PREDICTIONS OF CREEP BEHAVIOR OF SOME STAINLESS STEELS ON THE BASIS OF SHORT-TERM TENSILE PROPERTIES

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ABSTRACT

A concept of cumulative damage has recently been developed for evaluating the amount of damage incurred by the material under the creep process. The damage accumulation is stress-dependent and is a non-linear function of time. This new approach allows one to establish the creep curve in the $\sigma$-$T$ diagram ($\sigma$: applied stress, $T$: time at rupture) as well as to evaluate the remaining time to rupture when the material is subjected to several specified conditions of creep loading. The method takes into account the order effect of creep loading which has been observed experimentally and reported recently in the literature.

Only the procedure related to the determination of the creep curve is discussed in the present paper. The isothermal creep behavior is represented by a single equation in which two material constants must be known in order to describe the complete creep curve. A good fit with experimental results for some materials is observed when these constants are evaluated by means of two reference data points chosen in the $\sigma$-$T$ diagram.

Empirical relations are established for evaluating the two constants. It has been found that, for stainless steels, the creep strength at $T = 10^3$ and $10^5$ hours at failure may be related to the characteristics of the material obtained in an appropriate short-term tensile test at the temperature of interest. Tests with a controlled strain rate close to $8 \times 10^{-6}$/s are considered to be relevant for this purpose and analytical expressions are proposed.

The creep behavior predicted by the present method is in reasonably good agreement with available experimental results of stainless steels (Type 304, 316, 347) over a wide range of temperatures ($500$ - $900^\circ$C).
1. Introduction

The basic creep behavior of a material at high temperature is usually represented in a diagram where the stresses $\sigma$ are plotted in terms of the time at rupture $T$. Several analytical relations have been proposed in the past for describing this behavior on the basis of the curve fitting method \([1,2]\). Most of the proposed relations are valid for a limited region in the creep diagram.

A concept of cumulative damage has recently been developed for evaluating the amount of damage incurred by the material under the creep process \([3]\). The main characteristics of the concept stems from the consideration that the damage accumulation is stress-dependent and is a non-linear function of time. The new approach allows one to establish the complete creep curve in a $\sigma$-$T$ diagram as well as to evaluate the remaining time to rupture when the material is subjected to several conditions of creep loading. The method takes into account the order effect of creep loading which has been observed experimentally and reported recently in the literature \([4]\).

In contrast with many approaches, the complete creep curve for a given temperature in the $\sigma$-$T$ diagram is represented by a single equation in the present development. There are two constants which must be known in order to describe the creep curve. The procedure concerning the determination of the creep curve by using the proposed equation in conjunction with the results obtained in an appropriate short-term tensile test is outlined here and the correlation between the predicted behavior and available data on some austenitic stainless steels is then discussed.

2. The fundamental creep equation

2.1 Creep damage

At a given temperature, when a material is subjected to a stress $\sigma$, the exposure time has a significant effect on its strength properties determined subsequently. For example, the ultimate strength and the yield strength of an exposed material are considerably reduced with respect to those obtained from the unexposed material \([5]\). These reductions increase with an increase of the exposure time.

The material strength associated to the creep process, denoted by $\sigma_s$, has been considered as a parameter suitable for the definition of the creep damage \([3]\). During the creep process, this strength decreases from an original value $\sigma_0$ (at the beginning of the process) to a value equal to the applied stress $\sigma$, at the onset of failure.

In a form similar to that proposed for evaluating the damage caused to the material during the fatigue process \([6]\), the following equation has been suggested for describing the rate of reduction of the non-dimensional creep strength.

$$\frac{d\sigma_s}{dt} = -\frac{1}{K} e^b (\sigma_s - \sigma_p)^2$$  \hspace{1cm} (1)

where $K, b$ : material constants

$\sigma_u$ : ultimate tensile stress at test temperature

$\sigma_p$ : creep endurance limit
\( \varepsilon : \sigma / \sigma_u \) (non dimensional applied stress)

\( \varepsilon_s : \sigma_s / \sigma_u \) (non dimensional creep strength)

\( \varepsilon_p : \sigma_p / \sigma_u \) (non dimensional creep endurance limit)

The creep endurance limit \( \sigma_u \) is introduced in eq.(1) in order to take into consideration the fact that no damage is caused by a stress lower than this limit in the creep process.

### 2.2 Creep equation

For obtaining the solution of eq.(1), the form of the variation of the stress and the boundary conditions should be known. Under constant stress loading prescribed by \( \varepsilon \), these conditions are specified, as follows:

a) when \( t = 0 \) (undamaged material), \( \varepsilon_s = \varepsilon_0 \) where \( \varepsilon_0 = \sigma_0 / \sigma_u \)

b) when \( t = T \) ('failed material'), \( \varepsilon_s = \varepsilon \)

For the first boundary condition, it has been assumed that the following relation exists [3]:

\[ \varepsilon_0 = \varepsilon^d \]  \hspace{1cm} (2)

where \( d \) is a material constant which is positive and smaller than unity. For a relatively high stress, the value of \( \varepsilon_0 \) approaches unity when \( d \) is small.

The solution of eq.(1) yields:

\[ T = \frac{K}{\varepsilon_0} \left( \frac{1}{\varepsilon - \varepsilon_p} - \frac{1}{\varepsilon - \varepsilon_p^{(1)}} \right) \]  \hspace{1cm} (3)

The above equation describes the basic creep curves, i.e. the isothermal curve in the \( \sigma - T \) diagram. When \( \varepsilon \) approaches \( \varepsilon_p (\varepsilon > \varepsilon_p) \), i.e. in the low stress region, the term in parentheses tends toward infinity. On the other hand, when \( \varepsilon \) approaches unity, i.e. in the high stress region, this term becomes very small.

In eq.(3), constant \( K \) determines the position of the curve whereas constant \( b \) gives its overall slope in the intermediate-time range. For the range of values usually assumed for constant \( d \) (0.2 < \( d < 0.8 \)), this constant has little effect on the form of the creep curve; it does have, however, an influence on the characteristics of the damage function [3]. A typical value of \( d = 0.5 \) is used in the present evaluation.

### 2.3 The two constants \( K \) and \( b \)

These two constants may be determined by considering two reference data points in the creep diagram. Fig.1 shows a typical curve given by eq.(3) established by this procedure and the experimental curve suggested by Conway [7]. In the high stress region, when \( T \) decreases, the creep curve tends towards the maximum tensile stress at the temperature considered. On the other hand, at the low stress region, when \( T \) increases, this curve approaches the creep endurance limit.
For the evaluation of the creep endurance limit, the creep data for a long time at rupture is needed, say for $T = 3.5 \times 10^5$ hours at failure (40 years of continuous testing). However, little information is available for this purpose. With limited data on some stainless steels, it has been found that $\sigma_p$ is very small with respect to $\sigma_u$ ($\sigma_p \approx 0.05$ to 0.15). A change of $\sigma_p$ does affect the creep curve in the low stress region only. The role of the creep endurance limit in the creep diagram may be considered as the "equivalent" of the fatigue endurance limit in the fatigue diagram \cite{8}.

It is seen that the form of eq. (3) represents adequately the basic creep behavior of the material at elevated temperatures. In the following section, empirical relations are suggested in order to evaluate the two constants involved in this equation.

3. Characteristic creep strengths

It has been found that there is a close association between the stress at a specific time at rupture with the ultimate tensile stress of the material. For example, for the stress corresponding to $T = 10^3$ hours at rupture, denoted by $\sigma_3$, the following relation has been suggested \cite{9}:

$$\sigma_3 = A \exp \left( B \sigma_u \right)$$

(4)

where $A$ and $B$ are material constants. With $\sigma_u$ (in Ksi) obtained with a strain rate close to $8 \times 10^{-4}$ /s, $A = 1.32$ and $B = 0.058$ for 304 stainless steels \cite{10}.

A rational form for these characteristics is suggested in this work. This is based on the available data concerning the creep behavior and their short-term tensile properties on some austenitic stainless steels \cite{2,9,11}.

a) The creep strength $\sigma_3$ at $T = 10^3$ hours at rupture may be related to the ultimate tensile stress in the non-dimensional form, as shown in Fig. 2. The following relation is then suggested:

$$\frac{\sigma_3}{\sigma_u} = 0.95 \left( \frac{\sigma_u}{\sigma_u^*} \right)^{1.3}$$

(5)

where $\sigma_u^*$ is the ultimate tensile stress obtained in a static tensile test at room temperature.

b) With a similar approach, Fig. 3 shows the correlation between the creep strength at $T = 10^2$ hours at rupture, denoted by $\sigma_2$, and the ultimate tensile stress. In a non-dimensional form, the following relation is obtained:

$$\frac{\sigma_2}{\sigma_u} = 0.65 \left( \frac{\sigma_u}{\sigma_u^*} \right)^{1.8}$$

(6)

It should be pointed out that, for 304 stainless steel, with the results of an appropriate short-term tensile test (strain rate of the order of $8 \times 10^{-4}$ /s), eqs. (4) and (5) give approximately the same creep strength $\sigma_3$; however, the form of eq. (4) is more rational.

4. Correlation between experimental data and predicted curves

For describing the creep behavior, all the parameters in eq. (3) should be known. As noted earlier, $d$ may be assumed to be equal to 0.5. Regarding $\sigma_p$, as little creep data is
available in the low stress region, the following relation is assumed in the present evaluation:

$$\epsilon_p = 0.6 \left( \sigma_s / \sigma_u \right)$$

(7)

The above relation is suggested on the basis of the observation made on several sets of creep data \[4\]; furthermore, it is similar to that used in fatigue studies \[12\].

Thus, on the basis of a short-term tensile test (with a strain rate close to $8 \times 10^{-4}/s$) at the temperature considered, the creep strengths at $T = 10^3$ and $10^5$ hours at rupture are calculated by using eqs.(5) and (6). Then the two constants $K$ and $b$ in eq.(3) are evaluated and the creep curve is completely defined.

The above procedure is used to establish the creep behavior of some stainless steels, as shown in Fig.4a for 304 SS, in Fig.4b for 316 SS and in Fig.4c for 347 SS. The temperatures range approximately from 500 to 900°C. It is seen that the overall correlation between experimental data and the predicted curves is reasonably good. The predicted value stands within a factor of 3 with respect to the corresponding actual value for most cases (approximately 80% of cases studied).

5. Conclusion

On the basis of a cumulative damage concept recently developed, an equation has been proposed for describing the complete isothermal creep curve in the $\sigma$-T diagram. In particular, empirical relations have been established for calculating the two characteristic creep strengths (at $10^3$ and $10^5$ hours at rupture); this is based on the results obtained in short-term tensile tests on some stainless steels at the temperature considered (with a strain rate close to $8 \times 10^{-4}/s$).

A procedure has been then suggested for establishing the creep behavior of the material at elevated temperatures on the basis of these developments. It has been found that, for 304, 316, 347 stainless steels, for which suitable experimental data are available, the correlation between test results and predicted curves is reasonably good (within a factor of 3 for most cases) over a wide range of temperatures (500 - 900°C).

6. Acknowledgment

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7. References

3. BUI-QUOC, T., "Cumulative Damage in Metals under Creep Loading", to be published.


Fig. 1 Creep behavior of a Cr-Mo-V steel described by eq.(3).
Fig. 2 Correlation between the creep strength at $T = 10^3$ hours at rupture and the ultimate tensile stress.

Fig. 3 Correlation between the creep strength at $T = 10^5$ hours at rupture and the ultimate tensile stress.

### Table

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<tr>
<th>Material</th>
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Fig. 4 Correlation between experimental results with predicted curves given by the present procedure.