CREEP BEHAVIOUR OF 9Cr-1Mo FERRITIC STEEL USING THETA-PROJECTION APPROACH AND EVOLUTION OF A DAMAGE CRITERION

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ABSTRACT

A detailed analysis of creep behavior of 9Cr-1Mo ferritic steel in quenched and tempered condition has been performed by 4-θ approach over a wide range of stresses at 873 K. Large creep strain accumulation near rupture demanded the incorporation of cut-off strain (0.19) in tertiary regime to facilitate accurate representation of creep strain-time data. Appropriate description for the variation of theta parameters with stress has been evolved. Four-theta projection method has been used to successfully predict minimum creep rate, time to reach various strain levels and rupture life.

INTRODUCTION

Various methodologies have been developed for extrapolation of creep rupture life to long term service conditions than those for which experimental data is available [1,2]. However representation of the complex creep strain-time path, *i.e.* the whole creep curve, which leads to prediction of several useful creep parameters at a stretch, is largely ignored.

To overcome this, Evans *et al.* [3] has proposed a constitutive equation to describe the shape of the creep curve known as 4-θ projection technique which has an important outcome that creep is a first order kinetic process. In addition, the differences and similarities between continuum damage mechanics (CDM) approach and theta projection technique were brought about by Dyson [4]. In theta projection methodology, the decelerating primary and the accelerating tertiary stages of a creep curve are modeled and any steady state creep region is an inflection in the curve where the effects of a strain hardening and strain softening process are equal. There are two important modifications to theta methodology in order to improve its predictive capability. Firstly, six-theta methodology has been introduced to describe the primary creep behavior more accurately than the 4-θ approach [5]. In addition, a need for a weighing scheme is stressed. As theta parameters are estimated quantities, weight has to be attached to each theta value by some measure of its reliability [6]. It has been claimed that long term predictions can be improved by adopting a proper weighing scheme. This technique has been used successfully to describe the creep behavior of various materials [7-8]. The applicability of theta projection formalism can be further enhanced by implementing it within a finite element code [9]. This extends the predictive capability of theta projection technique to complex geometries undergoing creep deformation, multiple material problems such as weld joints, and non-steady temperature conditions.

In the present work, 4-theta projection method has been employed to represent the creep behavior of 9 Cr-1Mo steel over a wide range of stresses at 873 K followed by prediction of certain useful, design related creep properties. 9Cr-1Mo ferritic steel and its modified versions are important candidate materials for steam generator applications in power plants. The good weldability and good microstructural stability over long time exposure at elevated temperatures are the attractive features that have favoured the selection of 9Cr-1Mo steel and its variants for steam generator applications. In addition, plain 9Cr-1Mo ferritic steel has been chosen as wrapper material in future liquid metal cooled fast breeder reactors (LMFBRs). This steel has better resistance to irradiation induced swelling, lower thermal expansion coefficient and better thermal conductivity compared to austenitic counterparts which favored the selection of this material for wrapper applications.

THETA PROJECTION METHOD

The variation in creep strain ε_c with time t is represented by 4-θ equation as,

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

where, ε_t is the total strain and ε_o is instantaneous strain upon loading. Among four theta parameters, θ_1 quantifies the total primary strain and θ_3 scales with the tertiary creep strain. The parameters θ_2 and θ_4 characterize the curvatures or shapes of primary and tertiary portions of creep curve respectively. Each theta parameter can be represented as a function of stress and temperature as,

$$\log\theta_i = a_i + b_i\sigma + C_iT + d_i\sigma T \tag{2}$$

where, σ is stress, T is temperature and a, b, c, d are coefficients to be fitted by multiple regression procedure with"i" varying from 1 to 4. This function is used within theta projection technique to project the creep curve parameters obtained at accelerated test conditions to design stresses and temperatures. The functional form of the theta interpolation/extrapolation function is crucial for long-term creep life prediction. Alternative formalisms to represent theta values as a function of stress and temperature are available in literature [10].

Once theta parameters are known at a given stress and temperature, various useful creep properties can be extracted. Time to reach minimum creep rate (t_m) can be obtained by differentiating Eq. (1) and equating the resultant expression to zero.

$$t_m = \frac{1}{\theta_2 + \theta_4}\ln\left(\frac{\theta_1\theta_2^2}{\theta_3\theta_4^2}\right) \tag{3}$$

Minimum creep rate $\dot{\varepsilon}_m$ can then be evaluated by substituting t_m in Eq. (1).

$$\dot{\varepsilon}_m = \theta_1\theta_2 e^{-\theta_2 t_m} + \theta_3\theta_4 e^{\theta_4 t_m} \tag{4}$$

In addition, time to reach a particular level of creep strain can be obtained by substituting the strain value in Eq. (1) and solving for corresponding time.

EXPERIMENTAL DETAILS

The 9Cr-1Mo steel used in the present investigation was subjected to quenched and tempered treatment (1223 K/5 h, water quenched and 1023 K/8h, air cooled) prior to testing. Creep tests were carried out in the stress range of 60-125 MPa at 873 K. Creep strains to failure at various stress levels were between 0.4 to 0.54.

RESULTS AND DISCUSSIONS

Modeling of Creep Curves

Levenberg-Marqudt non-linear curve fitting technique was used to fit Eq.(1) for creep strain-time data at various stress levels. The level of fitting was indicated by low value of Chi^2 (of the order of 10^{-5} or less) and high value of R^2 (0.99 or above). Fig.1a shows a typical result obtained at 60 MPa. It was observed that the creep curve could not be represented well by 4-θ method. The reason was that the primary creep strain was comparatively low as compared to the large tertiary creep strain [7] which resulted in a mathematical difficulty. Hence it was necessary to define a cut-off strain in tertiary region. Various cut-off strains were tried and a value of 0.19 was found to be optimum for stress levels employed. Fig.1b shows the fitted curve after adopting the cut-off strain concept. It can be seen that the fitting has improved satisfactorily.

Figs.2 (a)-(d) show the stress dependency of theta parameters for constant load tests carried out on 9Cr-1Mo steel. Two important observations can be made. From Fig. 2a, it is evident that there is a change in slope characterizing the low and high stress regions and the transition stress level was 100 MPa. It can also be observed from Fig. 2 that the log(theta) showed a linear dependency on stress but with different slopes in low and high stress regimes except for θ_3. The linear relationships indicate that the theta projection technique can be confidently used for interpolation or long-term extrapolation of the creep data.

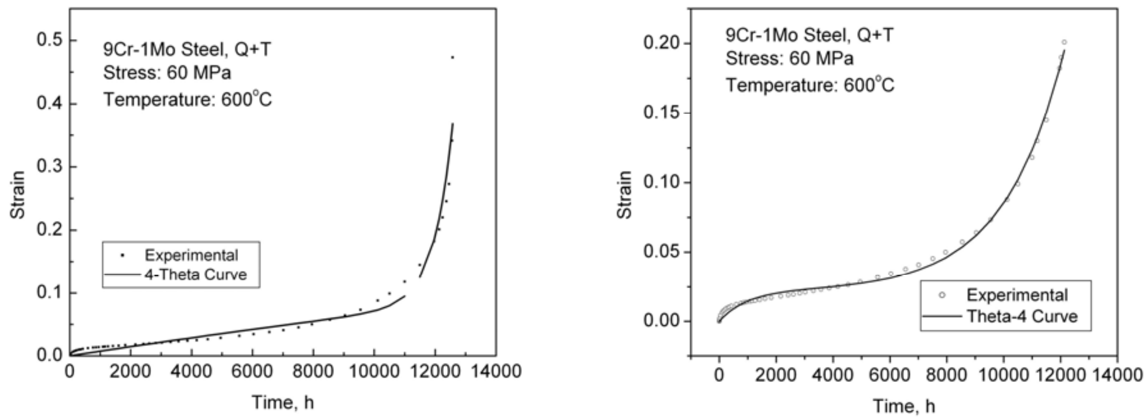

Fig. 1: Curve fitting by 4-θ projection (a) without cut-off strain and (b) with a cut-off strain of 0.19

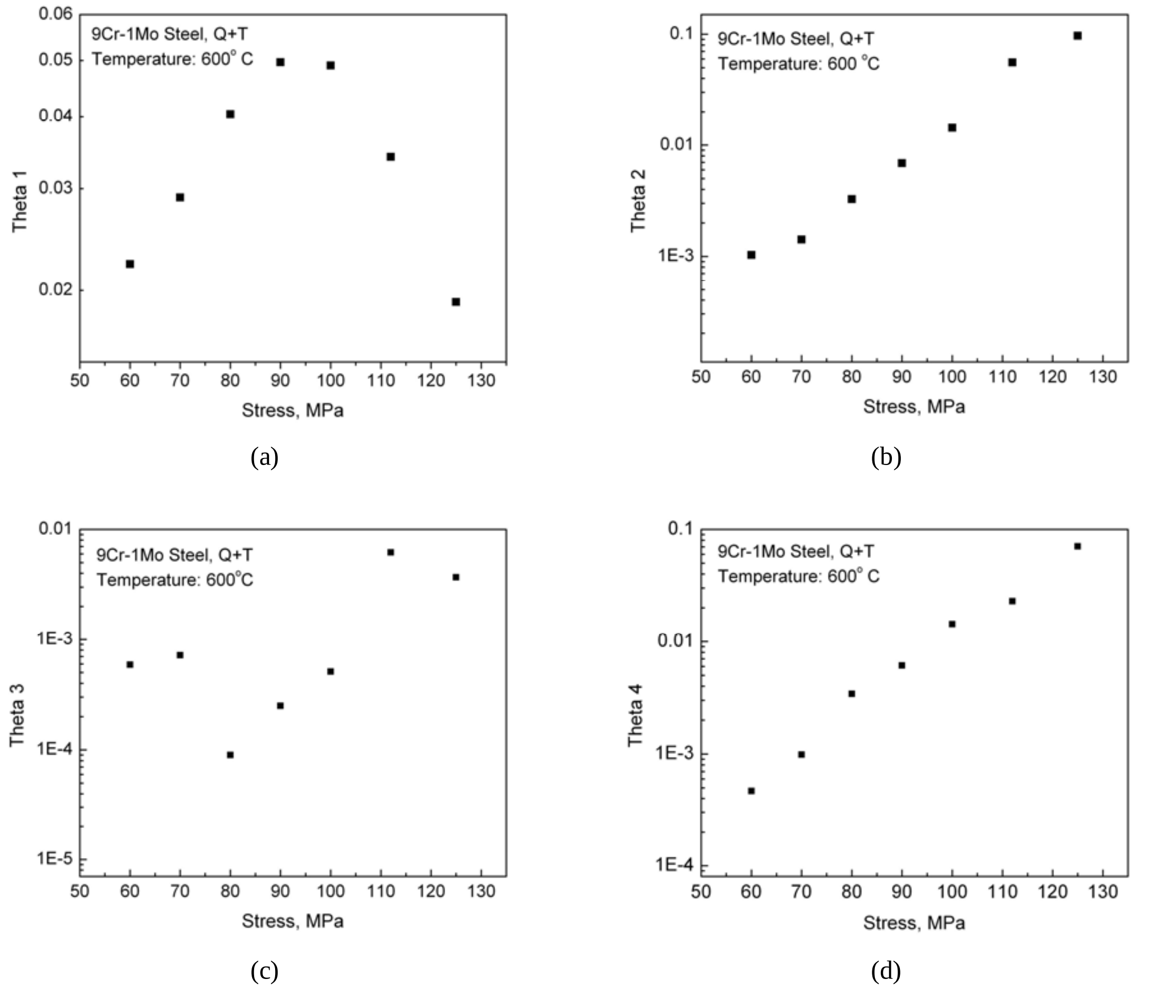

Fig. 2: Variation of theta parameters with stress

Using these linear relationships, time to reach a given strain value, minimum creep rate and rupture life were predicted in low stress level regime, i.e., between 60-90 MPa. This is also a region where rupture lives were above 1000 h.

Time to Attain a Given Strain

Time to reach a desired value of creep strain can be obtained by numerically solving Eq. (1). Time to reach various strain levels of 1%, 5%, 10% and 40 % (rupture strain) were estimated as a function of stress at 873 K and compared with experimental values (*See* Fig. 3). It can be seen from Fig. 3 that predictions are accurate for strain levels between 5-40%. On the other hand, predicted values deviated from experimental results significantly at 1% strain. It is well known that predictions at low strain values are less accurate in 4-θ technique [5].

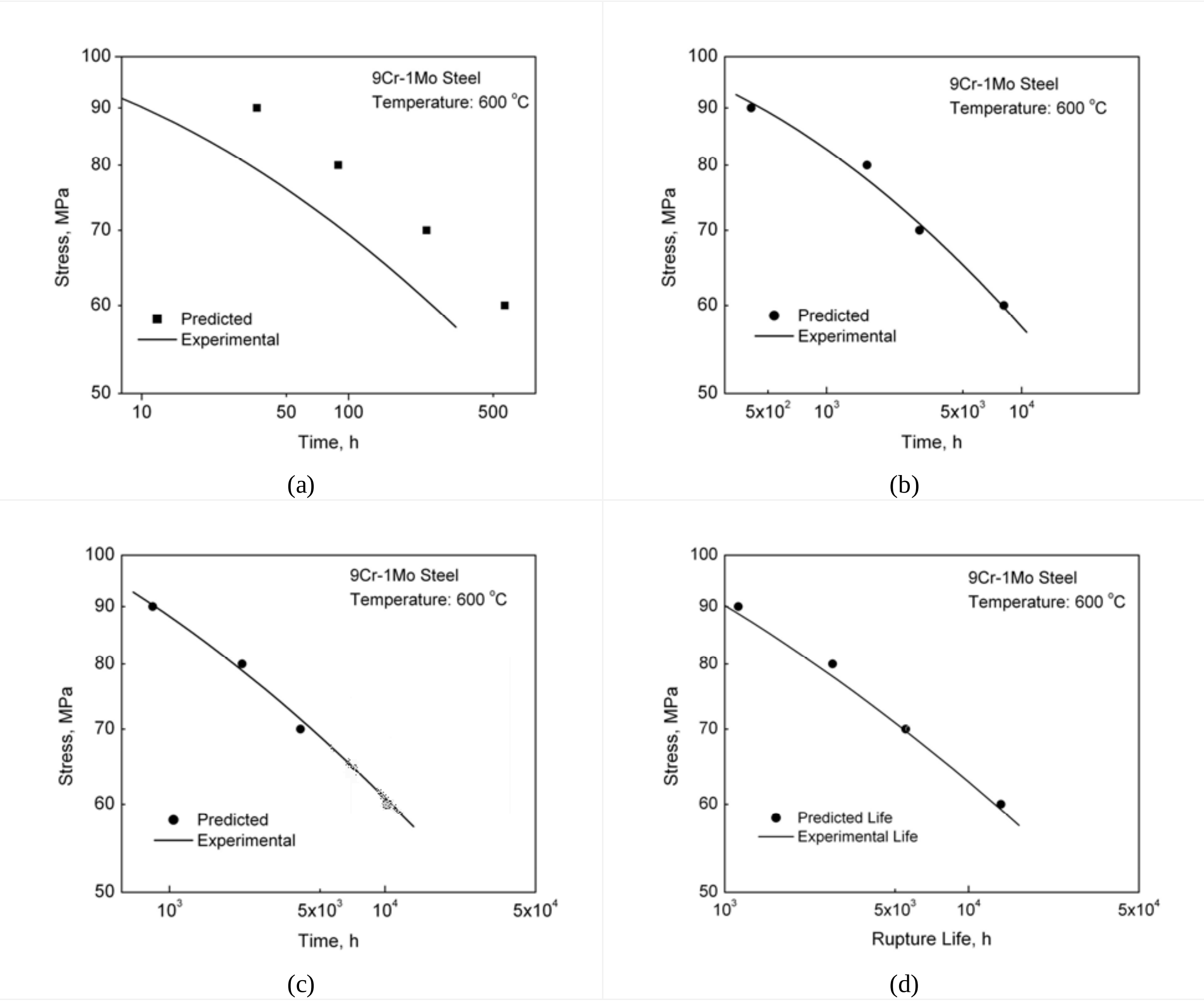

Fig. 3: Variation of time to reach various strain levels with stress (a) 1% strain (b) 5% strain (c) 10% strain and (d) 40% strain

It was observed that the fitting and predictions corresponding to low strain values (for example, time to reach 1% strain) can be improved by defining a low cut-off strain in 4-θ methodology or by adopting 6-θ technique (Compare Fig1(b) and Fig. 4). However 6-θ methodology is cumbersome as it involves many parameters. It will be therefore beneficial to develop a new relation similar to 4-θ projection which could represent the low strain regime well with high cut-off strain values.

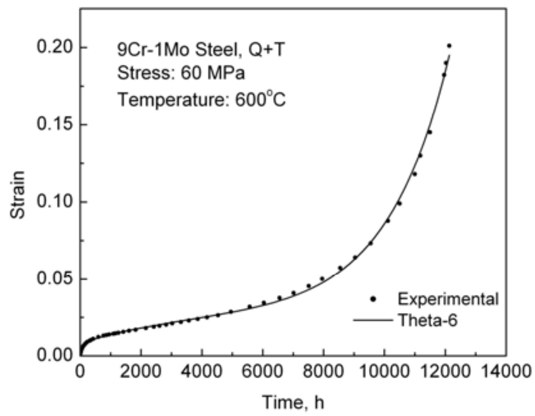

Fig. 4: Creep curve representation by 6-θ projection

Rupture Life Prediction

Stress to cause rupture is a very important parameter in the design of components under creep conditions. In order to predict the rupture life using Eq. (1), it is necessary to define a suitable failure criterion. In the present study, creep strain to failure varies non-systematically between 0.40 to 0.54 at various stresses. Hence it is appropriate to take a failure strain value of 0.4. The error of underestimating the exact time to fracture is generally very small, as the creep rate in final part of the tertiary region increases rapidly. Fig. 3(d) shows a comparison between the experimental and calculated rupture lives and demonstrates close agreement between them.

Minimum Creep Rate as a Function of Stress and Temperature

The minimum creep rate finds it use in life prediction methodology [11]. Knowing the four theta values at a given stress, the time at which the creep rate is minimum can be estimated from Eq. (3). The minimum creep rate can then be calculated by substituting the value of t_m in Eq. (4). Fig. 5 shows a comparison between the experimental and the calculated values of minimum creep rates as a function of stress. As estimating minimum creep rate involves differentiation, any small fluctuation in strain-time data may lead to larger error. However, it is evident from Fig. 5 that the predicted values are in reasonable agreement with the experimentally determined values and confirms that the theta projection concept is applicable to 9Cr-1Mo under conditions of constant-load creep tests.

CONCLUSIONS

Creep strain-time behavior of 9Cr-1Mo ferritic steel at various stresses have been modeled using 4-theta projection approach. A cut-off strain of 0.19 in tertiary regime was necessary for accurate description of creep curves. The variation of theta parameters with stress at 873 K clearly exhibited low and high stress regimes. Design related creep properties such as time to reach 1% strain, minimum creep rate and rupture life have been successfully predicted. Low strain quantities can be predicted more accurately by 6-θ approach.

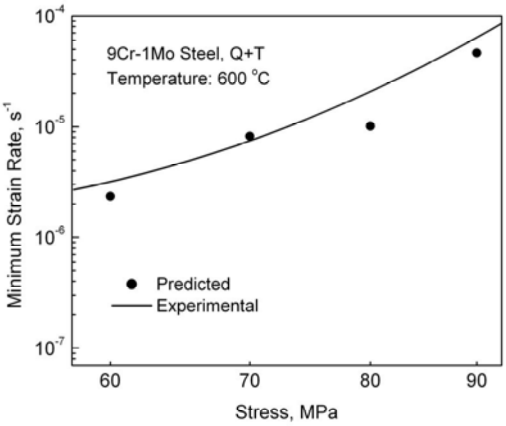

Fig. 5: Variation of minimum creep rate with stress

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