Transactions of the **14th International Conference on Structural Mechanics in Reactor Technology** (SMiRT 14), Lyon, France, August 17-22, 1997

L02/4

Application of Chaboche viscoplastic theory for predicting the cyclic behaviour of modified 9Cr-1Mo

Chellapandi P., Ramesh R., Chetal S.C., Bhoje S.B.
Indira Gandhi Centre for Atomic Research, India

ABSTRACT: Modified 9Cr 1Mo (grade 91) is the structural material for the Steam Generator (SG) of 500 MWe Prototype Fast Breeder Reactor (PFBR). This material is codified in RCC-MR(1993). SG top tubesheet and its connecting shell are in contact with the hot sodium at temperature of about 800 K. The steam temperature is about 770 K at 17 MPa. It is envisaged that this component can meet the creep fatigue damage rules of RCC-MR with 'elastic route' itself. One of the important material data needed to use the simplified rules recommended in RCC-MR (1993) is 'symmetrisation coefficient (Ks) which is not yet included in RCC-MR. Towards establishing Ks theoretically, the Chaboche model for grade 91 material has been defined with 20 material parameters which are identified based on the uniaxial monotonic and cyclic material data. The model thus derived shows satisfactory comparison with the experimentally determined uniaxial monotonic, cyclic, creep data. Finally using this model, Ks is established for the use of design calculations to compute creep and fatigue damage as per RCC-MR.

1. INTRODUCTION

The high temperature out of core components in an FBR are hot sodium pool components, hot secondary sodium piping, SG and turbine. Turbine being a standard equipment, analysis is not usually done in plant. Detailed elastic, inelastic and viscoplastic analysis have been done for hot pool components other than SG for 500 MWe Prototype Fast Breeder Reactor (PFBR), being designed at Indira Centre for Atomic Research Kalpakkam [1]. The creep fatigue damage assessment of SG is yet to be evaluated in accordance with design rules of RCC-MR (1993) towards checking its structural integrity at its operating temperatures (hot sodium temperature is 798 K and steam temperature is 766 K at 17 MPa pressure).

SG is an important component in the NSSS because of the risk of sodium-water reaction. Also, it decides the capacity factor of an FBR plant. The structural material chosen for SG is modified 9Cr-1Mo steel (grade 91) because of its adequate mechanical strength, freedom from the risk of stress corrosion cracking and also decarburisation. For the creep-fatigue damage analysis of SG, material data viz. monotonic and cyclic stress strain curves, creep curves, creep and relaxation curves are required in case 'inelastic route' of design code is followed. However, in the design stage, it is felt that the SG should meet the creep fatigue damage rules of RCC-MR through 'elastic route'. This also needs some minimum inelastic properties like saturation fatigue curve, isochronous stress strain curve, creep data, symmetrisation coefficient (Ks) and creep fatigue interaction curve. Eventhough modified 9Cr 1Mo material is codified in RCC-MR (1993), all the required material data for calculating damage are not available in the Appendix-Z of RCC-MR. The important properties which are yet to be included are saturation fatigue curve, isochronous stress strain curve, symmetrisation coefficient (Ks) and creep fatigue interaction curve. Except Ks, other data are available in the literature [2]. Hence it is required to develop Ks either numerically or experimentally so that creep-fatigue assessment can be done using the 'elastic route' of RCC-MR.

A methodology has been established to derive the symmetrisation coefficient from the theoretically generated material data on cyclic stress strain behaviour by using Chaboche viscoplastic theory. This methodology is validated by comparing the theoretically predicted Ks values for SS 316 LN (S1 material as per RCC-MR) with the values given in RCC-MR. It is worth mentioning that the values given in RCC-MR have been obtained from the cyclic stress strain data generated from tests at EDF [3]. Using the methodology, Ks values are obtained for grade 91 material for the future use of creep-fatigue damage assessment of SG tubesheet in accordance with RCC-MR.

In this paper, development of Chaboche model for modified 9Cr-1-Mo (grade 91) material, identification of material constants, methodology of computing Ks and symmetrisation coefficient curve which is recommended by the authors for the inclusion in RCC-MR are presented.

2. SALIENT FEATURES OF MODIFIED 9Cr-1Mo (GRADE 91) STEEL

- The material exhibits marked strain-rate sensitivity at elevated temperature. The strain-rate sensitivity increases with increasing temperature.
- The material displays strain softening at larger strains in elevated temperature, during monotonic tests. However, under lower temperature monotonic loading, the material primarily strain hardens. The temperature over which monotonic hardening/softening behaviour changes abruptly lies in the range of 650-750 K.
- The material cyclically softens in strain-controlled cyclic tests. The amount of cyclic softening appears to be independent of temperature.
- Under constant stress loading, the material exhibits an apparently very low primary creep stage in the 750-900 K temperature range. Though the amount of primary creep is insignificant, it increases with increasing temperature. Secondary creep rates also increase with increasing temperature and stress.

3. CHABOCHE VISCOPLASTIC THEORY FOR GRADE 91 MATERIAL

The '23 parameter Chaboche viscoplastic model' essentially developed for SS 316 LN [4] has been modified to model the mechanical behaviour of grade 91 steel at high temperature. The major modifications are:

- Elimination of (1) an exponential term which is to simulate the strain insensitivity in the intermediate temperature range, (2) coupling between kinematic and isotropic hardening and (3) plastic strain memorisation effects and

- Inclusion of (1) third term in the kinematic hardening variable to account for the large strain range effects, (2) two terms for the isotropic softening variable and (3) effect of isotropic hardening in the viscous stress for simulating correctly the cyclic softening behaviour.

With the above modifications, a viscoplastic model for grade 91 steel thus, involves 3 kinematic hardening tonsorial variable (X_1 X_2 & X_3) and 2 isotropic softening scalar variables (R_1, R_2). Totally 20 material parameters are used to define the material behaviour. The general expression of 20-parameter Chaboche model is as follows:

$$\varepsilon = \sqrt{3/2}p.\mathbf{n}$$

$$p = \langle \sigma_v / K(R) \rangle^n = [\,2/3.\varepsilon.\varepsilon\,]^{1/2}$$

$$\mathbf{n} = (\mathbf{S} - \mathbf{X}) / |(\mathbf{S} - \mathbf{X})|$$

$$\sigma_v = J(\sigma - \mathbf{X}) - k$$

$$J(\sigma\text{-}\mathbf{X}) = [3/2|(\mathbf{S}\text{-}\mathbf{X})|\,]^{1/2}$$

$$|(S\text{-}X)| = [(S_{ij} - X_{ij}).(S_{ij} - X_{ij})]^{1/2}$$

$$K(R) = Ko + \alpha.R$$

where, $R = R_1 + R_2$

$$\langle u \rangle = u.H(u).$$ H is the Heaveside's step function.

Kinematic hardening variables are:

$$\mathbf{X}_i = 2/3c_i\, a_i\varepsilon_i - c_i\, p.\mathbf{X}_i - \beta_{i.}|I(\mathbf{X}_i)|^{(mi-1)}.\mathbf{X}_i$$

where, $X = \sum X_i \quad (i = 1, 3)$

Isotropic hardening variables:

$$Ri = bi.(Qi - Ri).p \qquad (i = 1, 2)$$

$$J(\mathbf{X}) = (2/3\,|\mathbf{X}|\,)^{1/2}$$

n, k, K_o, α, a_1, c_1, a_2, c_2, a_3, c_3, β_1, β_2, β_3, m_1, m_2, m_3, b_3, b_2, Q_1 and Q_2 are the 20 material parameters which are functions of temperature.

4. IDENTIFICATION OF MATERIAL PARAMETERS

Moosbrugger [5] has developed a non-isothermal constitutive model based on Chaboche viscoplastic theory for the small strain behaviour of modified 9Cr-1Mo. Accordingly material parameters are identified by Moosbrugger as a coupled function of temperature over the temperature range of 298 to 873 K. A systematic approach by which the material parameters that are associated with Moosbrugger model are correlated with those of Chaboche model is made. The table 1 shows one to one correspondence between parameters of Chaboche and Moosbrugger models by understanding the physical meaning of each of the parameters. The mathematical expressions of the Moosbrugger model can be found in ref[5]. Table 2 shows the identified material properties at various temperatures.

Table 1: Relationship between the material parameters of Chaboche and Moosbrugger models

Chaboche	n	k	K_o	α	ai	ci	bi	mi	b_i	Q_i
Moosbrugger	1/m	k	$(1/\Theta)^m$	$(p1)^{-m}$	$\sqrt{3/2}b_i$	c_i	$(c_i b_i/K_i(3/2)^{(1/m-0.5)}\Theta$	1/m +1/2	μ_i	χ_i

Table 2: Values of 20 material parameters of Chaboche model for grade 91 steel

Constants	Temperature (K)				
	298	673	773	823	873
n	0.0	0.0	0.0	0.0	0.0
k	41.7	41.7	10.5	6.2	4.5
K_o	369.9	306.0	514.0	783.4	1076.6
α	1.3	1.3	2.5	4.7	8.5
a_1	150.0	150.0	146.5	141.1	105.0
c_1	7000.0	7000.0	7000.0	7000.0	7000.0
β_1	41.7	41.7	10.5	6.2	4.5
m_1	0.0	0.0	0.44×10^{-25}	0.61×10^{-15}	0.76206×10^{-11}
a_2	117.5	117.5	64.8	48.9	27.9
c_2	500.0	500.0	500.0	500.0	500.0
β_2	41.7	41.7	10.5	6.2	4.5
m_2	0.0	0.0	0.92×10^{-25}	0.1E-14	0.96319×10^{-11}
a_3	266.6	173.4	120.7	82.4	83.6
c_3	37.5	37.5	37.5	37.5	37.5
β_3	41.7	41.7	10.5	6.2	4.5
m_3	0.0	0.0	0.96×10^{-24}	0.95×10^{-14}	0.16254×10^{-9}
b_1	30.0	30.0	30.0	30.0	30.0
Q_1	-65.0	-65.0	-65.0	-65.0	-65.0
b_2	0.3	0.3	0.3	0.3	0.3
Q_2	-15.0	-15.0	-15.0	-15.0	-15.0

5. NUMERICAL SIMULATION OF UNIAXIAL MECHANICAL BEHAVIOUR

Fig 1 shows the monotonic stress strain curves in the temperature range 723 - 873 K up to 12 % strain. It is seen in this figure that the monotonic hardening decreases with increasing temperature. Above 823 K, a slight monotonic softening can be noted. The strain rate sensitivity of this material can be seen in Fig 2 at the temperature of 873 K wherein it is seen that monotonic softening is higher at higher strain rate. Creep curves relevant to FBR applications t are shown in Fig 3. The cyclic stress strain hysterisis loops derived from strain controlled cycling of ±1% at the constant strain rate of 6.7×10^{-4} /s are plotted in the Fig 4 and Fig 5 for the temperatures 723 K and 873 K respectively. Cyclic consolidation curves, i.e, variation of peak stress with the cycle number, are shown in Fig 6 which depicts clearly the cyclic softening behaviour of T91 material. It is noted that the softening behaviour is more or less independent of temperature.

It is worth mentioning that the simulation of the above curves matches satisfactorily with the uniaxial data published [2].

6. ESTABLISHING SYMMETRISATION COEFFICIENT

When long hold times and elevated temperatures are involved in the design loading cycles, creep effects are considered in RCC-MR as follows:

- In the assessment of fatigue damage fraction, addition of creep strain ($\Delta\varepsilon_c$) contribution at end of each cycle to the equivalent elastoplastic strain range.
- In the assessment of creep damage fraction, the maximum stress generated (σ_R) during the hold period of the cycle.

$\Delta\varepsilon_c$ depends upon σ_R. The value of σ_R is obtained as the sum of primary stress intensity encountered during hold time and the contribution due to secondary stress range (Ks.$\Delta\sigma_S$). $\Delta\sigma_S$ is the stress range corresponding to elastoplastic strain range $\Delta\varepsilon$. The Ks is the symmetrisation coefficient which accounts for the symmetrisation of the stress strain loop under large loadings. It is defined as a function of ratio R ($=0.5\Delta\sigma_S/\sigma_Y$). σ_Y is the minimum yield stress at the maximum temperature during hold period. For the small amplitude cycles, no plasticity arises; there in no symmetrisation and hence, Ks is equal to 1. For large amplitude cycles, full symmetrisation is possible and Ks is equal to 0.5. This function is usually determined by numerous strain controlled tests. With the absence of sufficient experimental data, required material data has been generated numerically using Chaboche viscoplastic model.

The methodology adopted to generate Ks as follows:

- Select the temperature and strain rate.
- Select the strain ranges of interest ($\Delta\varepsilon$)
- Determine stress cycling under repeated strain ranges (zero to maximum $\Delta\varepsilon$) by numerical solution of uniaxial formulation of Chaboche model.
- Extract stabilised peak stresses (σ_p) corresponding to various strain ranges 0 to $\Delta\varepsilon$ (Fig 7). Determine the stabilised stress range ($\Delta\sigma_S$) corresponding to strain range ($-\Delta\varepsilon/2$ to $+\Delta\varepsilon/2$) either by analysis or by using RCC - MR Appendix-Z data (Fig 7).

- Plot a curve X $(=0.5.\Delta\sigma_S/\sigma_Y)$ vs Y $(=2.\sigma_p/\Delta\sigma_S)$ which is the required symmetrisation coefficient curve (Fig 8).

7. DISCUSSION ON Ks

Following the aforementioned procedure, symmetrisation coefficients are also determined for austenitic stainless steel type SS 316 LN material which is compared with the curve given in RCC-MR (1993) appendix Z corresponding to S1 material. For theoretically establishing Ks, the 23 parameter Chaboche model [4] is used. The results compare well as seen in Fig 9. This demonstrates the adequacy of analytical methodology of establishing Ks values. Hence the symmetrisation coefficient established by this procedure for grade 91 material is recommended for the inclusion in the RCC-MR code for facilitating the computation of creep-fatigue damage assessment for modified 9Cr 1Mo (grade 91 material) as per the 'elastic route'.

It is also worth noting the difference between the symmetrisation co-efficient curves of austenitic stainless steel SS 316 LN and grade 91. In the case of grade 91, the symmetrisation occurs at relatively low secondary stress ranges.

8. CONCLUSION

Towards establishing symmetrisation coefficient curves for modified 9Cr 1Mo (grade 91 material) which are essential in the creep-fatigue damage computations as per 'elastic route' of RCC-MR, a new '20 parameter Chaboche viscoplastic model' has been derived. All the essential uniaxial data for establishing Ks values have been generated theoretically by solving uniaxial form of Chaboche model. The predicted behaviour have compared satisfactorily with the experimental data. Methodology has been established to determine Ks values in the form given in RCC-MR. Thus established curve has been recommended for the inclusion in RCC-MR in its future edition. For the sake of getting confidence in the methodology adopted to establish Ks values, symmetrisation curve is established using the material data generated from the use of '23-parameter Chaboche viscoplastic model' for SS 316 LN and compared with the one given in RCC-MR for the same material. The symmetrisation coefficient Ks for grade 91 material symmetrises under relatively lower secondary strain ranges during cycling loadings, as compared to SS 316 LN.

REFERENCES

1. Bhoje, S.B and P.Chellapandi, (1995). Operating temperature for an FBR, Nuclear Engineering and Design, 158 (1995).

2. Guntz. et.al. (1990). The T91 book on Ferritic tube and pipe for high tempearuture use in boilers, Vallourec Industries, France.

3. Regles de Conception et de Construction des Materials Me' caniques des ilots Nucle ' aire

RNR (RCC-MR), A.F.C.E.N. (1985).

4. Chaboche, J.L, and D.Nouailhas, (1989). A unified constitutive model for cyclic viscoplasticity and its applications to various stainless steels, ASME Jl. Engineering Materials and Technology, 111.

5. Moosbrugger, J.C. (1992) 'Nonisothermal constitutive model for the small strain behaviour of 9Cr-1Mo-V-Nb pressure vessel steel, ASME Jl. Engineering Materials and Technology, 114.

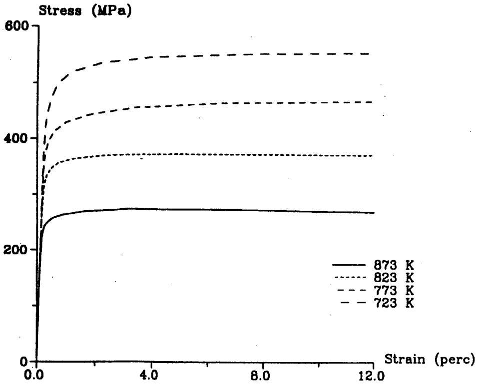

Fig.1 Monotonic stress strain curve for T91 material (strain rate 6.7X10^{-5} /s)

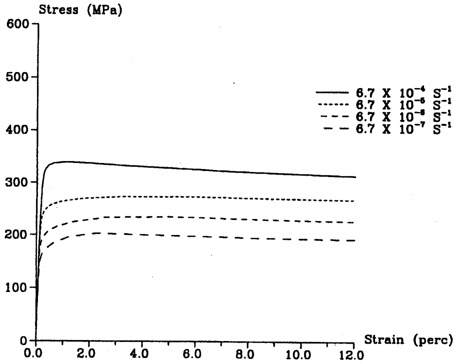

Fig.2 Simulation of monotonic stress strain curve at 873 K

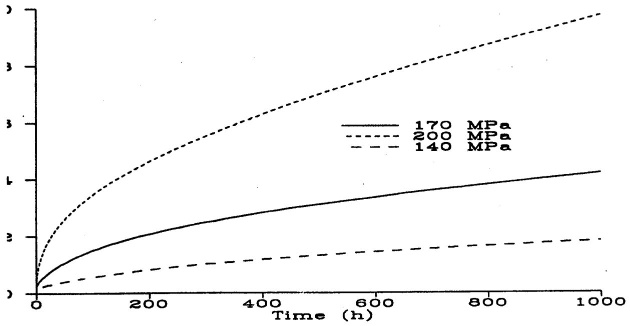

Fig.3 Simulation of creep curves at 873 K

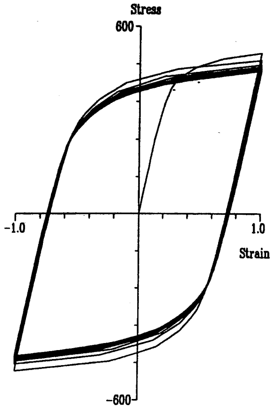

Fig.4 Simulation of strain controlled cycling at 723 K.

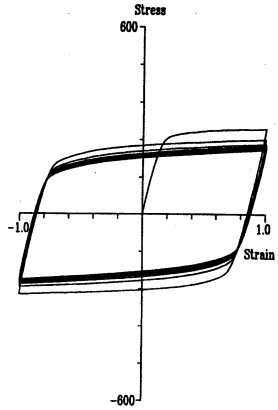

Fig.5 Simulation of strain controlled cycling at 873 K.

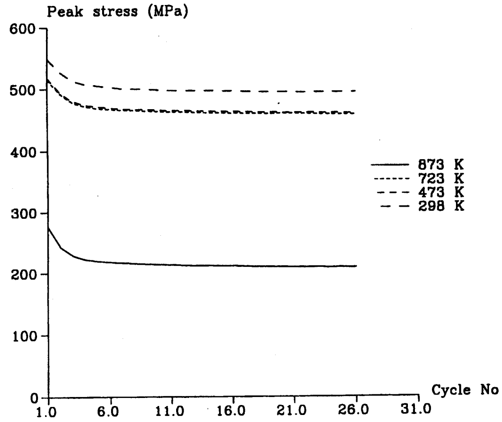

Fig.6 Cyclic softening behaviour of T91 (strain range ± 1% and strain rate 6.7 X 10^{-5})

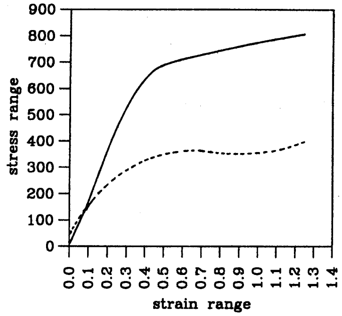

Fig.7 Stress range and peak stress under strain cycling at 773 K

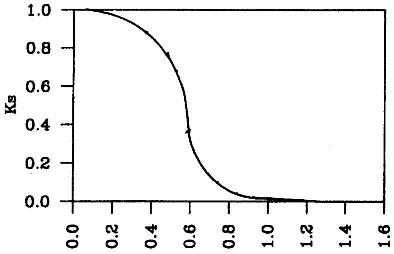

Fig.8 Symmetrisation coefficient for T91

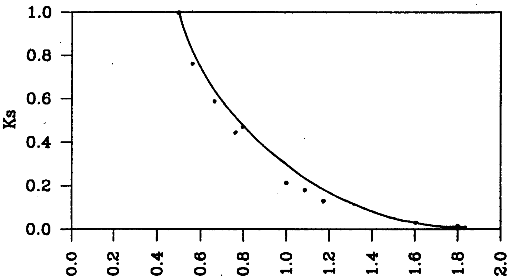

Fig.9 Symmetrisation coefficient for SS 316 LN