Inelastic Behaviours of $2\frac{1}{4}$Cr-1Mo Steel Under Plasticity-Creep Interaction Condition — Results of Joint Work

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Abstract

A part of interim results of bench mark project by the Subcommittee on Inelastic Analysis and Life Prediction of High Temperature Materials, JSMS, is presented.

Inelastic response of normalized and tempered 2 1/4 Cr-1Mo steel at 600°C was treated under four categories of bench mark problems in the uniaxial stress state; (I) tensile stress-strain relations and creep curves, (II) material response under mixed modes of plastic and creep loading, (III) ratcheting and deformation under program loads, and (IV) cyclic deformation under the combination of different strain rates.

Prediction of the deformation by seventeen constitutive equations of nine kinds were compared with each other as well as with the corresponding results of experiment to evaluate the accuracy of these constitutive models in simulating the actual behaviour of materials.

1. Introduction

Subcommittee on Inelastic Analysis and Life Prediction of High Temperature Materials (members are listed in footnote) was organized in 1982 under the sponsorship of the Committee on High Temperature Strength, the Society of Materials Science, Japan, which succeeded to a part of the activity of EPICC (Elastic Plastic Creep) Subcommittee [1] of Japan Society of Mechanical Engineers. The aim of the Subcommittee is to review the inelastic constitutive models relevant to the material response under the plasticity-creep interaction and to recommend some adequate methods to estimate material life under fatigue-creep interaction by use of the constitutive models. Cooperative experiments for high temperature materials are also under progress to evaluate the validity of constitutive models and life prediction methods currently available.

Members of the Subcommittee are T. Inoue(chairman), T. Igari(secretary), F. Yoshida, A. Suzuki and S. Murakami as coauthors, Y. Asada(Univ. of Tokyo), K. Ikegami(Tokyo Inst. of Technology), M. Kawai(Nagoya Univ.), S. Kubo(Osaka Univ.), S. Nagaki(Okayama Univ.), M. Ohnami(Ritsumeikan Univ.), R. Ohtani(Kyoto Univ.), M. Okazaki(Technological Univ. of Nagaoka), M. Sakane(Ritsumeikan Univ.), K. Tanaka(Univ. of Osaka Prefecture), H. Yokobori(Tohoku Univ.), K. Kanazawa(National Research Inst. of Metals), Y. Wada(Power Reactor and Nuclear Fuel Development Co.), K. Fujiyama(Toshiba Co.), T. Hiroe(Mitsubishi Heavy Ind.), T. Ishizaki (Babcock Hitachi K.K.), M. Iwata(Shikoku Electric Power Co.), S. Kishi(Toshiba Co.), H. Koto (Mitsubishi Heavy Ind.), A. Matsuzaki(Kawasaki Steel Co.), H. Mimura(Nippon Steel Co.), A. Nitta(Central Research Inst. of Electric Power Ind.), T. Shibazaki(Chiyoda Chemical Engineering and Construction Co.), T. Takao(Hitachi Zosen Co.), K. Tokimasa(Sumitomo Metal Ind.), N. Tsuta(Kawasaki Heavy Ind.) with S. Imatani(Kyoto Univ.) as a cooperative member.

The present paper is concerned with a part of interim results of bench mark project on the analysis of inelastic response of 2 $^1\!/_4$ Cr-1Mo steel at 600°C under sixteen paths of complex loading by use of nine types of constitutive models. The results of calculation were compared with each other as well as with some experimental data in some cases.

2. Fundamental Properties of Material

Throughout the project, normalized and tempered 2 $^1\!/_4$ Cr-1Mo steel (SA 387, Gr.22) was examined under uniaxial stress state at 600°C. Material data obtained from three kinds of conventional tests were prepared as fundamental characteristics to identify the material parameters involved in the constitutive models to be evaluated in this paper:

(1) Stress-strain diagrams at four kinds of strain rates (See, Fig.1) [2]. Since the strain-rate depdendence on the curve seems to be saturated approximately at the strain rate of $\dot{\varepsilon}$=0.5∿1 %/s, material behaviour in the range of strain rate is to be defined as "plastic" if necessary.

(2) Creep strain versus time data shown in Fig.2 under the several stress levels [3]. The solid lines in the figure are represented by the formula

$$\varepsilon^{c} = 2.659 \times 10^{-11}\ \sigma^{4.63}\ t^{0.509} + 2.006 \times 10^{-17}\ \sigma^{7.23}\ t \qquad (1)$$

with creep strain ε^{c} (%), stress σ (MPa) and time t (h).

(3) Cyclic softening characteristics under three levels of strain ranges as shown in Fig.3 [4]. Here, the stress-strain hysteresis is assumed to be expressed by the hardening coefficient k and the hardening exponent n by

$$\sigma = k\ (\varepsilon^{p})^{n} \quad ; \quad \varepsilon^{p} \text{ in mm/mm} \qquad (2)$$

as illustrated in the figure.

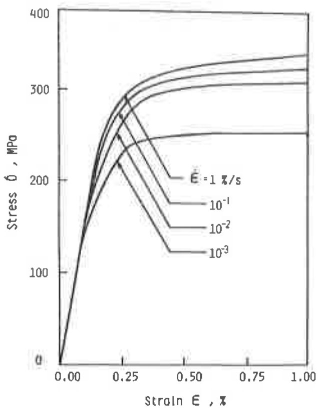

Fig.1 Strain rate dependence of tensile stress-strain diagram

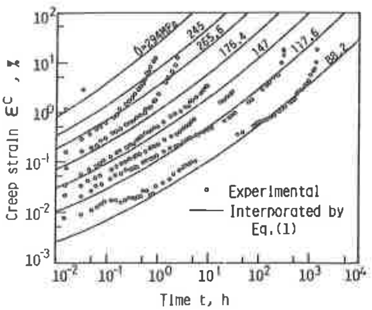

Fig.2 Creep strain versus time with the parameters of applied stress

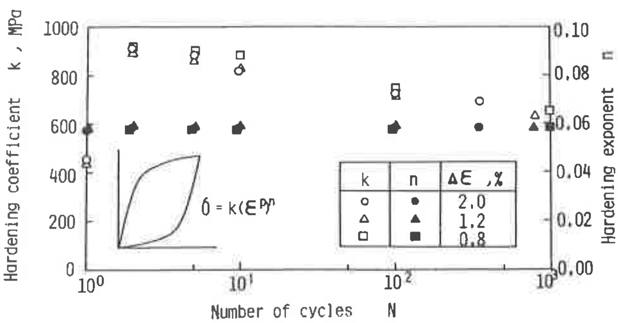

Fig.3 Variation of hardening coefficient and hardening exponent with strain cycles

3. Bench Mark Problems

Sixteen bench mark problems of four categories were propounded for the evaluation of constitutive models:

I. Tensile stress-strain relation and creep curve.

I-1 Tension at constant strain rates; $\dot{\varepsilon}$=0.5, 10^{-1}, 10^{-2}, 10^{-3}, 10^{-4}, 10^{-5} %/s

I-2 Creep under constant stress; σ=90, 120, 150, 180, 200, 250, 300 MPa

II. Material response under mixed modes of plasticity and creep. Here, "plastic" straining signifies the monotonic tensile straining ε=0.5 % at strain rate $\dot{\varepsilon}$=0.5 %/s and "creep" stress is kept constant as σ=150 MPa for 10 h.

II-1 Successive creep and plastic deformation of plastically prestrained material

II-2 Successive plastic and creep deformation of prestrained material by creep

II-3 Cyclic plastic straining of 20 cycles of strain range $\Delta\varepsilon$=1 % followev by creep

II-4 Creep followed by cyclic plastic straining of the same condition as II-3

II-5 Reversed creep of 10 cycles under $\Delta\sigma$=360 MPa with dwell time t_H of 1 h followed by 10 cycles of plastic straining under $\Delta\varepsilon$=2 %

II-6 Cyclic relaxation of N=10 cycles with $\Delta\varepsilon$=2 % of the precrept material of ε=1 % for 10 h.

III. Ratcheting behaviour and deformation under program loads.

III-1 Variations of maximum stress σ_{max} and stress rate $\dot{\sigma}$

III-2 Variation of stress ratio $R=\sigma_{min}/\sigma_{max}$

III-3 Change in stress rate $\dot{\sigma}$ and maximum stress σ_{max} with constant dwell time

IV. Cyclic stress-strain behaviour to 10 cycles under constant strain range $\Delta\varepsilon$=2 % with different strain rate.

IV-1 PP-pattern with $\dot{\varepsilon}$=0.5 %/s

IV-2 CP-pattern with $\dot{\varepsilon}$=0.01 and 0.5 %/s

IV-3 PC-pattern with $\dot{\varepsilon}$=0.5 and 0.01 %/s

IV-4 CC-pattern with $\dot{\varepsilon}$=0.01 %/s

IV-5 Same pattern as IV-1 containing dwell time t_H=5 min in tension side

4. Constitutive Models Examined

Nine types of inelastic constitutive models were examined on the basis of the bench mark problems in Sec.3. The selection of these models is more or less casual and is due to the simple structure of the theories and the easiness in determining the material parameters by conventional tests mentioned in Sec.2. This does not reject further applications of constitutive rules proposed by many researchers e.g. Hart [5], Bodner and Merzer [6], Craggs [7], Valanis [8], Eisenberg and Yen [9], Weng [10], Ponter and Leckie [11], and so on.

Since some of the following models were employed for analyses by plural members of the subcommittee independently, the detail of analytical method and the way to determine material parameters were left at each member's disposal.

(1) Superposition model, or, in another word, classical model in which inelastic strain rate is divided into plastic and creep strain rates. Kinematic hardening rule is adopted in most analyses of the present problems when considering cyclic softening, while creep flow rule based on the modified strain hardening rule due to ORNL model [12] is employed in the majority of the analyses.

(2) Modified superposition model proposed by Pugh [13]: In this model, plastic and creep strain rate are defined independently, but the effect of creep on the plastic hardening is considered, and vice versa.

(3) Mróz model superposed by creep [14]: Since the inelastic strain does not occur below yield stress in the original form by Kujawski and Mróz [15], creep rate under low stress

level is superimposed to the unified inelastic strain rate.

(4) Chaboche model [16] is the one that gives the unified inelastic strain rate due to the excess stress. Two internal variables representing kinematic and isotropic hardening effects are introduced.

(5) Robinson model [17]: Inelastic strain rate is furnished by the flow potential of stress in high order exponent.

(6) Miller model [18] is based on creep theory by Garofalo and developed by incorporating the physical mechanism of inelastic deformation.

(7) Krempl model [19] treated here is characterized as the nonlinearization of simple linear viscoelasticity, where time dependence of material is exhibited by the overstress beyond equilibrium state.

(8) Fraction model by Suzuki and Tsuchiya [20]: The model is the extension of the theory by Besseling [21], which is conceptionally based on the parallel overlay of elements with different kinds of material properties.

(9) Murakami-Ohno-Suzuki model (for brevity, MOS model) is a modification of the creep and the cyclic plasticity model of Murakami-Ohno [22] and Ohno [23] on the basis of recoverable or non-hardening strain region to the coupled plasticity-creep.

5. Results of Analyses

Sixteen bench mark problems in four categories were calculated numerically by seventeen members (or institutions) of the subcommittee, and the results were published in approximately 400 figures as the interim report [24] of 440 pages. Due to the lack of space, several summarized results are presented in the following.

5-1 Problem I: Tensile stress-strain diagrams and creep curves

The flow stress at ε=1 % versus strain rate reproduced from the rate dependent stress-strain curves calculated at $\dot{\varepsilon}$=0.5, 10^{-1}, 10^{-2}, 10^{-3}, 10^{-4}, 10^{-5} %/s are shown in Fig.4, as an example, with the experimental values. The results, in spite of some scatter owing to the difficulty in extrapolation of material data, represents the increase in flow stress with strain rate, except for a result by superposition model. While experimental data represented by hollow circles show the deceleration of stress increase in higher strain rate, this trend is not described by the models by Chaboche, Robinson and Miller. The numerical results of the superposition, modified superposition and Krempl models fall in a narrow band of scatter because of the easiness in determing material parameters. Some discrepancies as seen in Chaboche model, on the other hand, results from the disposal of the analists.

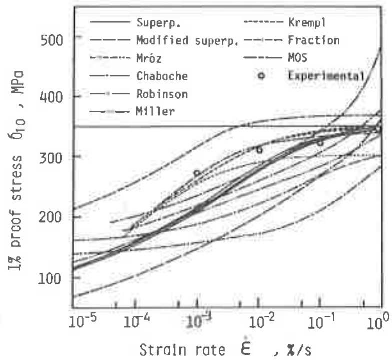

Fig.4 Strain rate dependence of 1 % proof stress — Problem I-1 —

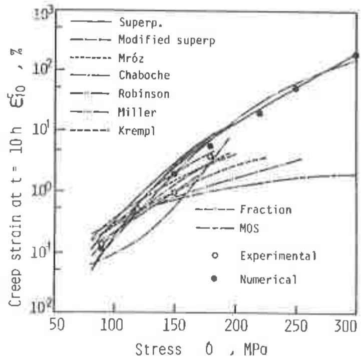

Fig.5 Creep strain at 10 h exposed to given stress — Problem I-2 —

Figure 5 represents the relation between creep strain at 10 h and applied stress, reproduced from the creep curves. Here, solid circles indicate the creep strain calculated by eq.(1) while hollow symbols correspond to the original data in Fig.2. One of the reasons of the scattering in the data observed in high stress range originates from the arbitrariness in employing the solid circled or hollow data in the calculation. Most results by simple and modified superposition models agree well with experimental data with little scatter, and other results by unified theories understimate the creep strain in high stress level. It follows that there exist some difficulties in adopting the same material parameters in either case of plasticity and creep.

5-2 Problem II: Material response under mixed modes of plasticity and creep

Difference in the estimation of the effect of prestrains by plastic tension and creep on the subsequent stress-strain relation is schematically illustrated by thin lines in Fig.6, with the thick lined experimental data for the material of the same kind. Most results predicted by superposition models fall in curve C, since the creep does not affect the subsequent plastic behaviour. However, some modified models give the results of the type B when considering the kinematic hardening by creep, or of type E due to the creep affected decrease in yield stress. The results by other unified models may be classified into two types: the models of Chaboche, Robinson and Miller, in which creep strain is not completely the same as plastic strain, show the tendency like curve B, whereas models of Krempl, fraction and MOS based on the equivalence of both kinds of strain gives the response of type A.

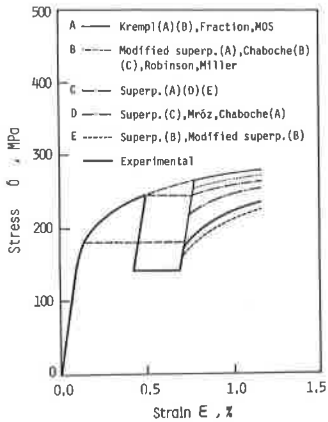

Fig.6 Classification of the results by different model on the effect of creep on plastic deformation — Problem II-1 —

The effect of plastic straining on the subsequent creep calculated for both Problems II-1 and II-2 are shown in Fig.7. Denoting the creep strain in Problem II-1 by ε_C^c and II-2 by ε_A^c, ε_B^c (induced under the same condition of σ=150 MPa for 10 h), the ratio of $\varepsilon_C^c/\varepsilon_A^c$ and $\varepsilon_B^c/\varepsilon_A^c$ mean the effects of preloaded plastic strain and of preloaded creep and plastic strain, respectively. The ratio $\varepsilon_C^c/\varepsilon_A^c$ predicted by the simple, modified superposion and Mróz model takes approximately unity since the plastic strain exerts no influence on creep, while the value by other unified models are less than unity because of the effect of plastic strain on creep hardening. The values of $\varepsilon_B^c/\varepsilon_A^c$ entered by hollow circles, on the other hand, take about 0.72 for the models where creep strain is not affected

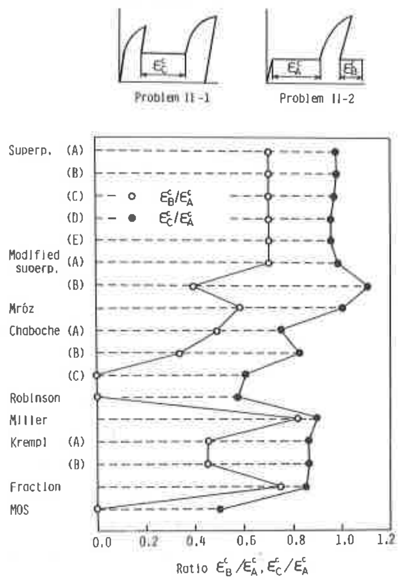

Fig.7 Effect of plastic prestrain on creep deformation — Problem II-1 and II-2 —

by plastic loading, and the models predicting small values of $\varepsilon_C^c/\varepsilon_A^c$ give the values of $\varepsilon_B^c/\varepsilon_A^c$ smaller than 0.72.

5-3 Problem III: Ratcheting and deformation under program loads

As an example of calculated results, Fig.8 represents the effect of dwell time on ratcheting strain in Problem III-3 where stress pattern is shown by the illustration. Here, the amount of strain in the first cycle in block I and III is represented by shadowed histogram, and the accumulated ratcheting strain induced by the following cycles by white ones. Due to the lack of experimental data in this stage, no comment can be made on the calculations. However, the models of Chaboche and Miller give the large value of accumulated strain owing to cyclic softening tendency.

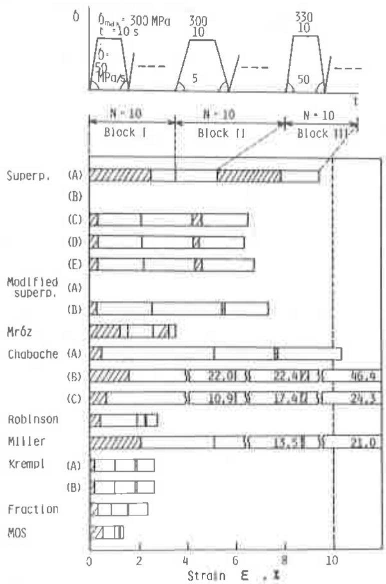

Fig.8 Accumulated strain due to ratcheting — Problem III-3 —

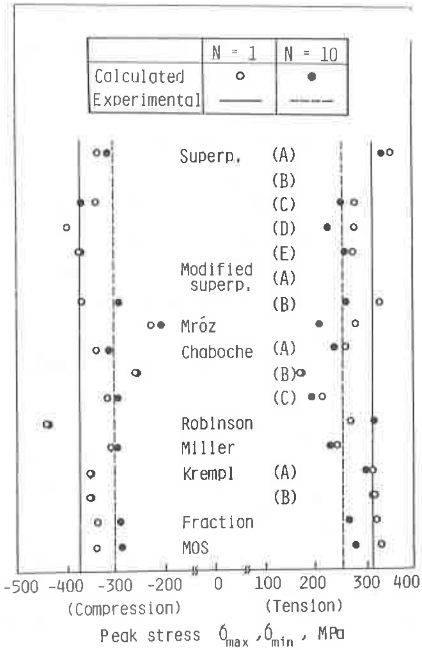

Fig.9 Peak stresses at the first and the tenth cycle — Problem IV-2 —

5-4 Problem IV: Cyclic deformation behaviour

Figure 9 shows the peak stress at the first and the tenth cycles under the CP strain pattern (Problem IV-2), as an example of cyclic softening phenomena. The stresses of smaller magnitude are predicted by the Chaboche and Mróz models as compared with experiment, and higher stress by Robinson in which cyclic softening is neglected. Hysteresis loops calculated by three kinds of representative models are illustrated in Fig.10. The loop (a) by the superposition model gradually moves to compression side in CP condition (it moves to tension in PC test), while stable loops are obtained by the Chaboche and fraction models as seen in Fig.10(b) and (c), respectively. This may be attributed to the fact that plasticity-creep interaction has been taken into account in the latter two models.

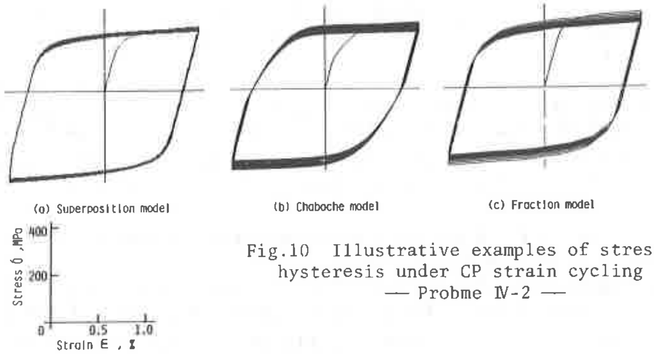

Fig.10 Illustrative examples of stress-strain hysteresis under CP strain cycling
— Probme Ⅳ-2 —

6. Concluding Remarks

As a first step to evaluate the applicability of the existing inelastic constitutive models to the plasticity-creep interaction condition, interim results of bench mark project is reported in this paper.

The calculated results of the problems can provide the following remarks:

1) Strain rate effect on stress-strain relation can be represented, in some degree, even by simple superposition model of classical type, and some of unified models show the saturation of increase in flow stress with higher strain rate.

2) The characteristics of plasticity-creep interaction were predicted by modified superposition model as well as by unified ones in the actual numerical calculations for the propounded problems.

3) Although sophisticated unifed constitutive models give the better results of simulation qualitatively, the complicated method in determing material parameters from the data of conventional simple tests need some improvements.

The final decision of what kind of model is suitable for the inelastic analysis will be an open question until the numerical results of the present paper will be compared with the undergoing experimental results.

Acknowledgement

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