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NUMERICAL INTERPRETATION OF TEST RESULTS OF LARGE SCALE STRUCTURAL TESTS UNDER LONG-TERM CREEP FATIGUE LOADING

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ABSTRACT

To validate the design methodology for metallic structures under long-term creep fatigue loading, representative large scale structural tests have been performed. The structural material under consideration is type 304 stainless steel. Particular attention is paid to welded structures.

The work presented deals with the numerical interpretation of test results in terms of cyclic stress strain behaviour, creep relaxation during hold time, damage estimation using inelastic material models and damage assessment criteria provided by design codes.

Results of calculations are given and discussed with respect to the experimental results from large scale tests and of a complementary cast specific small specimen test programme.

There was considerable deviations between the numerical prediction and the test results in terms of number of cycles to failure when using a reference material data set. An improved accuracy could however be achieved by adjustment of the cyclic hardening - and creep behaviour based on the test results from the cast specific small specimen test programme.

Since there was a need to use test parameters (max. temperature and max. strain range) which are above the design conditions in order to 'accelerate' the accumulation of creep fatigue damage, a critical review of the test parameters chosen is also presented.

1 INTRODUCTION

The reactor vessel wall of a loop-type LMFBR experiences cyclic loading in the creep domain in terms of stress and strain ranges due to transient thermal loading and changes of coolant

levels during startup, shutdown and load following conditions. Because of the cyclic nature of the loadings and the inelastic strains produced by a moving axial thermal gradient along the vessel wall, a long term interaction between creep/relaxation and fatigue takes place. A minor contribution to creep loading is given through the dead weight of the vessel, internal structures, sodium and low cover gas pressure.

This causes problems for the design of such components, which cannot easily be solved on the basis of existing design codes. An extended approach is therefore necessary for a reliable design of the reactor vessel wall with additional requirements concerning analysis and damage evaluation procedures. For verification purposes, a large scale specimen testing facility has been installed. Tests on component like welded specimens under loading conditions similar to service and a complementary cast specific small specimen test programme were carried out. Inelastic finite element calculations were conducted for numerical interpretation of the test results of the large scale structural tests.

A general overview of the component and test conditions and the experimental results obtained so far from large scale specimen testing has already been reported in Ref. [1] and [2]. This paper concentrates on current experimental results from the complementary cast specific small specimen tests and the related impact on the numerical interpretation of the large scale specimen test results.

2 COMPONENT DESIGN AND FEATURE SPECIMEN TESTING

The vessel wall is fabricated from German type AISI 304 stainless steel (DIN no. X6 CrNi 1811). Submerged Arc Welding (SAW) procedure was used for the weldments of the part of vessel wall under consideration. The following major generic requirements were taken into account when planning the test rig with regard to the transferability of the test results to the component:

- component like loading conditions
- component like dimensions of the specimens
- service like damage mechanisms
- practicable test duration
- recording of local deformation which enables a comparison with calculated results
- recording of initiation and time dependent development of damage

The test model plate was made from German type AISI 304 stainless steel (see Fig. 1) with 40 mm original wall thickness and dimensions of 800 mm x 460 mm. The test model plate contains a SAW-welded T-shape seam and is subjected to loadings, which simulate mechanically the calculated loadings of the vessel wall.

Two plates one of which has spark eroded flaws to simulate corrosion cracks were tested. These flaws were located in the base metal, weld metal and the heat affected zone.

The plates are loaded under a constant primary tensile stress of 10 MPa to simulate the dead weight load.

A displacement controlled bending stress is superimposed to create a strain amplitude of 0.2 % in tension, which is reversed after a 40 h hold time. The same strain amplitude is applied in compression without inclusion of any hold time. Thus the plates are loaded in a load cycle with a bending strain range of $\Delta\varepsilon = 0.4$ %. This alternating bending strain simulates the load cycle from cyclic temperature variations in the vessel wall. A schematic view of the test rig is given in Fig. 2 while Fig. 3 shows the load histogram of the test.

A practical test duration was achieved by a time-lapse process: An increase of temperature and bending strain range will accelerate the creep deformation rate and the fatigue loading and hence the corresponding damage development in terms of creep-fatigue damage.

The test temperature of 570 °C is 25 °C higher than the maximum service temperature of the component and the strain range of $\Delta\varepsilon = 0.4$ % is a factor of two higher the service condition of the component but these will not induce a significant change of the creep-fatigue damage mechanism. This assumption was made based on the knowledge available subject to confirmation by the results of a small scale specimen test programme conducted in parallel with the large scale tests.

Local deformations are continuously monitored during the large scale tests by means of capacitive strain gauges which have been placed on the base metal, welded seams and heat affected zone in the longitudinal and transverse direction.

3 EXPERIMENTAL RESULTS OF WIDE PLATE TESTING

The tests were terminated earlier than initially expected (after 117 load cycles) corresponding to a test duration of about 4700 h. In order to carry out nondestructive metallographic examinations and to observe the damage development of the two plates, the tests were interrupted and inspection took place after 50, 75 and 100 load cycles (corresponding to 2000 h, 3000 h and 4000 h). Termination of the two tests was initiated by the existence of a macroscopic crack which was found in the cross weld seam of the plate with the spark eroded flaws.

The description of time dependent process of crack initiation and crack growth is given in Ref. [2]. Metallurgical post test investigations on the fracture surface have not been conducted to date but there is no doubt that the macroscopic crack is a result of the exhaustion of the weld metal rather than a result of the spark eroded flaws. Inspection after 50 load cycles

showed a crack initiation at the flaw edges of the spark eroded flaws but there was only negligible crack growth observed at the end of the tests.

The difference in damage development in both plates can be explained by the different strain accumulation in the weldment. Fig. 4 shows the measured axial strain at different positions of the transverse weldment of the plate containing spark eroded flaws. First indications of damage were observed after 75 load cycles equivalent to about 3000 h test duration.

The characteristic of the axial strain measured at the plate without spark eroded flaws, Fig. 5, is similar to that described above. The stage of increasing incremental tensile strain per cycle has not yet been reached which is consistent with the experimental visual evidence that macrocracks have not yet been observed.

As already mentioned above, the tests were carried out under strain-controlled conditions. The time-dependent strain measured in the base metal by the respective strain gauges located on the plate surface in tension during the hold time were used as a control variable for applying the $\Delta\varepsilon = 0.4\%$ strain range on the wide plate specimen.

4 EXPERIMENTAL RESULTS OF COMPLEMENTARY CAST SPECIFIC SMALL SPECIMEN TESTING

For the purpose of material characterisation of the specific cast under consideration a small specimen test programme was carried out.

The test programme comprises tensile tests, creep tests, fatigue tests and fatigue tests with 40 h hold time at temperatures of 540 °C and 570 °C on specimens from base metal, weld metal and weldments.

The test matrix initially established within the test programme is given in Table 1. Tensile-, Creep- and Fatigue tests have been loaded until rupture of the specimen occurred. The aim of the fatigue tests with 40 h hold time at the maximum of tension stress was to investigate the cyclic hardening/softening behaviour of base metal/weld metal. These tests were terminated at about 30 load cycles.

Tensile properties of the cast used were found slightly higher than average strength values. The specified minimum values for uniform elongation of the base metal are clearly surpassed by this specific cast ($> 30\%$ for base metal and $> 20\%$ for weld metal).

Maximum test durations reached for determination of creep rupture properties were about 10⁴ h. Creep rupture strength for base metal of the specific cast was found to be slightly higher than the mean value for the alloy and the values of the weld metal agree closely with the mean values of 18 Cr 11 Ni SMA

weld metal. The weldment efficiency factor on creep rupture strength of $J_r = 0.73$ was confirmed by the creep rupture tests.

Determination of fatigue properties was carried out using cylindrical specimens, Fig. 6, with the strain being controlled by an extensometer clamped directly on to the specimen gauge length. No significant differences in fatigue strength between the base metal and weld metal could be observed. There was also good agreement with the average behaviour of 18 Cr 11 Ni base metal properties.

Fig. 7 shows the cyclic hardening behaviour of the base metal and weld metal at 570 °C. The maximum stress is plotted vs. the number of cycles for different strain ranges. The base metal cyclically hardens, whereas the weld metal - except for a short period at the beginning - cyclically softens. As a result the curves for base metal and weld metal will intersect at a certain number of cycles (e. g. 10^4 cycles for a strain range of $\Delta\varepsilon = 0.4$ %).

All of the generated data from the cast specific small specimen test programme addressed so far (tensile properties, creep rupture properties and fatigue properties) are as expected and in compliance with the current knowledge on the specific alloy material.

Fatigue tests with a strain range of $\Delta\varepsilon = 0.4$ % and representative hold times of 40 h were conducted for base metal and weld metal. Fig. 8 shows the cyclic hardening behaviour from tests with and without hold time expressed in max. stress of the cycle vs. number of cycles. The inclusion of a hold time period has a significant influence on the cyclic hardening of the base metal.

Such a behaviour was not expected because results of previous tests with < 1 h hold time showed some effect of softening rather than hardening when compared with continuous cycling test results. Since the cyclic hardening of the material has an important influence on the creep damage estimation the test programme was extended to incorporate lower strain ranges (0.2 % and 0.3 %) in order to provide data to be used for interpretation of component representative loading levels.

Fig. 9 shows a comparison of cyclic hardening/cyclic softening of base metal/weld metal under 40 h hold time conditions expressed in terms of $\Delta\sigma/2$ vs. number of cycles for strain ranges of $\Delta\varepsilon = 0.2$ and 0.4 %. Early crossover of base metal and weld metal max. stress in the cycle occurs in the case of $\Delta\varepsilon = 0.4$ % while no significant cyclic hardening/softening occurs in the case of $\Delta\varepsilon = 0.2$ %.

The influence of the temperature level (570 °C for the test condition and 540 °C for service condition of the component) on the cyclic hardening/cyclic softening behaviour is shown in Fig. 10. Once more a significant influence especially on the cyclic softening of the weld metal is identified when comparing

the results for the two temperature levels. Early crossing of max. stress of base- and weld metal takes place after roughly 20 cycles in the case of 570 °C while such a cross over would be far beyond 20 cycles in the case of 540 °C.

Detailed examination of the obtained test results from the cyclic tests with 40 h hold time shows that there is a need for a critical review of the test parameters (temperature and strain range) chosen for the large scale specimen testing. Also for the numerical interpretation of the large scale specimen test results, the material parameters used to describe the cyclic behaviour and the creep relaxation behaviour have to be adjusted.

5 NUMERICAL CALCULATIONS AND DAMAGE ESTIMATION BASED ON INELASTIC MATERIAL MODELS

To calculate stresses and strains in the welded plate (without considering the existence of spark eroded flaws) elastic and inelastic finite element (FE) calculations were carried out using the ABAQUS code. According to the state of the art of design practice the weld was not explicitly taken into account in these calculations. In the case of damage prediction weldment efficiency factors derived from creep rupture tests were used. When performing inelastic calculations, the ORNL constitutive law was used to model cyclic elastic-plastic and creep/creep relaxation behaviour. The respective material data for the first approximation were taken from a reference material data set. Table 2 contains the material parameter values using a bilinear approximation of the elastic-plastic material behaviour based on data obtained from the material reference book and cast specific continuous cycling data.

The FE-Model employed is shown in Fig. 11 while Fig. 12 shows the calculated stress-strain cycle at the centre of the plate for the first one and a half cycles in the inelastic calculation using the first approximation of cast specific material data. The experimentally and numerically determined axial strain in the base metal coincidence satisfactorily at the point of maximum tension stress and during the 40 h hold time.

In contrast the prediction of stress relaxation due to creep during the 40 h hold time seems to be significantly overestimated when compared with results obtained from the cyclic tests of the cast specific small specimen tests.

The computation of the number of cycles to failure of the welded plates is based on the stress correlated time fraction damage rule of ASME CC N47 taking into account a weldment efficiency factor of $J_r = 0.73$. The number of load cycles predicted by this method can be seen from Table 3.

The predicted number of load cycles to failure given in the third column of Table 3 is obtained when cast specific continuous cycling data are taken into account. Here the description of the cyclic hardening behaviour was adjusted. There is a need

for further adjustments concerning the cyclic hardening (effect of hold time on cyclic hardening) and the description of stress relaxation behaviour due to creep during hold time. These adjustments will be the subject of future work. When considering the ASME CC N47 creep-fatigue interaction diagram for stainless steel the location of interaction is in the region where creep damage is predominant.

In evaluating these results, some important aspects have to be considered:

- The weld properties were not explicitly addressed in the calculation model. Reduced creep rupture strength of the weldment was taken into account in accordance with the current design practice using a weldment efficiency factor.
- The adjustment of the cyclic hardening of the specific cast material in the material model does not take into account the reported effect of hold time.
- The creep law used for description of stress relaxation needs adjustment for adequate description of stress relaxation due to creep.
- Significant differences exist in the creep behaviour of base metal and weld metal.

An improved prediction of the number of cycles to failure will be expected by the following measures:

- Using an improved set of material data describing creep and cyclic hardening based on cast specific material data for base metal and weld metal.
- Consideration of the weld in the design methodology not only by application of a weldment efficiency factor for creep rupture damage, but by taking into account explicitly the weld material behaviour in the calculation model. However, this procedure would be ahead of current design practice and difficult to use in component design calculations.

6 INTERIM CONCLUSIONS AND FUTURE ACTIVITIES

Based on the evaluation of experimental and first numerical results of the welded plates and experimental results of the cast specific small specimen tests the following interim conclusions are drawn:

- using the reference material data set for a $\Delta\varepsilon = 0.4\%$ strain range a significant underestimation in the description of cyclic hardening and a significant overprediction of stress relaxation during hold time takes place. Both effects lead to a significant underestimation of creep rupture damage.

- The choice of $\Delta\varepsilon = 0.4 \%$ strain range in the welded plates tests causes unexpected problems due to the significant cyclic hardening which is not expected in such an extent for $\Delta\varepsilon = 0.2 \%$, which is more representative of service conditions of the component.

These findings have to be considered when comparing test- and service conditions in order to avoid misinterpretation of the test results with respect to component behaviour.

- The theoretical damage prediction for the welded plates needs an adjustment of the material parameters used (cyclic hardening and description of stress relaxation).
- Special attention seems necessary in the treatment of weldments under creep conditions when superimposed with large strain range cyclic loading. The weldment efficiency factor for creep rupture damage derived from constant load creep rupture tests could be too optimistic since this coefficient does not reflect any influence of the effect of cyclic hardening under strain controlled loading conditions.

Future activities planned within an ongoing CEC BRITE EURAM Technology Programme comprise:

- An extension of the cast specific small specimen cyclic testing with hold time for strain ranges below $\Delta\varepsilon = 0.4 \%$ in order to allow an interpretation of the welded plates test results with respect to representative service conditions of the component under consideration.
- Revised numerical damage predictions for the welded plates based on cast specific material data.

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**Table 1 Test Matrix of Small Specimen Test Programme
German Type AISI 304 Stainless Steel (1.4948)**

Type of Test	T [°C]	Type of Metal		
		Base metal	Weld metal	Weldment
Tensile	540	x	x	x
	570	x	x	x
Creep Rupture	540	x	x	x
	570	x	x	x
Fatigue $\Delta\varepsilon = 1.0, 0.6, 0.4, 0.3 \%$	540	x	x	x
	570	x	x	x
Fatigue with hold time $\Delta\varepsilon = 0.4 \%, t_h = 40 \text{ h}$	540	x	x	
	570	x	x	

Table 2 Bilinear Approximation of Elastic-Plastic Material Behaviour

	Reference material*)	Specific cast**)
1. Cycle		
S_{y0} [MPa] 1)	104	104
E [MPa] 2)	$1.524 \cdot 10^5$	$1.524 \cdot 10^5$
$E(0)_T$ [MPa] 3)	$1.532 \cdot 10^4$	$1.532 \cdot 10^4$
10. Cycle		
S_{y1} [MPa]	107	135
E [MPa]	$1.524 \cdot 10^5$	$1.524 \cdot 10^5$
$E(1)_T$ [MPa]	$1.532 \cdot 10^4$	$1.532 \cdot 10^4$

*) data according to ASME CC N47 for 304SS

**) data obtained from specific cast continuous cycling tests

1) fictitious yield strength

2) Young's modulus

3) plastic slope

**Table 3 Predicted Number of Load Cycles to Failure
(Based on Reduced Margin Design Curve)**

	Number of cycles to Failure calculated by		
	simplified inelastic analysis, reference material data set	inelastic analysis, reference material data set	inelastic analysis, first approximation of specific cast material data
Base metal	339	430	293
Weld metal	214	261	176

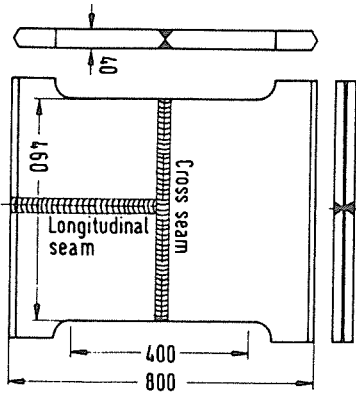


Fig. 1 Welded test plate

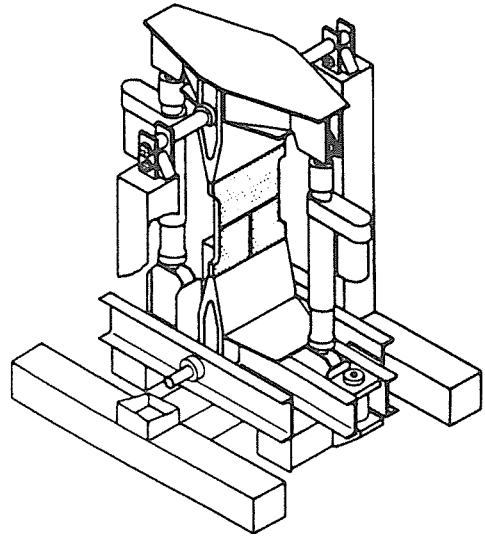


Fig. 2 Schematic view of the test rig

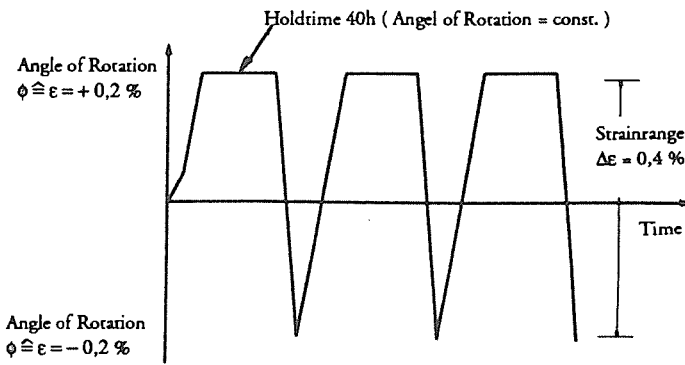


Fig. 3 Load histogram of the test

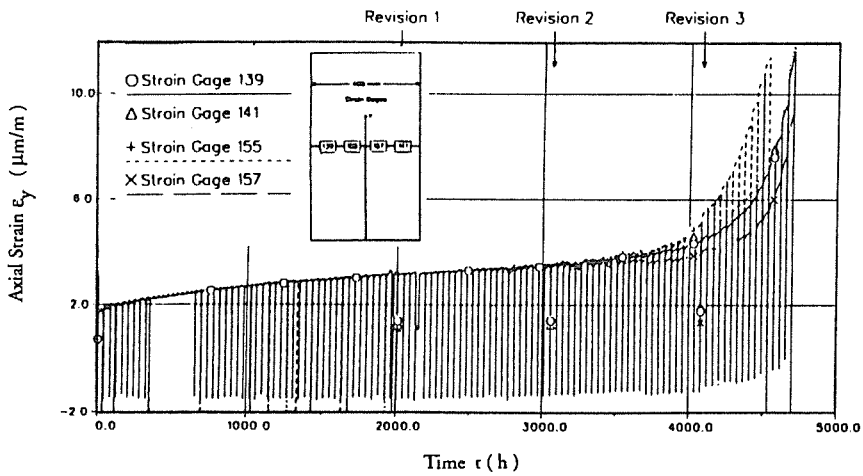


Fig. 4 Axial strain ϵ_y vs. time in the weld of the test plate with spark eroded flaws

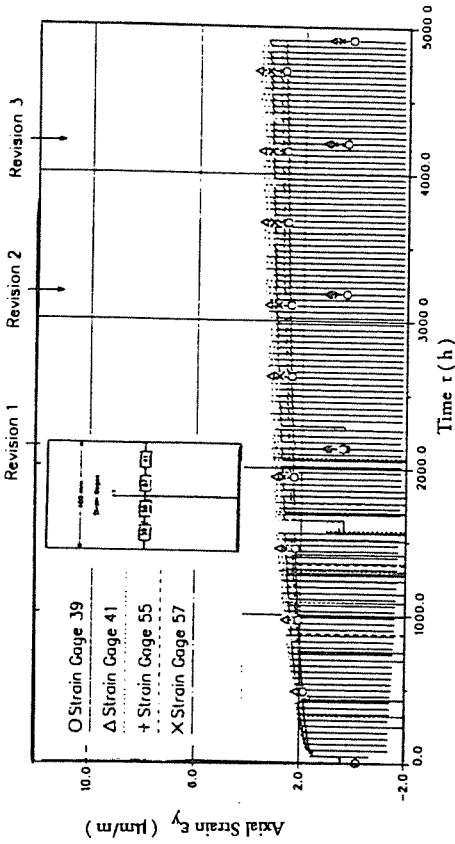


Fig. 5 Axial strain ϵ_y vs. time in the weld of the test plate without spark eroded flows

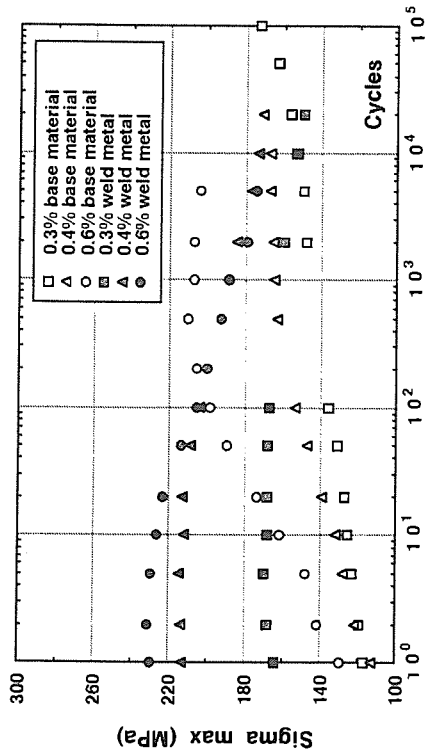


Fig. 7 Cyclic hardening/softening of base metal and weld metal at 570 °C

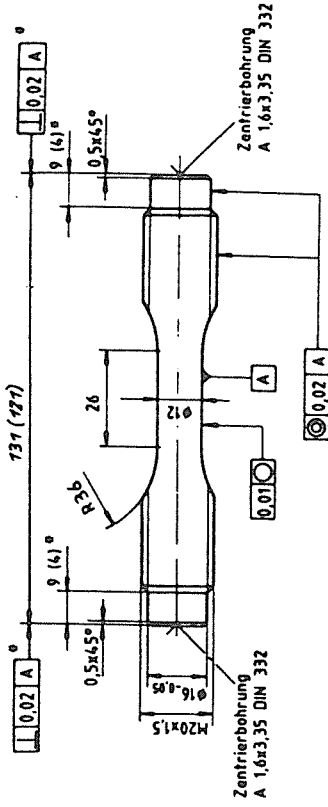


Fig. 6 Specimen of low cycle fatigue tests

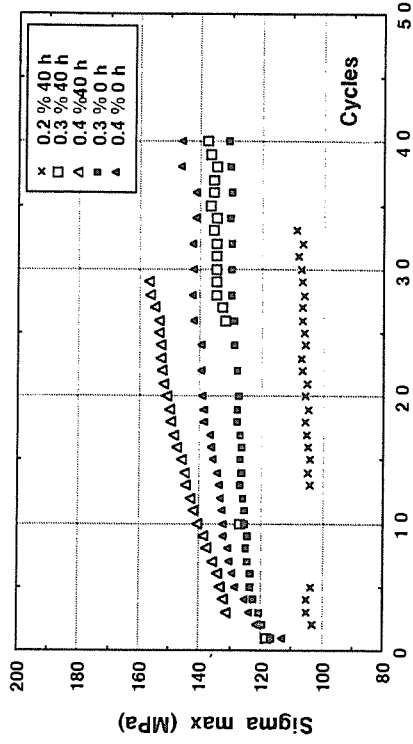


Fig. 8 Cyclic hardening of base metal with and without holdtime - maximum stress in tension

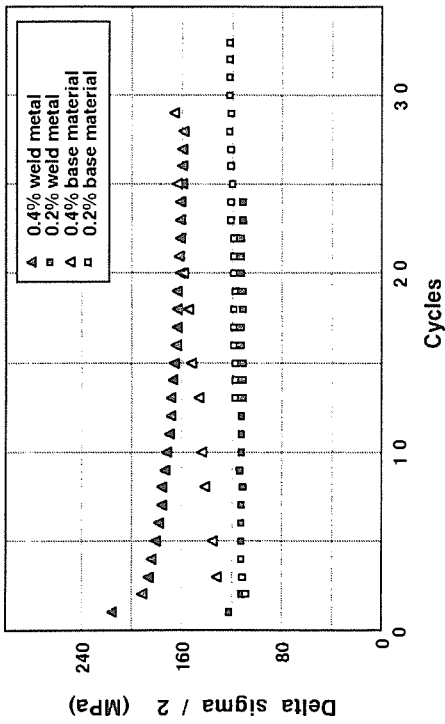


Fig. 9 Cyclic hardening/softening of base metal and weld metal at 570 °C with 40 h holdtime

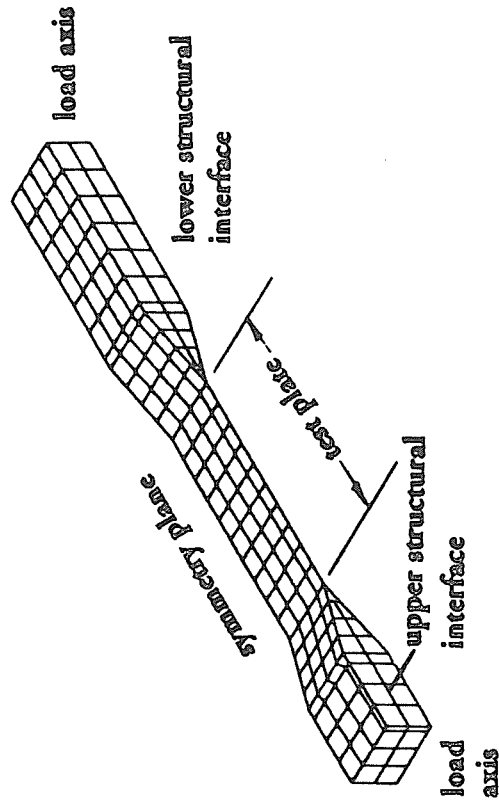


Fig. 11 Finite Element model of test unit

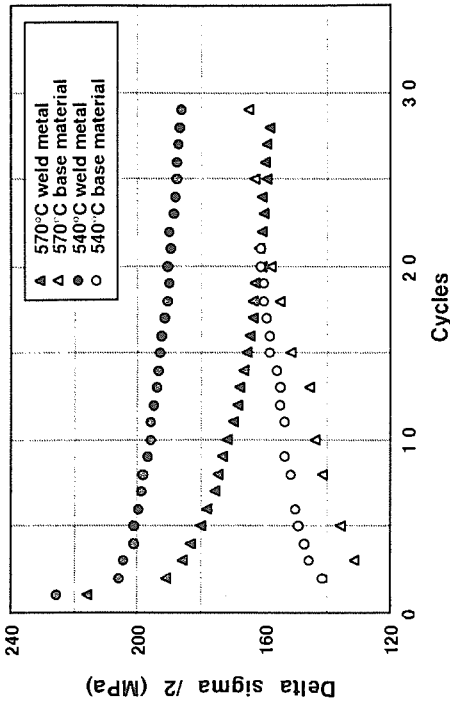


Fig. 10 Cyclic hardening/softening of base metal and weld metal at 540 °C and 570 °C with 40 h holdtime

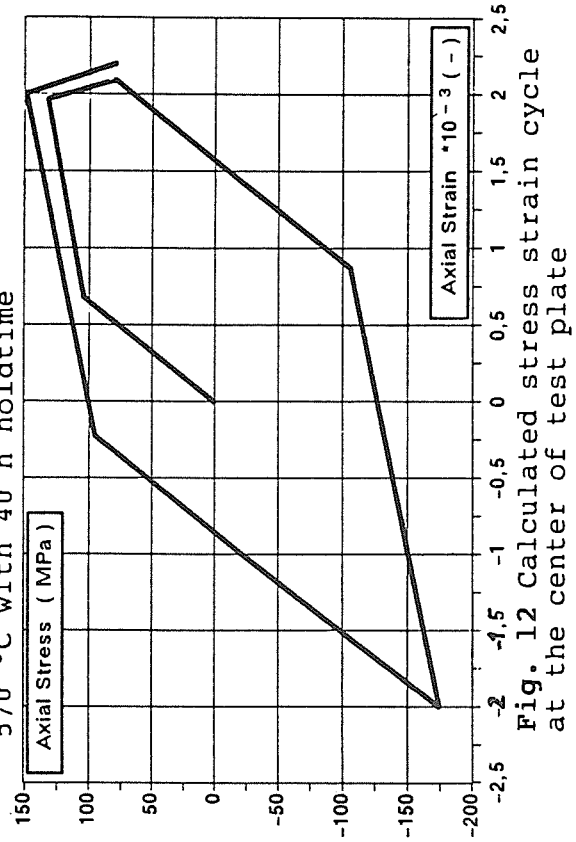


Fig. 12 Calculated stress strain cycle at the center of test plate