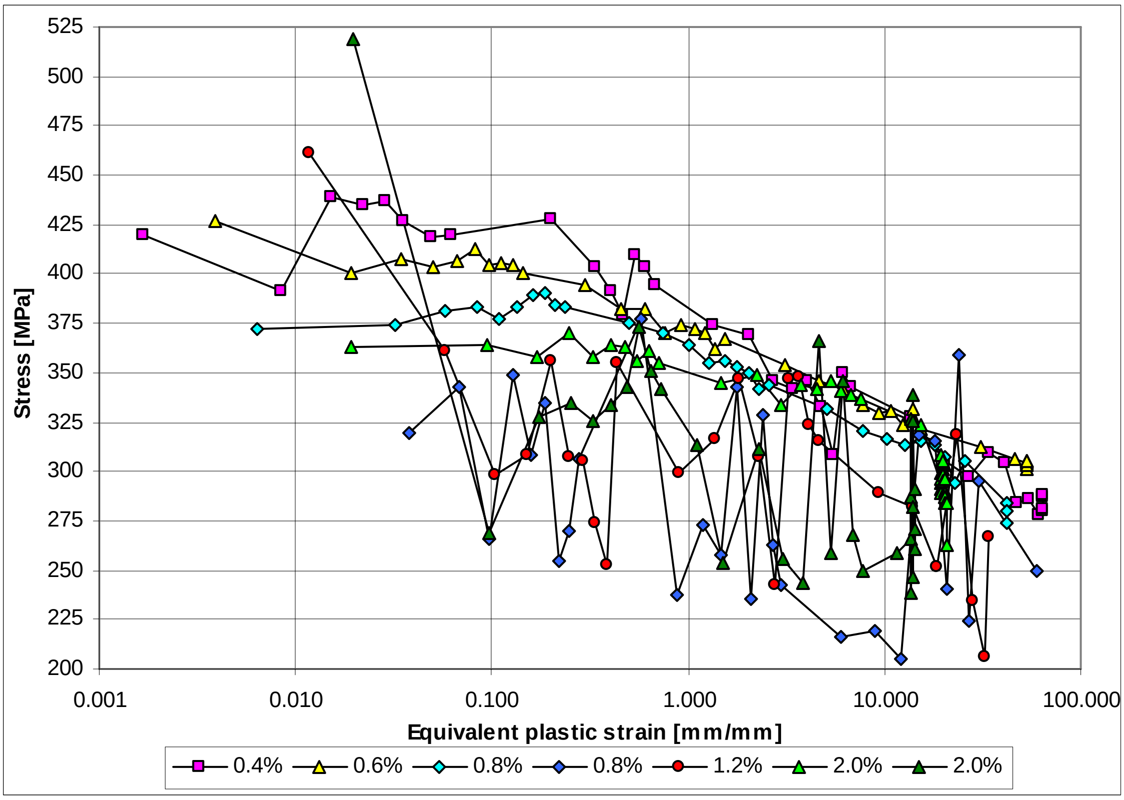


Figure 4.5 Cyclic hardening of austenitic weld material (softening tendency).

5 Trimming of the parameters

5.1 Needs to trim data

The developed code is able to process all cyclic data of a fatigue test with symmetrical strain amplitude. The output is, however, either smooth or fluctuating, as illustrated in Figs. 4.4 and 4.5. As for the stress amplitudes, the diagrams are smooth, which means that hardening and softening do not progress in a fluctuating manner. Therefore, there is a need to take a closer look at the data to reach smooth diagrams for the cyclic hardening. Two approaches have been taken into consideration, the first of which requires pre-processing of results but the latter one is written in the code.

5.2 Average ratio of stress amplitude and elastic range

There are two kinds of diagrams of cyclic hardening: smooth and fluctuating. Fig. 5.1 (left) illustrates a sample of smooth diagrams for elastic range. There are also the stress amplitude and ratios of the stress amplitude and elastic range. Fig. 5.1 (right) is a similar chart of a sample with a strongly fluctuating elastic range. In Fig. 5.1 (left) the ratio remains rather stable, whereas in Fig. 5.1 (right) there is a large deviation. The approach to trim the diagram of the elastic range is to define an average value for the ratio and to define a modified diagram for the elastic range. The approach includes an attempt to simplify the trimming. There are statistical tools to process all data, but the attempt was to limit the processing to the first ten cycles. The basis for the limitation is the idea that only the first ten cycles would be studied thoroughly and the rest could be processed using the average ratio and stress amplitudes, which data is easily obtained from fatigue tests.

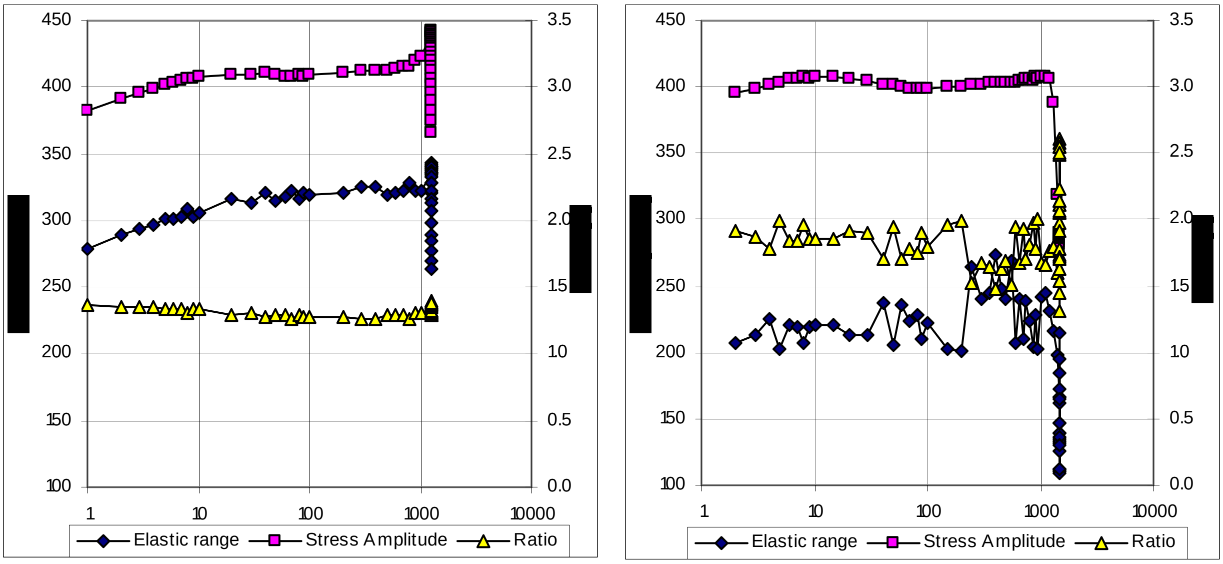


Figure 5.1 Ratio (Stress amplitude/Elastic range) with a small deviation (left) and a large deviation (right).

Fig. 5.2 shows ratios with average values of the first and tenth value. In Fig. 5.3 there is an example of a modified elastic range. The form of the diagram is the same as the stress amplitude. In Chap. 6.1 there is a sample ABAQUS analysis that shows the accuracy of this trimming procedure.

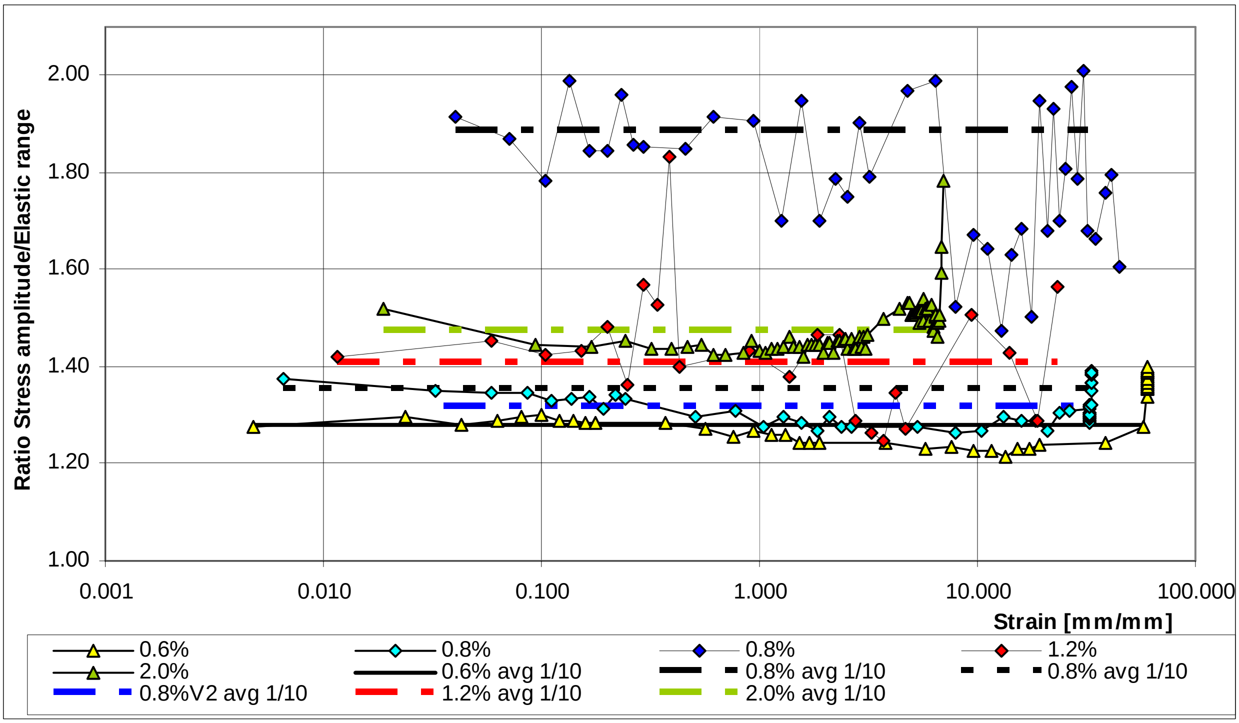


Figure 5.2 Ratios (Stress amplitude/Elastic range) and average values.

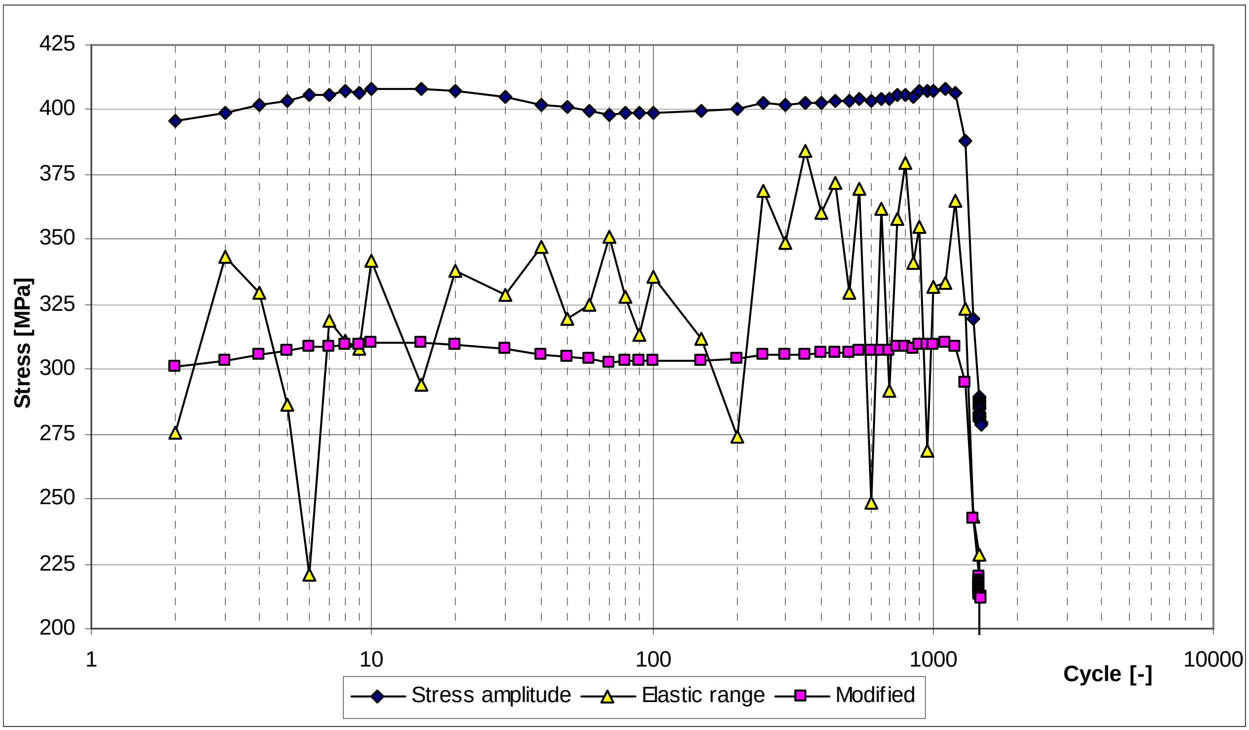


Figure 5.3 Elastic range modified using stress amplitude and average ratio.

In Fig. 5.4 there are modified diagrams for cyclic hardening of an austenitic base material with various strain amplitudes. The two diagrams for strain amplitude 0.8% are close to each other whereas in Figs. 4.4 and 5.1 there is a gap of ca. 100 MPa between them. They are supposed to lie close because their stress amplitudes are nearly the same and the kinematic hardening is supposed to be similar. Therefore the cyclic hardening should not differ. In fact, these two tests were cases that lead to consider trimming procedures.

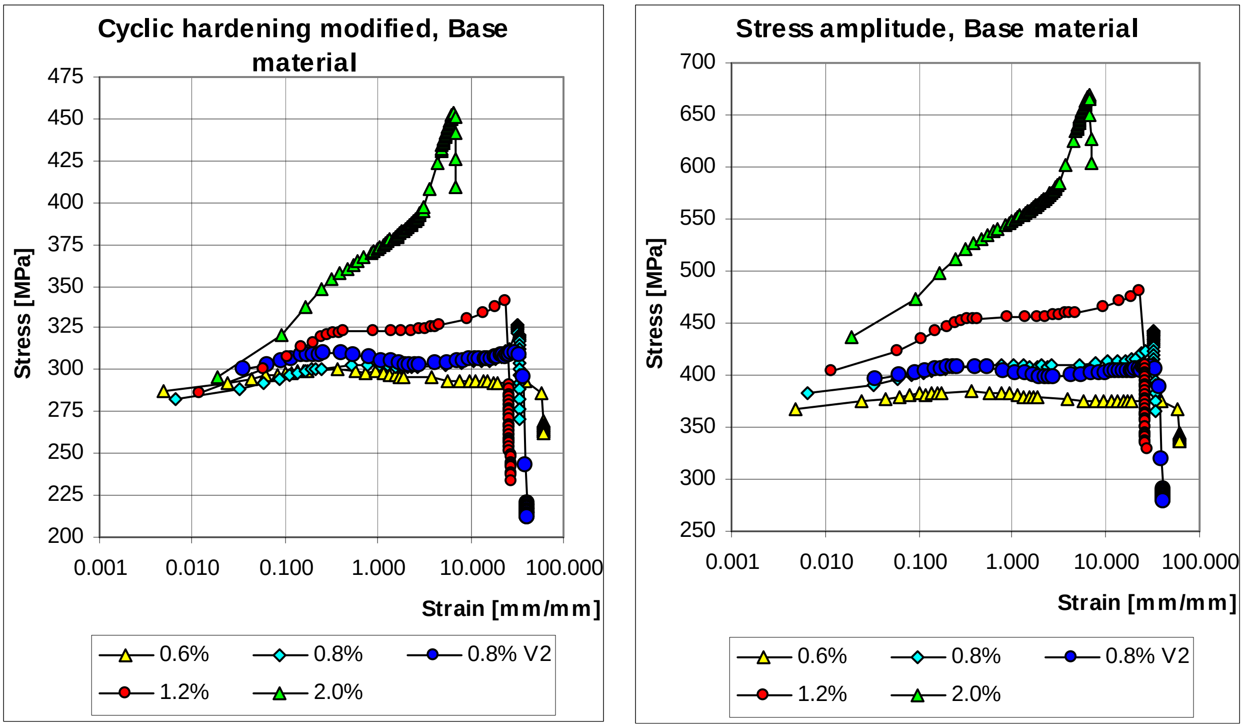


Figure 5.4 Cycling hardening modified using stress amplitudes and average ratios.

5.3 Definition of elastic range by constant elastic modulus

When taking a closer look at the cycles of the two tests with the same strain amplitude, one can see the difference between the resolutions of the data. Fig. 5.5 is a magnification of the peak and valley of the tenth cycle of a test where the strain rate was low. Scattering is absent, peak and valley points are accurate and slopes can be defined easily. In Fig. 5.6 data scattering is prominent at peaks and valleys due to effects caused by a higher strain rate. Note, that a different strain rate had no effect on material behaviour, as the stress amplitude and lifetime were close nearly the same in the two tests. In Fig. 5.6 there are illustrations of various possibilities to define the slope - and possibilities to get various inaccurate ones. The first versions of the code defined the slope like the blue line causing narrow elastic ranges. By adding calculation points various options were obtained, but like the green line shows the result was not adequate. By fixing the peak point to the absolute maximum stress and strain values the accuracy could be enhanced but still a variation of slopes could be reached: the red lines illustrate sample values.

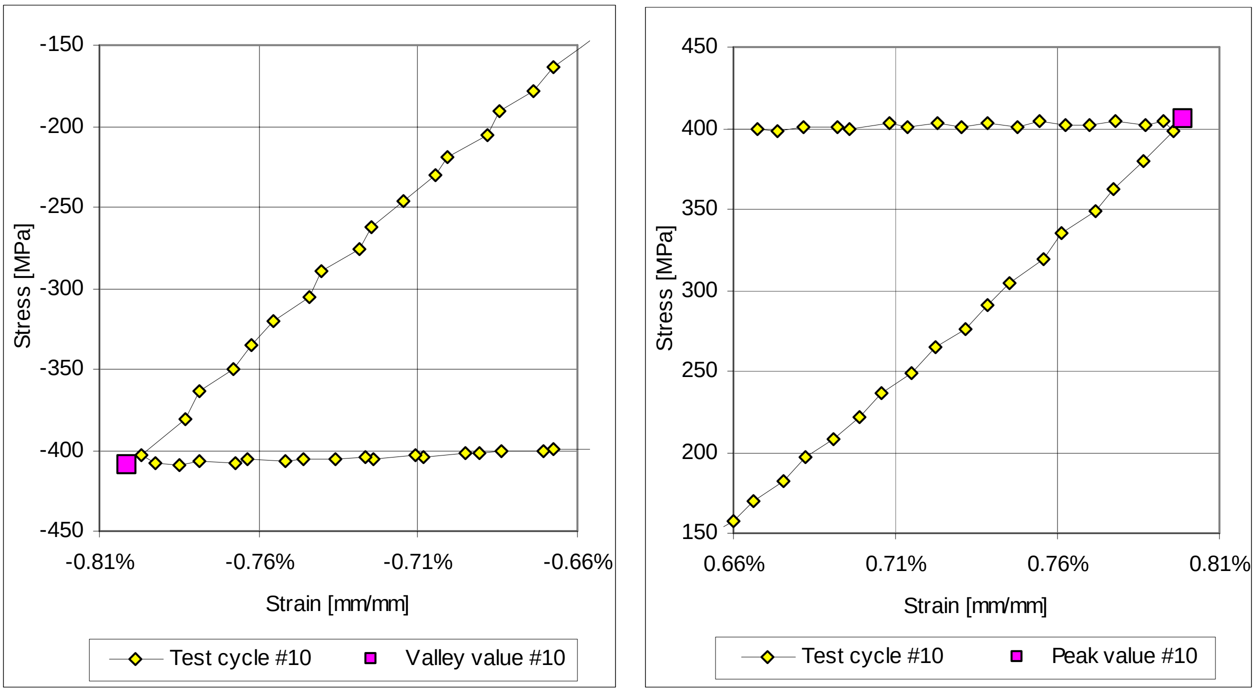


Figure 5.5 Data points at cycle valley and peak with no scattering.

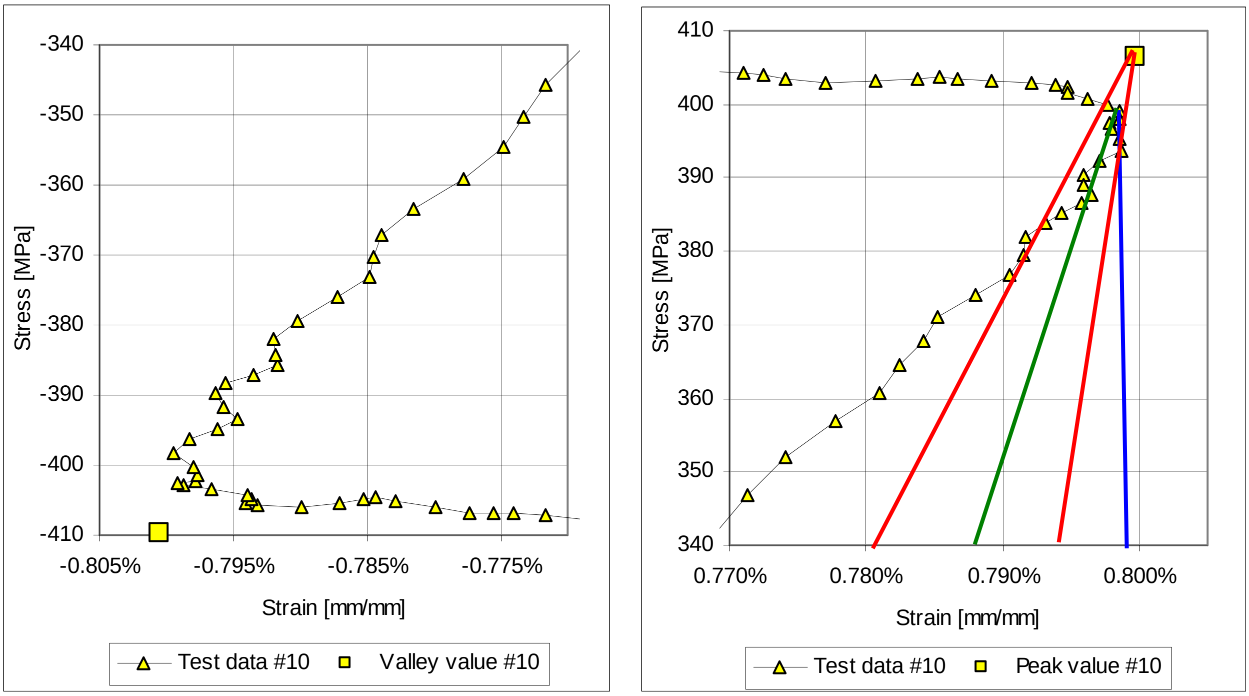


Figure 5.6 Scattered data points at cycle valley and peak illustrated with various slopes.

Fig. 5.7 shows a case where the peak point is fixed to maximum values and the slope is calculated with an average value of the first five points of the falling edge of the curve. The differences between cycles reveal that the scattering of data points is irregular. The result is that the progress of elastic range is vague. In Fig. 5.7 there is also the elastic modulus as defined from the start of the test data. Most of the slopes are greater than the elastic modulus but there are some lower values as well.

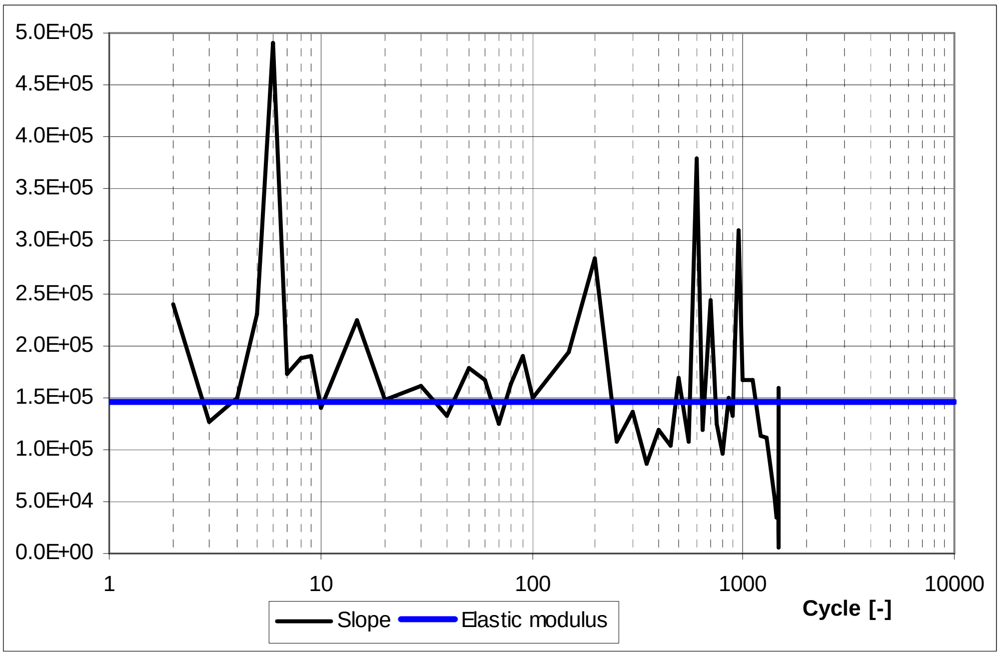


Figure 5.7 Slopes vs. elastic modulus.

Fig. 5.8 illustrates the form of cycles from ABAQUS analysis. Within the elastic range ABAQUS uses the elastic modulus for the material. Hence, a reasonable approach is to define the cyclic hardening with a constant slope, i.e. with the elastic modulus. Fig. 5.9 shows that the curve for cyclic hardening is smooth when elastic range is defined with the elastic modulus. The values are also higher in this case. The differences to test data are represented in Chap. 6.1.

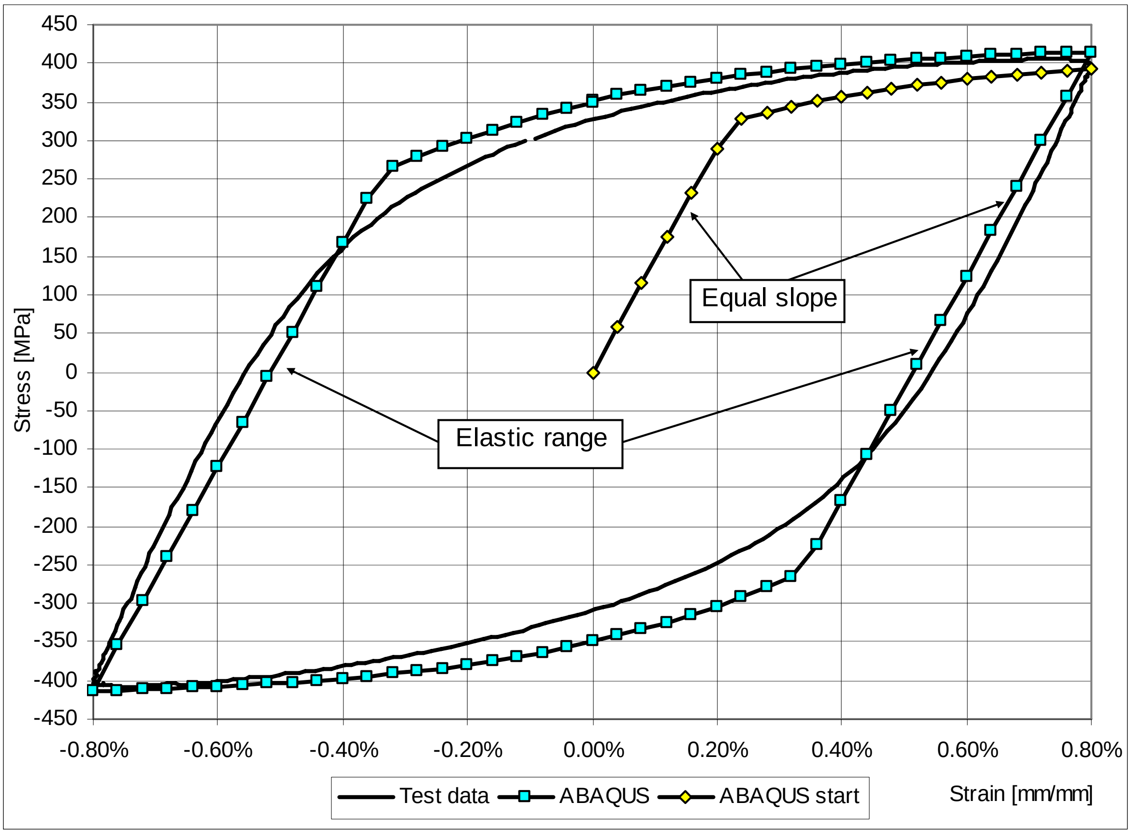


Figure 5.8 Schematic cycle from ABAQUS analysis compared with test data.

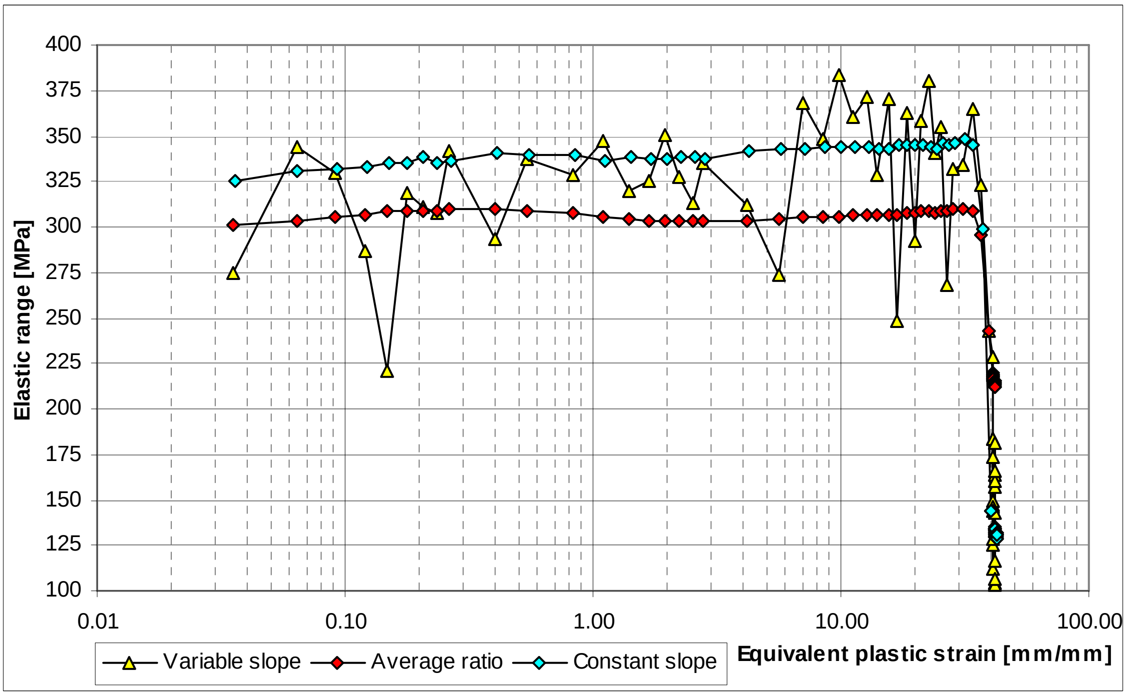
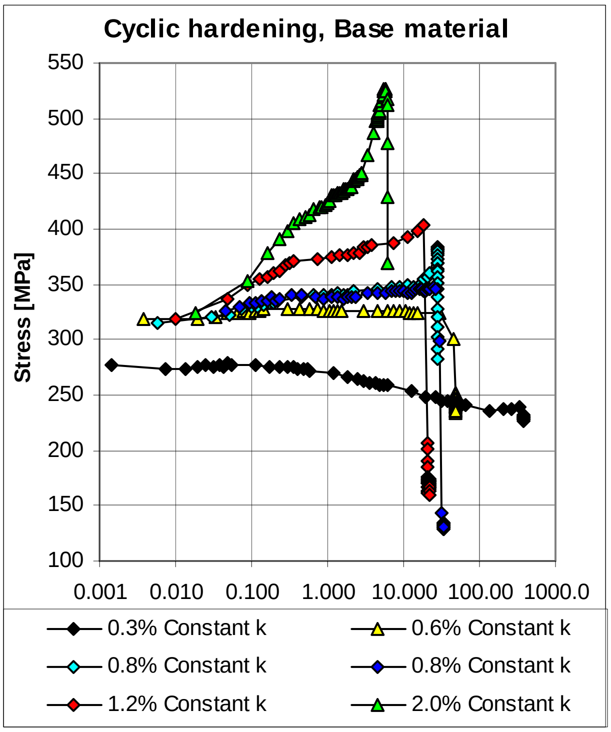


Figure 5.9 Difference between cyclic hardening defined with different approaches.

The curves for cyclic hardening of an austenitic base material with various strain amplitudes are gathered in Fig. 5.10. In some cases there may appear a deviating point in the curve. In that case the combination of the two approaches is helpful: first, the elastic ranges are defined using constant slope and subsequently the curve is smoothed using an average ratio.



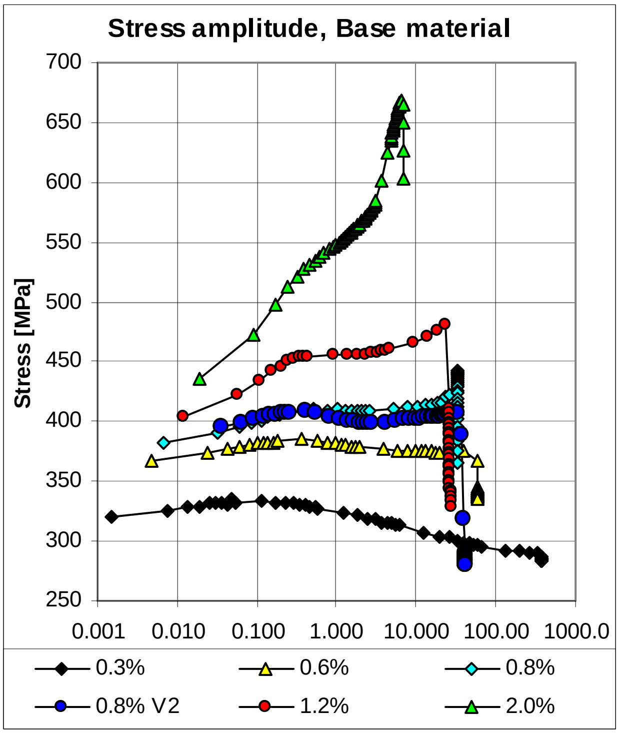


Figure 5.10 Cyclic hardening using stress amplitudes and constant slopes.

When using the elastic modulus as a constant slope the kinematic hardening had to be redefined, while the yield stress was shifted. Naturally, there is no need for redefinition when data is processed using a constant slope from the start. Fig. 5.11 shows the curves for kinematic hardening with constant slopes. Compared to Fig. 4.2 the yield stresses are higher and the deviation between the strain amplitudes is smaller. Furthermore, the curves do not cross each other like in Fig. 4.2 where the slopes are somewhat indeterminate.

The curve for strain amplitude 0.3% deviates obviously, because the yield stress was defined using a different yield criteria *viz.* 0.1% strain instead of 0.2% (strain offset in Fig. 4.1). This was done because of the low degree of plastic deformation with strain amplitude 0.3%.

The fact that ABAQUS requires a throughout ascending curve for kinematic hardening leads to a need to filter the scattering illustrated in Fig. 5.6. The code omits a value lower than the previous one when proceeding from the yield point to the peak (visible in Fig. 5.11 as larger gaps between data points). Moreover, if the data point with the highest strain value has a stress value lower than the latest one in kinematic hardening curve, the code adds a data point calculated with the largest strain value and the absolute maximum stress value of the cycle.

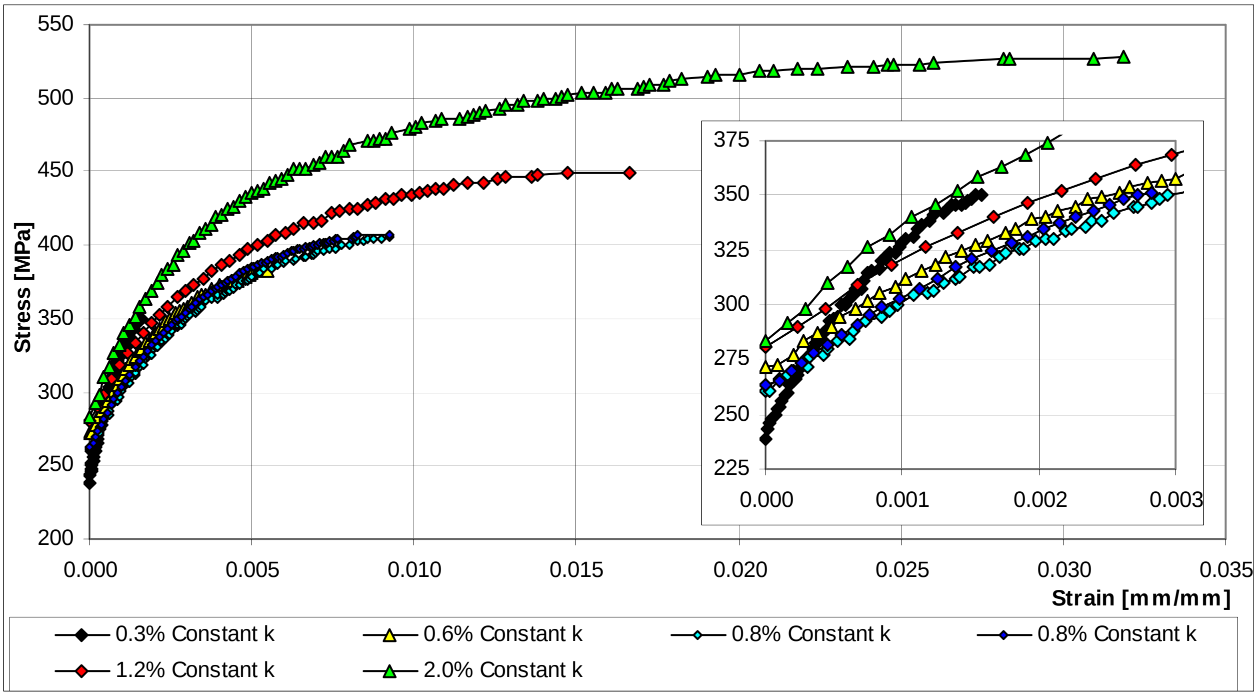


Figure 5.11 Kinematic hardening using constant slopes.

6 Compatibility with test data

A stress-strain curve from an ABAQUS analysis contains two parts: linear elastic and plastic. The form of the plastic part is defined by kinematic hardening and the level of the highest stress by cyclic hardening. The transition from elastic to plastic part is fit according to the two parameters. Fig. 6.1 illustrates a sample stress-strain curve together with the test data. The actual linear elastic part of the test data is very limited: the diagram is curved soon after the reversal of the load. In order to follow the curve accurately the elastic range should be limited as well, i.e. the offset strain should be very small. There is also an opposite effect: it takes a longer time for ABAQUS solver to compute the plastic range than to compute the elastic range. The larger the elastic range, the faster the solving is.

In this project, the offset strain is set to the so called 0.2-limit, which often stands for the yield criterion for austenitic steels. The deviation within cycles was not defined. Instead, the deviation of maximum and minimum stresses was studied in order to define the accuracy of both the kinematic hardening and the cyclic hardening.

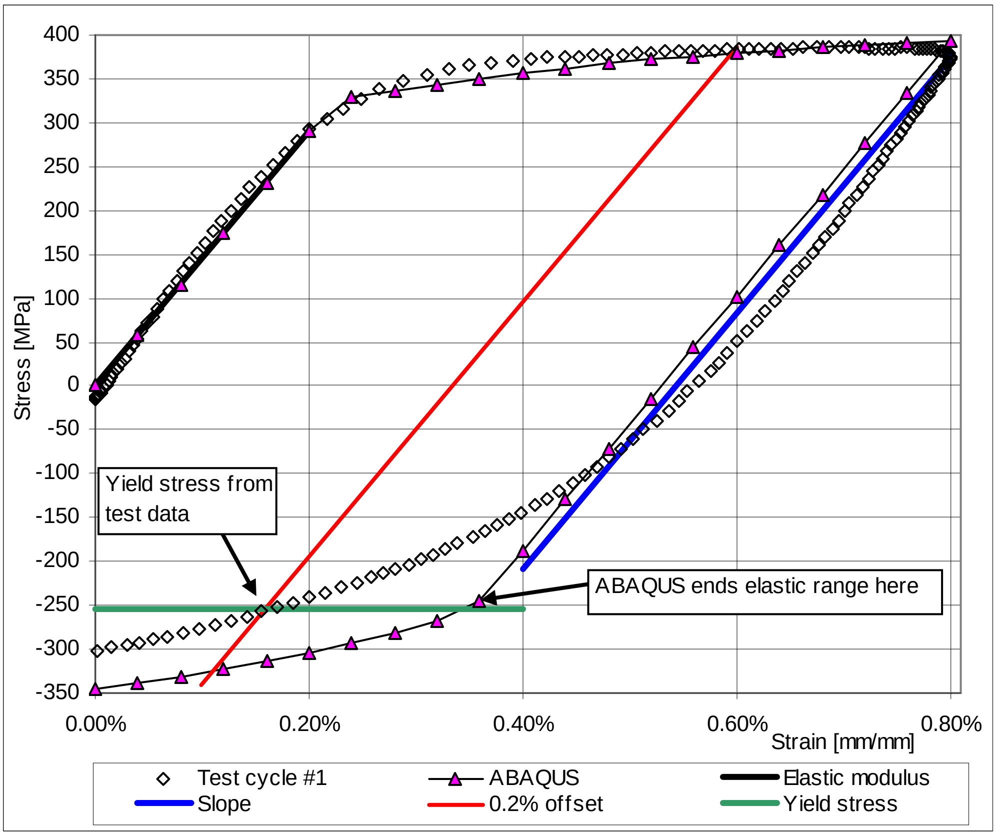


Figure 6.1 Basic forms of a test cycle and an ABAQUS cycle.

6.1 Comparison with trimmed parameters

In the first comparison it is studied if the trimming approaches are adequate. In the case illustrated in Fig. 6.2 the stress amplitude of ABAQUS analysis (cyclic hardening produced with average ratio) is higher than that of the test data, the deviation altering from 5 to 10 %. In Fig. 6.3 the cyclic hardening is produced using elastic modulus as a constant slope. The stress amplitude of ABAQUS analysis is slightly higher than that of the test data. On the other hand, the deviation is reduced being 1 to 4 %. Fig. 6.4 shows the reduction of the deviation. All in all, constant slope seems to be a more accurate trimming factor than average ratio of stress amplitude and elastic range.

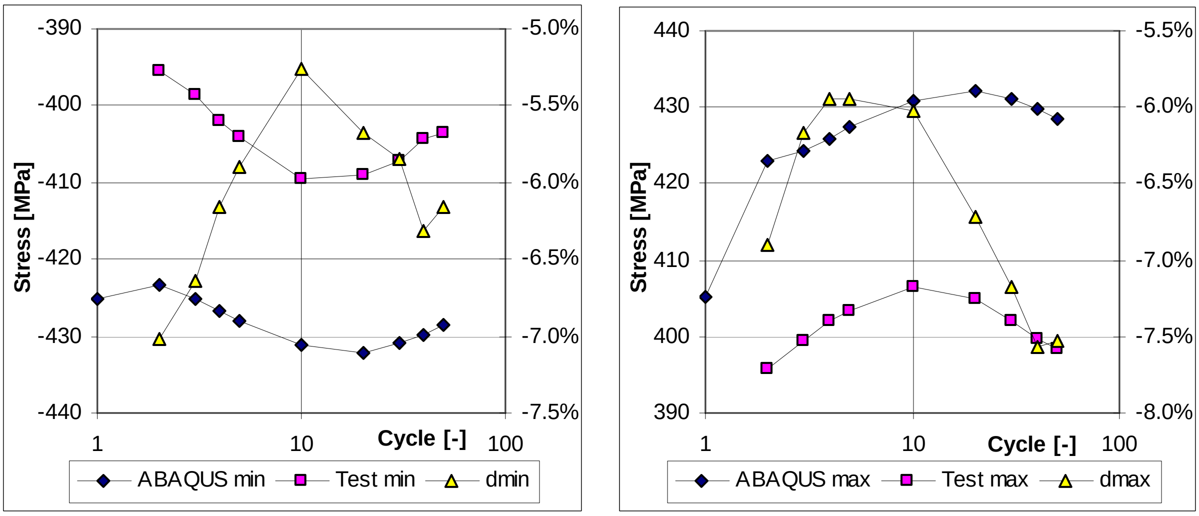


Figure 6.2 ABAQUS data vs. test data; strain amplitude 0.8%, both kinematic and cyclic hardening defined from strain amplitude 0.8% using average ratio (Chap. 5.1).

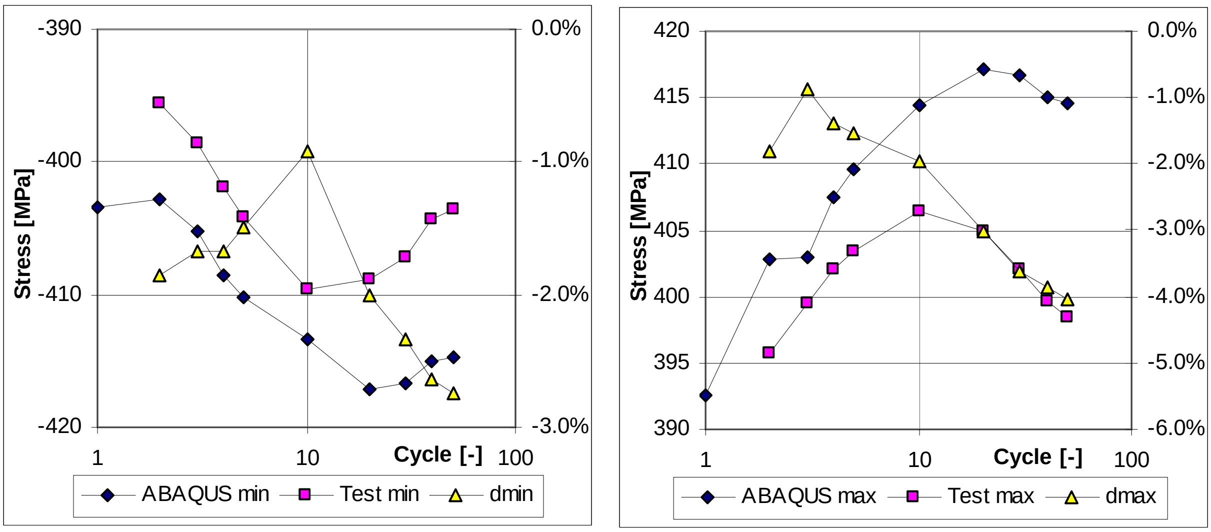


Figure 6.3 ABAQUS data vs. test data; strain amplitude 0.8%, both kinematic and cyclic hardening defined from strain amplitude 0.8% using constant slope (Chap. 5.2).

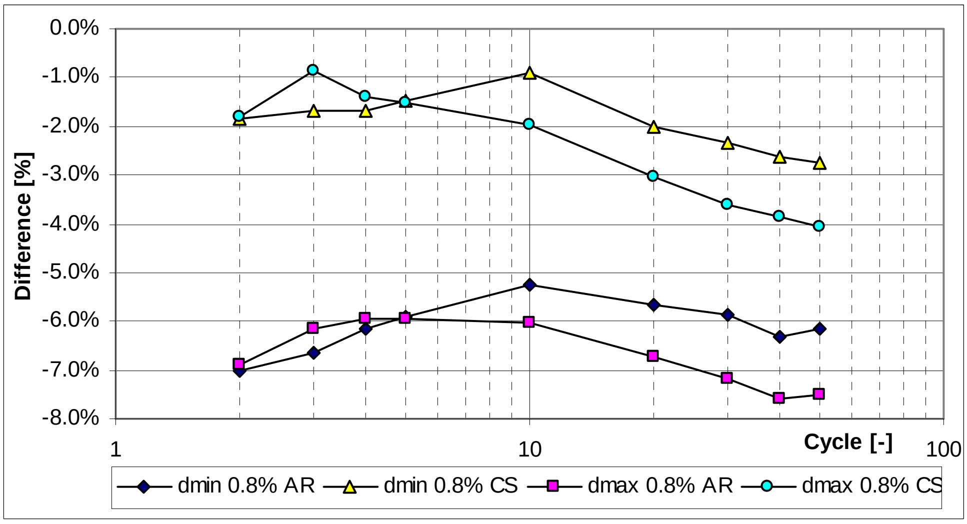


Figure 6.4 Comparison between differences in minimum and maximum stresses (AR= average ratio, CS= constant slope)

6.2 Comparison when combining parameters

As Fig. 5.11 shows, the curves for kinematic hardening are close to each other regardless of the strain amplitude. A study was carried out to assess how accurate it is to use a common kinematic hardening. In Fig. 6.5 there are minimum and maximum stresses of both test data with strain amplitude of 0.8% and of ABAQUS analysis results where the kinematic hardening is taken from the strain amplitude of 2.0% and cyclic hardening from the strain amplitude 0.8% itself.

Further, it was studied whether the cyclic hardening of some other strain amplitude could be used. Fig. 6.6 shows a sample from ABAQUS analysis results for strain amplitude of 0.8% using both the kinematic and the cyclic hardening of strain amplitude 2.0%. As Fig. 5.10 shows, the higher the strain amplitude, the stronger the hardening is with equal equivalent plastic strain. Therefore the result presented in Fig. 6.6, i.e. an ascending deviation from test data, is predictable.

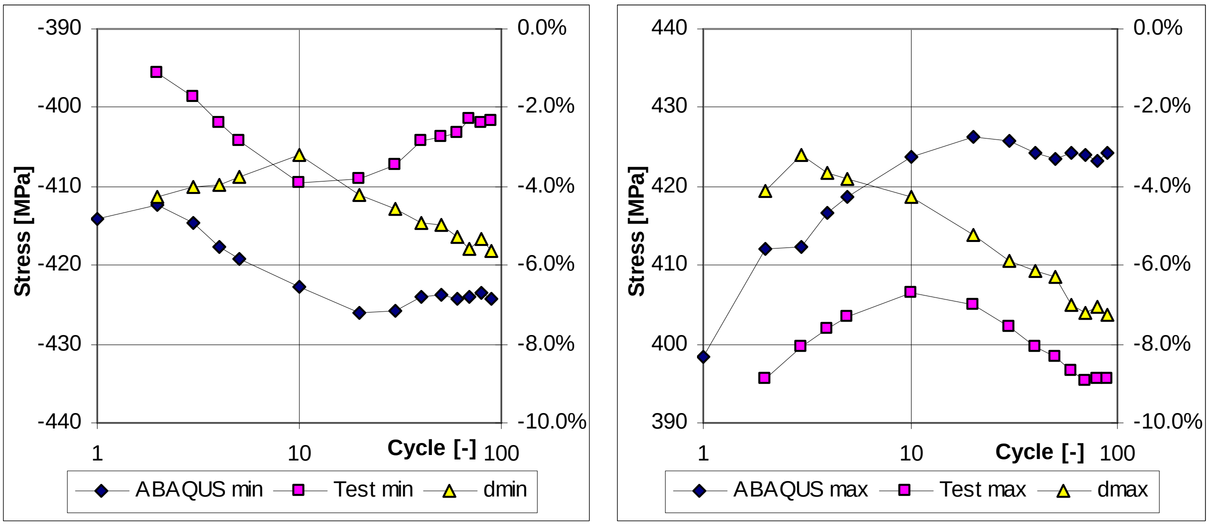


Figure 6.5 ABAQUS data vs. test data; strain amplitude of 0.8%, kinematic hardening defined from strain amplitude of 2.0%, cyclic hardening defined from strain amplitude of 0.8%; constant slope (Chap. 5.2).

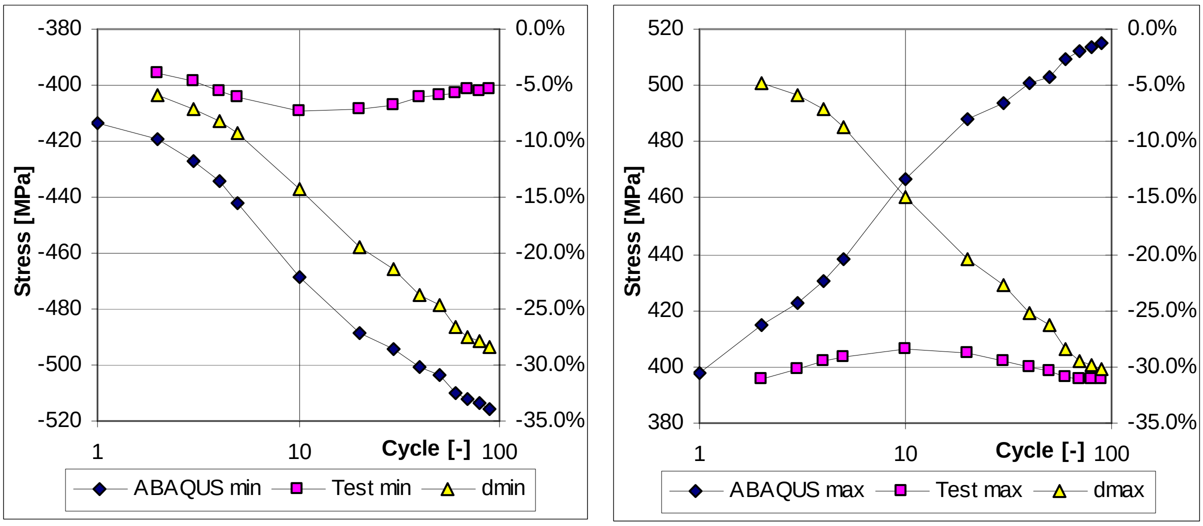


Figure 6.6 ABAQUS data vs. test data; strain amplitude 0.8%, both kinematic and cyclic hardening defined from strain amplitude of 2.0% using constant slope (Chap. 5.2).

Fig. 6.7 illustrates that the best result is achieved when using both kinematic and cyclic hardening produced from test data while the strain amplitude is the same as in ABAQUS analysis. On the other hand, kinematic hardening can be defined with high strain amplitude without losing accuracy. It is not recommended, however, to use cyclic hardening of different strain amplitude.

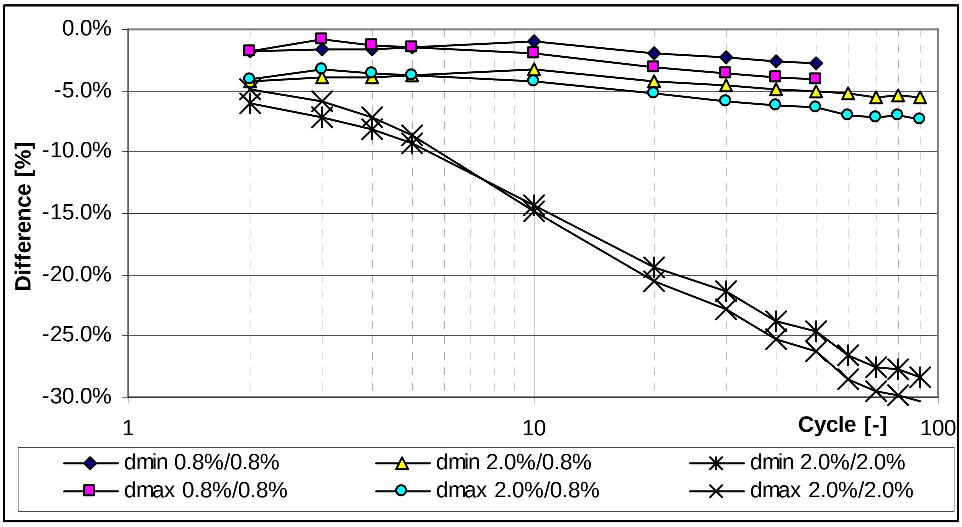


Figure 6.7 Comparison between differences in minimum and maximum stresses; strain amplitude of 0.8% (0.8%/0.8%= both kinematic and cyclic hardening by strain amplitude of 0.8%, 2.0%/0.8%= kinematic hardening by strain amplitude of 2.0% and cyclic hardening by strain amplitude of 0.8%, 2.0%/2.0%= both kinematic and cyclic hardening by strain amplitude of 2.0%)

6.3 Test run up to end of lifetime

A test run up to the end of symmetric cycles could be carried out with strain amplitude of 2.0%. In one of the tests cracking appeared after 90 cycles. By using coarse steps (20 steps per load cycle), the ABAQUS run could be carried out within a reasonable time. Fig. 6.8 illustrates the result that the difference between maximum stresses remained within ±3%. The difference between minimum stresses ascended but did not exceed 10%. In Fig. 6.9 there are, together with the kinematic hardening based on test cycle #10, curves for test cycle #80 as well as for cycles #10 and #80 from the ABAQUS analysis results. The curves were defined in the same way as in case of kinematic hardening. The shift due to cyclic hardening is visible as well as the accuracy of the ABAQUS analysis results with coarse steps.

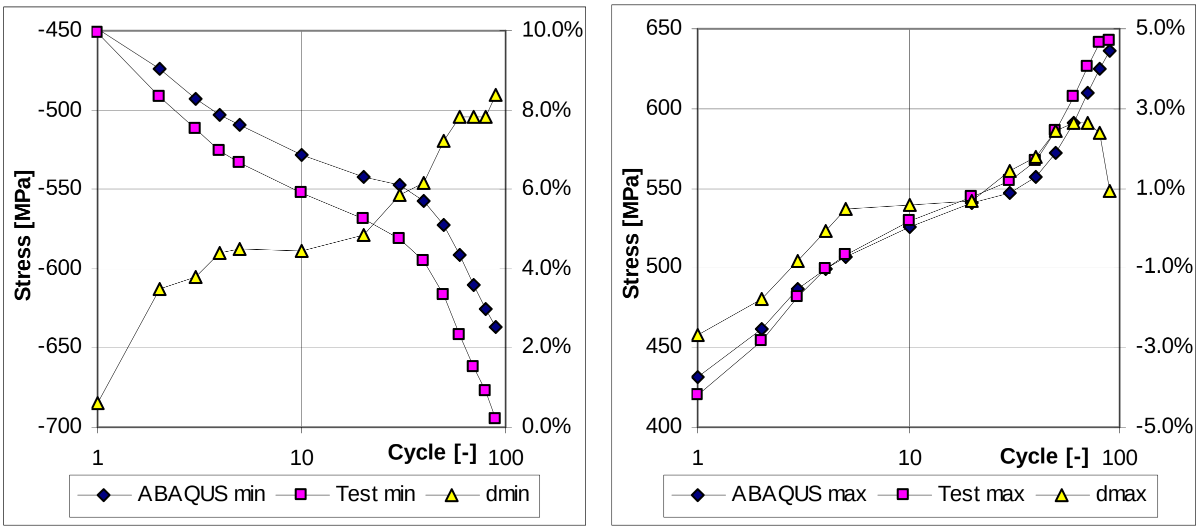


Figure 6.8 ABAQUS data vs. test data; strain amplitude of 2.0%, both kinematic and cyclic hardening defined from strain amplitude of 2.0% using constant slope (Chap. 5.2).

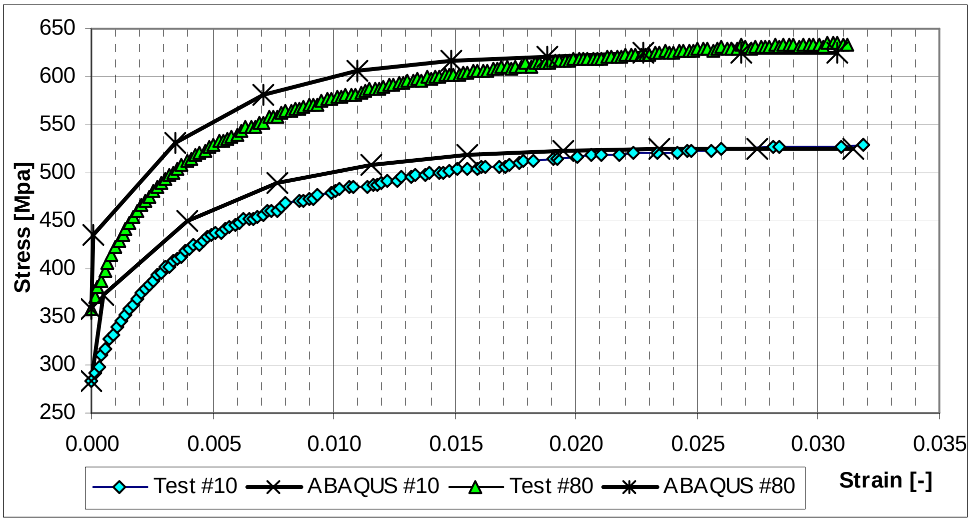


Figure 6.9 Comparison of kinematic hardening of test data and ABAQUS data.

6.4 Comparison with softening material

The samples in Chaps. 6.1-6.3 deal with austenitic base metal, which tends to harden in low cycle fatigue tests. In this chapter there are two samples of a hardening material, *viz.* austenitic weld metal without heat treating. Fig. 6.10 shows the elastic range up to 100^{th} cycle and a comparison between minimum and maximum stresses with strain amplitude of 1.2%. The diagrams show also the accuracy of modelling softening tendency with kinematic and cyclic hardening as well as defining the cyclic hardening using elastic modulus as constant slope.

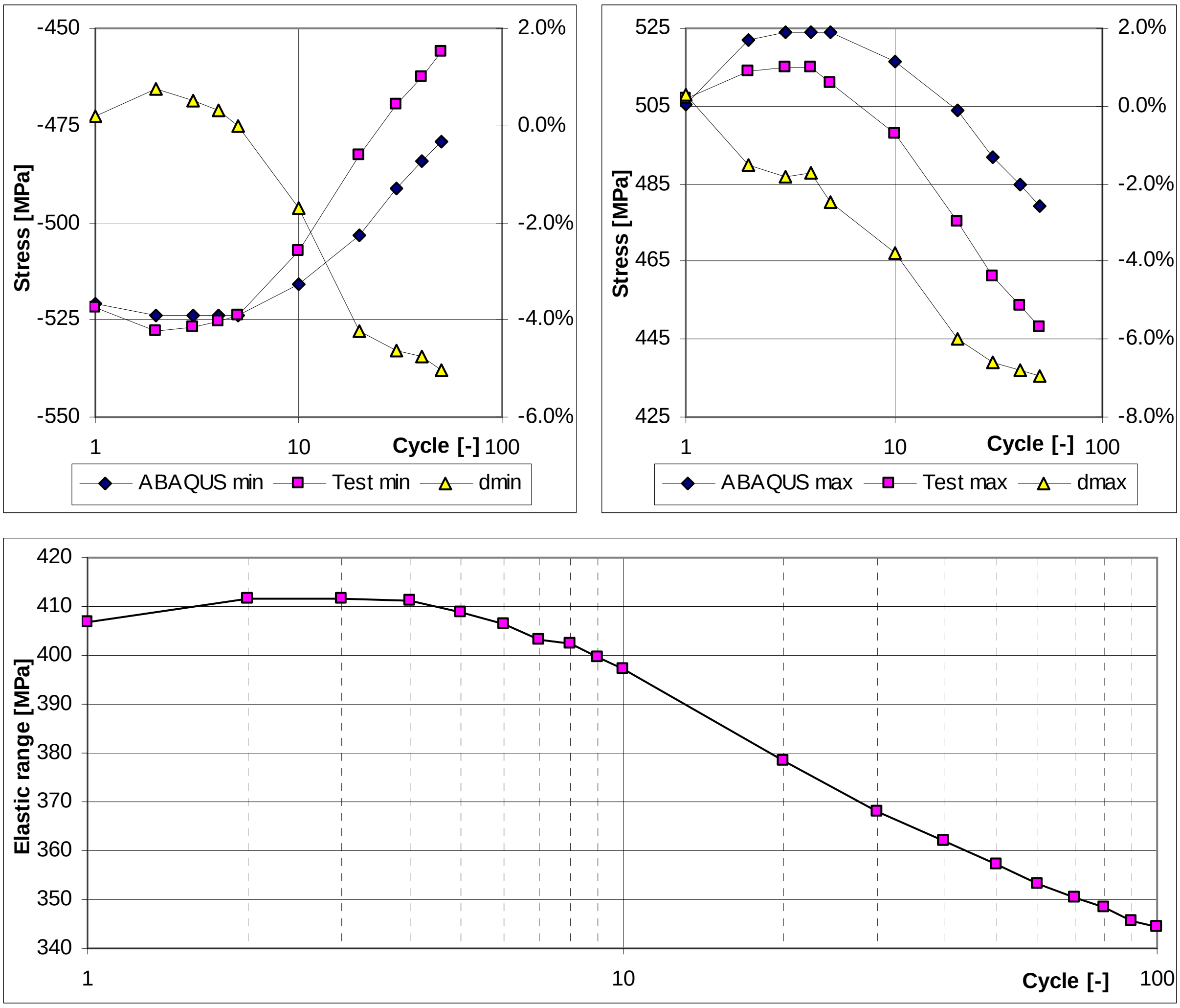


Figure 6.10 Comparison between differences in minimum and maximum stresses of a strongly softening material (austenitic weld; strain amplitude 1.2%) using constant slope (Chap. 5.2).

Fig. 6.11 shows a case where ca. 80% of the specimen lifetime (200 cycles) has been analysed. In this case the accuracy of minimum and maximum stresses improves towards the end of the lifetime. The maximum deviation is, however, 7.5% (minimum stress) vs. 4% (maximum stress).

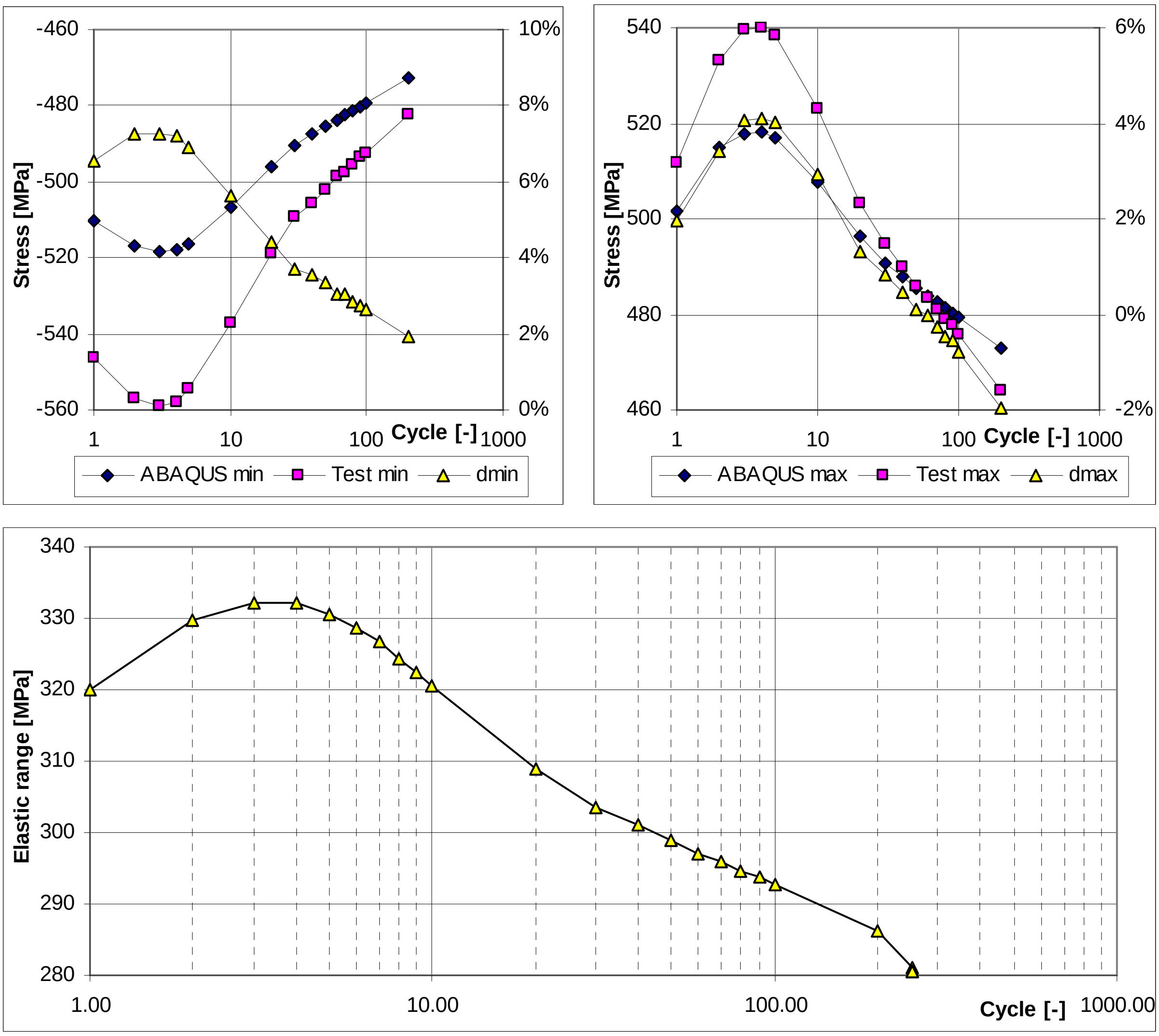


Figure 6.11 Comparison between differences in minimum and maximum stresses of a strongly softening material up to 80% of life time (austenitic weld; strain amplitude 2.0%) using constant slope (Chap. 5.2).

7 Conclusions and plans for the future

After finding a procedure to trim result data to get smooth curves for cyclic hardening, hardening and softening can be reproduced in ABAQUS analysis with a reasonable accuracy. Fig. 7.1 shows the deviation of minimum and maximum stresses between test data and ABAQUS analysis for three strain amplitude levels. The best accuracy is reached by using parameters generated from tests with the same strain amplitude as in the analysis. Kinematic hardening defined from high strain amplitude can be used for lower strain amplitudes. Cyclic hardening, however, depends on strain amplitude, which can be seen e.g. in Fig. 5.10. Not only the elastic range is higher with higher strain amplitude, but the difference grows with growing equivalent plastic strain. Figs. 7.2 and 7.3 illustrate cycles with different strain amplitudes and the same equivalent plastic strain.

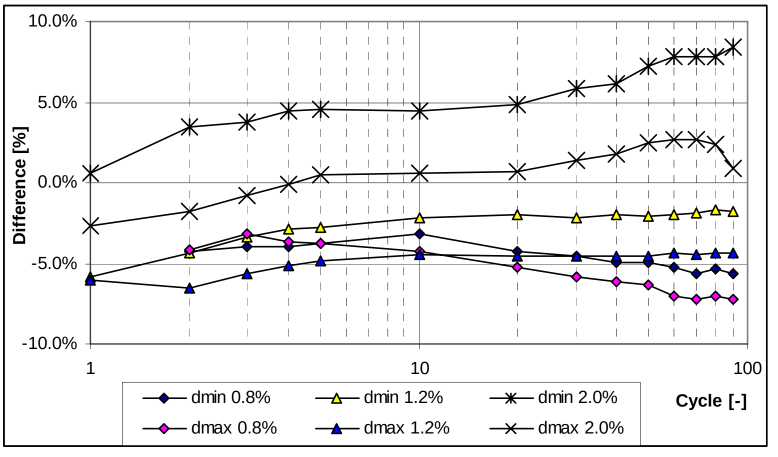


Figure 7.1 Differences in minimum and maximum stresses for different strain amplitudes.

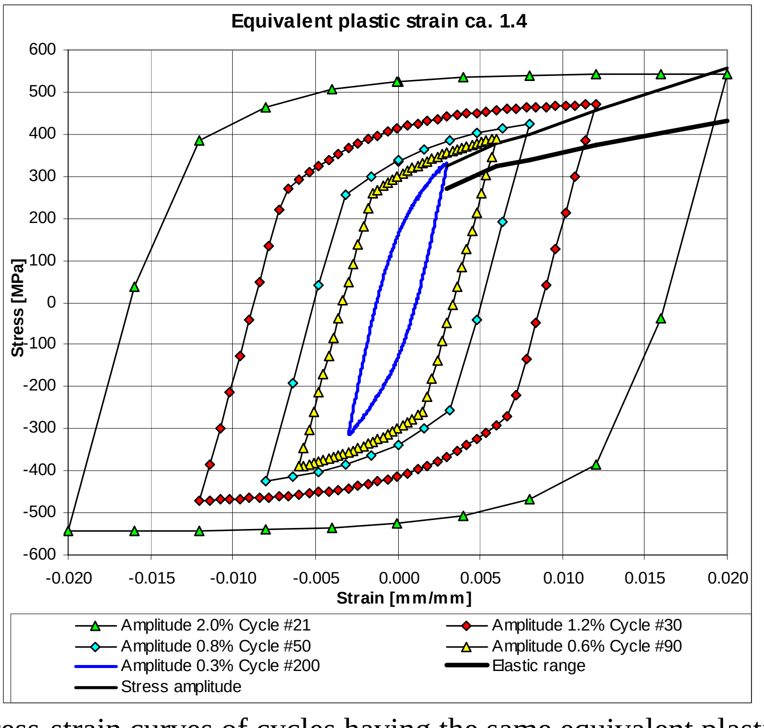


Figure 7.2 Stress-strain curves of cycles having the same equivalent plastic strain 1.4.

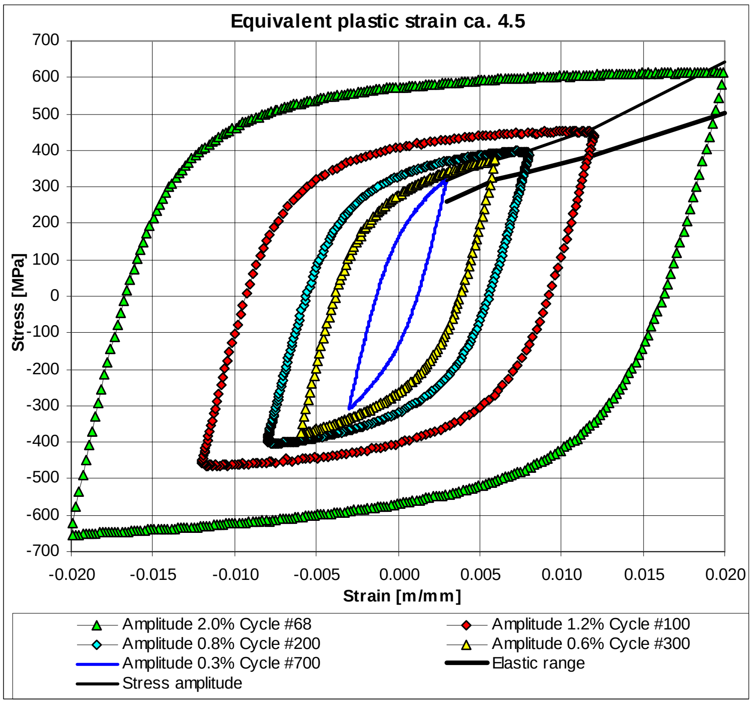


Figure 7.3 Stress-strain curves of cycles having the same equivalent plastic strain 4.5.

The elastic ranges and stress amplitudes from Figs. 7.2 and 7.3 are collected in Fig. 7.4. The ratio between different strain amplitudes changes with growing equivalent plastic strain. In many analysis cases cyclic loading contains variable amplitudes instead of constant amplitude. Therefore the usability of parameters for constant amplitudes will be tested when strain amplitudes are variable. There is test data available for comparisons to be run during 2006. Interest will be set on the possibilities to model the progress of the cyclic hardening with a range of strain amplitudes, i.e. the progress of CSSC (=cyclic stress strain curve).

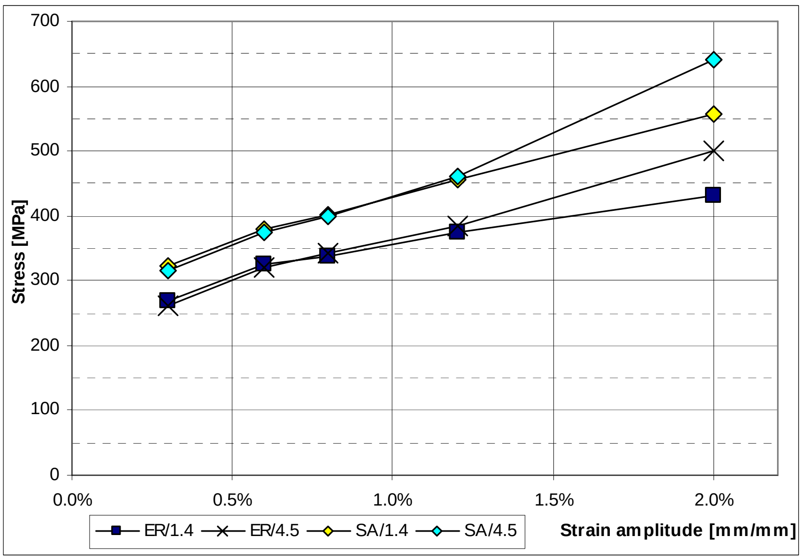


Figure 7.4 Elastic ranges and stress amplitudes with various strain amplitudes and equivalent plastic strains (ER= elastic range, SA= stress amplitude, 1.4=equivalent plastic strain 1.4, 4.5=equivalent plastic strain 4.5).

The future research plans and needs are discussed in the following.

By simulating with ABAQUS the fatigue data of particular stainless steels under particular cyclic loadings, the overall aim is not only to be able to repeat very accurately the original data, but moreover to find through the analyses such material and work hardening models together with suitable model parameter values which would be transferable to actual piping components.

It is necessary to analyse more austenitic stainless piping steel fatigue test data of more varying nature before the full capabilities of the applied numerical models can be assessed. Only then it is possible to decide if the applied numerical models are capable enough for describing the fatigue behaviour of austenitic stainless piping steels under low-cycle loading, or whether it would be necessary to develop a separate material model for this purpose. Through such analyses it would be possible to find those material and work hardening models together with suitable model parameter values which would best suit to be transferable to actual piping components.

In particular it would be of interest to simulate with ABAQUS the fatigue behaviour of austenitic stainless piping steels under fast loading transients, and under variable amplitude loading.

The data reading procedure of the fatigue test data treatment application should be extended to the capability of reading continuous data. Also, the analysis procedure should be upgraded with cycle analysis, i.e. the capability to identify individual loading cycles from a data stream.

Further, the application should be developed to be capable of recognizing variable amplitude loading - this far the considered data has been limited to output from constant loading amplitude tests. The analysis procedure for variable amplitude loading is more complicated than the one for constant amplitude loading. Still, there is a growing amount of interest and need for studies of effects of variable amplitude loading.

References

1. Cronvall, O. Numerical modelling of low-cycle fatigue behaviour of austenitic stainless piping steel. Technical Research Centre of Finland (VTT), Research Group Structural Integrity, Research Report BTUO72-031200. Finland, 2004. 42 p.

2. Cronvall, O., Sarajärvi, U. Treatment and numerical simulation of fatigue data of austenitic stainless piping steel. Technical Research Centre of Finland (VTT), Research Group Structural Integrity, Research Report BTUO72-041317. Finland, 2005. 47 p.

3. Lubarda, V. Elastoplasticity Theory. CRC Press. U.S., 2002.

4. Lubliner, J. Plasticity Theory. New York 1990, Macmillan Publishing Company. 495 p.

5. Drucker, D. J. of Appl. Mech. 26, 101. 1959.

6. ABAQUS Theory manual, Version 6.4. ABAQUS Inc., 2003. Pawtucket, Rhode Island, U.S.A.

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Abstract

The simulation and analysis of data for enhancing low cycle fatigue test procedures is discussed in this report. The analysed materials are an austenitic stainless piping steel and an austenitic weld material. This project continues the work performed in 2003 and 2004. The fatigue test data treatment application developed within the project in 2004 for the preparation of the fatigue data has been developed further. Also, more fatigue test data has been analysed with the application than in 2004. In addition to this numerical fatigue simulations were performed with FEM code ABAQUS. With the fatigue test data treatment application one can e.g. both calculate cyclically certain relevant characteristic values, e.g. elastic range, and form a set of certain cyclical parameter values needed as a part of ABAQUS analysis input files. The hardening properties of metals were modelled with both isotropic and kinematic hardening models.

The further development of the application included trimming of the analysed data, and consequently trimming of resulting hardening parameters. The need for the trimming arose from the fact that the analysed fatigue test data presents some scatter caused by the limited accuracy of the test equipment and the sampling rate. The hardening parameters obtained from the application analysis results were used in the subsequent ABAQUS analyses, and then the fatigue test data were compared with the ABAQUS simulation results. After finding a procedure to trim result data to get smooth curves for cyclic hardening, hardening and softening could be reproduced in ABAQUS analysis with a reasonable accuracy.

The modelling of the fatigue induced initiation and growth of cracks was not considered in this study. On the other hand, a considerable part of the fatigue life of nuclear power plant (NPP) piping components is spent in the phase preceding the initiation and growth of cracks.

Key words: low cycle fatigue, steel, stainless, austenitic, material model, finite element model

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