JMEPEG (2011) 20:1310–1314
DOI: 10.1007/s11665-010-9761-7

Creep Constitutive Model and Component Lifetime Estimation: The Case of Niobium-Modified 9Cr-1Mo Steel Weldments

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(Submitted May 11, 2010; in revised form August 14, 2010)

The θ-projection parametric method was used to analyze the creep strain versus time data, obtained in uniaxial tension, from weldments fabricated using a niobium-modified 9Cr-1Mo steel as the weld metal (Ellis, Private communication, 1991, provided the data). We used these data to illustrate a methodology whereby the θ-projection method may be used to obtain estimates of component design creep lifetimes, for specified sets of design stress, temperature, and strains. Furthermore, it is suggested that the creep strain results may be consistent with dislocation climb being the creep deformation mechanism in the alloy.

Keywords creep deformation, Cr-Mo steel weldments, θ-projection method

1. Introduction

Because of their bulk and geometrical complexity, many components in power engineering plants (such as those in reheat steam piping systems and joints and seams of superheater loaders in boilers) contain many weldments. The service milieu of these components includes elevated temperature (usually, above 500 °C) and creep cracking is known to occur frequently at these weldments. In fact, these weldments are a weak link in these components because of, among other things, the complex microstructure and pattern of stresses in the weldments. For such applications, it is important to develop relations that may be used to estimate design thermal-creep lifetimes of the weldments themselves and to have knowledge about the governing mechanism (to aid explanation of weldment material thermal-creep behavior).

These aspects are the subject of the present work, with experimental tensile creep data for a named weldment provided by Dr. Ellis (Ref 1) and the θ-projection parametric method (TPPM) (Ref 2) being used. This particular body of experimental data is part of a very limited resource base in that there is a dearth of creep data obtained from specimens of the parent metal, the weld metal, and the cross-section of weldments (Ref 3, 4). The TPPM is finding extensive use among designers and users of elevated-temperature components and structures (Ref 5).

2. The θ-Projection Method

The rationale for using a parametric method to obtain estimates of long-term creep strain (for a given creep time) or creep time (for a creep strain) from short-term experimental creep data is well established (Ref 6). The merits and drawbacks of the most popular of these methods have been detailed (Ref 6) and thus will not be repeated here. Suffice it to say that, among these approaches, a consensus has emerged that the θ-projection method is particularly attractive.

The essence of this method is the mathematical description of the entire thermal-creep strain, ε vs. time t, curve through the use of simple-to-use relations. In the case where the specimens are fabricated from CrMo steels, the creep curve is composed of a decreasing creep rate zone and an increasing creep rate zone. Then, it has been shown that the ε-t relation is

$$\varepsilon = \theta_1\left(1 - e^{-\theta_2 t}\right) + \theta_3\left(e^{\theta_4 t} - 1\right), \qquad \text{(Eq 1)}$$

where θ_i are the θ coefficients.

Through utilization of the fact that the shape of the ε-t curve is unique [for a specified combination of stress (σ) and temperature (T)], the dependence of the values of θ coefficients on σ and T can be derived, thus leading to the estimation of the creep lifetime of a component (for a given combination of σ, T, and design creep strain, ε_d).

3. Data Analysis

Uniaxial tensile creep test data for weldments made of a low-niobium-modified 9Cr-1Mo steel weld metal (Table 1), obtained in air in the stress range of 65-125 MPa and temperature range of 923-973 K, were provided by Dr. F. Ellis of Tordonato Energy Consultants, Inc., Chattanooga, TN (Ref 1). All the datasets are presented in Fig. 1.

For each data set, Eq 1 and a nonlinear minimization method (the Marquardt-Levenberg method), contained in a commercially available software (Matlab®7.1; The MathWorks,

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Table 1 Composition of the weld metal (niobium-modified 9Cr-1Mo steel) and weldment fabrication conditions(a)

(A) Composition of metal (in wt/wt.%)				
C: 0.0955	Mn: 0.53	P: 0.007	S: 0.011	Si: 0.285
Ni: 0.08	Cr: 8.405	Mo: 0.915	V: 0.192	Nb: 0.0255
Ti: 0.0225	Co: 0.013	Cu: 0.06	Al: 0.005	B: <0.001
W: <0.01	As: 0.0065	Sn: 0.01	Zr: <0.001	N: 0.03
O: 0.04				
(B) Weldment fabrication conditions				
Electric shielded metal arc welding process (120 A; 25 V; preheat temperature: 204 °C; maximum interpass temperature: 343 °C; post-weld heat treatment temperature: 749 °C)				

(a) *Source*: Ref 1

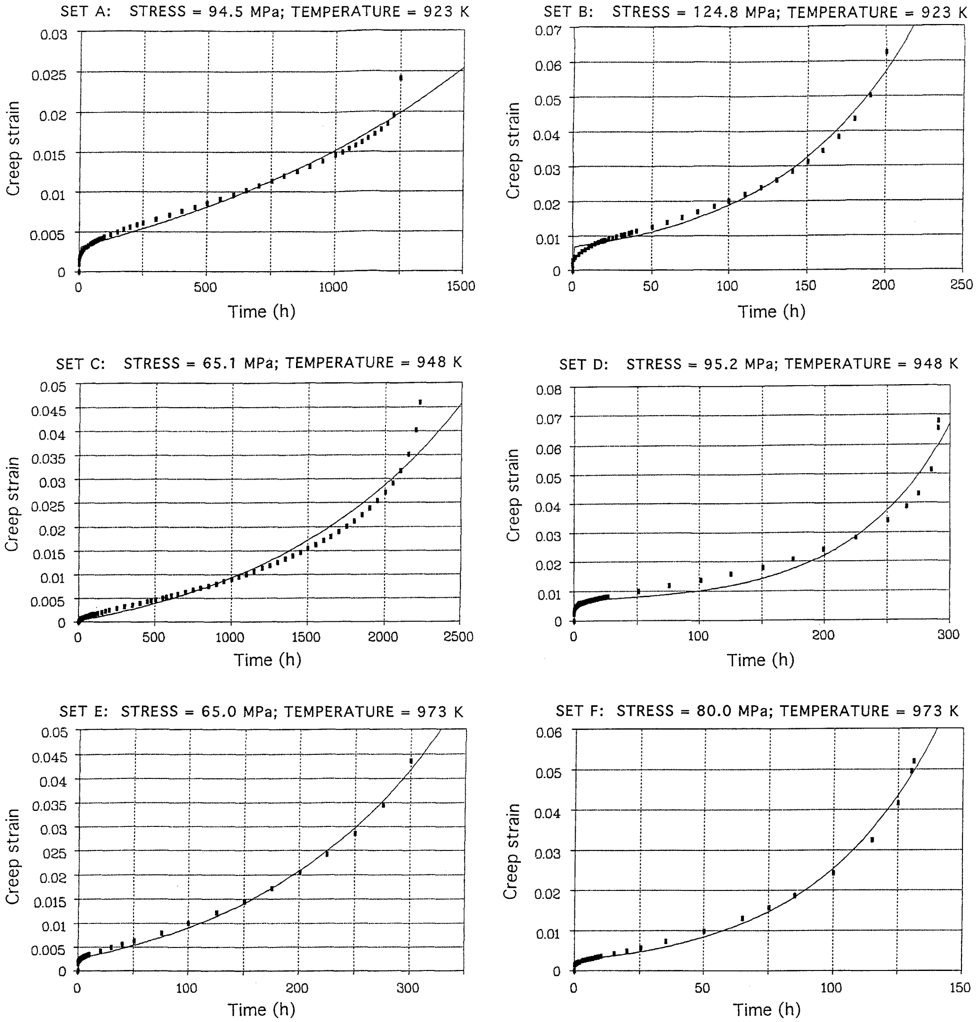

Fig. 1 (a-f) Creep strain curves for niobium-modified 9Cr-1Mo steel weldments at various combinations of applied stress and temperature (Experimental data taken from Ref 1). In each data set, experimental points are shown as filled rectangles and the fit is shown as the continuous curve

Inc., Natick, MA, USA) were used to obtain the best-fit estimates of the θ coefficients. The results (Fig. 1 and Table 2) show that the aforementioned relation provides an excellent goodness-of-fit to the data. The variations of the values of θ coefficients with σ and T are summarized in Fig. 2.

4. Component Lifetime Estimation

In many cases, designers and users of elevated-temperature structures and/or components are interested in the use of a parametric method to facilitate estimation of reliable component

Table 2 Summary of the estimates of the θ coefficients(a)

	Value of				
Stress/temperature (MPa/K)	θ_1	θ_2	θ_3	θ_4	**SEE(b)**
94.5/923	31.20×10^{-4}	4.68×10^{-1}	11.63×10^{-3}	0.71×10^{-3}	7.42×10^{-4}
124.8/923	67.31×10^{-4}	49.49×10^{-1}	5.42×10^{-3}	11.66×10^{-3}	14.85×10^{-4}
65.1/948	2.10×10^{-4}	72.47×10^{-1}	7.89×10^{-3}	0.76×10^{-3}	16.80×10^{-4}
95.2/948	68.74×10^{-4}	11.73×10^{-1}	1.19×10^{-3}	13.12×10^{-3}	22.65×10^{-4}
65.0/973	25.34×10^{-4}	85.05×10^{-1}	8.16×10^{-3}	5.86×10^{-3}	17.53×10^{-4}
80.0/973	24.88×10^{-4}	23.13×10^{-1}	3.16×10^{-3}	21.11×10^{-3}	8.92×10^{-4}

(a) To give thermal-creep strain, with time, *t*, being in *h*
(b) Standard error of estimate of the creep strain, adjusted for degrees-of-freedom

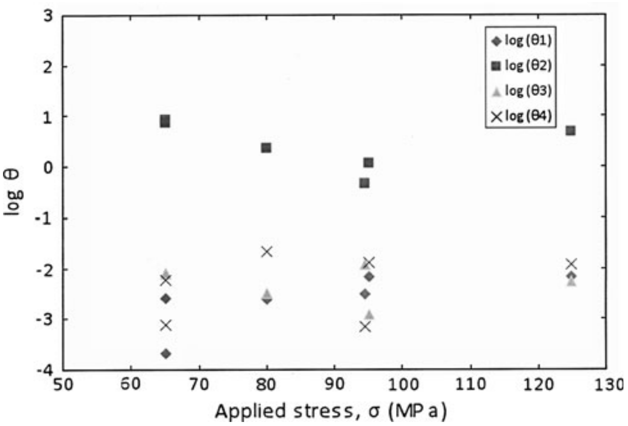

Fig. 2 Variation of log θ_1, log θ_2, log θ_3, and log θ_4 with stress at three temperatures for niobium-modified 9Cr-1Mo steel weldments

lifetimes, given a specific combination of σ, *T*, and ε_d. TPPM lends itself admirably for this purpose. This is mainly because the systematic changes in the values of the θ coefficients, as a function of σ and *T*, may be described using simple-to-use expressions.

As in previous studies (Ref 6, 7), these changes are described using the multi-linear expression

$$\log \theta_i = a_i + b_i\sigma + c_iT + d_i\sigma T, \qquad \text{(Eq 2)}$$

where a_i, b_i, c_i, and d_i are coefficients.

The following steps were followed in obtaining estimates of the component lifetime (t_D). First, the results in Table 2, in conjunction with Eq 2 and a commercially available software (Minitab®12; Minitab Inc., State College, PA, USA) were used to obtain the values of the coefficients a_i, b_i, c_i, and d_i in Eq 2. These results are presented in Table 3. Second, for a given set of values of design stress and design temperature, the corresponding values of θ_1, θ_2, θ_3, and θ_4 were calculated using the results in Table 3 and Eq 2. Finally, with these values and a specified value of ε_d, the value of the t_d was obtained by numerically solving the equation

$$\theta_1\left(1 - e^{-\theta_2 t_d}\right) + \theta_3\left(e^{\theta_4 t_d} - 1\right) - \varepsilon_d = 0 \qquad \text{(Eq 3)}$$

For this purpose, a commercially available software (Mathcad®12; Adept Scientific plc, Letchworth Garden City, Herts, UK) was used. The results of this exercise are summarized, for three selected values of ε_d in Fig. 3.

It is contended that the t_d estimates reported here have direct design usefulness because they are derived from tensile creep test data; it is known that, in elevated-temperature service, weldments are subject to tensile stress. It should be noted, however, that these estimates would be affected by a number of variables, chief among which is the extent of the differences between the weldment used in the actual component and the experimental test specimen used to obtain the present ε vs. *t* data set, in terms of geometry and stress field. Furthermore, there are many life-limiting phenomena (other than creep deformation) as far as weldments are concerned. These include fatigue crack propagation, stress corrosion cracking, and creep-fatigue interaction.

Table 3 Values of the coefficients in Eq 2 (a)

	Value of				
Parameter	***a***	***b***	***c***	***d***	**SEE(b)**
log θ_1	-13.35	0.86×10^{-2}	-0.60×10^{-1}	9.56×10^{-5}	0.487
log θ_2	-90.34	9.68×10^{-2}	10.14×10^{-1}	-108.59×10^{-5}	0.488
log θ_3	-49.08	5.13×10^{-2}	7.35×10^{-1}	-80.00×10^{-5}	0.239
log θ_4	-30.69	2.63×10^{-2}	-1.18×10^{-1}	16.68×10^{-5}	0.121

(a) $\log \theta_i = a_i + b_i\sigma + c_i T + d_i\sigma T$. Units are: MPa for σ and K for *T*
(b) Standard error of estimate of parameter, adjusted for degrees-of-freedom

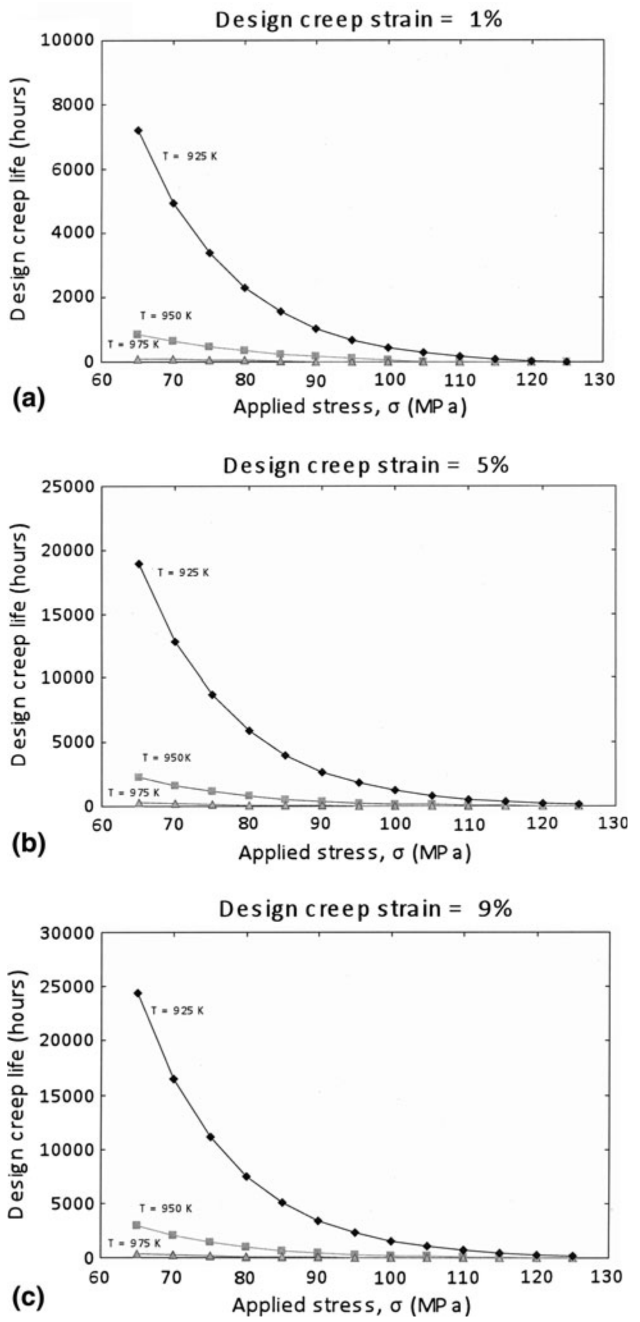

Fig. 3 (a-c) Stress and temperature dependence of the estimated thermal-creep lifetime, for various design strain levels, for niobium-modified 9Cr-1Mo steel weldments

5. Creep Mechanism

In order to gain some insight into the possible creep deformation mechanism, we obtained estimates of (1) the exponent (n) in the Norton relationship

$$\text{Minimum creep strain rate} = B\sigma^n, \qquad \text{(Eq 4)}$$

where σ is the applied stress and B and n are material constants; and (2) the activation energy (Q), using the Arrhenius relationship, which is given by

Table 4 Summary of minimum creep strain rate at various combinations of applied stress and temperature

Stress (MPa)	Temperature (K)	Minimum creep strain rate (10^{-5} h^{-1})
94.5	923	1.33
124.8	923	19.95
65.1	948	1.10
95.2	948	13.30
65.0	973	10.01
80.0	973	34.14

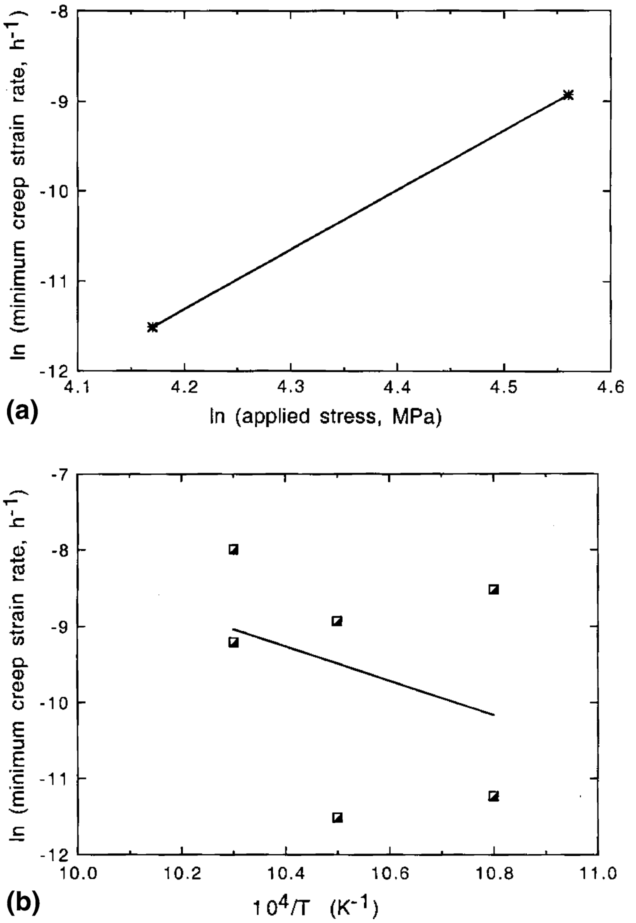

Fig. 4 Fit between minimum creep strain rate results for niobium-modified 9Cr-1Mo steel weldments and the Norton equation (Eq 4), at $T = 948$ K (a) and the Arrhenius equation (Eq 5) (b)

$$\text{Minimum creep stain rate} = A\exp[-Q/(RT)], \qquad \text{(Eq 5)}$$

where A is a process constant, T is the test temperature, and R is the molar gas constant (=8.314 J mol^{-1} K^{-1}).

We obtained the minimum creep strain rate of the alloy for each pair of applied stress and temperature and these are presented in Table 4. The fit between these minimum creep strain rate values and Eq 4 and 5 yielded the best-fit values for (1) n to be 9.7, 6.6 (Fig. 4a), and 6.0 at $T = 923$, 948, and 973 K, respectively; and (2) Q to be 194 kJ mol^{-1} (Fig. 4b). These n and Q estimates suggest that the creep of this alloy may be dislocation climb-controlled (Ref 8). For two reasons, however, this suggestion should be taken as tentative. First, the data set is limited (data obtained at only two stress levels at each of three temperatures) and, second, there is no microstructural information that could provide corroborating evidence.

6. Conclusions

- We have presented the application of the TPPM to the analysis of creep strain vs. time data obtained using weldments fabricated using niobium-modified 9Cr-1Mo steel as the weld metal.
- We posit that the estimates of design creep lifetimes of weldments, for specified combinations of design stress, temperature, and creep strain, are realistic.
- The creep strain results may be consistent with dislocation climb being the creep deformation mechanism in the steel.

Acknowledgments

The authors are grateful to Dr. F. V. Ellis of Tordonato Energy Consultants, Inc., Chattanooga, TN, for providing the creep test data.

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