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APPARENT ACTIVATION ENERGY FOR CREEP CONTROLLED BY JOG-DRAG AND CELL-FORMATION

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The expression for the apparent activation energy for creep controlled by jog-drag and cell-formation is given in terms of the parameters of the physical model. It is shown that, in general, this energy does not coincide with that for self-diffusion. The results are applied to actual experimental data obtained in stress-relieved Zircaloy-4 at 673 K.

1. Introduction

Gittus [1] has deduced a theoretical equation for steady-state dislocation creep controlled by jog-drag and cell-formation. In this model, the creep rate, $\dot{\epsilon}$, and the applied stress, σ, are related by

$$\alpha\sigma = (\dot{\epsilon}/\dot{\epsilon}^*)^{1/3} + \sinh^{-1}\left[(\dot{\epsilon}/\dot{\epsilon}^*)^{1/3}\beta\right], \qquad (1)$$

where:

$$\alpha = b^2 l/kT, \qquad (2)$$

$$\dot{\epsilon}^* = K^6 c_j (kT)^2 D_v/G^2 b l^3, \qquad (3)$$

$$\beta = bK^6 c_j/20l, \qquad (4)$$

$$D_v = D_0 \exp(-U_d/kT), \qquad (5)$$

$$c_j \sim \exp(-U_j/kT), \qquad (6)$$

b is the Burgers vector, G is the shear modulus, l is the distance between neighbouring jogs, T is the absolute temperature, k is Boltzmann's constant, D_v is the volume self-diffusion coefficient, c_j is the jog concentration, K is the ratio of cell-diameter to mean dislocation spacing, U_d is the energy (strictly enthalpy) for self-diffusion, U_j the energy to form a jog and D_0 the pre-exponential factor for self-diffusion. By considering two limiting cases of eq. (1), Gittus concluded that the apparent activation energy for creep will generally vary between $U_d - 2U_j$ and $U_d + U_j$ and the average value will be close to that for volume self-diffusion.

It is the purpose of this paper to show that when the temperature dependence of all the parameters included into eq. (1) is considered, the apparent activation energy for creep might differ substantially from that for self-diffusion. Finally, the results will be applied to creep data obtained in Zircaloy-4.

2. Theory

The apparent activation energy for creep, Q, is defined by

$$Q = -\partial \ln \dot{\epsilon}/\partial(1/kT)|_\sigma \qquad (7)$$

and it is obtained experimentally by measuring the change in the plastic strain rate induced by abrupt and small changes in temperature, at constant stress. The logarithmic derivative, at constant stress, of eq. (1) with respect to $1/kT$ can be written as

$$\alpha\sigma\frac{\partial \ln(\alpha\sigma)}{\partial(1/kT)} = (\dot{\epsilon}/\dot{\epsilon}^*)^{1/3}\frac{\partial \ln(\dot{\epsilon}/\dot{\epsilon}^*)^{1/3}}{\partial(1/kT)} + \frac{\partial u}{\partial z}\frac{\partial z}{\partial(1/kT)}, \qquad (8)$$

where

$$u = \sinh^{-1}\left[(\dot{\epsilon}/\dot{\epsilon}^*)^{1/3}\beta\right]$$

and

$$z = (\dot{\epsilon}/\dot{\epsilon}^*)^{1/3}\beta. \qquad (9)$$

In addition, since

$$\partial u/\partial z = 1/\left[1 + (\dot{\epsilon}/\dot{\epsilon}^*)^{2/3}\beta^2\right]^{1/2},$$

$$\frac{\partial z}{\partial(1/kT)} = \tfrac{1}{3}\beta(\dot\epsilon/\dot\epsilon^*)^{1/3}\left(\frac{\partial \ln(\dot\epsilon/\dot\epsilon^*)^{1/3}}{\partial(1/kT)} + 3\frac{\partial \ln \beta}{\partial(1/kT)}\right),$$

$\partial \ln \sigma/\partial(1/kT) = 0$,

eq. (8) can be written as

$$3y\frac{\partial \ln \alpha}{\partial(1/kT)} = (1+x)\frac{\partial \ln(\dot\epsilon/\dot\epsilon^*)}{\partial(1/kT)} + 3x\frac{\partial \ln \beta}{\partial(1/kT)} \tag{10}$$

with

$$y = \alpha\sigma/(\dot\epsilon/\dot\epsilon^*)^{1/3}, \tag{11}$$

and

$$x = \beta/(1+z^2)^{1/2}. \tag{12}$$

According to eq. (2)

$$\frac{\partial \ln \alpha}{\partial(1/kT)} = \frac{\partial \ln l}{\partial(1/kT)} + kT = \xi + kT, \tag{13}$$

where

$$\xi = \partial \ln l/\partial(1/kT). \tag{14}$$

On taking into account eqs. (3) and (5) it can be easily seen that

$$\frac{\partial \ln \dot\epsilon^*}{\partial(1/kT)} = 6\frac{\partial \ln K}{\partial(1/kT)} + \frac{\partial \ln c_j}{\partial(1/kT)} - U_d - 2kT - 2\frac{\partial \ln G}{\partial(1/kT)} - 3\frac{\partial \ln l}{\partial(1/kT)}. \tag{15}$$

In general, G changes linearly with temperature, i.e.,

$$G = G_0 - q(T - 273\ \mathrm{K}), \tag{16}$$

where G_0 and q are constants for a given material and do not depend on temperature. Then,

$$\partial \ln G/\partial(1/kT) = (q/G)kT^2 = \Phi(T), \tag{17}$$

where Φ is a function of T.

U_j in eq. (6) is the energy to form a jog in thermal equilibrium and if as suggested by Gittus [1]

$$U_j = Gb^3/8\pi, \tag{18}$$

then

$$\frac{\partial \ln c_j}{\partial(1/kT)} = -U_j - \Gamma\frac{\partial \ln G}{\partial(1/kT)} = -U_j - akT, \tag{19}$$

where

$$\Gamma = U_j/kT \tag{20}$$

and

$$\Gamma\Phi = a. \tag{21}$$

In addition, according to Gittus [2]

$$K \sim c_j^{-\varphi} \tag{22}$$

and

$$\partial \ln K/\partial(1/kT) = \varphi(U_j + akT). \tag{23}$$

On substituting eqs. (14), (17), (19) and (23) into eq. (15) this leads to

$$\frac{\partial \ln \dot\epsilon^*}{\partial(1/kT)} = U_j(6\varphi - 1) - U_d + kTa(6\varphi - 1) - 2(1+\Phi) - 3\xi. \tag{24}$$

Furthermore, from eq. (4) and taking into account eqs. (14), (19) and (23) it is easy to show that

$$\frac{\partial \ln \beta}{\partial(1/kT)} = U_j(6\varphi - 1) + akT(6\varphi - 1) - \xi. \tag{25}$$

Finally, substituting eqs. (13), (24) and (25) into eq. (10), taking into account eq. (7) and rearranging terms, leads to

$$Q = U_d + cU_j + d\xi + e, \tag{26}$$

where

$$c = (6\varphi - 1)\left(\frac{2x-1}{x+1}\right), \tag{27}$$

$$d = 3\left(\frac{1-y}{x+1}\right), \tag{28}$$

$$e = 2(1+\Phi) + a(6\varphi - 1)\left(\frac{2x-1}{1+x}\right) - \frac{3y}{1+x}. \tag{29}$$

Eq. (26) gives the apparent activation energy, which can be obtained experimentally in terms of the temperature, the applied stress, the plastic strain rate and the parameters of the physical model.

3. Discussion

Gittus [1] has analyzed the apparent activation energy for creep for two limiting cases of eq. (1). In the first case he assumed that the second term on the right hand side of eq. (1) is negligible compared with the first, i.e.,

$$\alpha\sigma = (\dot\epsilon/\dot\epsilon^*)^{1/3}. \tag{30}$$

Then

$x = 0$; $y = 1$; $c = 1 - 6\varphi$; $d = 0$;

$e = (2\Phi - 1) - a(6\varphi - 1)$

and eq. (26) reduces to

$$Q = U_d + (1 - 6\varphi)U_j + [2\Phi - 1 - a(6\varphi - 1)]kT. \tag{31}$$

According to Gittus, if eq. (30) is valid then $Q = U_d + U_j$ but, from eq. (31) this is possible only if $\varphi = \Phi = 0$ and the contribution due to the term involving kT is negligible. In the second limiting case Gittus assumed that the second term on the right hand side of eq. (1) is dominant and

$$\alpha\sigma = \sinh^{-1}\left[(\dot{\epsilon}/\dot{\epsilon}^*)^{1/3}\beta\right]. \qquad (32)$$

In this limit it is easy to show that eq. (26) reduces to

$$Q = U_d + 2(6\varphi - 1)U_j + 2[(1 + \Phi) + a(6\varphi - 1)]kT. \qquad (33)$$

According to Gittus, if eq. (32) is valid then $Q = U_d - 2U_j$ but, from eq. (33) this is valid only if $\varphi = \Phi = 0$ and the contribution due to the term involving kT is neglected. From eq. (22) it can be seen that $\varphi = 0$ means that K is independent of c_j, i.e., independent of temperature. In addition, $\Phi = 0$ means that G is temperature independent, which is not the case. By using a thermodynamic argument Gittus [2] has shown that $\varphi \simeq 0.4$, so that the contribution due to the temperature dependence of K to the measured apparent activation energy cannot be neglected. Furthermore, from eqs. (31) and (33) it can be clearly seen that Q does not vary, in general, between $U_d + U_j$ and $U_d - 2U_j$, as assumed by Gittus, so that $Q \neq U_d$. In fact, the terms including kT and U_j in eqs. (31) and (33) are of the order of U_d even if kT and U_j are much smaller than U_d. Measurements of the apparent activation energy for creep, at 673 K, of both cold-worked and stress-relieved Zircaloy-4 have given an average value of (300 ± 20) kJ/mol, for stresses between 110 and 250 MPa [3,4]. Since these data have been interpreted in terms of eq. (1), Q will be expressed in terms of the parameters of the physical model by eq. (26). Furthermore, it has been shown [4] by an approximate calculation of Q that the influence of the terms adding to U_d, in eq. (26) cannot be neglected and, consequently, $Q \neq U_d$. This is confirmed by the fact that $U_d \simeq 100$ kJ/mol, as obtained from the creep and stress relaxation data in Zircaloy-4 [4,5] and from an extrapolation, to 673 K, of recent measurements of the self-diffusion coefficient of zirconium by ion-beam-sputtering techniques [6].

To demonstrate its applicability, eq. (26) was used to calculate ξ as defined by eq. (14). Table 1 gives the data obtained during steady-state creep in stress-relieved Zircaloy-4 at 673 K [4]. The values for the apparent activation energy given in the table were obtained by making abrupt and small changes in the temperature (±20 K) and measuring the corresponding changes in the strain rate, as suggested by eq. (7). The numbers marked with an asterisk correspond to values obtained by decreases in temperature. Also given in the table are the corresponding stresses, the strain level and the strain rate before the change in temperature, and the parameters α, $\dot{\epsilon}^*$ and β obtained by fitting the creep curves to eq. (1) [4].

Once α, $\dot{\epsilon}^*$ and β are known, the parameters c, d and e of eq. (26) can be easily obtained. In fact, x and y needed for eqs. (27) to (29) can be calculated by using eqs. (11) and (12) and the parameters given in table 1. Φ for eq. (29) can be obtained by using eq. (17) and the values for q and G reported by Rosinger et al. [7]. φ for eqs. (27) and (29) can be obtained from the experimental K values reported by Povolo and Capitani [5], obtained at 633 and 673 K on stress relaxation in the bending of stress-relieved Zircaloy-4; the value $\varphi = 0.9$

Table 1

Apparent activation energies for steady-state creep of stress relieved Zircaloy-4 at 673 K, obtained by making changes in temperature of ±20 K. The Q values marked with an asterisk were obtained on decreasing the temperature. The corresponding parameters obtained when the data are fitted to eq. (1) and the strains, before the change in temperature, are also given

σ (MPa)	$\epsilon \times 10^{-2}$	$\alpha \times 10^{-3}$ (MPa^{-1})	$\dot{\epsilon}^* \times 10^{-4}$ (s^{-1})	β	$\dot{\epsilon}$ (s^{-1})	Q (kJ/mol)
120	0.57	19.1	1.9	229	9.2×10^{-10}	296
	0.69	19.4	2.2	288	3.6×10^{-9}	291*
147	1.19	20.1	3.4	478	3.3×10^{-9}	297
169.4	1.90	20.7	4.5	661	6.9×10^{-9}	298
188.9	4.89	21.1	5.6	855	1.8×10^{-8}	298
	6.21	21.1	5.6	855	7.5×10^{-8}	281*
216	7.14	21.1	5.6	855	7.9×10^{-8}	303*
	7.70	21.1	5.6	855	1.1×10^{-8}	315
242	10.31	21.1	5.6	855	3.3×10^{-7}	302*
	11.90	21.1	5.6	855	4.9×10^{-8}	315

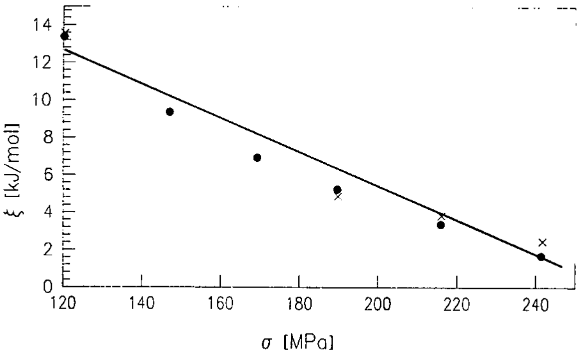

Fig. 1. $\xi = \partial \ln l/\partial(1/kT)$ for stress-relieved Zircaloy-4, obtained by solving eq. (26) with the parameters given in table 1.

is obtained on assuming that eq. (22) is valid. Finally, once Φ is known, a can be obtained by using eqs. (20) and (21) with $U_j = 21$ kJ/mol, as obtained by using eq. (18) with $b = 3.23 \times 10^{-10}$ m and $G = 26$ GPa at 673 K [7].

Once eq. (26) is solved for ξ, taking $U_d = 105$ kJ/mol, the values shown in fig. 1 are obtained, as a function of the applied stress. The circles correspond to values obtained by increasing the temperature and the dots to values obtained by decreasing the temperature. Furthermore, on assuming that

$$l \sim \exp\left[\bar{U}_j(\sigma)/kT\right] \tag{34}$$

then, according to eq. (14)

$$\xi = \bar{U}_j(\sigma). \tag{35}$$

Eq. (34) means that the average distance between neighbouring jogs is not only given by the jogs produced thermally, in which case $\bar{U}_j(\sigma) = U_j$, but there is also a contribution from the external work. If it is further assumed that

$$\bar{U}_j(\sigma) = U_{j0} - \sigma V, \tag{36}$$

where V is the activation volume and U_{j0} is the energy to form a jog without applied stress, V and U_{j0} can be obtained from the slope and the intercept, respectively, of the average straight line shown in fig. 1. The following values were obtained by this procedure

$V = 1.05 \times 10^{-26}\ \text{m}^3 \simeq 4b^3$,
$U_{j0} \simeq 22$ kJ/mol.

It can be seen that $U_{j0} \simeq U_j$ and the activation volume is of the order of b^3, as should be expected. These approximate calculations further confirm the validity of eq. (26) since no assumptions were made and the physical parameters were obtained directly from the experimental data.

4. Conclusions

The apparent activation energy for creep controlled by jog-drag and cell-formation does not, in general, coincide with that for self-diffusion. Furthermore, the apparent activation energy measured during creep experiments has a physical significance only within a specific model. Finally, the energy to form jogs, as a function of the applied stress and the activation volume have been obtained from creep data in Zircaloy-4 at 673 K.

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