An Analysis of High Temperature Creep as Relaxation Processes with Special Reference to CrMoV Steels*

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Creep of three CrMoV steels containing different amounts of chromium was analyzed using the following formula as a constitutive equation for creep curve:

\[ \varepsilon = \varepsilon_0 + A \left( 1 - \exp \left( -\alpha t \right) \right) + B \left( \exp (\beta t) - 1 \right) \]

where \( \varepsilon_0 \), \( A \), \( B \) and \( \alpha \) are parameters to be experimentally determined. The second and third terms represent strain-hardening and strain-weakening, respectively. Minimum creep rates of the steels have higher activation energies than that for diffusion in alpha iron, and their values vary depending on the material. In contrast with the inconsistency in the minimum creep rates, the rate-constant \( n \) and the strain parameter \( A \) showed systematic trends. \( \alpha \) of all the three steels took the same activation energy as that for the self-diffusion and did not vary with changing chromium content, being in accordance with the fact that chromium does not change diffusivity in iron. \( A \) was always independent of temperature, and depended only moderately on the materials. The higher activation energies and the variation with materials observed in the minimum creep rates were ascribed to temperature and material dependence of another strain parameter \( B \) related to the weakening.

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I. Introduction

In creep of pure metals and simple alloys at high temperatures, a steady-state stage appears and the steady-state creep-rates \( \dot{\varepsilon} \) are customarily treated as one of the most significant parameters for describing creep behavior. The following equation,

\[ \dot{\varepsilon} = \dot{\varepsilon}_0 (\sigma / E)^n D \]  

has frequently been used in discussing creep mechanisms\(^{(1)}\). Here, \( \dot{\varepsilon}_0 \) is a constant, \( \sigma \) the applied stress, \( E \) Young’s modulus, \( D \) the diffusion coefficient, and \( n \) a constant called as the stress exponent. In practical alloys, however, the steady-state stage is often less evident and only a minimum creep-rate \( \dot{\varepsilon}_m \) can be determined in many instances.

Recently, Evans et al.\(^{(2),(3)}\) have proposed an equation describing creep curves of the latter type on the assumption that two relaxation-type processes proceed independently during creep:

\[ \varepsilon = \varepsilon_i + \theta_1 \left( 1 - \exp \left( -\theta_2 t \right) \right) + \theta_3 \left( \exp (\theta_4 t) - 1 \right) \].  

(2)

Here, \( \varepsilon_i \) is the instantaneous strain upon loading\(^{(4)}\), \( \theta_1 \) and \( \theta_3 \) are strain parameters, and \( \theta_2 \) and \( \theta_4 \) rate-constants. The second term, \( \theta_1 \left( 1 - \exp \left( -\theta_2 t \right) \right) \), represents strain-hardening, and the third (last) term relates to strain-softening or -weakening.

The strain-hardening can arise out of many processes, so that a Blackburn-type equation, which consists of two relaxation terms, has been adopted for describing the primary creep stage\(^{(5)}\). The weakening results from many causes, such as dynamic restoration, grain boundary migration, changes in microstructures, void nucleation and its growth, crack ex-

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\(^{(1)}\) Although \( \varepsilon_i \) did not appear in refs. (2) and (3), the term \( \varepsilon_i \) was introduced in practice\(^{(4)}\).
tension, etc. Hence, strain during creep must be represented strictly by the sum of many relaxation-type terms, i.e.,

\[ \varepsilon = \varepsilon_0 + A_1 [1 - \exp(-a_1 t)] + A_2 [1 - \exp(-a_2 t)] \\
+ B_1 \{ \exp(b_1 t) - 1 \} + B_2 \{ \exp(b_2 t) - 1 \} \\
+ \ldots, \]

(3)

where \( A_i, B_i, a_i \) and \( b_i \) are constants and \( a_1 > a_2 \) and \( b_1 > b_2 \).

It is, however, impractical to determine experimentally every constant in eq. (3). The term with a large rate-constant, such as \( A_1 [1 - \exp(-a_1 t)] \), will be saturated within a short time, as easily expected from unelastic deformation at low temperature. Therefore, if the behavior at the very beginning is taken of little significance, the initial two terms, \( \varepsilon_0 \) and \( A_1 [1 - \exp(-a_1 t)] \), may be combined and represented by a new constant, \( \varepsilon_0 \). When the deformation near the fracturing is not taken into consideration, the terms, whose \( b \) value is small, can be neglected. Then, eq. (3) may be simplified as

\[ \varepsilon = \varepsilon_0 + A [1 - \exp(-at)] + B \{ \exp(bt) - 1 \}. \]

(4)

Here, \( \varepsilon_0 \) is not the instantaneous elongation, but is a parameter to be determined together with other parameters, \( A, B, a \) and \( b \) in a regression analysis of a creep curve.

Actual creep curves of 1CrMoV steel(6)(7) and H46 steel(7)(6) can well be represented by a further simplified equation,

\[ \varepsilon = \varepsilon_0 + A [1 - \exp(-at)] + B \{ \exp(at) - 1 \}, \]

(5)

which has only one rate-constant, \( \alpha \). Some characteristic features of eq. (5) have been discussed elsewhere(9).

In this report, the nature of each constant in eq. (5) is discussed, based on analysis of creep in three ferritic steels.

II. Creep Behavior in Three Ferritic Steels

1. Fundamental creep data

In the present work analyzed are creep data of three heat-resisting ferritic steels containing different amounts of chromium: 1/2CrMoV steel, 1CrMoV steel and H46(12CrMoVNb) steel. Fundamental creep properties of these steels were reported in detail in refs. (10); (6), (7) and (11); and (7) and (8). These data were obtained in temperature ranges close to the Curie temperature of iron, where elastic moduli depend greatly on temperature. Therefore, stress normalized by Young's modulus, \( \sigma/E \), is used throughout this report, instead of the applied stress \( \sigma \) itself. Values of \( E \) at test temperatures \( T \) were calculated by the following equation(12)(13),

\[ E/\text{GPa} = 445.2 - 899.6 \times 10^{-3} T/\text{K} \]
\[ + 1098.8 \times 10^{-3} (T/\text{K})^2 \\
- 494.5 \times 10^{-3} (T/\text{K})^3. \]

(6)

The chemical composition of each steel is shown in Table 1, its heat-treatment condition as well. The concentration of chromium is one of the most significant differences among the three steels. The addition of chromium affects only slightly the diffusion coefficients of

| Material     | Cr  | Mo  | V   | Nb | Ni | C  | Si | Mn | P  | S   | Heat Treatment                  |
|--------------|-----|-----|-----|----|----|----|----|----|----|-----|---------------------------------|
| 1/2CrMoV     | 0.38| 0.52| 0.27| —  | 0.11| 0.11| 0.18| 0.47| 0.028| 0.035| Normalizing (1238 K–3.6 ks) \\
|              |     |     |     |    |     |     |     |     |     |      | → Tempering (973 K–10.8 ks)     |
| 1CrMoV       | 0.94| 1.10| 0.30| —  | 0.50| 0.32| 0.29| 0.54| —   | —    | 1283 K–75.6 ks \\
|              |     |     |     |    |     |     |     |     |     |      | → 1153 K–25.2 ks → AC            |
|              |     |     |     |    |     |     |     |     |     |      | → 993 K–216 ks → FC             |
|              |     |     |     |    |     |     |     |     |     |      | → 1288 K–90 ks → Mist C          |
|              |     |     |     |    |     |     |     |     |     |      | → 943 K–306 ks → FC             |
| H46          | 11.90| 0.47| 0.30| 0.26| 0.12| 0.16| 0.18| 0.66| 0.012| 0.014| 1313 K–3.6 ks → OC \\
|              |     |     |     |    |     |     |     |     |     |      | → 893 K–7.2 ks → WC             |
iron\(^{(14)}^{(15)}\). Provided that eq. (1) is applicable to the steels, the temperature dependence of creep would be almost the same in the three steels.

\(\dot{\varepsilon}_m\) of the three steels is shown in Fig. 1 as a function of reciprocal temperature. The activation energy for diffusion, \(Q_D\), of iron in Fe-Cr alloys is about 350 kJ/mol in the temperature range of interest\(^{(15)}\). The activation energy for creep \(Q_C\), or precisely speaking, the temperature dependence of \(\dot{\varepsilon}_m\) under a given \(\sigma/E\), of the 1CrMoV steel is close to \(Q_D\). In the other two steels, however, \(Q_C\) is obviously larger than \(Q_D\).

Dependence of \(\dot{\varepsilon}_m\) on the normalized stress is shown in Fig. 2: \(\dot{\varepsilon}_m\) values are converted to those at 823 K using \(Q_C\) shown in Fig. 1. The creep rate depends significantly on material, though \(D\) takes similar values in the three steels. The difference in \(\dot{\varepsilon}_m\) is as large as two orders of magnitude among the steels.

These results indicate that eq. (1) does not necessarily hold in the three ferritic steels. There are no simple, or systematic, correlation of \(\dot{\varepsilon}_m\), or \(Q_C\), among the steels.

### 2. Transient creep

Some examples of changes in strain-rate, \(\dot{\varepsilon}\), with strain, \(\varepsilon\), are shown in Figs. 3 and 4. Creep curves of H46 steel, in which \(Q_C > Q_D\), are compared at two temperatures in Fig. 3; the data at 873 K are normalized using \(Q_D\) to 823 K. The values of \(\dot{\varepsilon}\) at an early stage of primary (decelerate) creep coincide well with one another, whereas at latter stages they do not. This fact suggests that the activation energy for \(\dot{\varepsilon}\) is close to \(Q_D\) at an early stage of creep, even though \(Q_C\) is different from \(Q_D\). Similar results have been observed in creep of zinc bicrystals\(^{(16)}\).

Variation of \(\dot{\varepsilon}\) in 1CrMoV steel and H46 steel are compared in Fig. 4. Values of \(\dot{\varepsilon}\) at an early stage of primary creep are again very close to one another, though \(\dot{\varepsilon}_m\) values in both steels differ by an order of magnitude.

These results suggest that creep behavior of steels of the same kind is similar at an early stage and agrees with that expected form the relation of eq. (1). With increasing strain, however, creep behavior may become charac-
characteristic of each material and $\dot{e}_m$ can hardly be treated with eq. (1). In such cases, it is desirable to analyze not $\dot{e}_m$ but the creep curve itself as a whole, in order to discuss the creep behavior.

### III. Analyses as Relaxation Processes

Some creep data have been analyzed according to eq. (5) and reported in detail elsewhere: 1CrMoV steel\(^6\)\(^7\) and H46 steel\(^8\). Creep data of 1/2CrMoV steel\(^10\) have been analyzed according to eq. (2). When $\theta_3 \gg \theta_4$ as is the case of the 1/2CrMoV steel\(^10\), $\dot{e}_m$ of eq. (2) is given by

$$\dot{e}_m \approx \theta_3 \dot{\theta}_4. \quad (7)$$

Therefore, $\theta_3$ and $\theta_4$ are especially important to discuss $\dot{e}_m$. From comparison between eqs. (2) and (5), $\theta_3$ and $\theta_4$ in eq. (2) may be recognized as $B$ and $\alpha$ in eq. (5). In the following, the nature of each parameter of $A$, $B$ and $\alpha$ of the 1CrMoV steel and the H46 steel will be discussed together with $\dot{\theta}_B(\approx B)$ and $\dot{\theta}_\alpha(\approx \alpha)$ of the 1/2CrMoV steel.

#### 1. Rate constant $\alpha$

The parameter $\alpha$ corresponds to the reciprocal time of relaxation. This parameter may be a reasonable source for discussing the rate-determining processes of creep.

Temperature dependence of $\alpha$ is shown in Fig. 5. The (apparent) activation energy obtained from the slope of this figure will be called the activation energy for $\alpha$, $Q_\alpha$, hereafter. In all the three steels, $Q_\alpha$ values are about 350 kJ/mol which is very close to $Q_D$.

The value of $Q_\alpha$ in the H46 steel increases as temperature approaches the Curie temperature. The value of $Q_D$ has been known to show the same trend\(^17\).

![Fig. 3](image1)

**Fig. 3** The creep rate $\dot{e}$ as a function of strain $\varepsilon$ in H46 steel at two temperature under the same $\sigma/E$. Values of $\dot{e}$ at 873 K are normalized to those at 823 K using the activation energy for self-diffusion, $Q_0 = 350$ kJ/mol, in iron.

![Fig. 4](image2)

**Fig. 4** The creep rate $\dot{e}$ as a function of strain $\varepsilon$ in 1CrMoV and H46 steels under a creep condition.

![Fig. 5](image3)

**Fig. 5** Temperature dependence of the rate constant $\alpha$ of eq. (5) in three steels. $Q_\alpha$ is the apparent activation energy for $\alpha$. 

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The stress dependence of $\dot{\varepsilon}$ is shown in Fig. 6; values of $\alpha$ at each temperature are normalized to those at 823 K using $Q_\alpha$ obtained from Fig. 5. Except in the higher stress range, $\dot{\varepsilon}$ takes very close values in the three steels. Though values of $Q_c$ for the three steels have no correlation with one another, the temperature dependence of $\dot{\varepsilon}$ is always close to that of diffusion which is the thermally-activated rate-controlling process of creep. Values of $\dot{\varepsilon}_m$ are different by more than an order of magnitude among the three steels, but the absolute values of $\alpha$ are similar among them. This insensitiveness of $\alpha$ to the chromium concentration coincides with the insensitiveness of $D$ to the chromium concentration in Fe-Cr dilute alloys\(^{14,15}\). These characteristics of $\dot{\varepsilon}$ suggest that this parameter is a key parameter, from which some fundamental informations on creep mechanisms and/or the rate-determining processes may be obtained.

2. Strain parameters $A$ and $B$

Values of $A$, the strain parameter for the hardening process, are shown in Fig. 7. These values, as far as the two steels are concerned, are independent of temperature and there is only moderate difference between these two materials.

Values of $B$, the strain parameter for the weakening process, are shown in Fig. 8 as a function of temperature. In the 1CrMoV steel, in which $Q_c=Q_D=Q_\alpha$, $B$ is independent of temperature. A similar result has been observed in creep of zinc\(^{18}\), which takes a $Q_c$ value also close to $Q_\alpha$. In the other two steels, in which $Q_c>Q_\alpha$, $B$ depends on temperature; the apparent activation energy for $B$, $Q_B$, cannot be neglected in these cases.

When a creep curve is represented by eq. (5), $\dot{\varepsilon}_m$ is given by the equation,

$$\dot{\varepsilon}_m = 2\alpha \sqrt{AB}.$$  \hspace{1cm} (8)

Fig. 6 Stress dependence of the rate constant $\dot{\varepsilon}$ in three steels. All values are converted into those at 823 K using $Q_\alpha$ shown in Fig. 5.

Fig. 7 The strain parameter $A$ for the strain-hardening process of eq. (5) in 1CrMoV and H46 steels.

Fig. 8 Temperature dependence of the strain parameter $B$ for the strain-weakening process of eq. (5) in three steels. $Q_B$ is the apparent activation energy for $B$. 

The large difference in $\dot{\varepsilon}_m$ among the three steels should be ascribed to the difference in $B$, since $\alpha$ and $A$ do not depend significantly on the materials. Values of $B$ compensated with $Q_B$ are shown in Fig. 9 as a function of stress. It is obvious that $B$ changes greatly with the materials, in constant with $\alpha$ and $A$. The order of $\dot{\varepsilon}_m$ of the three steels is well correlated with the order of $B$ of these materials.

3. Activation energy for creep

From eq. (8), the temperature dependence of $\dot{\varepsilon}_m$ is correlated with those of $\dot{\varepsilon}_m$ and $B$ as

$$Q_c = Q_\alpha + Q_B/2,$$

(9)
since the parameter $A$ is invariable with temperature. Temperature dependence of every parameter is listed in Table 2 as a form of the apparent activation energy. It is evident that in the 1CrMoV and the H46 steels, the relation of eq. (9) holds well.

When a creep curve is described by eq. (2) and $\theta_3 > \theta_4$, $\dot{\varepsilon}_m$ is given by eq. (7), which leads to the relation of the temperature dependence among the parameters as,

$$Q_c = Q_\theta_3 + Q_\theta_4.$$  

(10)

It is also evident in Table 2, that this relation holds in the 1/2CrMoV steel, whose creep curves have been analyzed with eq. (2).

It follows from these results that the high $Q_c$ results mainly from $Q_B$ in analyses with eq. (5), or with eq. (2).

4. Strain rate variation

Some examples of creep curves reproduced by eq. (5) using the four parameters are shown in Fig. 10 together with the measured ones. The three examples correspond to those shown in Figs. 3 and 4. It is evident that eq. (5) holds far beyond the strain to $\dot{\varepsilon}_m$, which is indicated by an arrow in Fig. 10. In the 1CrMoV steel the calculated curve well represents the data up to near the fracture, and in the H46 steel the curves well represent the data to the strain 2–3 times as large as the strain to the onset of engineering tertiary stage\(^\dagger\).

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\(\dagger\) The strain at the intersection of a creep curve and a line parallel to $\dot{\varepsilon}_m$ but with 0.2% offset.
In Fig. 10 also shown are the strains of the first and second terms (strain-hardening), and of the third (strain-weakening) term in eq. (5). The strain related to the work-hardening does not differ much between the two steels; it lies within factor 2 in the examples shown in Fig. 10 and saturates itself within relatively short time, i.e., at $a t = 2$.

When $B$ is small, for example $B = 3.9 \times 10^{-5}$ in the H46 steel at 823 K under $\sigma = 1.08 \times 10^{-3} E$, the contribution of the strain-weakening is not significant. A long period is necessary before reaching $\dot{\varepsilon}_m$ and the value of $\dot{\varepsilon}_m$ itself is low. When $B$ is large, for examples $B = 4.1 \times 10^{-4}$ in the H46 steel at 873 K under $\sigma = 1.11 \times 10^{-3} E$ and $B = 1.3 \times 10^{-3}$ in the 1CrMoV steel at 823 K under $\sigma = 1.13 \times 10^{-3} E$, the contribution of the strain-weakening becomes significant. The minimum in creep-rate appears within a relatively short time and the value of $\dot{\varepsilon}_m$ is high.

The results obtained using eq. (5) indicate that the shape of creep curves is mainly determined by the strain relating to the weakening, for which the constant $B$ has the dominant role. The parameter $B$ may be affected by many processes, such as the coarsening of precipitates, recovery, the migration of grain boundaries and recrystallization, nucleation of voids and their growth. It will be the next problems how these processes affect the weakening and why the value of $B$ and its temperature dependence differ greatly among materials.

When a creep curve is represented by eq. (5), $\dot{\varepsilon}_m$ is given by eq. (8) and the creep rate at a very early stage $\dot{\varepsilon}'$ is given by the equation,

$$\dot{\varepsilon}' = \alpha(A + B) \equiv \alpha A.$$  \hspace{1cm} (11)

Since $Q_A = Q_D$ and $Q_A = 0$, the strain-rates at the beginning of creep does not depend on temperature, provided that they are normalized with $Q_D$. The creep rate also does not change with the material, because $\alpha$ and $A$ are similar among the materials. These circumstances can actually be observed in Figs. 3 and 4. On the other hand, $\dot{\varepsilon}_m$ is proportional to $\sqrt{B}$. The value of $B$ depends on temperature in the H46 steel and changes with the material, resulting in the temperature and material dependence of $\dot{\varepsilon}_m$. When $B$ does not depend on temperature as in the 1CrMoV steel, the shape of $\dot{\varepsilon}-\varepsilon$ curves does not change with temperature(7). When $B$ depends on temperature as in the H46 steel, $\dot{\varepsilon}-\varepsilon$ curves at different temperatures do not coincide with each other, as shown in Fig. 3.

In conclusion, based on analyses using eq. (5), not only $\dot{\varepsilon}_m$ but also deformation at an early stage can systematically be discussed.

IV. Summary

A creep equation has been proposed based on the concept that a strain-hardening process and a strain-weakening process, both of which are exponential-type functions of time, work independently during creep. Creep data of three practical CrMoV steels, whose chromium concentrations are greatly different with one another, have been analyzed with this equation, and each constituent parameter has been compared between the three steels.

(1) The rate-constant $\alpha$ does not depend on steel. This fact corresponds well with the fact that the diffusion in Fe–Cr alloys does not depend greatly on the chromium concentration. The temperature dependence of $\alpha$ is close to that of the diffusion $Q_D$ in all the steels.

(2) The strain parameter $A$ relating to the strain-hardening process is independent of temperature and depends only moderately on the materials.

(3) Although minimum creep-rates $\dot{\varepsilon}_m$ in the three steels do not show any systematic relation, both $\alpha$ and $A$ show clearly systematic relations in the ferritic steels.

(4) The strain parameter $B$ relating to the strain-weakening process does not depend on temperature in the steel whose activation energy for creep rates $Q_C$ is the same as that for diffusion $Q_D$. In steels in which $Q_C > Q_D$, however, $B$ increases with increasing temperature. The absolute value of $B$ depend greatly on materials similar to the case of $\dot{\varepsilon}_m$. Characteristics of $B$ affect greatly deformation behavior.

(5) It is suggested that characteristics of the whole creep stages, except near fracture, can well be analyzed using the proposed equation.
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REFERENCES

(1) L. Bendersky, A. Rosen and A. K. Mukherjee: Intern. Met. Rev., 30 (1985), 1.
(2) R. W. Evans, J. D. Parker and B. Wilshire: Recent Advances in Creep and Fracture of Engineering Materials and Structures, ed. by B. Wilshire and D. R. J. Owen, Pineridge Press, Swansea, (1982), p. 135.
(3) R. W. Evans and B. Wilshire: Creep of Metals and Alloys, The Inst. of Met., London, (1985), Chapt. 6.
(4) B. Wilshire: Private communication.
(5) H. Kraus: Creep Analysis, Wiley, New York, (1980), p. 23.
(6) K. Maruyama, C. Harada and H. Oikawa: Zairyo (J. Soc. Mater. Sci. Jpn.), 34 (1985), 1289.
(7) K. Maruyama and H. Oikawa: Proc. Intern. Conf. on Creep, JSME, Tokyo, (1986), p. 373.
(8) K. Maruyama, C. Harada and H. Oikawa: Trans. Iron Steel Inst. Jpn., 26 (1986), 212.
(9) K. Maruyama and H. Oikawa: Scr. Metall., 21 (1987), (in press).
(10) R. W. Evans, I. Beden and B. Wilshire: Creep and Fracture of Engineering Materials and Structures, ed. by B. Wilshire and D. R. J. Owen, Pineridge Press, Swansea, (1984), p. 1277.
(11) K. Kawada, S. Yokoi, C. Tanaka, Y. Monma and N. Shinya: Tetsu-to-Hagané (J. Iron Steel Inst. Jpn.), 56 (1970), 1034.
(12) Z. Hashin and S. Shtrikman: J. Mech. Phys. Solids, 10 (1962), 343.
(13) D. J. Dever: J. Appl. Phys., 43 (1972), 3293.
(14) H. Oikawa: Technol. Rep. Tohoku Univ., 48 (1983), 7.
(15) B. Millon and J. Kucera: Kovove Mater., 22 (1984), 372.
(16) K. Maruyama, Y. Watanabe and H. Oikawa: Grain Boundary Structure and Related Phenomena, Suppl. to Trans. JIM, 27 (1986), p. 899.
(17) H. Oikawa: Tetsu-to-Hagané (J. Iron Steel Inst. Jpn.), 68 (1982), 1489.
(18) K. Maruyama, N. Horie and H. Oikawa: Unpublished work.