

## CREEP BEHAVIOR AND CREEP LIFE ASSESSMENT OF HP40Nb REFORMER STEEL

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### ABSTRACT

Centrifugally cast high Cr steels are widely used in petroleum and chemical industries as reformer tubes. In this paper, creep behavior of HP40Nb microalloyed tube steel has been examined at temperatures in the range of 1073 K – 1173 K at different stress levels. The creep deformation behavior follows the Dorn law equation. The constitutive creep equation was obtained using the data obtained from the accelerated creep tests. Following the Orr-Sherby-Dorn parametric technique, the creep life of the material at a service temperature of 1273 K was 10.7 years at a stress of 10 MPa.

**Key Words:** HP40Nb steel, Creep, Activation energy, Orr-Sherby-Dorn parameter, Creep life.

### Introduction

HP40Nb microalloyed steel is used as reformer furnace tubes in chemical and petroleum industries for continuous production of hydrogen gas by catalytic reaction of hydrocarbons and steam [1-2]. The operating temperature of these tubes are generally in the range from 1073 K to 1273 K with an expected design life  $10^5$  h. Degradation of the microstructure resulting from the prolonged service exposure at high temperature and stress, many a times, results in premature failure of the tubes. This leads to forced shutdown of the plant and severe economic loss for the industry. A clear understanding of the creep behavior of the steel is required for a proper design of the components for the intended service life.

Material behavior during creep deformation is often complicated. Correlation between the applied stress ( $\sigma$ ), test temperature ( $T$ ) and minimum creep rate ( $\dot{\epsilon}_m$ ), are often expressed by constitutive equations [3]. A number of different creep constitutive relationships have been proposed for modeling creep deformation behavior of metals and alloys [4]. Among the various constitutive equations, the widely accepted relationship is Dorn law [5] expressed as:

$$\dot{\epsilon}_m = A \exp(\beta\sigma) \exp\left(-\frac{Q}{RT}\right) \quad (1)$$

where  $A$  and  $\beta$  are constants,  $\sigma$  is applied stress in MPa,  $Q$  is the activation energy for creep in J/mol,  $R$  is gas constant (= 8.314 J/ K- mol) and  $T$  is the absolute temperature in Kelvin. The constitutive parameters *i.e.*  $A$ ,  $\beta$  and  $Q$  is determined from the creep test data.

Padilha et al. [6] studied the effect of precipitation behavior of 316L(N) stainless steel during creep test. Latha et al. [7] compared the creep properties of alloy D9 and 316 stainless steel in which alloy D9 exhibited higher creep rupture strength than 316L steel. The time independent plasticity and creep behavior of 316 stainless steel at 823 K was investigated by Hayhurst et al. [8] and the constitutive equation for creep deformation was obtained. Tahami et al. [9] compared creep behavior of cold drawn

304L stainless steel using two different constitutive equations. Sawada et al. [10] predicted long term creep curve and proposed constitutive equations for various stainless steels. Damage characterization of HP40Nb steels after 10 years of service exposure at 1223 K was reported by Alvino et al. [11]. To the best of our knowledge, study related to creep behavior of the microalloyed HP40Nb reformer steel based on constitutive equation have not been reported.

Various creep rupture parametric techniques have been developed to predict the long-term creep life of high temperature components. These are mainly by Orr-Sherby-Dorn parameter [12], Larson-Miller parameter [13], Manson-Haford parameter [14], Manson-Succop parameter [15] etc. Among these, Orr-Sherby-Dorn parametric ( $P_{O-S-D}$ ) technique is an accepted model and is expressed as:

$$P_{O-S-D} = \log_{10} t_r - \frac{Q}{2.3RT} \quad (2)$$

where  $t_r$  is the rupture time in hours.

The present work is aimed at investigating the creep behavior and predicting the creep life of HP40Nb microalloyed steel by  $P_{O-S-D}$  technique. Accelerated creep tests were carried out for various combinations of temperature and stresses. The data obtained from these experiments was used to develop the constitutive equations for creep deformation behavior.

## 2. Material and methodology

### 2.1 Material and specimen preparation

Material used for investigation was centrifugally cast reformer tube. The inside diameter and thickness of the tube are 106 mm and 15.3 mm, respectively. The chemical composition of the steel analyzed by optical emission spectrometer is shown in Table 1. Flat tensile creep specimens of 25 mm gauge length, 6.5 mm width and 3 mm, were machined by wire-cut electric discharge machining. The axis of the specimen was kept parallel to the longitudinal axis of the reformer tube.

**Table -1:** Chemical composition of the steel in wt. %.

C	Si	Mo	Cr	Ni	Nb	Ti	Fe
0.4	1.3	0.037	23.6	34.9	0.8	0.037	Balance

### 2.2 Creep test

Nine tensile creep tests were carried out at various combinations of stresses (47 MPa, 68 MPa and 80 MPa) and temperatures (1073 K, 1123 K, and 1173 K). The specimen was heated to the test temperature by an impedance heater. The temperature of the specimen was measured by an Infrared pyrometer and controlled within an accuracy of  $\pm 3$  K till failure of the sample. A high definition video camera was used for on-line recording of the specimen gauge length extension during the creep test. The digital frames extracted from the video recording were used to determine the time dependent creep strain by image analysis technique. The minimum creep rate  $\dot{\epsilon}_m$  for various combinations of temperatures and stresses were determined from the creep curve.

## 3. Results and discussion

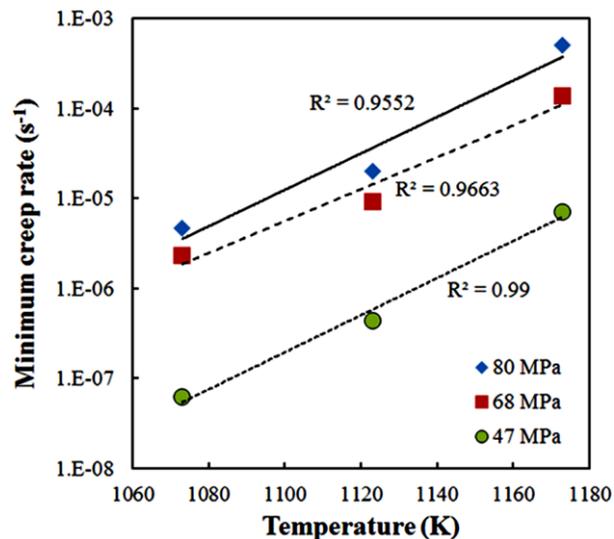
### 3.1 Minimum creep strain rate

Fig. 1(a) and (b) show the semi-logarithmic plots of  $\dot{\epsilon}_m$  vs. temperature and  $\dot{\epsilon}_m$  vs. stress, respectively. The figures show that the value of  $\dot{\epsilon}_m$  increases with the increase in temperature and/or stress. In both

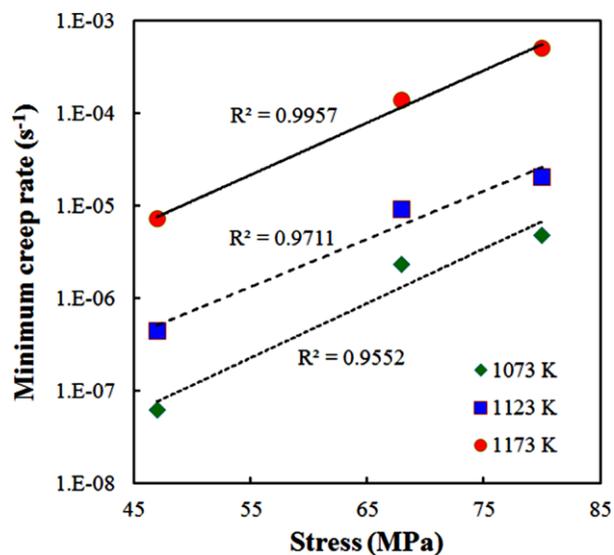
the figures (Fig. 1(a) and (b)), the lines are the best least squares fit to the data points. From the figures, it can be seen that a linear relationship exists between the logarithm of  $\dot{\epsilon}_m$  and temperature or applied stress. The maximum and minimum  $\dot{\epsilon}_m$  values are  $5.05 \times 10^{-4} \text{ s}^{-1}$  and  $6.25 \times 10^{-8} \text{ s}^{-1}$  at 80 MPa/1173 K and 47 MPa/1073 K, respectively.

### 3.2 Rupture time

Fig. 2(a) and (b) show semi-logarithmic plots of creep rupture time  $t_r$  vs. test temperature and applied stress, respectively. The figures reveal that the rupture time of the steel increase with decrease in temperature and/or stress. The lines in Fig. 2(a) and (b), represents the best least squares fit to the data points. The maximum and minimum rupture times are 441728 s and 197 s at 47 MPa/1073 K and 80 MPa/1173 K, respectively.



(a)



(b)

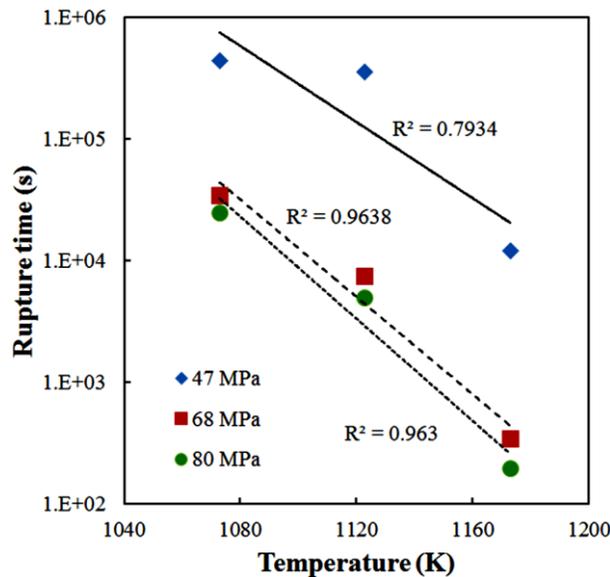
Fig – 1: Plot of minimum creep rates. (a) temperature and (b) stress.

### 3.3 Constitutive equation

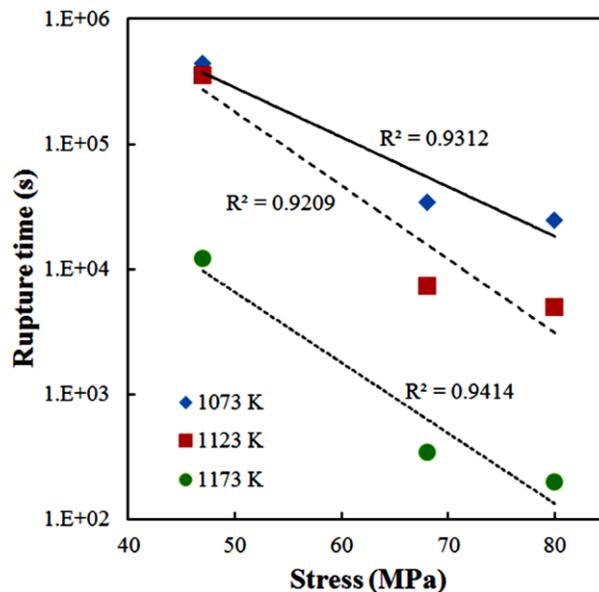
The values of  $\dot{\epsilon}_m$  obtained from creep curves were used to determine the constitutive parameters viz. constants  $A$  and  $\beta$ , and activation energy for creep  $Q$ , of Eq. 1. The constitutive parameters were determined by the least squares by minimizing the functional error  $e_i$ , between the experimental and predicted values of  $\dot{\epsilon}_m$ . The error  $e_i$  was defined by

$$e_i = \ln(\dot{\epsilon}_m) - \ln A - \beta\sigma + \frac{Q}{RT} \quad (3)$$

where  $i$  is the number of observations. The three unknown parameters,  $A$ ,  $\beta$  and  $Q$  of Eq. 1 was determined by minimizing the error. The values obtained for  $A$ ,  $\beta$  and  $Q$  by the optimization technique is  $1.05 \times 10^{13} \text{ s}^{-1}$ , 0.52 and 468.5 kJ/mol, respectively.



(a)



(b)

Fig -2: Variation of the rupture time with (a) temperature and (b) stress.

Substituting these values in Eq.1, the constitutive equation for creep deformation within the domain of experimental conditions is expressed as:

$$\dot{\epsilon}_m = 1.05 \times 10^{13} \exp(0.52 \sigma) \exp\left(-\frac{468500}{RT}\right) \quad (4)$$

The reported value of activation energy for lattice diffusion in austenitic steel is 270 kJ/mol [16]. In the present investigation, the activation energy for creep is found to be 468.5 kJ/mol. Higher activation energy obtained for the present material is due to the presence of carbides particles in the matrix which impedes the dislocation motion during the creep deformation.

The predicted minimum creep rate ( $\dot{\epsilon}_m^p$ ) for combination of stresses and temperatures were determined using Eq. 4. Comparison of minimum creep rate obtained from the experiment ( $\dot{\epsilon}_m^e$ ) and by Eq. 4 for 68 MPa and 80 MPa stresses are shown in Fig. 3. Experimental and predicted minimum creep rates at 68 MPa/1173 K are found to be  $1.38 \times 10^{-4} \text{ s}^{-1}$  and  $1.15 \times 10^{-4} \text{ s}^{-1}$ , respectively indicating a good agreement between experimental and the predicted values.

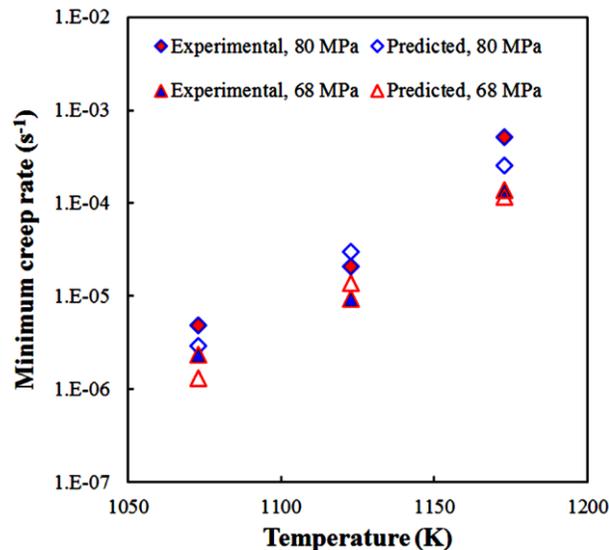


Fig -3: Plot of minimum creep rate vs. temperature of experimental data and predicted data.

The semi-logarithmic plot of  $\dot{\epsilon}_m$  vs.  $\sigma$  for experimental data and calculated values for constant test temperatures are shown in Fig. 4. Predicted and experimental minimum creep rate values at 80 MPa/1073 K are  $4.76 \times 10^{-6} \text{ s}^{-1}$  and  $2.87 \times 10^{-6} \text{ s}^{-1}$ , respectively. Fig. 4 indicates good agreement between both experimental and calculated values of minimum creep rate.

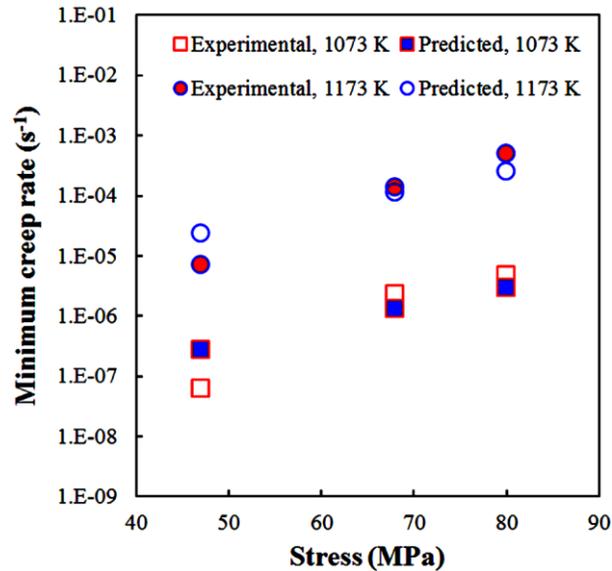


Fig -4: Plot of minimum creep rate vs. stress of experimental data and predicted data.

The percentage error between  $\ln(\dot{\epsilon}_m^e)$  and  $\ln(\dot{\epsilon}_m^p)$  was calculated. The maximum percentage error is found to be 14%, which is obtained for creep test at 47 MPa/ 1123 K. The result shows that Eq. 4 is indicative of the creep deformation behavior of the material within the domain of present experimental conditions.

### 3.4 Creep life prediction

Rupture time obtained from the accelerated creep test was used to calculate the Orr-Sherby-Dorn parameter  $P_{O-S-D}$ . In this technique, the activation energy for creep ( $Q = 468.5$  kJ/mol) obtained from the constitutive model was used for the analysis. Fig. 5 shows the semi-logarithmic plot of  $\sigma - P_{O-S-D}$ , master curve for the investigated steel. The average value of  $P_{O-S-D}$  for each stress levels was used to plot the master curve. In Fig. 5, the continuous line represents the trend line fitting the data points with a coefficient of determination  $R^2 = 0.988$ . The trend line was used for the extrapolation of  $P_{O-S-D}$  values corresponding to a stress of 5 MPa.

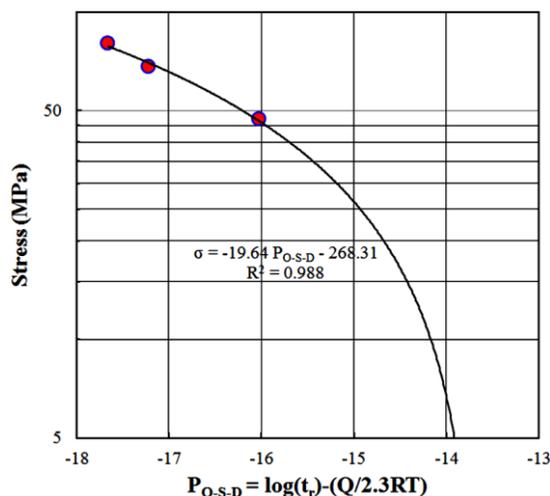


Fig -5: Plot of stress vs. Orr-Sherby-Dorn parameter for the investigated steel.

The creep life of the steel was estimated from the master curve plot.  $P_{O-S-D}$  values for the steel at stresses 5 MPa, 10 MPa, 15 MPa and 20 MPa were obtained by drawing horizontal lines corresponding to these stresses to meet the extrapolated curve and subsequently projecting to the  $P_{O-S-D}$  axis. The respective values of  $P_{O-S-D}$  for the above stresses obtained are -13.92, -14.17, -14.43 and -14.67. The creep life  $t_r$  of the steel for various temperatures were determined by substituting the  $P_{O-S-D}$  values in the equation:

$$t_r = 10^{\left(P_{O-S-D} + \frac{Q}{2.3RT}\right)} \quad (5)$$

Fig. 6 shows the plots of creep life vs. temperature for the steel at different stresses. The plot indicates that the creep life of the steel increases with the decrease in temperature and /or decrease in stress. Life of the steel for a designed hoop stress of 10 MPa and at 1273 K is found to be 10.7 years.

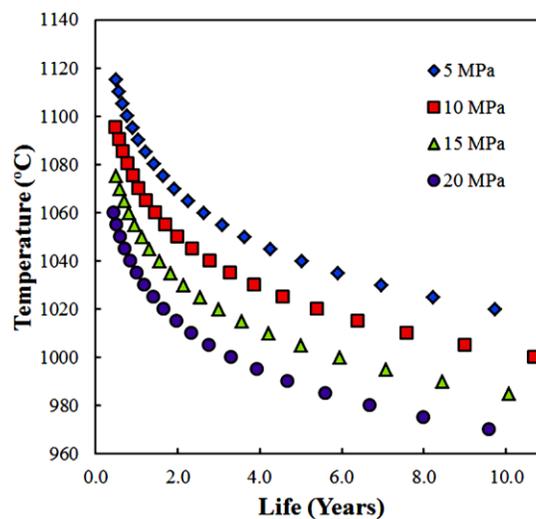


Fig. 6. Plot of temperature vs. life at different stresses of the steel.

The result of the study indicates that the material can be safely used at 1273 K/10 MPa for 11½ years. However, extreme caution should be taken so that the service conditions are not exceeded during the application.

#### 4. Conclusion

Accelerated creep tests using constant stress creep setup have been carried out to analyze the creep behavior and to predict the creep life of the steel. Conclusions of the present investigation are summarized as follows:

- Minimum creep rate increases non-linearly with the increase in stress or temperature. Rupture time increases non-linearly with the decrease in stress or temperature.
- Dorn law equation provides an acceptable result to predict minimum creep rate. The value of  $A$ ,  $\beta$  and  $Q$  are obtained as  $1.05 \times 10^{13} \text{ s}^{-1}$ , 0.52 and 468.5 kJ/mol, respectively, for the investigated steel.
- Dislocation creep is the dominant deformation mechanism of the steel at higher temperature and stress.

- The creep rupture life of the steel has been evaluated by using the Orr-Sherby-Dorn parameter. A creep life of 10.7 years at 1273 K and 10 MPa was predicted by  $P_{O-S-D}$  technique.

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