APPLICATION OF CHABOCHE VISCOPLASTIC THEORY FOR PREDICTING THE CYCLIC BEHAVIOUR OF MODIFIED 9Cr-1Mo (T91)

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Abstract

Modified 9Cr 1Mo (grade 91) is the structural material for the SG of 500 MWe Prototype Fast Breeder Reactor. This material is codified in RCC-MR (1993). SG top tubesheet and its connecting shell see the hot sodium 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 given in RCC-MR (1993) is `symmetrisation coefficient' (Ks) which is not yet included in RCC-MR. Ks values are established from numerous stress strain cyclic data generated theoretically by using Chaboche viscoplastic model and recommended for the inclusion in the RCC-MR. The Chaboche model for grade 91 material has 20 material parameters which are identified based on the uniaxial monotonic and cyclic data available in RCC-MR (1993) as well as the published data and many uniaxial monotonic, cyclic, creep data are compared well with the predictions.

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 done. 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 this component 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 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 structural analysis of SG, material properties 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. 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 data, 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.

The symmetrisation coefficient is evaluated by generating required cyclic stress strain data theoretically by using Chaboche viscoplastic theory. The methodology adopted to establish Ks values have been verified by comparing the Ks values for SS 316 LN (S1 material) given in RCC-MR which have been obtained from the cyclic stress strain data generated at EDF. Such methodology is repeated for grade 91 material for the use of damage assessment of SG tubesheet in accordance with RCC-MR.

In this paper, the aspects, viz. development of Chaboche model for modified 9Cr-1-Mo (grade 91) material, identification of material constants, methodology of computing Ks and symmetrisation 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 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 in the isotropic softening variable and (3) effect of isotropic hardening in the viscous stress. With these, the model for grade 91 steel now involves only 3 kinematic hardening tensorial variables ($\mathbf{X}_1$ $\mathbf{X}_2$ **&** $\mathbf{X}_3$) and 2 isotropic softening scalar variables ($\mathbf{R}_1$, $\mathbf{R}_2$). Totally 20 material parameters are used to define the material behaviour. The constitutive equations are stated as follows.

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

$$p \quad = \quad \langle \sigma_v / K(R) \rangle^n$$

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

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

$$K(R) \quad = \quad Ko + \alpha R \qquad R = R_1 + R_2 \text{ Isotropic hardening variables}$$

$$\mathbf{S} \quad = \quad \sigma - 1/3.\sigma_{kk}\mathbf{I}$$

$$\mathbf{X} \quad = \quad \mathbf{X}_1 + \mathbf{X}_2 + \mathbf{X}_3 \qquad \text{(kinematic hardening variables)}$$

$$J(\sigma - \mathbf{X}) \quad = \quad \sqrt{3/2}.\ \|\mathbf{S}-\mathbf{X}\|$$

$$\|\mathbf{S}-\mathbf{X}\| \quad = \quad [(\mathbf{S}_{ij} - \mathbf{X}_{ij}).(\mathbf{S}_{ij} - \mathbf{X}_{ij})]^{1/2}$$

$$p \quad = \quad \sqrt{2/3}.\ \|\varepsilon\| \qquad \text{(effective strain rate)}$$

$$\mathbf{X}_i \quad = \quad 2/3.a_i.c_i.\varepsilon_i + c_i.p + \beta_i.\ I(\mathbf{X}_i)^{(mi-1)}\mathbf{X}_i$$

$$R_i \quad = \quad b_i.(Q_i - R_i).p$$

$$J(\mathbf{X}) \quad = \quad \sqrt{2/3}.\ \|\mathbf{X}\|$$

The material parameters viz. n, k, Ko, α, a_1, c_1, a_2, c_2, a_3, c_3, β_1, m_1, β_2, m_2, β_3, m_3, b_1, Q_1, b_2 and Q_2 are temperature dependent constants.

4. IDENTIFICATION OF MATERIAL PARAMETERS

Moosbrugger [3] 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

Table 1

Relationship between parameters of Chaboche and Moosbrugger models

Chaboche model	Moosbrugger [3]
n	$1/m$
k	k
Ko	$(1/\Theta)^m$
α	$(p_1)^{-m}$
a_i	$\surd 3/2b_i$
c_i	c_i
β_i	$(ci.bi/Ki).\ (3/2)^{(1/m-0.5)}.\ \Theta$
m_i	$1/m - 0.5$
b_i	μ_i
Q_i	χ_i

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 Moosebrugger models by understanding the physical meaning of each of the parameters. The mathematical expressions of the Moosbrugger model can be found [3]. Table 2 shows the identified material properties at various temperatures.

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, slight monotonic softening can be noted. The strain rate sensitivity of this material can be seen in Figs 2-3 for 773 K and 873 K respectively. At 873 K, monotonic softening is higher at higher strain rate. Some creep curves of FBR interest are shown in the Fig 4. The cyclic stress strain hysterisis loops are plotted in the Figs 5-8 for various temperatures (298-873 K) under strain controlled cycling of ±1%. at the constant strain rate of 6.7×10^{-4} 1/s. Cyclic consolidation curves which are shown in Fig 9 depicts clearly the cyclic softening behaviour of T91 material. 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].

Table 2

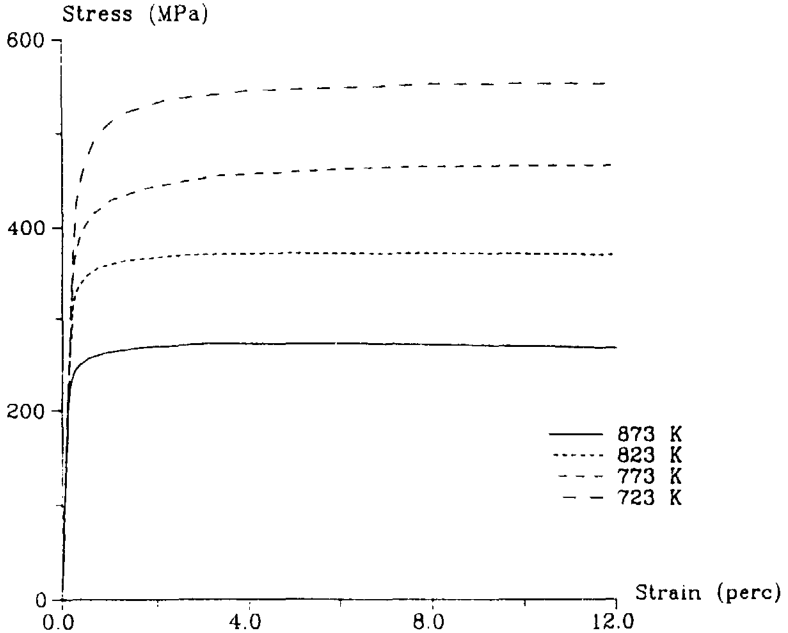
Values of material parameters of Chaboche model for grade 91 steel

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
Ko	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	0.44E-25	0.61E-15	0.76206E-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	0.92E-25	0.1E-14	0.96319E-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	0.96E-24	0.95E-14	0.16254E-09
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

6. ESTABLISHING SYMMETRISATION COEFFICIENT

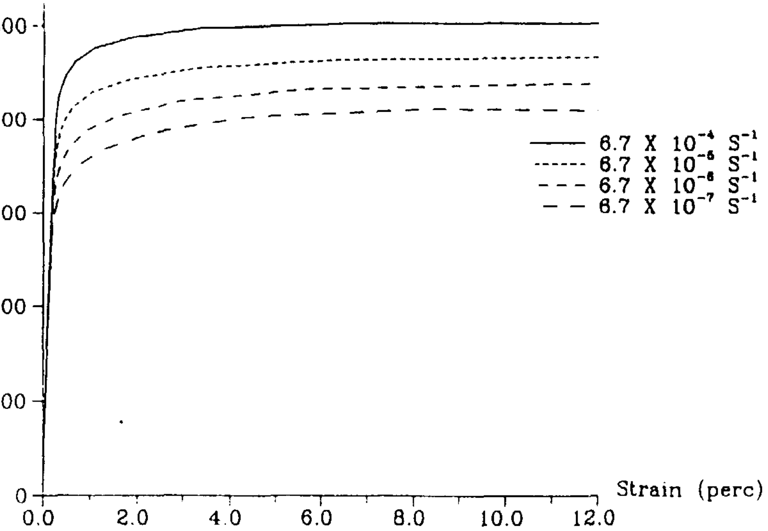
When long hold times and elevated temperatures are involved in the considered loading cycles, creep effects are considered in RCC-MR as follows:

- 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.



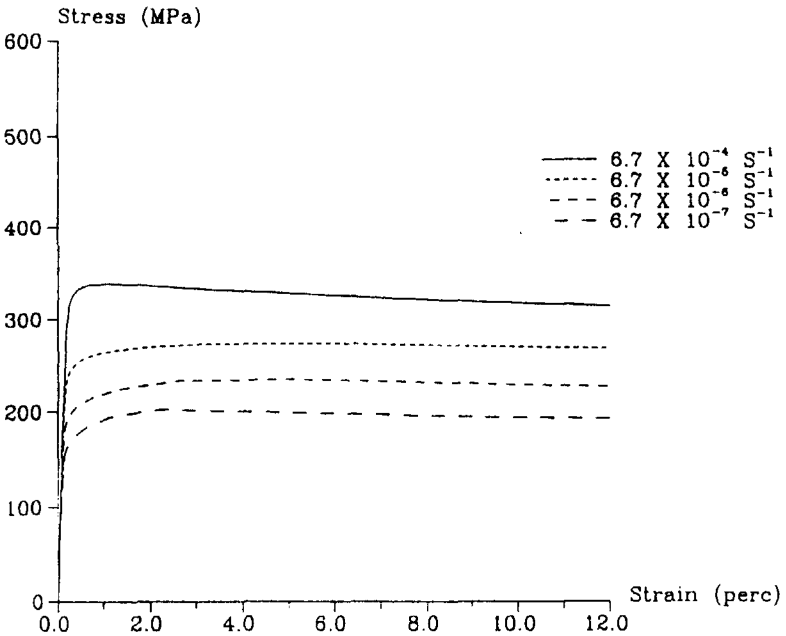
Monotonic stress strain curves for T91 material
(strain rate 6.7×10^{-5} 1/s)

Fig _ 1



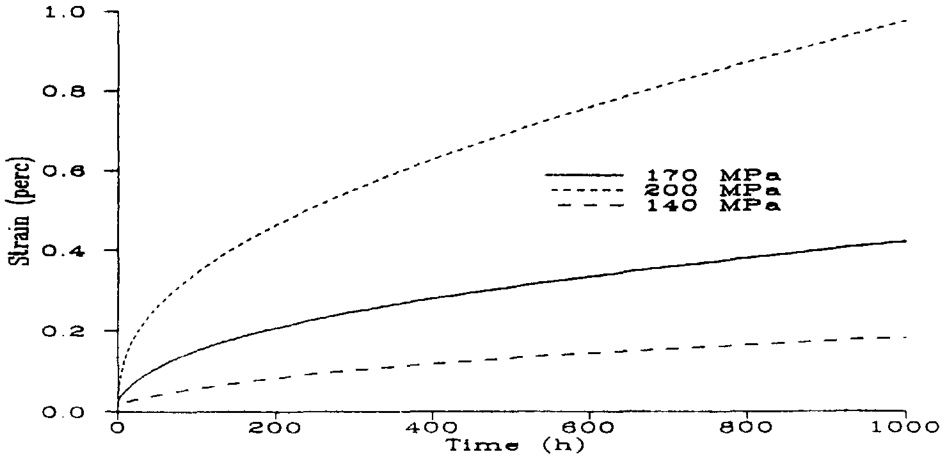
Simulation of monotonic stress strain curve at 773 K
(Mod. 9Cr 1 Mo)

Fig _ 3



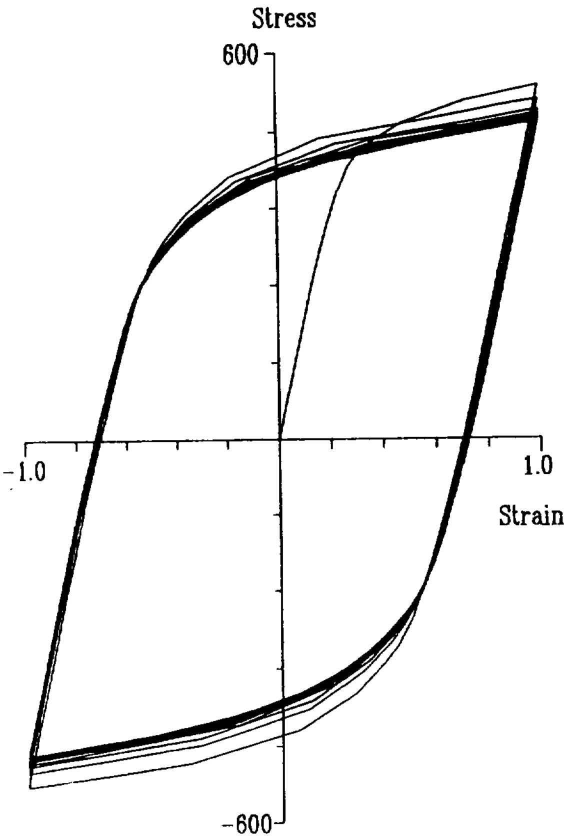
Simulation of monotonic stress strain curve at 873 K
(Mod. 9Cr 1 Mo)

Fig _ 2



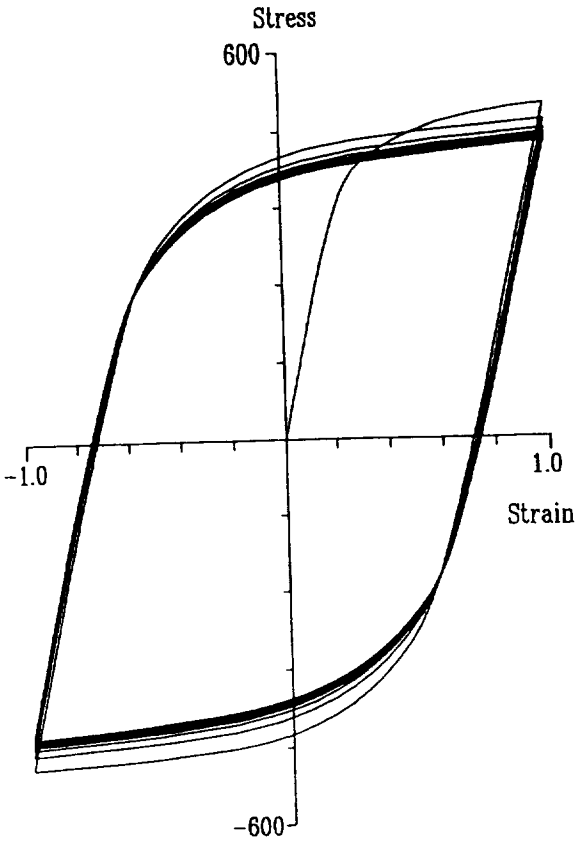
Simulation of creep curves at 873 K for T91

Fig _ 4



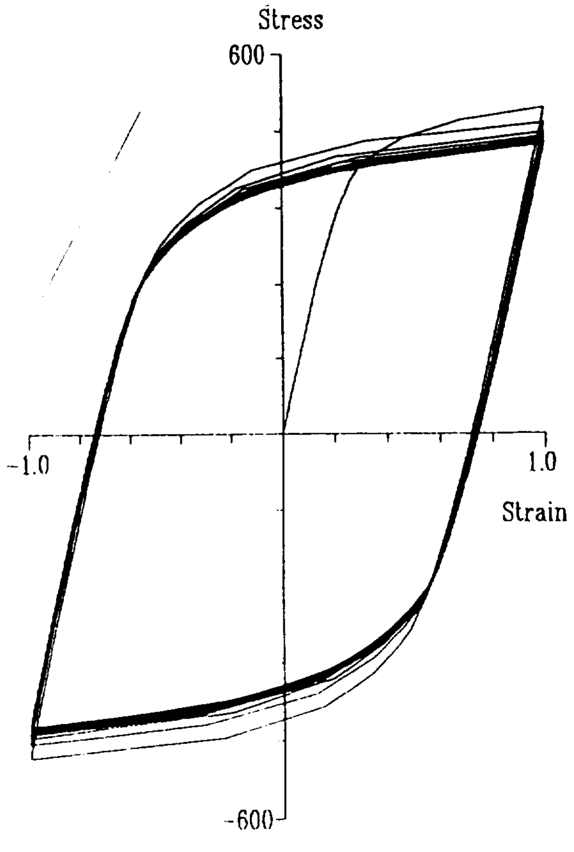
Simulation of strain controlled cycling at 298 K
(Mod. 9Cr 1 Mo)

Fig _ 5



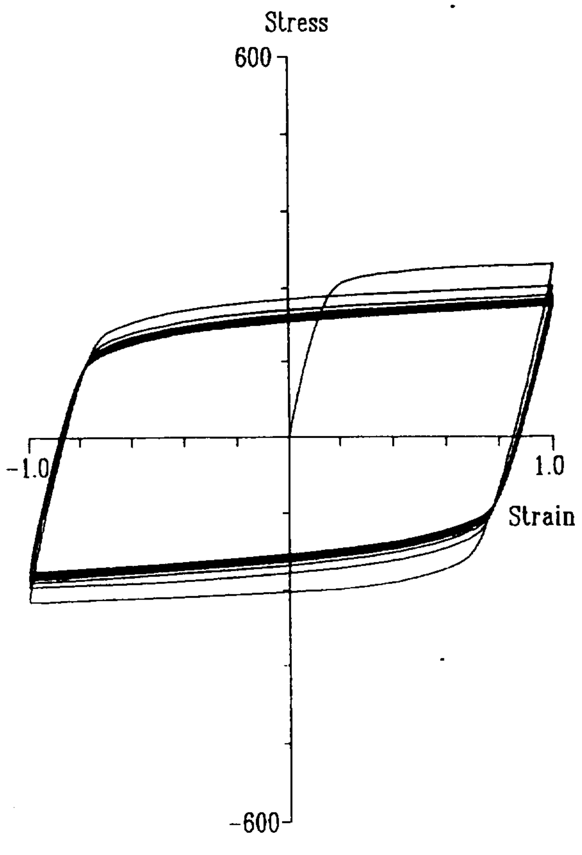
Simulation of strain controlled cycling at 473 K
(Mod. 9Cr 1 Mo)

Fig _ 6



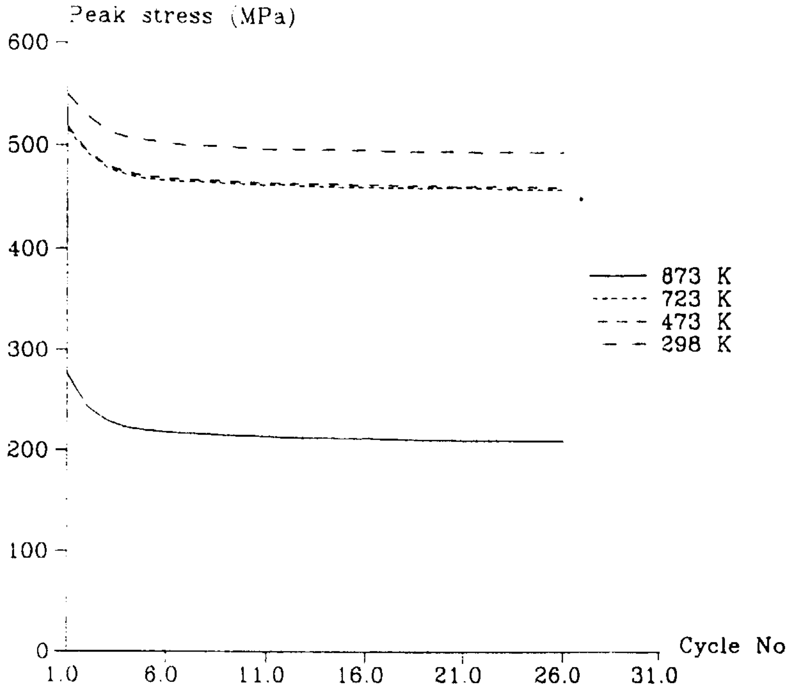
Simulation of strain controlled cycling at 723 K
(Mod. 9Cr 1 Mo)

Fig _ 7



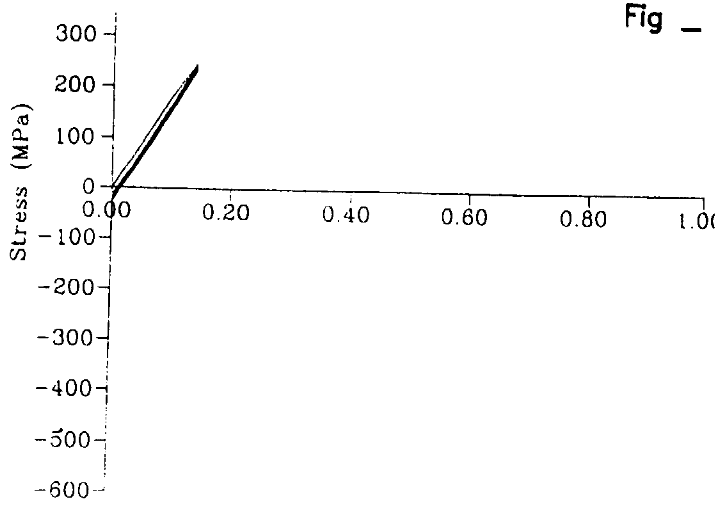
Simulation of strain controlled cycling at 873 K
(Mod. 9Cr 1 Mo)

Fig _ 8



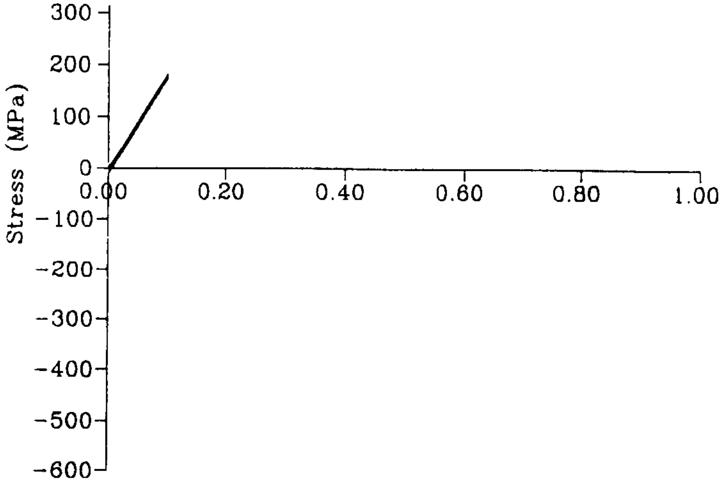
Cyclic softening behaviour of T91 material
(strain range + 1 and strain rate $6.7x10^{-5}$)

Fig _ 9



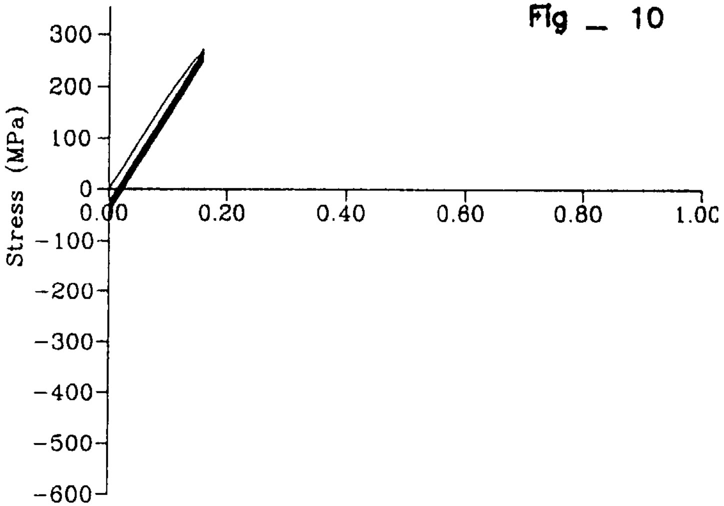
Stress cycling under repeated strain cycling
(strain range 0.14 at 773 K)

Fig _ 11



Stress cycling under repeated strain cycling
(strain range 0.1 at 773 K)

Fig _ 10



Stress cycling under repeated strain cycling
(strain range 0.1593 at 773 K)

Fig _ 12

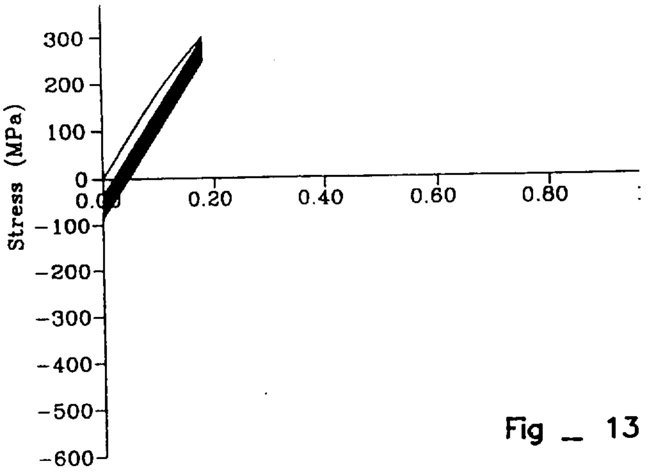


Fig _ 13

Stress cycling under repeated strain cycling
(strain range 0.1811 at 773 K)

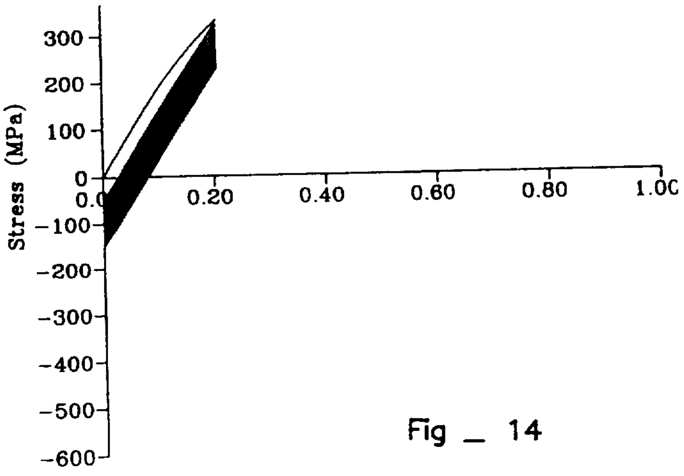


Fig _ 14

Stress cycling under repeated strain cycling
(strain range 0.2068 at 873 K)

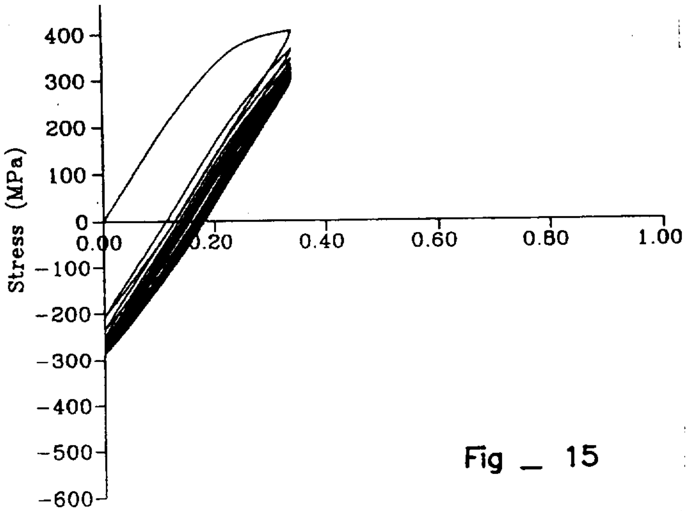


Fig _ 15

Stress cycling under repeated strain cycling
(strain range 0.3414 at 873 K)

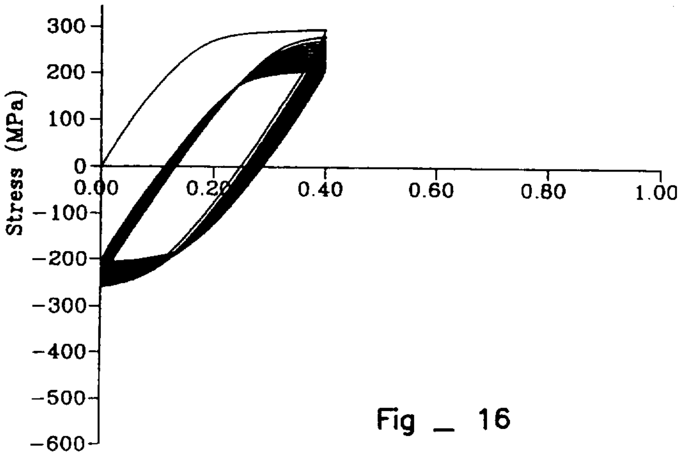


Fig _ 16

Stress cycling under repeated strain cycling
(strain range 0.4 perc at 873 K)

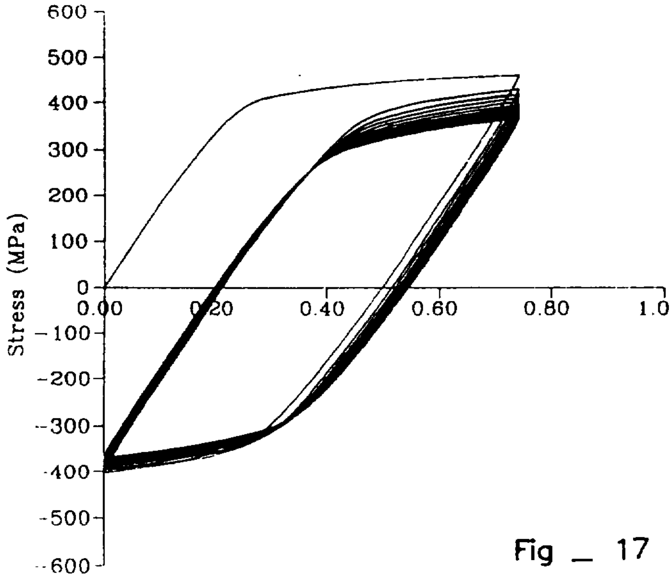


Fig _ 17

Stress cycling under repeated strain cycling
(strain range 0.7432 at 873 K)

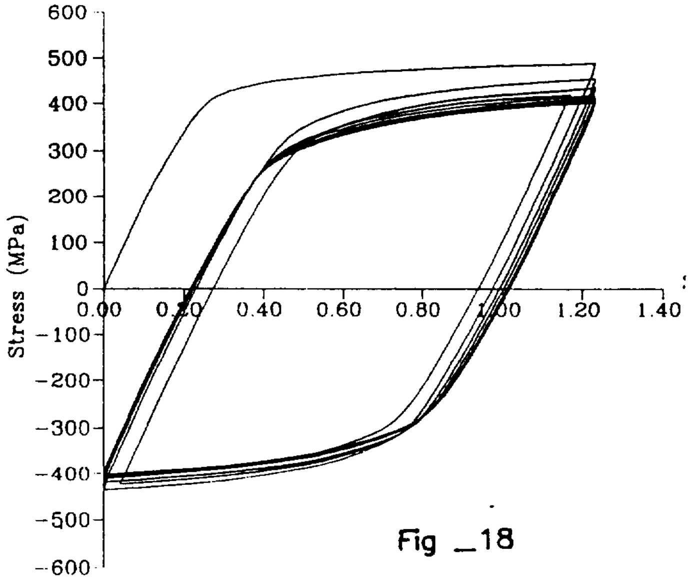
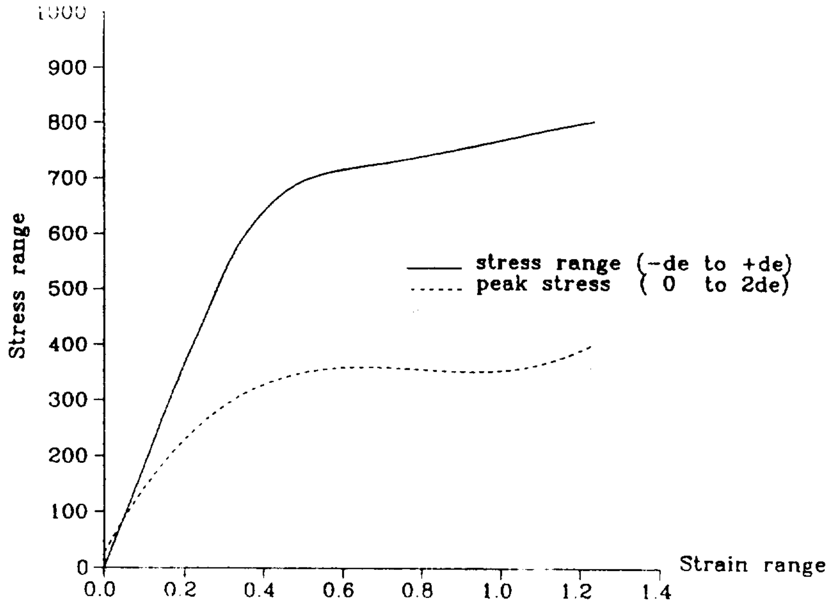


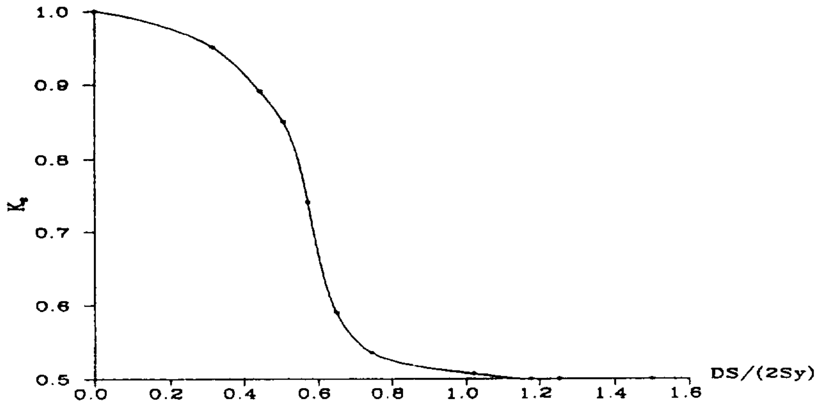
Fig _18

Stress cycling under repeated strain cycling
(strain range 1.233 at 773 K)



Stress range and peak stress under strain cycling
(for T91 material at 773 K)

Fig-19



Symmetrisation coefficient for mod,9 Cr 1 Mo

Fig-20

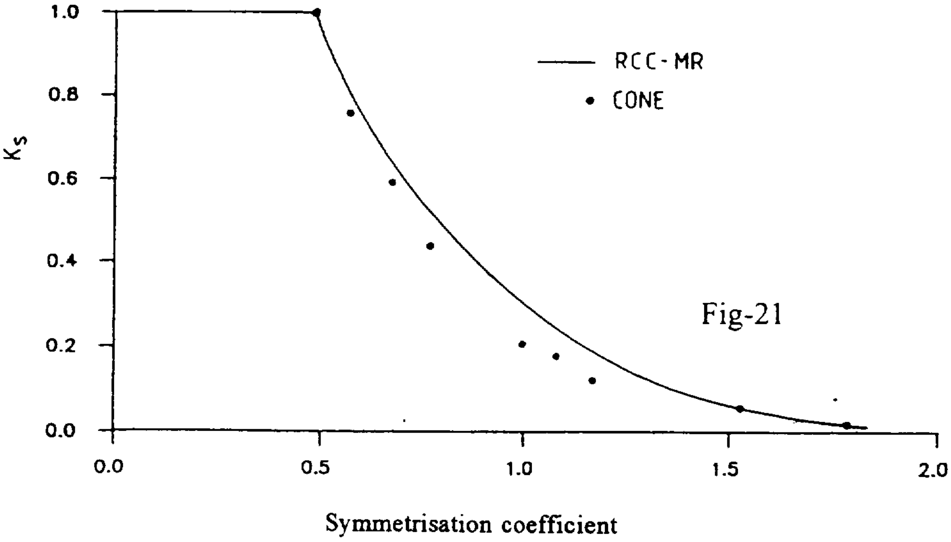


Fig-21

$\Delta\varepsilon_c$ 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($K_S.\Delta\sigma_S$). $\Delta\sigma_S$ is the stress range corresponding to elastoplastic strain range $\Delta\mathcal{E}$. The K_S is the symmetrisation coefficient which accounts for the symmetrisation of the stress strain loop under large loadings. It is given as the 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 and there is no symmetrisation and K_S is equal to 1. For large amplitude cycles full symmetrisation is possible and K_S is equal to 0.5. This function is usually determined by numerous strain controlled tests. In the absence of sufficient experimental data, required material data is generated numerically using Chaboche viscoplastic model.

The methodology adopted to generate K_S is as follows:

- Select the temperature and strain rate.
- Select the strain ranges of interest ($\Delta\mathcal{E}$).
- Determine stress cycling under repeated strain ranges (zero to maximum $\Delta\mathcal{E}$) by numerical solution of uniaxial formulation of Chaboche model (Fig 10-18 show the stress cycling under repeated strain cycling imposed in the range 0.1 % to 1.233 % at 773 K)
- Extract the stabilised peak stresses (σ_P) corresponding to various strain ranges + $\Delta\mathcal{E}$ (Fig 19).
- Determine the stabilished stress range ($\Delta\sigma_S$) corresponding to strain range (-$\Delta\mathcal{E}$/2 to + $\Delta\mathcal{E}$/2) either by analysis or by using RCC-MR Appendix-Z data (Fig 19).
- Plot a curve X (= 0.5. $\Delta\sigma_S/\sigma y$) vs Y (= 2.$\sigma p/\Delta\sigma_S$) which is the required curve for determining K_S. (Fig 20).

7. DISCUSSION ON Ks

Following the aforementioned procedure, symmetrisation coefficients are determined for SS 316 LN material which is compared with the curve given in RCC-MR (1993) appendix Z corresponding to S1 material. The numerical analysis is done with 23 parameter chaboche model [4]. The results are compared well (Fig 21) and thus 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 values by 'elastic route' for modified 9 Cr 1 Mo (grade 91).

It is also worth mentioning the difference between the Ks values for 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 Ks values which are essential in the creep-fatigue damage computation as per 'elastic route' of RCC-MR for the material modified 9 Cr 1 Mo, '20 parameter Chaboche viscoplastivc model' has been identified. All the essential uniaxial data for establishing Ks values have been generated theoretically by solving uniaxial form of Chaboche model. 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 analysis methodology, Ks values are determined for SS 316 LN also and compared with the one given in RCC-MR for S1 material. The symmetrisation coefficient Ks for grade 91 symmetrises under relatively lower secondary strain ranges during cycling loadings, as compared to SS 316 LN.

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