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CONSTITUTIVE DESIGN EQUATIONS FOR THERMAL CREEP DEFORMATION OF HT-9

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In this paper, we present the results of analysis of data provided by SANDVIK Steel Research Center for the high temperature properties of HT-9. We develop design equations for use in inelastic structural mechanics applications, for the most important thermal creep parameters. Empirical correlations for creep rupture time and the complete description of elongation vs. time are presented. A phenomenological description of steady-state creep is also developed. It is found that dislocation creep can explain the measured data.

1. INTRODUCTION

HT-9 is a ferromagnetic iron-base alloy that has been optimized to operate at high temperatures. It contains a relatively high chromium content, on the order of 12%, with additions of other alloying elements to achieve its design goal.

This alloy, developed by Sandvik Steel Company, has been proposed as a potential candidate alloy for fusion reactor applications [1]. The primary reasons for this choice can be summarized as:

1. Ferritic and Martensitic steels exhibit great resistance to void swelling under neutron bombardment.
2. The thermal stress resistance is greater than austenitic alloys allowing the use of thicker sections for first wall applications.
3. Limited evidence indicates that helium generation by neutron irradiation does not significantly degrade the mechanical properties[2].

In order to perform detailed structural analyses for fusion reactor blankets, designers must be provided with appropriate design equations. In this paper, we develop design equations for use in structural mechanics applications. Theoretically based creep equations may not be accurate enough to predict creep deformation. We will therefore develop empirical equations that are accurate in a limited, yet important range. We will later develop a phenomenological description of the creep rates to explain the measured experimental data.

2. DATA BASE

We consider here two classes of creep data: the creep rupture life of tested specimens as a function of operating temperature and stress, and elongation as a function of time. This information is provided by the Sandvik Steel Company for temperatures of 500°C, 550°C, and 600°C, and stresses ranging from 12.5 - 50 ksi. These data are the result of up to 5 years testing time of nine melts of HT-9. It consists of times to 1% strain, 5% strain and rupture, and elongation to fracture for different stresses at each temperature. More details of the supplied creep test data are provided in reference (3).

3. EMPIRICAL LAWS FOR CREEP DEFORMATION

3.1. CREEP RUPTURE

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Creep rupture data have been studied extensively, with the objective of extrapolating the data to design lives on the order of 30-40 years. In a review of available methods, Le May[4] considered five different functional forms for creep rupture data. There is, however, no universally acceptable "standard" method.

3.1.1. Minimum Commitment Method:

As a result, the Minimum Commitment Method, a general formulation[5], was developed in 1971 for NASA to avoid forcing data through a set pattern. The equation based on this method has the following form:

$$\ln t_r + A \cdot P(T) \ln t_r + P(T) = G \cdot \ln \sigma_r \quad (1)$$

where t_r = rupture time, and σ_r = rupture stress.

3.1.2. Modified Commitment Method:

Ghoniem[1] has developed a general design equation which is a modified form of the Minimum Commitment Method. This equation has the following form:

$$\ln \sigma_r = K(T) - \frac{1}{m(T)} \ln t_r \quad (2)$$

$$K(T) = \sum_{i=0}^{2} a_i T^i \quad (3)$$

$$m(T) = \sum_{i=0}^{2} b_i / T^i \quad (4)$$

T is in °K, t_r is in hrs., and σ_r is in ksi.

The data for HT-9 were fit to the above relation using a least-squares method. The coefficients a_i and b_i are provided in Table (1).

Table (1)

Coefficients for Rupture Time vs. Stress

a_0= 138.4149302	b_0= -1531.358687
a_1= -0.3233496513	b_1= 2506695.289
a_2= 1.946588668E-4	b_2= -1017186681

3.2. CREEP DESIGN EQUATIONS

A plot of elongation versus time provides insight into the nature of material creep behavior. It is therefore important to preserve the overall shape of this curve for design purposes. The elongation versus time curve consists of the three following regions: (1) primary transient regime, (2) secondary linear regime, (3) tertiary regime extending to creep rupture.

3.2.1. Elongation for Three Creep Regimes:

It is found that over most of the temperature range, the 1% strain falls in the primary region or at the beginning of the secondary region. The 5% strain is on the borderline of the secondary-tertiary boundary, or well into the tertiary region. Extrapolating to 0.9^*t_5, where t_5 = time to 5% strain, provides a point in the secondary region. Coupled with the 1% strain point, this yields the following form for the primary-secondary region:

$$\varepsilon(t) = [1 - \exp(bt^\alpha)] \cdot 100 \ \% \quad (5)$$

The constants b and α are fit in the following manner: Let t_1 = time to 1% strain, and ϵ_1 = 0.01. Then

$$t' = 0.9 t_5 \quad (6)$$

$$a = \ln 5 / t_5^2 \quad (7)$$

$$\varepsilon_2 = 0.01 \exp(a t'^2) \quad (8)$$

$$\alpha = \ln(\ln(1-\varepsilon_2)/\ln(1-\varepsilon_1))/\ln(t'/t_1) \quad (9)$$

$$b = \ln(1-\varepsilon_1)/t_1^{\alpha} \quad (10)$$

Here a, α > 0 and b < 0. This fit is good for $0 < t < 0.9^*t_5$.

In the region between 0.9^*t_5 and t_5, the fit is determined by equations (6-8), with the expression:

$$\varepsilon(t) = \exp(a t'^2) \ \% \quad (11)$$

Finally, in the tertiary-rupture region, the fit is an exponential of the following form:

$$\varepsilon(t) = \exp(ct^{\gamma})\ \% \qquad (12)$$

where $\gamma = \ln(\ln\varepsilon_R/\ln\varepsilon_5)/\ln(t_r/t_5)$,

$$c = \ln(\varepsilon_R)/t_r^{\gamma}$$

and ϵ_R = elongation to fracture. This is good for $t_5 < t < t_r$.

3.2.2. Rupture Time Dependence:

It is necessary to fit these characteristic points to a reliable parameter, such as the time to rupture discussed in section (3.1.2). Equation (2) can be re-written in the following form:

$$t_r = \exp\left(m(T)\cdot K(T)\right)/\sigma^{m(t)} \qquad (13)$$

where σ is now the applied stress.

The time to 1% strain, t_1, is found to be best fit to the rupture time by the following form:

$$\ln t_1 = J(T)\cdot\ln t_r + L(T) \qquad (14)$$

$$J(T) = \sum_{i=0}^{2} J_i T^i \qquad (15)$$

$$L(T) = \sum_{i=0}^{2} L_i T^i \qquad (16)$$

and the coefficients L_i, and J_i are listed in Table (2).

Table (2)

Coefficients for t_1 vs. Rupture Time

J_0= -119.4828446	L_0= 1707.558058
J_1= 0.2860065163	L_1= -4.091847968
J_2= -1.687029056E-4	L_2= 2.435742087E-3

The time to 5% strain is fit to a polynomial function of both temperature and rupture time:

$$t_5 = \sum_{i=0}^{2}\sum_{j=0}^{2} a_{ij} T^j t_r^{\ i} \qquad (17)$$

with coefficients a_{ij} found in Table (3).

Table (3)

Coefficients for t_5 vs. Rupture Time

a_{00} = 5.800300737E4	a_{12} = -4.906002324E-6
a_{01} = -142.9532355	a_{20} = 1.275428065E-3
a_{02} = 8.746716625E-2	a_{21} = -2.979495964E-6
a_{10} = -2.257160655	a_{22} = 1.745094673E-9
a_{11} = 7.669299551E-3	

Finally, the elongation to fracture ϵ_R is found to roughly fit the rupture time in the following functional form:

$$\ln\varepsilon_R = n(T)\cdot\ln t_r + p(T) \qquad (18)$$

$$n(T) = \sum_{i=0}^{2} n_i T^i \qquad (19)$$

$$p(T) = \sum_{i=0}^{2} p_i T^i \qquad (20)$$

The coefficients n_i, and p_i are in Table (4).

Table (4)

Coefficients for Elongation vs. Rupture Time

n_0= 54.32308035	p_0= -465.7071298
n_1= -0.1286025719	p_1= 1.110624330
n_2= 7.581206028E-5	p_2= -6.547203129E-4

3.2.3. Accuracy and Range of Applicability:

For the creep rupture curves, errors on a log scale for calculating the rupture time versus stress may translate into substantial errors (Figure (1)). Therefore, a given stress level can only provide a fair but reasonable estimate of the time to rupture, based on the nature of the data. This amounts to about 20%-30% error in rupture times for the given stress and temperatures.

There is considerable error in the functional determination of times to 1% and 5% strain, as much as 50%, but the data spread is so wide for these two particular times as a function of stress that such a deviation can be expected. These characteristic times also depend on the accuracy of the determination of rupture time.

In spite of these differences, the primary and secondary regions were fit with reasonable accuracy to the data, as can be seen in Figure (2). The tertiary and rupture regions are generally underestimated. As seen in Figure (2), this can amount to an error of about 20%-30%.

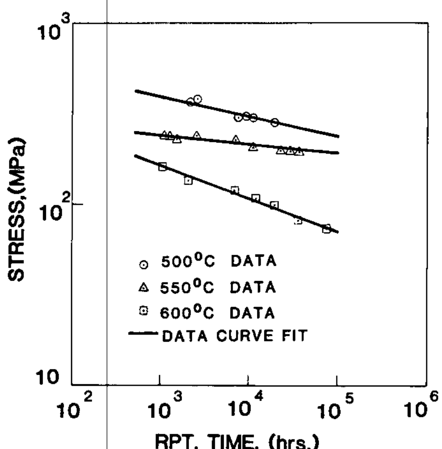

FIGURE 1
HT-9 rupture stress vs. rupture time

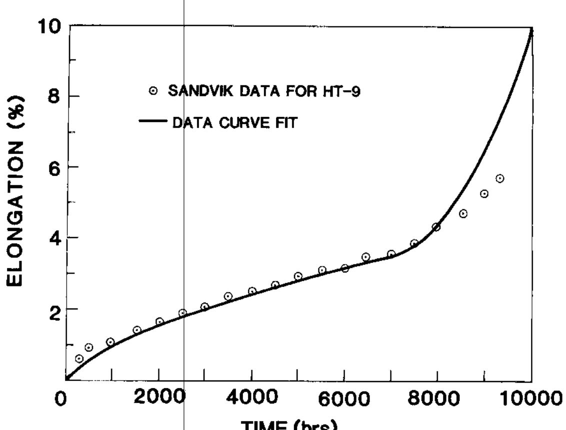

FIGURE 2
Elongation vs. time for test temperature 600°C and stress level 15.2 ksi

In general it can be concluded, however, that the overall form of the creep strain curve is preserved with a certain degree of accuracy. The range of applicibilty is defined by the temperature limits 500°C - 600°C. The upper and lower limits of the stress in ksi versus temperture in °K are given by:

$$\sigma_u = -\frac{T}{5} + 202.63 \text{ ksi} \qquad (21)$$

$$\sigma_l = -\frac{T}{5} + 189.63 \text{ ksi} \qquad (22)$$

4. PHENOMENOLOGICAL MODEL

The dependence of the steady state creep rate on applied stress and temperature can be analyzed using an Ashby-type deformation map[6]. In particular, it is found that for HT-9 the phenomenon of dislocation creep is characteristic of the data supplied by Sandvik Laboratories. Steady state dislocation creep involves the climb and glide of dislocations by means of stress-assisted vacancy movement, and is described by phenomenological expressions such as[7]

$$\dot{\varepsilon} = A\sigma^n \exp(-Q_c/RT) \qquad (23)$$

where Q_c is the activation energy for self-diffusion.

It is found that for most pure metals n is usually in the range of 4-6, but in dispersion hardened alloys, the value of n has been found to be significantly higher[8].

To explain this anomalous behavior, it has been suggested[7] that the creep takes place under the influence of an active or effective stress $\sigma - \sigma_0$, where σ is the applied stress and σ_0 is the friction stress which the dislocation must overcome to move through the lattice.

The dependence of creep rate on temperature and stress can be represented by the following form[4] due to the process of dislocation creep:

$$\dot{\varepsilon} = (16\pi^3 D_v b c_j / G^2 KT)(\sigma - \sigma_o)^3 \quad (24)$$

where
$\dot{\varepsilon}$ = steady-state creep rate, c_j = concentration of jogs, σ_o, = Av/b, v = velocity of mobile dislocations, and A = temperature dependent time constant. For HT-9, it is found that the above expression can be written using least squares :

$$\dot{\varepsilon} = \frac{B}{KT} (\sigma - \sigma_o)^3 \exp(-Q^*/KT) \quad (25)$$

where B = 7.385 x 10^{-3} , Q* = 1.23 eV, σ_o = aT + C, a =-0.2185, and C = 198.178. T is in °K, σ and σ_o, are in ksi.

The value of Q* is close to the migration energy of vacancies, 1.2 - 1.3 eV, which may suggest that the dislocation creep mechanism in HT-9 is controlled by vacancy movement. This phenomenological formulation is good for the temperature range of 500°C - 600°C and stress levels limited by equations (21,22).

5. SUMMARY AND CONCLUSIONS

In this paper, we have developed useful design correlations for a number of commercial heats of HT-9. The design equations cover the following properties:

1. Rupture time as a function of applied stress and temperature, using a modification of the minimum comittment method.
2. Time to 5% strain as a function of stress and temperature.
3. Time to 1% strain as a function of stress and temperature.
4. Rupture strain as a function of stress and temperature.
5. Creep strain, as a function of time, temperature, and stress. This covers the primary, secondary and tertiary regimes of creep.

The representation of creep strain determined in this report can be described by the following equation:

$$\varepsilon = f\{t_1(t_r(\sigma,T),T),\ t_5(t_r(\sigma,T),T), t_r(\sigma,T), \varepsilon_R(t_r(\sigma,T),T)\}$$

The coefficients for the correlations should be carried out to as many digits as possible for increased accuracy. The equations should not be used outside the range of applicability.

The HT-9 creep data in the range 500-600°C is found to represent behavior typically described by dislocation creep. The phenomenological equation used to represent the data is based on an effective stress acting on dislocations. The friction stress was found to be only a function of temperature. This approach indicates that dislocation climb is controlled by vacancy absorption at dislocations.

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