BEHAVIOR OF CADMIUM WHISKERS CLOSE TO THE MELTING POINT

K. K. Ziling

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Calculations of the rate of diffusional creep in bending show that this mechanism cannot make any appreciable contribution to the deformation even at a temperature close to the melting point. The absence of creep, except for the first stage, has been demonstrated experimentally on filamentous tungsten crystals.

This work was undertaken to clarify the question of whether any creep mechanism exists in a crystal without dislocations. Such crystals were studied in tension in reference [1], no appreciable creep deformation (except for the first stage) being observed. It was decided to conduct experiments in bending, because in the nonuniform stress state effects associated with the directional diffusion of vacancies in the stress field may be observed [2].

In order to evaluate the contribution of these effects to the deformation, we shall consider the behavior of a cantilever beam of length L, whose cross section is a square of side h. The coordinate origin is taken at one of the edges at the fixed end. The z axis is directed along the axis of the beam, and the y axis parallel to the applied force. A constant deflection Y is impressed on the end of the beam with coordinate z = L.

In solving the problem no account is taken of a certain change in stresses due to the initial redistribution of vacancies (see [3]).

As is known, the vacancy flux density j at constant temperature may may be written in the form

$$j = -\frac{Dc}{kT}\nabla\mu. \qquad (1)$$

Here D is the vacancy diffusion coefficient, c the vacancy concentration, k Boltzmann's constant, and T the absolute temperature. In this case, the chemical potential μ is understood as the change in the corresponding thermodynamic potential of the crystal—source system upon formation of a vacancy at a given point of the crystal. In this case, the excess atom is transported to the surface of the source, that is, the same crystal but without stresses.

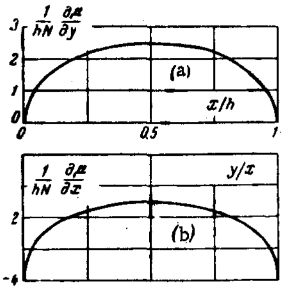

Fig. 1

Using the continuity condition and assuming that the fluxes are quite weak, and that there are no sources of vacancies inside the crystal, we have

$$\operatorname{div}(c\nabla\mu) = 0. \qquad (2)$$

The relation between μ and c is given by

$$\mu = \text{const} + kT\ln c + U. \qquad (3)$$

The energy of interaction U can be represented in the form [4]

$$U = \alpha\omega(\sigma_{11} + \sigma_{22} + \sigma_{33}).$$

Here ω is the atomic volume, σ_{nn} are the principal stresses, and α is a numerical coefficient $|\alpha| \sim 10^{-1}$.

The value of the chemical potential at the surface μ_s is found by the method proposed by Herring [5], i.e., from the condition that the change in the free energy of the crystal—source system upon formation of a vacancy close to some point of the surface is equal to the change in free (in our case elastic) energy upon removal of an atom directly from the surface. In both cases the atoms are placed in the source.

By the methods of the theory of slender beams it is easy to show that this change is approximately equal to $-\omega\sigma_{33}^2 / 2E$, where E is Young's modulus. If we assume that $L \gg h$, we may neglect the flux along the z axis and solve the problem as for the plane case. To be specific, we choose the cross section z = 0. Then

$$\mu_s = N(2y - h)^2, \qquad N = -\frac{9}{8}\frac{YE\omega}{L^4}. \qquad (4)$$

Using (3), by an obvious change of variables we can transform equation (2) in dimensionless coordinates to the form

$$\Delta V - A^2\varepsilon^2 V = 0 \qquad (A = \alpha\omega\nabla\sigma_{33} / kT\varepsilon, \quad \varepsilon = 10^{-3}), \qquad (5)$$

$$V_s = \exp\{-A\varepsilon y + B\varepsilon^2(2y - 1)^2\}, \qquad B = N / kT\varepsilon^2. \qquad (6)$$

For reasonable values of the maximum stresses, for example 10^7 dyne/cm^2, the quantities A and B are close to unity.

The solution of (5) can be found in the form of a series

$$V = V_0 + \varepsilon V_1 + \varepsilon^2 V_2 + \ldots, \qquad (7)$$

the functions V_n of which satisfy the recurrence system

$$\Delta V_0 = 0, \qquad \Delta V_1 = 0, \qquad \Delta V_n = A^2 V_{n-2} \qquad (n = 2, 3, \ldots).$$

The boundary conditions for V_n are found from the expansion of (6) in powers of ε. Retaining only terms not higher than ε^2, we can write the solution as

$$V = 1 - A\varepsilon y + {}^1\!/_2 A^2 y^2\varepsilon^2 + BW\varepsilon^2 + \ldots,$$

where W is the solution of the equation $\Delta W = 0$ for $W_s = (2y - 1)^2$.

Returning μ, it is easy to see that the solution of Eq. (2) with boundary conditions (4), correct to terms of the order of ε^2 inclusive, coincides with the solution of the equation $\Delta\mu = 0$ for the same boundary conditions.

The figure shows the dependence of $(1/hN)(\partial\mu/\partial n)$ (n is the outward normal to the surface) at the surface of the beam y = (a), x = = h(b) on the coordinates, as obtained from the solution of the latter equation by the method of nets. Since the atomic flux moves in the opposite direction to the vacancy flux, we see that in time the thickness of the beam must decrease and the width increase. However, the rate of this process is negligible.

Thus, in the case of bending of a crystal without dislocations, there should not be any appreciable deformation, even at a temperature close to the melting point. In order to confirm this we performed an experiment. As specimens we used filamentous tungsten crystals, grown by vapor deposition, without any surface defects visible under the microscope. We selected crystals from 2 to 8 microns thick and 1–2 mm long, having a square or almost square cross section. The axis of the specimens coincided with the [1000] crystallographic direction. The load was applied by impressing a constant deflection on the end of the crystal. The value of this deflection was such that (assuming E ≈ 2 ·

$\cdot 10^{11}$ dyne/cm^2) the maximum stress in the specimen was $4 \cdot 10^7$ dyne/ /cm^2. The experimental temperature was 290° C, and the total duration of the experiment 40–50 hr. To prevent oxidation the experiment was conducted in a helium atmosphere.

Every 8–10 hr the specimens were removed from the heater, together with the loading device, and after removal of the load the cross-sectional dimensions and the residual deflection were measured. After these measurements, the specimens were loaded tothe original stress. The accuracy of the measurements was ±0.6 microns.

In no case was any change in dimensions observed, as was to be expected. In fact, using Eq. (1), it is easy to calculate that under the above conditions the absolute rate of displacement of the surface does not exceed 10^{-10} cm/sec, even for crystals with h = 2 microns, if the value of Dc obtained in [6] is used.

We present values of the residual deflection F as a function of the time t for a whisker with dimensions $2 \cdot 10^3 \times 3 \times 2.6$ microns

t, hr =	0	8	16	26	34	44
F, microns =	0	21	21	21	21	21

These data show that after the end of first stage the subsequent deformation does not exceed the error of the measurements.

The existence of a first stage, also noted in [1], may be related to the presence in the crystals of a small number of dislocation sources. Apparently, crystals more than 5 microns thick are not free of dislocations and usually appreciable creep is observed right up to failure.

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