Inelastic Stress/Strain Response of 2·1/4Cr-1Mo Steel under Combined Tension-Torsion at 600°C

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Some of the results of the benchmark study on the evaluation of constitutive models by the Subcommittee on Inelastic Analysis and Life Prediction of High Temperature Materials, JSMS, are presented. Inelastic stress/strain responses of 2.1/4Cr-1Mo steel at 600°C under seven types of multiaxial loading of tension and torsion are simulated by seven types of constitutive models. The accuracy of the constitutive models are evaluated by comparing the simulated results with the corresponding experimental results.

1 INTRODUCTION

The Subcommittee on Inelastic Analysis and Life Prediction of High Temperature Materials, the Society of Material Science, Japan, whose members are listed in the footnote, has been performing a cooperative work consisting of four projects: [A-I] evaluation of constitutive models for multiaxially varied stress condition, [A-II] examination of the methods of fatigue-creep life prediction in multiaxial stress state, [B-I] inelastic stress/strain analysis at circumferencially notched root of a specimen, and [B-II] fatigue-creep life prediction of the notched specimen.

This paper deals with the results of the first project A-I on the

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evaluation of constitutive models, which was performed as the extension of the previous projects of the same purpose[1-3], while the companion reports are concerned with the other three projects of A-II, B-I and B-II.

In project A-I seven types of benchmark tests were performed with 2.1/4 Cr-1Mo steel at 600°C in combined stress state of tension and torsion. The experimental results of these benchmark tests were compared with the corresponding predictions by seven constitutive models to evaluate the accuracy in simulating the actual stress/strain response of the material.

2 FUNDAMENTAL PROPERTIES OF MATERIAL

Throughout the project, normarized and tempered 2.1/4 Cr-Mo steel (SA287, Gr.22) was employed in the multiaxial stress states at 600° C. The material parameters in the constitutive models were identified by using the following test data under uniaxial stress which have been given in the previous paper by the Subcommittee[1]:

(1) Stress-strain diagrams at five kinds of strain rates: $\dot{\varepsilon}$ =0.5, 0.1, 10^{-2}, 10^{-3} and 10^{-4}.

(2) Creep strain versus time data under seven stress levels σ of 275, 250, 220, 180, 150, 120 and 90 MPa.

(3) Stress-strain hysteresis loops in the strain controlled cyclic tests under three levels of strain ranges $\Delta\varepsilon$ of 2.0, 1.2 and 0.8% at the strain rate $\dot{\varepsilon}$ of 0.5%/s.

3 BENCHMARK PROBLEMS

Stress/strain responses for the following twelve benchmark problems of seven categories, as illustrated in Table 1, were simulated by the constitutive models, and compared with the experimental results.

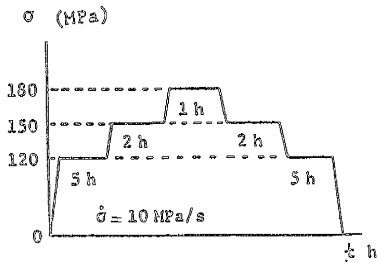
- **Problem A-I:** Step-up/down creep in uniaxial tension with hold-stress σ of 120, 150, 180, 150 and 120 MPa.
- **Problem A-II:** Uniaxial tension with a series of strain-rate change of 0.5 to 0.01, 0.0001, 0.01 and 0.5%/s.
- **Problem A-III:** Cruciform stressing on the stress plane (σ, $\sqrt{3}\,\tau$) with peak stresses σ =200 MPa or $\sqrt{3}\,\tau$ =200 MPa at two stress rates $\dot{\sigma}$ (or $\sqrt{3}\,\dot{\tau}$) = 1.0 MPa/s [case (a)] and 0.1 MPa/s [case (b)].
- **Problem A-IV:** Biaxial mechanical ratcheting under steady tension σ =120 MPa combined with cyclic torsion with shear stress range $\sqrt{3}\Delta\tau$ =360 MPa having mean shear stress $\sqrt{3}\,\tau$ =20 MPa at two stress rates $\sqrt{3}\,\dot{\tau}$ =1.0MPa/s [case (a)] and 0.1 MPa/s [case (b)].
- **Problem B-I:** Cyclic torsion with shear strain range $\Delta\gamma/\sqrt{3}$=0.8% at two strain rates $\dot{\gamma}/\sqrt{3}$=0.5%/s [case (a)] and $\dot{\gamma}/\sqrt{3}$=0.01%/s [case (b)].
- **Problem B-II:** In-phase cyclic straining with equivalent strain range $\Delta\bar{\varepsilon}$ =0.8% at two strain rates $\dot{\bar{\varepsilon}}= \sqrt{\dot{\varepsilon}^2+\dot{\gamma}^2/3}$ =0.5%/s [case (a)] and $\dot{\bar{\varepsilon}}$ =0.01%/s [case (b)].
- **Problem B-III:** Out-of-phase cyclic straining with equivalent strain range $\Delta\bar{\varepsilon}$=0.8% at two strain rates $\dot{\bar{\varepsilon}}$ =0.5%/s [case (a)] and $\dot{\bar{\varepsilon}}$ =0.01%/s [case (b)].

4 CONSTITUTIVE MODELS EXAMINED

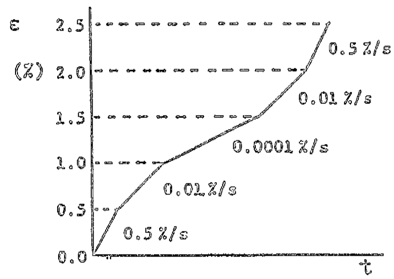
Seven types of inelastic constitutive models were examined on the basis of the benchmark problems stated in the preceding section. The selection of

Table 1 Benchmark problems

A-I Step-up/down creep



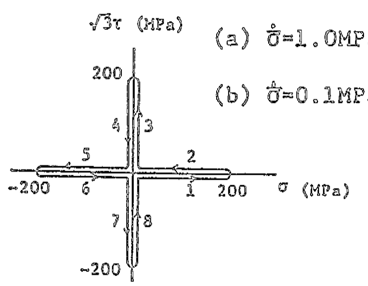
A-II Uniaxial tension with strain-rate change



A-III Cruciform stressing

(a) $\mathring{\sigma}$=1.0MPa/s

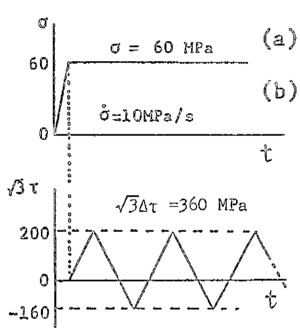
(b) $\mathring{\sigma}$=0.1MPa/s



A-IV Biaxial mechanical ratcheting

(a) $\sqrt{3}\mathring{\tau}$=1.0MPa/s

(b) $\sqrt{3}\mathring{\tau}$=0.1MPa/s

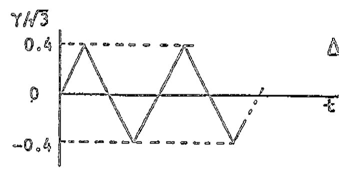


B-I Cyclic torsion

(a) $\mathring{\gamma}/\sqrt{3}$=0.5%/s

(b) $\mathring{\gamma}/\sqrt{3}$=0.01%/s

$\Delta\gamma/\sqrt{3}$=0.8%

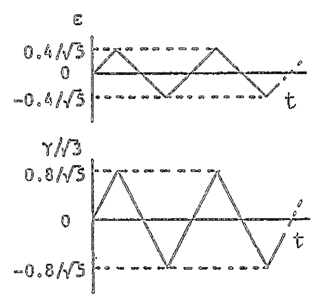


B-II In-phase cyclic straining

(a) $\mathring{\bar{\varepsilon}}$=0.5%/s

(b) $\mathring{\bar{\varepsilon}}$=0.01%/s

$\Delta\bar{\varepsilon}$=0.8%

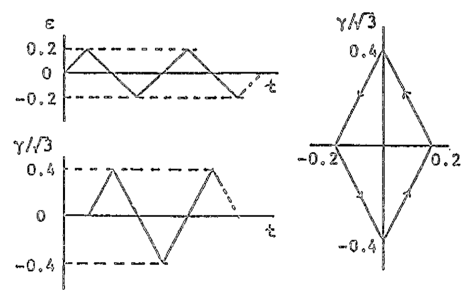


B-III Out-of-phase cyclic straining

(a) $\mathring{\bar{\varepsilon}}$=0.5%/s

(b) $\mathring{\bar{\varepsilon}}$=0.01%/s

$\Delta\bar{\varepsilon}$=0.8%



these models is more or less arbitrary.

(1) Superposition model, or in other words, the classical model.
(2) Modified superposition model[4].
(3) Chaboche model[5].
(4) Fraction model[6].
(5) Ohno-Murakami model[7, 8].
(6) Niitsu model[9].

Brief statement of the above mentioned models is presented in Ref.[2].

(7) Bodner model[10]; this model is a unified model which describes the isotropic and directional hardenings of materials as well as thermal recovery by a set of constitutive equations independent of the yield function concept.

5 RESULTS OF ANALYSES

Stress/strain response for the benchmark problems listed in Table 1 were simulated numerically by nine members (or institutions) of the Subcommittee. Some of the results are given in the following.

Details of the calculation method and the process to determine the material parameters depend on each member's interpretation of the constitutive models, and some models were examined by several members independently. Predicted results of these models will be indicated, for example, as Superp.(B), (D) in the following, of which specifications (B), (D) etc. are correspond to the models indicated in the previous paper[3].

5.1 Problem A-I; Step-up/down creep in uniaxial tension

Cumulative strain versus time curves calculated by the constitutive models in the step-up/down creep in uniaxial tension in Problem A-I is plotted in Fig.1., together with the experimental result. The calculated results by the superposition models (B) and (D) and modified superposition model can simulate fairly well the actual strain accumulation, although all the unified models, especially the Chaboche model (A), the fraction model and the Ohno-Murakami model, overestimate the strain rate in the high hold-stress of $\sigma \gtrsim 150$ MPa. The same tendency is found in the results of uniaxial creep without stress change in the previous benchmark test[3].

Most of the unified constitutive models examined in this benchmark tests, such as the Chaboche model (A), the fraction model and the Ohno-Murakami model, the material parameters are determined on the

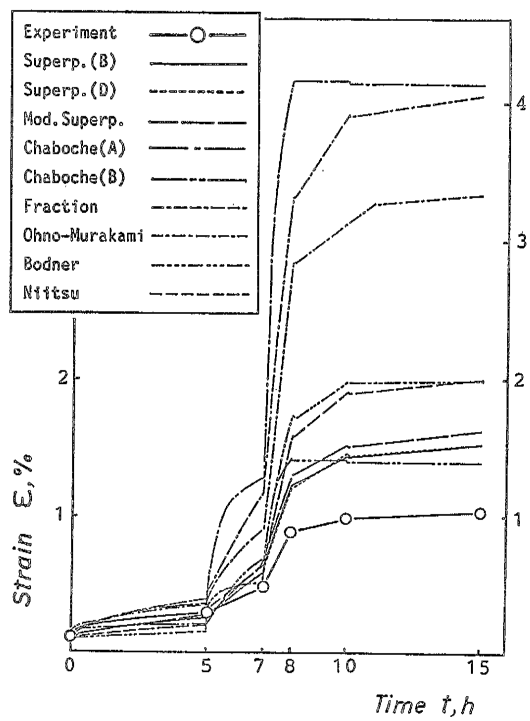


Fig. 1 Cumulative strain vs time curves in step-up/down creep -- Problem A-I --

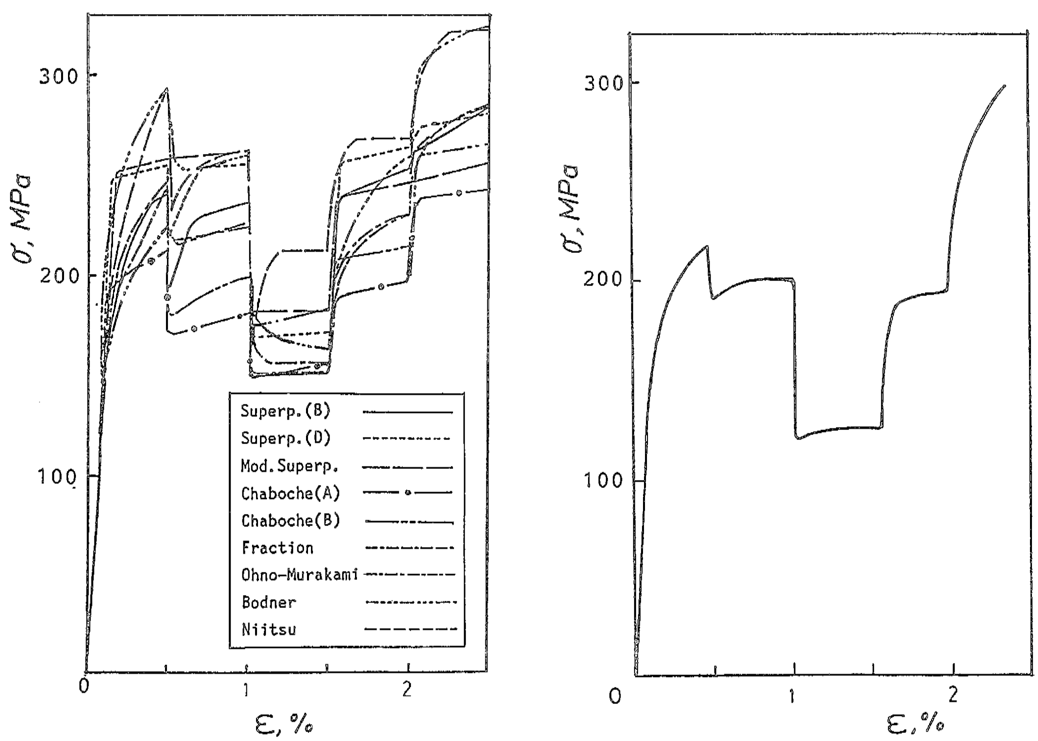
basis of the tension test data rather than the creep data, hence an accurate prediction for creep is not always assured by these models. In the simple and modified superposition models, the creep data were used for the determination of the parameters. This is why the simple and modified superposition models predict the creep strain accumulation in this test.

5.2 Problem A-II; Uniaxial tension with a series of strain-rate change

Stress-strain curves in the uniaxial tension with a series of strain-rate change calculated by the constitutive models are shown in Fig.2(a), and the corresponding experimental result is shown in Fig.2(b). Almost the same calculated results are given by the simple and modified superposition models, in which the difference in flow stress levels between the strain-rate conditions of $\dot{\varepsilon}$ =0.5 and $\dot{\varepsilon}$ =0.01%/s is not so much as seen in the experimental results. On the other hand, all the unified models can well describe the remarkable stress change due to the strain-rate change, although some of the constitutive models, such as the Bodner model and the Niitsu model, overestimate the actual stress level.

5.3 Problem A-III; Cruciform stressing

Figure 3 shows the strain trajectory in the experiment of the cruciform



(a) Simulations (b) Experiment

Fig. 2 Stress-strain curves in the uniaxial tension with a series of strain rate change -- Problem A-II --

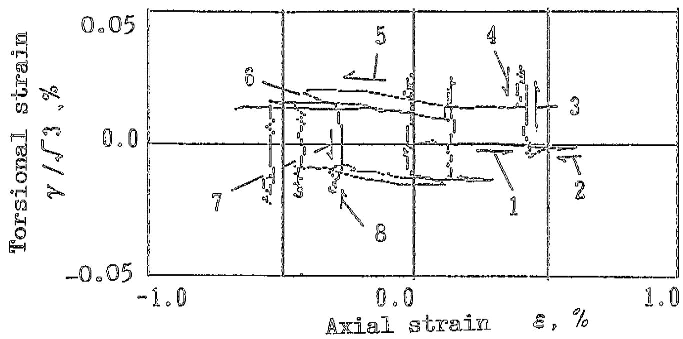
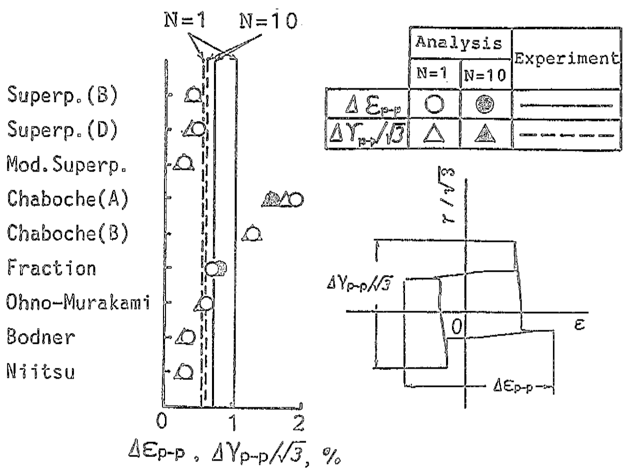
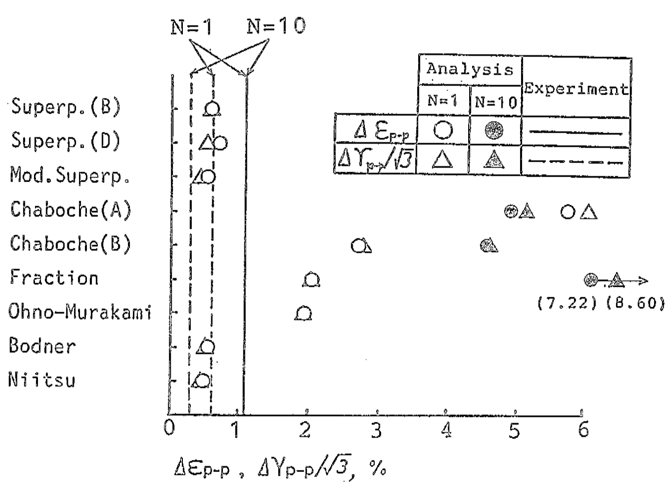


Fig. 3 Strain trajectory in the experiment of the cruciform stressing under fast stress rate at the first few cycles -- Problem A-III(a) --



(a) Fast cycling in Problem A-III(a)



(b) Slow cycling of Problem A-III(b)

Fig. 4 Axial- and shear-strain ranges in the cruciform stressing -- Problems A-III(a) and (b) --

stressing at the fast stress rate of $\dot{\sigma}$=1.0 MPa/s. The shapes of simulated strain trajectories by all the constitutive models are almost the same as the experimental one. Here, let us discuss the strain ranges $\Delta\varepsilon_{p-p}$ and $\Delta\gamma_{p-p}/\sqrt{3}$ in the tests. Figures 4(a) and (b) show the comparison of the calculated strain ranges by the constitutive models with the corresponding experimental results at the two stress-rate conditions of $\dot{\sigma}$=1.0 and 0.1 MPa/s, respectively. For the case of fast stress rate of $\dot{\sigma}$=1.0 MPa/s [See Fig.4(a)], the discrepancies between the calculated results by all the models and the corresponding experimental results are not large. For the case of slow stress rate of $\dot{\sigma}$=0.1 MPa/s [see Fig.4(b)], much difference is found in the calculated strain ranges between the employed constitutive models. The superposition models (B) and (D), the modified superposition model, the models by Ohno-Murakami and Bodner can simulate the strain ranges fairly well. The calculated strain ranges by the Chaboche models (A) and (B) are larger than the actual ones, because these models overestimate the inelastic strain accumulation at high stress level above 150 MPa, as already seen in Fig. 1. The calculated results by the fraction model shows a remarkable increase in the strain ranges with an increasing number of the cruciform-stress cycles. It may come from too strong softening characteristics in this model appearing in the stress-direction changes.

5.4 Problem A-IV; Biaxial mechanical ratcheting

In the stress-controlled mechanical ratcheting with mean stress, both axial and shear strains accumulate with an increasing number of torsional stress cycles, being shown in Fig. 5. All the constitutive models can simulate qualitatively well the actual behavior of ratcheting strain accumulation.

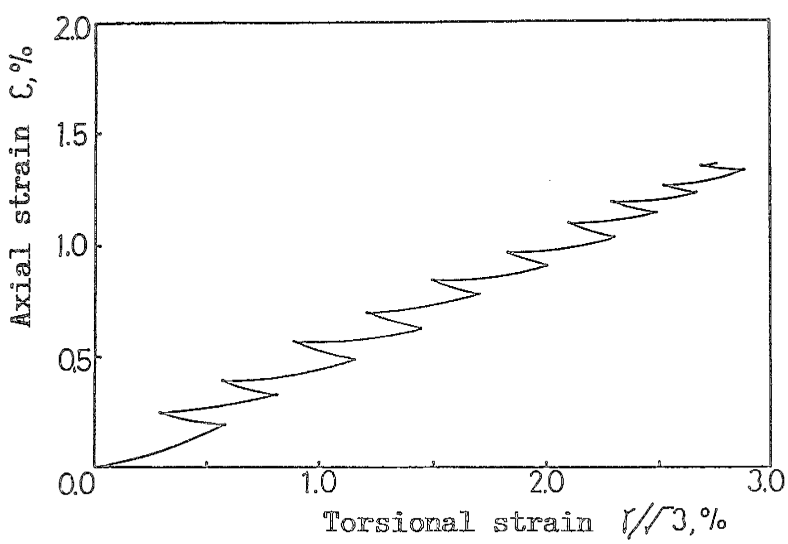


Fig. 5 Ratcheting strain accumulation in the experiment
-- Problem A-IV(b) [Slow cycling] --

In order to discuss the ratcheting behavior quantitatively, let us define the ratchet-strain vector ε^r whose norm is $|\varepsilon^r|$ and the direction θ_r, as schematically illustrated in Fig.6. The comparison of the direction θ_r of ratcheting strain accumulation between the experimental results and the predictions by the constitutive models is depicted in Fig.6. In the experiment, angle θ_r indicating the direction of strain accumulation in the fast cycling of Problem A-IV(a) is larger than in the slow cycling of Problem A-IV(b). The superposition models (B) and (D), the fraction model and the Ohno-Murakami model can describe the effect of stress rate on the direction of ratchet strain accumulation, especially by the superposition model (B), the fraction model and the Ohno-Murakami model, the calculated angles θ_r, both in fast and slow cyclings, agree quantitatively well with the experimental results. Not all the models can describe the effect of stress rate. The modified superposition model, the Chaboche model (B) and the Niitsu model predict almost the same angle θ_r between in the fast cycling and the slow cycling, and the Chaboche model (B) and the Bodner model give the results that the angle θ_r in the fast cycling is less than that in the slow cycling.

The comparison of the accumulated strain $|\varepsilon^r|$ between the experimental data and the predictions by the constitutive models is represented in Fig.7. In the experiment, the amount of strain accumulation $|\varepsilon^r|$ in the fast cycling of Problem A-IV(a) is smaller than in the slow cycling of Problem A-IV(b), because in the stress-controlled ratcheting tests strong creep effect appears in the slow cycling. All the constitutive models can describe this effect of stress rate on strain accumulation qualitatively, especially the superposition models (B) and (D) and the modified superposition model can predict the strain accumulation fairly well. The Chaboche model (A), the fraction model and the Ohno-Murakami model give the larger strain accumulation in the slow cycling, since these models predict higher inelastic strain rate at high stress level, as already seen in the creep tests of Problem A-I.

5.5 Problem B-I; Cyclic torsion, Problem B-II; In-phase cyclic straining and Problem B-III; Out-of-phase cyclic straining

Figures 8, 9 and 10 show the comparison of the stress amplitudes $\sqrt{3}\Delta\tau$, $\Delta\sigma$, and $\Delta\bar{\sigma}$ at 10th cycle in the cyclic torsion in Problem B-I, the in-phase cyclic straining in Problem B-II and the out-of-phase cyclic straining in Problem B-III, respectively, between the calculated results by the constitutive models and the corresponding experimental results. In these three problems, maximum equivalent strain ranges $\Delta\bar{\varepsilon}$ are the same value of 0.8%.

The difference in the equivalent stress ranges $\Delta\bar{\sigma}$ between in the cyclic torsion and in the in-phase cyclic straining is not large, both in the experimental results and the calculated results. The superposition models (B) and (D), the modified superposition model and the Ohno-Murakami model can simulate the actual stress ranges in the cyclic torsion and the in-phase cyclic straining fairly well. The Chaboche models (A),(B) and the fraction model give the lower stress ranges, and the Bodner model predicts them higher than the experimental data.

In the out-of-phase cyclic straining, especially in fast straining, the stress ranges become larger compared with the cyclic torsion and the in-phase cyclic straining. However all the constitutive models hardly describe this additional material hardening.

The material life prediction in fatigue-creep regime based on the analytical stress/strain responses will be discussed in the companion report[11].

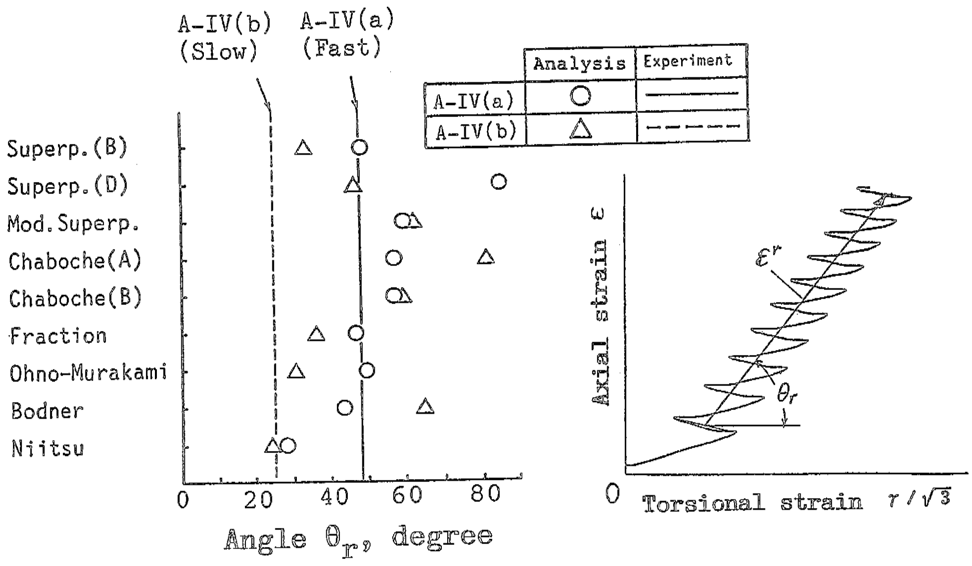


Fig. 6 Direction of ratchet strain accumulation
-- Problem A-IV(a) and (b)--

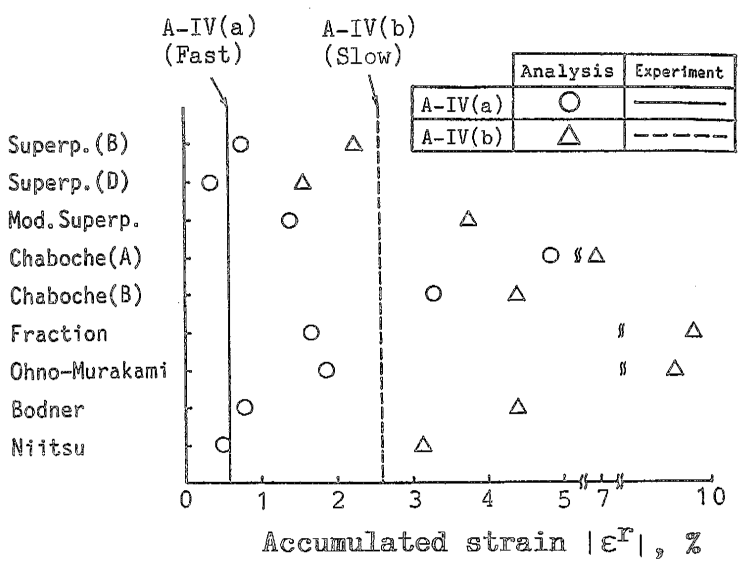


Fig.7 Accumulated strain in the mechanical ratcheting
-- Problem A-IV(a) and (b) --

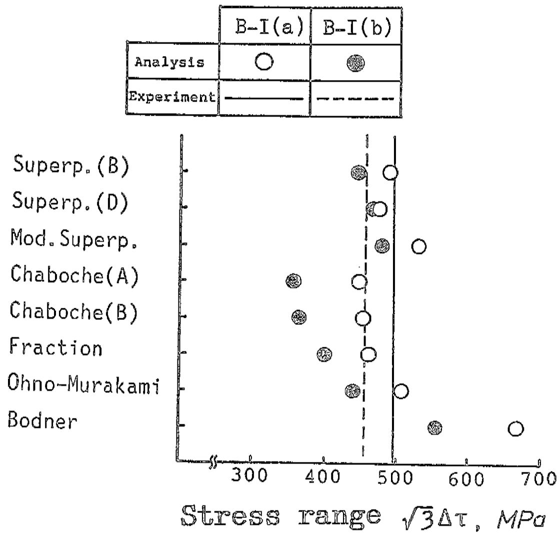


Fig. 8 Stress ranges in the cyclic torsion
-- Problem B-I(a) and (b) --

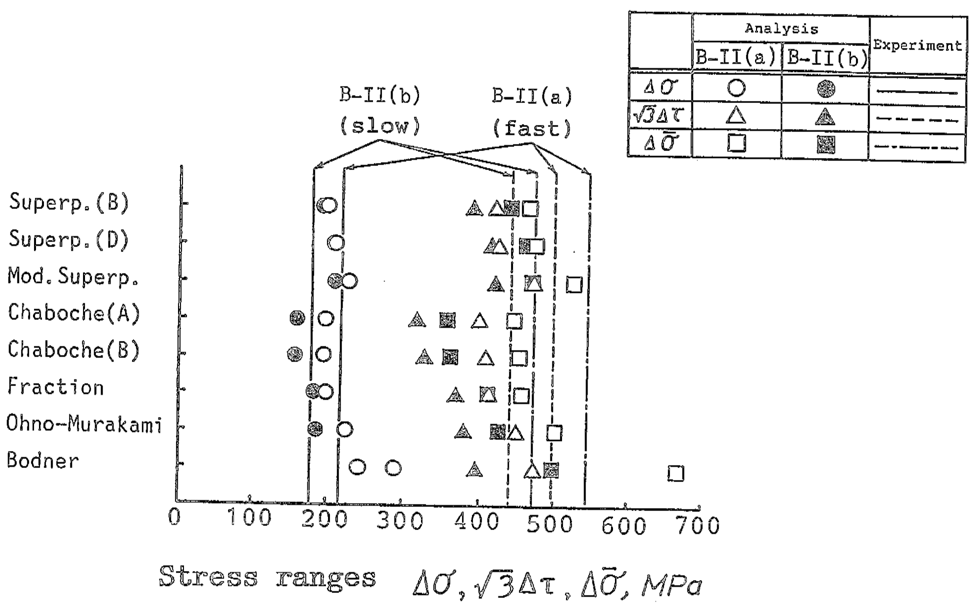


Fig. 9 Stress ranges in the in-phase cyclic stressing
-- Problem B-II(a) and (b) --

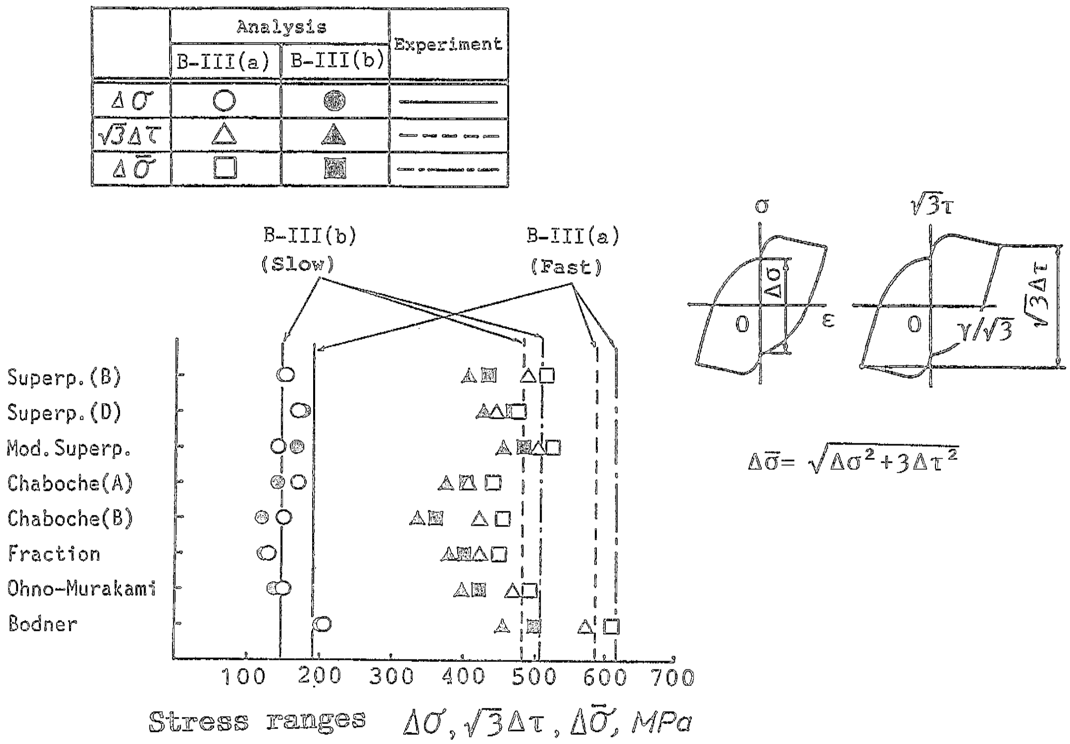


Fig. 10 Stress ranges in the out-of-phase cyclic stressing
-- Problem B-III(a) and (b) --

CONCLUDING REMARKS

To evaluate the validity of existing inelastic constitutive models under the condition of plasticity-creep interaction in multiaxial stress state of combined tension and torsion, seven kinds of constitutive models were applied to twelve benchmark problems of seven categories, and the calculated results were compared with the experiments of 2.1/4Cr-1Mo steel at 600°C. The present benchmark project provides the following remarks:

(1) In general the unified constitutive models have an advantage to describe the plasticity-creep interaction. Actually in some of the benchmark problems, such as uniaxial tension with a series of strain-rate change, apparent differences in the calculated results were found between by the classical superposition models and by the unified models. However, not all the unified models could give better results for all the benchmark tests compared with the classical ones.

(2) Since the results of simulations strongly depend on the material parameters in the constitutive modeling, especially in the unified models, establishment of the scheme for "best-fit" is required.

It is still very difficult to say what kind of model is the most suitable for inelastic analysis even among these constitutive models. However, the benchmark tests show us the characteristics which each constitutive model provides, together with the problems in modeling to be overcome in future.

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