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Procedia Engineering 55 (2013) 599 – 606

Procedia Engineering

www.elsevier.com/locate/procedia

6th International Conference on Creep, Fatigue and Creep-Fatigue Interaction [CF-6]

Creep Life Predictions of Engineering Components: Problems & Prospects

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Abstract

The paper critically examines the advantages and limitations of empirical and constitutive equation based approaches for creep strain prediction. While both may give similar predictions, the latter provides physical insight into the underlying mechanisms and suggests ways and means of improving creep resistance of high temperature materials. None of the methods as of now can estimate the reliability of material parameters required because of limited availability of creep strain time data. This is where more attention needs to be given otherwise practicing engineers would continue to depend on more readily available stress rupture data for life prediction of high temperature components.

Keywords: 2.25CrMo / 9CrMoNbV steel;damage mechanics; particle coarsening; LMP;CDM

1. Introduction

Reliable creep life prediction of existing and new generation of materials being developed for super critical and ultra super critical power plants is indeed a great challenge. Proven materials like low alloy Cr-Mo steels have extensive long term creep database to allow design of high temperature components which could survive at least 25–30 years. However their temperature capability is limited to 550°C. In order to increase the efficiency of power plants and cut down emission of CO_2 / MW of power generated it is necessary to raise operating temperature to 600°-650°C. Candidate materials for such applications are martensitic grades of steel having 9-12%Cr 1%Mo with several other alloy additions like Nb, V, W, B, N etc [1]. Many of these became commercially available during the last couple of decades. Therefore creep database on these is very limited. The extrapolation of such data using the conventional empirical methods may not be reliable. Mechanism based models to describe creep behavior of such steels need too many microscopic parameters that are often difficult to estimate. As against this a middle path based on continuum damage mechanics (CDM) describing evolution of creep strain and several other coupled structural features like redistribution of stresses between the matrix and precipitates, kinetics of precipitate coarsening, depletion of solute elements from the matrix, nucleation,

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doi:10.1016/j.proeng.2013.03.301

growth and coalescence of grain boundary cavities or environmental interaction has received considerable attention in recent years [2-3]. A recent work suggests that if material parameters for an established grade of steel are known it may be possible to predict creep strain time plots of a new grade whose composition has been slightly altered to improve its micro-structural stability by slightly modifying a few of the material constants [4]. This no doubt looks promising keeping in view the time and effort needed to collect creep strain time data over a wide range of temperature and stress for a new grade of steel. The paper presents highlights of such an approach and its limitation.

2. Modeling shape of creep curve

Design of high temperatures components needs predictive models describing creep strain evolution as function of time under any given stress and temperature. These are derived from uniaxial creep test data on the specific material over a range of stress and temperature. Most of these tests are conducted under constant load. With accumulation of creep strain the cross sectional area of the test specimen would decrease and the stress would keep rising. Earliest attempt to model the shape was purely empirical. There are numerous algebraic expressions that have been used to represent creep strain (ε) as function of time (t), stress (σ) and temperature (T). One of the simplest forms is given below:

$$\dot{\varepsilon} = A\, exp\left(-\frac{Q}{RT}\right) \sigma^n\, t^m \tag{1}$$

In the above equation Q denotes activation energy, R is universal gas constant, n & m are stress and time exponents and A is a constant. Such forms clearly cannot represent creep curves having three distinct stages consisting of primary, secondary and tertiary. One would need more complex expressions as the one known as theta projection popularized by Evans et al [5]. This needs 20 material constants as against 4 in eq. (1) to be estimated from limited creep strain time plots. Nevertheless such expressions are easy to link with most commercial finite element packages used for stress analysis. This helps identify critical locations of components that are most vulnerable to creep strain (damage) accumulation thus provide valuable guidance in monitoring structural integrity during service. However a major limitation of this approach is the uncertainty associated with extrapolation of test data beyond the experimental domain. It is often critical in cases of newer grades of steel that are being introduced to improve the efficiency of power generation units.

As against this the approach developed by Dyson & McLean [2-3] based on Continuum Damage Mechanics (CDM) provides a frame work to incorporate dominant mechanisms determining creep strain evolution as normalized damage parameters. The relations between these are expressed in the form of a set of coupled differential equations. Recently one of the variants of their model was used to describe creep behavior of CrMo steel by Hore et al [4]. Dominant mechanisms considered were stress redistribution between matrix & particle, strain softening, and particle coarsening. The effect of precipitate dissolution was also incorporated by introducing a parameter which is a function of solvus temperature. The exact form of the model and the description of various parameters are as follows:

$$\begin{aligned}
\dot{\varepsilon} &= \dot{\varepsilon}_0 (1 + D_d) \exp\left[-\frac{Q_d}{RT}\right] Sinh\left[\frac{\sigma(1-H)}{\sigma_0 (1-D_p)}\right] \\
\dot{H} &= \frac{h'}{\sigma}\left(1 - \frac{H}{H^*}\right)\dot{\varepsilon} \\
\dot{D}_d &= C\dot{\varepsilon} \\
\dot{D}_p &= \frac{K_p}{3}(1-D_p)^4 \\
\dot{\sigma} &= \sigma\dot{\varepsilon}
\end{aligned} \tag{2}$$

Where: $\dot{\varepsilon}_0$	is a characteristic strain rate and depends on precipitate volume fraction and mobile dislocation density.
Q_d	is the activation energy associated with diffusion of vacancies and formation of jogs
σ	is the applied stress
σ_0	is a normalizing stress that is related to the dislocation-particle interactions (see subsequent eq. (3) & eq. (4))
h'	is the effective modulus
H^*	Limiting value of H. Occurs on completion of stress transfer. Its initial value is zero.
D_p	is the coarsening damage defined as $\left(1-\frac{\lambda_i}{\lambda}\right)$ where λ_i is the initial inter-particle spacing.
λ	is the inter-particle spacing at any given time.
D_d	is the dislocation damage defined as $\left(1-\frac{\rho_i}{\rho}\right)$ where ρ_i is the initial dislocation density
ρ	is the dislocation density at any given time.
K_p	is the rate constant for particle coarsening at a temperature T
C	is a model parameter governing the evolution of dislocation density.

The parameters, which need to be defined, are Q_d, $\dot{\varepsilon}_0$, σ_0, h', H^* and K_p. Two of these viz, σ_0 and K_p are strong functions of temperature. These are given by

$$\sigma_0 = \sigma_{0m}\left[1-\exp\left(-\frac{\Delta H_s}{RT_s}\left(\frac{T_s}{T}-1\right)\right)\right] \tag{3}$$

$$K_p = K_{p0}\exp\left(-\frac{Q_p}{RT}\right) \tag{4}$$

T_s is the temperature at which the precipitates dissolve. Enthalpy change, ΔH_s, is a measure of how easily the process of dissolution takes place. σ_{0m} is the maximum strength of the matrix. The form of this expression clearly shows that as the temperature approaches T_s lattice friction stress becomes negligibly small. Q_p is the activation energy associated with coarsening of precipitate and K_{p0} is the base value of K_p.

The main advantage of such an approach is that it allows unlimited scope of extrapolation within the domain in which the same mechanisms control the process of creep damage accumulation. Surprisingly the number of parameters required is only 10 which is significantly less than those needed for theta projection. It also allows estimation of some of the parameters by examination of microstructures of creep exposed samples. This aspect has recently been exploited by Oruganti et al [6] to model creep behavior of modified 9CrMoNbV steel. Also it is worth noting that the equations are dimensionally balanced. Therefore it is possible to compare and correlate the effect of alloy modification, thermal exposure or heat treatment on the performance of high temperature materials during service. This aspect was highlighted by Hore et al [4]. The material parameters were estimated empirically for 2.25Cr1Mo steel for which extensive long term creep strain time plots are available over a wide range of temperatures and stresses. By changing only a few of the parameters it was shown that the predicted

creep curves for modified 9CrMoNbV steel were fairly close to the experimental plots. Table 1 gives a comparison of the material constants for the two grades of steel. Higher solvus temperature in the case of 9CrMoNbV steel indicates that the precipitates are relatively more stable. Activation energies are marginally higher. The two parameters which are significantly higher are h' and C. The former determines the rate of stress redistribution from the matrix to precipitate where as the latter controls strain softening. This is why primary creep is quite prominent in case of 9CrMoNbV in comparison to 2.25Cr1Mo. Higher C denotes more strain softening. However this is more common in case of Ni base super-alloy where initial dislocation density is known to be much less [2]. 9CrMoNbV has tempered martensitic structure characterized by relatively high initial dislocation density [1]. Therefore strain softening here is more likely to be due to localized deformation (necking). Ruptured samples in these cases do show prominent necking. This also indicates absence of creep cavitation in stress temperature domains considered in this work.

Table 1. Material parameters for model based creep strain prediction.

Material	ε_0	Q_d	σ_{om}	ΔHs	Ts	h'	H*	Qp	Kp0	C
	s^{-1}	kJ/mol	MPa	kJ/mol	K	MPa		kJ/mol	s^{-1}	
2.25CrMo	2.71E08	298	28	137	936	1.06E03	0.3	200	2.5E05	10
9CrMoVNb	3.00E08	300	30	140	950	1.03E04	0.3	210	2.2E05	27

3. Results and discussions

Using the material parameters estimated by Hore et al [4] and given in Table 1 creep curve has been simulated for 2.25Cr1Mo steel subjected to 98MPa stress at 500° C. The results are shown in Fig.1. Experimental data reported Hore et al [4] have been superimposed on the graph. The predictions are indeed very close. Since these data were used to estimate the material parameters it may not be a good test for the validity of the model based approach discussed above. This is why Hore et al [4] attempted to explore if by changing only a few of the parameters it was possible to predict creep behavior of modified 9CrMoNbV steel. The data set suggested by them for this steel is also included in Table 1. Figure 2 gives a comparison of predicted creep strain time plot with experimental data for 9CrMoNbV steel at 260MPa, 540°C. The two are indeed very close except for the tertiary regime. This may be due to necking. Although to some extent its effect may be taken care of by the strain softening parameter (C) but it cannot fully take care of local deformation associated with necking.

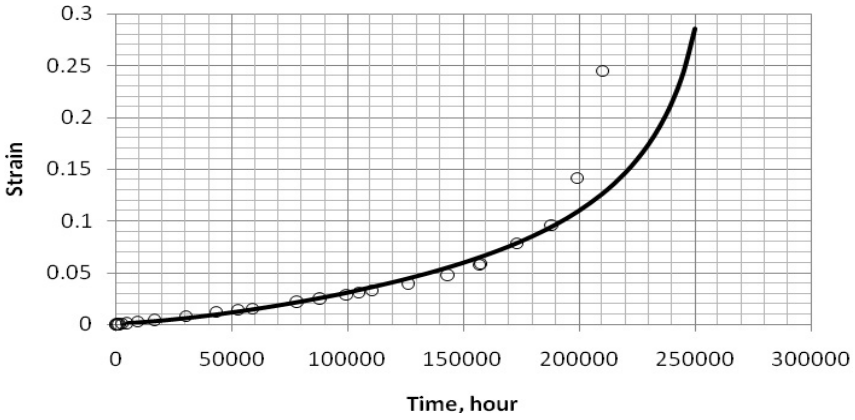

Fig. 1. A comparison of model based prediction using material data for 2.25Cr1Mo steel with experimental data shown as points at 500°C 98MPa.

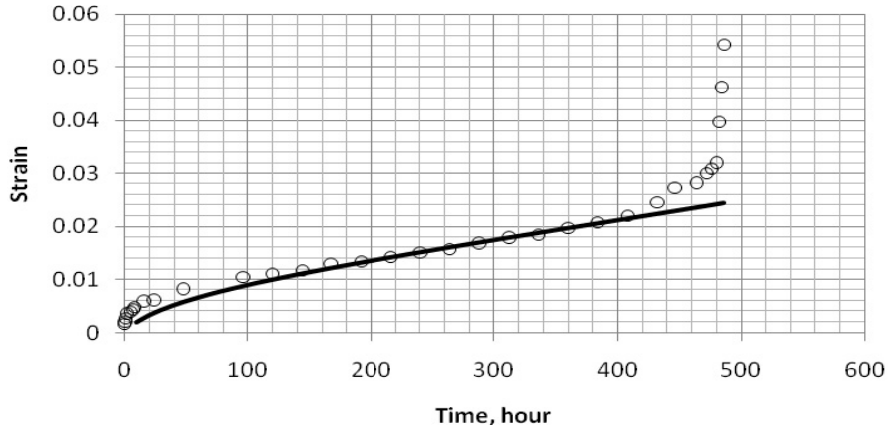

Fig. 2. A comparison of model based prediction using the material data for 9CrMoVNb steel at 540°C 260 MPa with experimental data.

Figure 3 presents a comparison of predicted creep curve using purely empirical model based on eq. (1) superimposed on the experimental data. In this case material parameters were obtained from creep strain time plots for 9CrMoNbV steel over a range of stresses and temperatures. Therefore predictions based on physically based constitutive equations appear to have a distinct advantage because parameters gives us an idea about various underlying mechanism and allow estimation of material parameters for similar class of materials. The obvious question that comes up why then the use of this has not so been popular amongst practicing engineers in the design of high temperature components. Answer lies in the simplicity of the algebraic expressions used in empirical approach which can easily be incorporated in most of the commercially available finite element packages for stress analysis. As against this a separate user routine needs to be written which could solve coupled differential equations to estimate incremental creep strain and link it with the stress analysis procedure. One often apprehends that this may take longer computational time. With the ever growing power of computation this may longer be true.

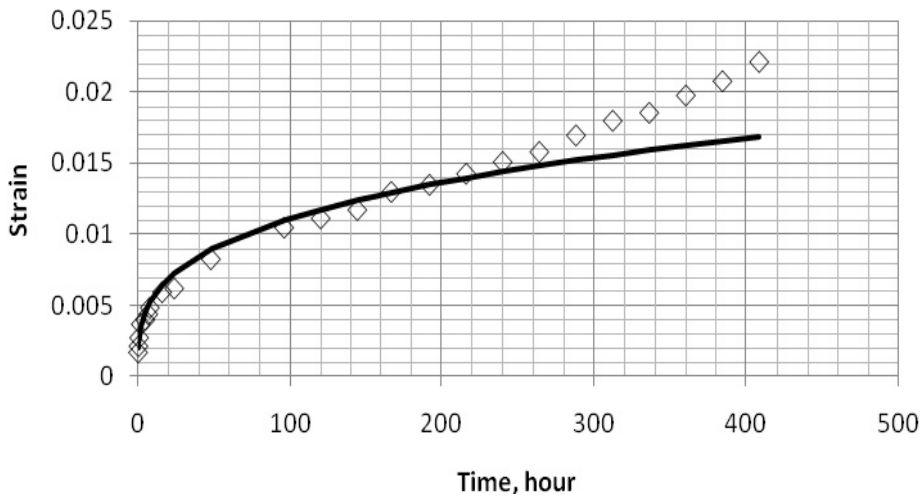

Fig. 3. A comparison of experimental and predicted creep strain time plot using eqn. 1 under the same test condition as that in fig. 2. Parameters were estimated from a set 19 creep curves over a wide range of stress and temperatures. These are as follows: A = 2.01, Q = 188 kJ/mol, n = 3.8 and m = 0.3

In fact physics based constitutive models have been linked to show the effect of creep anisotropy in single crystal superalloy [7]. Another reason could be the accuracy with which the parameters can be estimated. A small change in the material constants, particularly those appearing either in exponential or in Sinh functions are very sensitive. In the absence of repeat test data under identical test conditions it is impossible estimate the error band. Some attempts have been made to analyze the scatter in creep data by Roy et al [8] to analyze the creep data on 316 stainless steel reported by Garofalo et. Al. [9] using a stochastic approach. An alternative method to address the problem is to simulate creep strain evolution using a range of material constants. The best way to generate a set of material parameter is to obtain a random set within a specified range using random number generator. Four sets of such parameters are given in Table 2.

Table 2. Four different sets of material parameter for 2.25CrMo steel within ±10% of the values given in Table 1 obtained using random number generator to simulate four creep tests.

Material	ε_0	Q_d	σ_{om}	ΔHs	Ts	h'	H*	Qp	Kp0	C
	s^{-1}	kJ/mol	MPa	kJ/mol	K	MPa		kJ/mol	s^{-1}	
Set 1	2.65E08	289	27.3	138	972	1.08E03	0.27	194	2.29E05	10.9
Set 2	2.97E08	278	28.3	126	1001	1.03E03	0.30	215	2.34E05	10.3
Set 3	2.76E08	272	28.8	129	1020	1.10E03	0.29	207	2.58E05	10.2
Set 4	2.89E08	302	26.0	126	899	1.12E03	0.33	191	2.59E05	9.1

These have been used to generate four creep strain time plots for 2.25CrMo steel at 550˚C, 145 MPa. These are shown in Fig. 4 as lines along with experimental data recently obtained by Roy et al [10]. It is worth noting that the creep strains are well within the predicted range. This is quite significant particularly because these data were not used to estimate the material parameters. It also suggests the importance of repeat creep tests under identical test conditions.

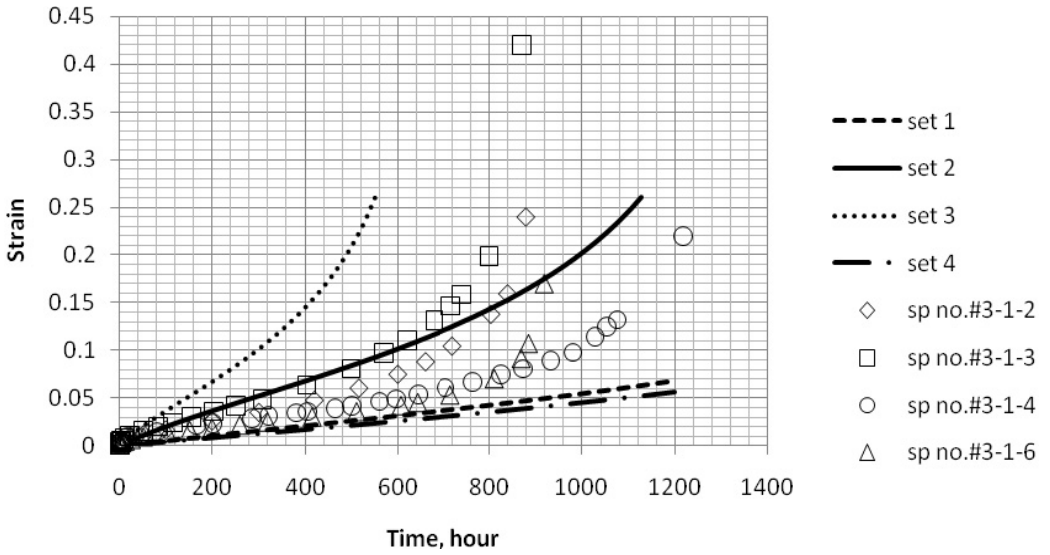

Fig. 4. Comparison between experimental (shown by markers) and predicted (shown by lines with different style) creep strain time plots using material parameters given in Table 2. Stress 145 MPa & temperature 550°C. Note that experimental data on samples from same cast show significant scatter.

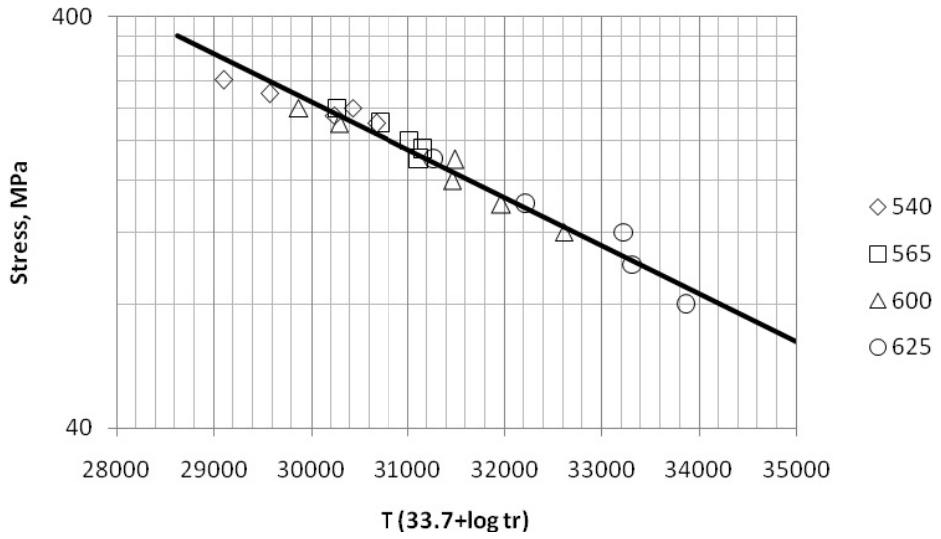

Fig. 5. Stress rupture plot for 9CrMoVNb steel obtained from a single cast. Optimum parameter C here is 33.7 although similar linear trend may be observed using C as 20.

Amongst practicing engineers the most common method for creep life estimation is based on stress rupture data. Rupture stress if plotted against a common time temperature function gives a master rupture plot. Larson Miller parameter (LMP) given by $T(C+\log tr)$ is the most commonly used time temperature function. T is temperature in ^{o}K and *tr* is the time to rupture in hours. C can be estimated using least square fit. A typical plot is given in Fig. 5 for 9CrMoNbV steel. One of the main advantages of using this is easy accessibility of test data from various sources. If data from various sources are super imposed one gets a large scatter band. The lower bound gives the minimum specified rupture strength. These are included in most design codes for high temperature structural components. Quite often LMP is used as a measure of service exposure. Attempts are being made to correlate this with parameters such as magnetic properties which can be easily evaluated without causing any damage on the engineering components [11]. It appears dependence on this simple procedure for life assessment of engineering components would continue until we have more easily available creep strain time database from multiple sources.

4. Conclusion

Continuum damage mechanics based model for creep life prediction has distinct advantages over conventional empirical methods. However slight variation in model parameters can give widely different creep strain time plots. In view of limited availability of creep strain time database in open literature reliable estimation of model parameters is difficult. This is why creep life assessment of engineering components continues to depend on empirical methods based on time temperature parameters.

Acknowledgement

Much of the work reported here were done when the author was at National Metallurgical Laboratory, Jamshedpur. The work would not have been possible without the support received from my former colleagues Dr R Singh, Dr S Chaudhuri, Dr J Swaminathan, Ms S Hore, Dr N Roy, Mr S C Bose, Dr A K Roy, and Mr G Krishna.

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