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Prediction of Creep Curves of High Temperature Alloys using θ-Projection Concept

C.M.Omprakash*, A.Kumar, B.Srivathsa, D.V.V.Satyanarayana

Defence Metallurgical Research Laboratory, Kanchanbagh, Hyderabad-500058, India

Abstract

A computer program based on "MATLAB" was developed to predict creep curves of two high temperature alloys viz. a near α titanium alloy and Fe-Ni-Cr-Al alloy using θ-projection concept. Experimental creep curves generated at 600°C at different stress levels were used. This technique involves fitting of experimental creep curves according to eq $\varepsilon_c = \varepsilon_t - \varepsilon_o = \theta_1(1-e^{-\theta_2 t}) + \theta_3(e^{\theta_4 t} - 1)$ to obtain θ_i parameters for different stress levels. Different θ-values obtained from fitting are then fitted according to eq $\log\theta_i = a_i + b_i\sigma + c_i T + d_i\sigma T$ and experimental strain to fracture values are fitted according to eq $\log\varepsilon_f = a + b\sigma + cT + d\sigma T$ to obtain a set of twenty material constants (a_i, b_i, c_i, d_i and ε_i), which are further used along with eq $\varepsilon_c = \varepsilon_t - \varepsilon_o = \theta_1(1-e^{-\theta_2 t}) + \theta_3(e^{\theta_4 t} - 1)$ to determine four θ-values and fracture strain for each desired combination of stress and temperature in order to generate new creep strain curve. The predicted creep curves for both the alloys have been validated by generating experimental curves. Further, in order to simulate creep behaviour of components of complex geometry such as gas turbine blades and vanes this user defined material model i.e, θ-projection concept has been interfaced with ANSYS. Simulations have been carried-out and validation of the simulation results will be presented in this paper.

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Keywords: θ-Projection; α titanium alloy; Fe-Ni-Cr-Al; creep

1. Introduction

Engineering components and structures operating under creep conditions have traditionally been designed on the basis of long-term, constant- load, stress rupture properties. Even when full creep strain-time curves have been determined, most theoretical and practical investigations of creep and creep fracture have relied on measurements of only a few parameters, commonly, the time and strain to failure and either the secondary creep rate or time to some fixed creep strain. Thus the older methods of design-to-code could operate on abbreviated measures of material performance (e.g. rupture life, minimum creep rate, time to an arbitrary strain), ignoring a very considerable amount of information by not quantifying the creep curve shape. Evans et

* Corresponding author:
E-mail address: cmo@dmrl.drdo.in

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al. [1, 2] have introduced the θ-projection concept to describe creep curve accurately. The equation of a creep strain ε_c with time t is given by the following form,

$$\varepsilon_c = \varepsilon_t - \varepsilon_o = \theta_1(1 - e^{-\theta_2 t}) + \theta_3(e^{\theta_4 t} - 1) \quad (1)$$

where ε_t is the total creep strain at time t and ε_o is the instantaneous strain on loading. The theta projection approach has been extensively used for a variety of materials such as 1.25Cr-0.5Mo and 2.25Cr-1Mo steels [3], modified 9Cr-1Mo steel [4], austenitic stainless steels [5], eutectic Sn-Ag alloy [6], aluminium alloys [7] and superalloys [8] to successfully predict the entire portion of creep curves. The objective of the present effort is to develop a "Matlab" based program and to investigate the ability of the θ - projection approach to establish model parameters and predict the entire portion of creep curves of two high temperature alloys viz. (i) near α titanium alloy and (ii) aluminium containing austenitic steel (Fe-Ni-Cr-Al).

2. Experimental procedure

Two high temperature alloys viz., a near α titanium alloy and an aluminium containing austenitic stainless steel (Fe-Ni-Cr-Al) were used in this study. The chemical composition of these alloys in wt% is given in Table 1. Constant load creep tests were conducted in air till rupture of the specimens at 600°C in the stress range 300 to 400 MPa in case of titanium alloy and at 600° in the stress range 250 to 300 MPa in case of aluminium containing austenitic stainless steel (Fe-Ni-Cr-Al).

Table 1. Chemical composition of the titanium alloy and FeNiCrAl in wt (%).

Near α Titanium alloy									
Element	Al	Sn	Zr	Nb	Mo	Si	C	O	Ti
Wt%	5.8	4.0	3.5	0.7	0.5	0.35	0.06	0.07	Balance

Aluminium containing austenitic stainless steel (Fe-Ni-Cr-Al)						
Element	Ni	Cr	Al	Zr	Y	Fe
Wt%	21	15	4.5	0.12	0.02	Balance

3. Results and discussions

Experimental creep strain-time data at different stresses and temperatures were fitted according to Eq.1 using the program developed and four theta values were determined. The three experimental as well as fitted (using eqn.1) creep strain curves of the titanium alloy (at 300, 350 and 400MPa) and Fe-Ni-Cr-Al alloy (at 250, 275 and 300 MPa) at 600°C are shown in Figs. 1 and 2, respectively. As can be seen from Figs. 1 and Fig. 2, Eq.(1) provides the best fit of experimental creep curves and the fitting lines match experimental creep curves well over the entire portion of the curves. However, the fracture strains of the curves generated by fitting do not match exactly with experimental values of rupture strain and exhibit marginal difference as shown in Fig. 1 and Fig. 2. The reason for such behavior could be that Eq. 1, which is used for fitting, accounts only for curvature and not for fracture strain. For interpolation/extrapolation of the creep curves, different θ-values obtained from fitting are fitted according to eq. $\log\theta_i = a_i + b_i\sigma + c_i T + d_i \sigma T$ and experimental strain to fracture values fitted according to eq. $\log\varepsilon_f = a + b\sigma + cT + d\sigma T$. The fitting of experimental data has resulted in a set of twenty material constants (a_i, b_i, c_i, d_i). It must be noted that in case if either temperature or stress is fixed, the number of these constants is reduced. These constants are further used along with Eq.(1) to determine four θ-values and fracture strain for each desired combination of stress and temperature in order to generate new creep curve. These constants were used to predict the creep curves of near α titanium alloy for stresses 320, 380 and 500 MPa and at 600°C and Fe-Ni-Cr-Al alloy for stresses 230 and 260 MPa at 600°C. The predicted creep curves together with experimental creep curves are shown in Figs. 3 and Figs. 4. As shown in Fig. 3 the creep curves predicted for titanium alloy at 320, 380 and 500 MPa follow the expected trend i.e., the creep curve for 320 MPa stress lies between the experimental creep curves at 300 and 350 MPa, the creep curve for 380 MPa lies between the experimental creep curves at 350 and 400 MPa and creep curve for 500 MPa lies beyond the experimental creep curve at 400 MPa. Similar trend was also observed in case of FeNiCrAl alloy as illustrated in Fig.4. i.e., predicted curves show the expected trend. Further, the predictions of creep curves at 600°C/325 MPa and 650°C/225MPa is validated by generating experimental creep curve at those test conditions. As shown in Figs. 5 and 6 the predicted curves match with experimental creep curve almost over most portion. As can be seen from Figures 5 and 6, the predicted creep curves for different test conditions fall within 10% scatter band of respective experimental creep curves. Minor deviations with respect to time and strain to fracture values of predicted curves in comparison to those of experimental values are observed. Though the method described above [1, 2] was developed for prediction of creep strain curves for any combination of stress and temperature, it can be utilized only either for constant temperature or stress. The procedure described here in its present form fails to predict for different stress and temperature combinations based on the data available at either fixed stress or temperature. For example, if the experimental creep strain curves were recorded at different stresses but at fixed temperature, prediction of creep strain curves can be done only for different stress values but at the same fixed temperature and vice versa. The efforts to predict the creep curves at different stress and temperature combinations are presently in progress. Further, the θ - projection technique is interfaced using ANSYS programmable features to successfully predict the complete creep curves of the titanium alloy with notch specimen geometry as illustrated in Fig.7. As can be seen from Fig.7, the predicted creep curves of notched specimens with notch root radius R4 and R8 match well with experimental creep curves over the entire portion for titanium alloy at 600°C/300 MPa. R4 and R8 indicate that the notch root radius or radii of curvature in the notch portion are 4 and 8 mm, respectively, with the severity of the notch being more in case of R4 than R8.

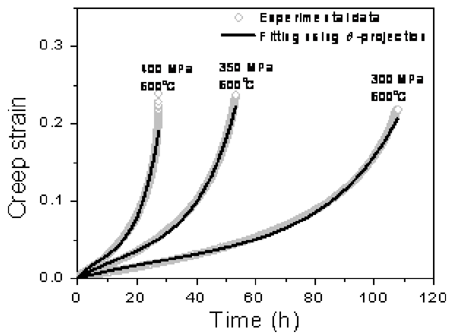

Fig. 1. Experimental creep curves and creep curves fitted using θ - projection method, of the titanium alloy

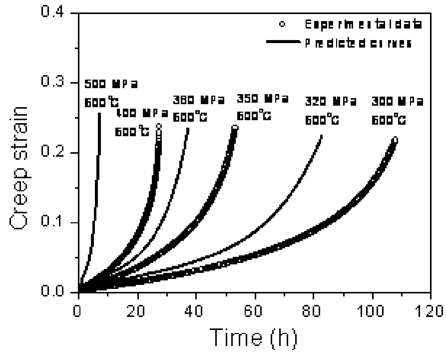

Fig. 2. Predicted and experimental creep strain-time curves of titanium alloy.

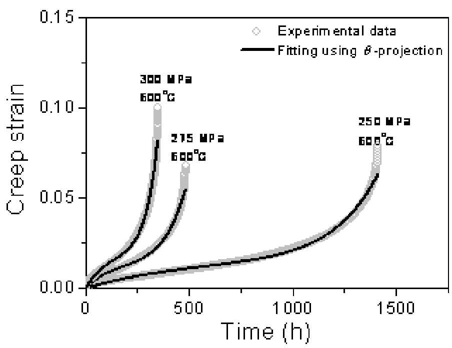

Fig. 3. Experimental creep strain-time curves of FeNiCrAl alloy fitted employing θ−projection.

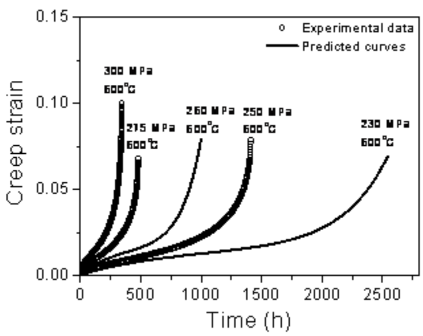

Fig. 4. Predicted and experimental creep strain-time curves of FeNiCrAl alloy.

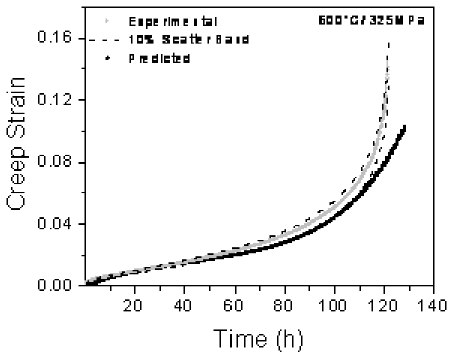

Fig. 5. Predicted and experimental creep curves of FeNiCrAl at 600°C and 325MPa.

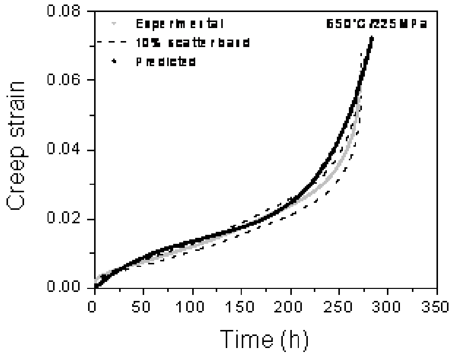

Fig. 6. Predicted and experimental creep curve of FeNiCrAl at 650 C and 225 MPa.

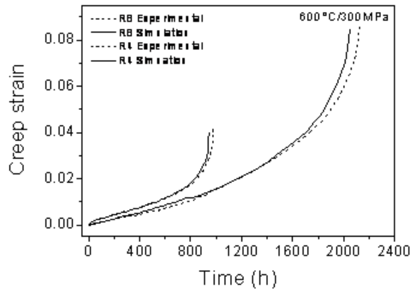

Fig. 7. The predicted creep curves of notched titanium alloy specimens with notch root radii R4 and R8 using ANSYS with θ- projection interface at 600°C/300 MPa.

4. Conclusions

A computer program based on "MATLAB" was developed to predict creep curves of two high temperature alloys viz. a near α titanium alloy and Fe-Ni-Cr-Al alloy using θ-projection concept. Experimental creep curves generated at different stress levels but at one fixed temperature were used. The predicted creep curves for both the alloys have been validated by generating experimental curves and it has been found that the predicted curves quite match with experimental creep curves. The predicted creep curves for different test conditions fall within 10% scatter band of respective experimental creep curves. Further, this technique has been successfully employed to predict creep curves of notched specimens using finite element analysis (ANSYS) *with* θ - projection interface.

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