CREEP OF VAPORIZATION-DEPOSITED COPPER FILMS

K. K. Ziling and V. Yu. Pchelkin

The characteristics of short-term creep of copper films deposited by vaporization are determined, and the application of different variants of the hardening hypothesis to this material is considered.

The experiments were performed on films with a thickness of 5-7 μ, obtained by vaporizing 99.997% pure material from a molybdenum crucible in a vacuum of (3-5) · 10^{-6} torr. The material was deposited on glass backings covered with a NaCl buffer layer, which were heated to (200 ± 10)°C. The preparation technique has been described in [1]. Flat specimens with a 12 × 1 mm^2 gauge section were tested for creep under uniaxial tension in a microtesting machine [2] which was modified for this purpose. The accuracy of displacement measurements was 1 μ. The tests were performed at (21 ± 1.5)°C. If the temperature varied by 1-2° during an experiment, a correction for the thermal expansion of the specimen and the machine parts was used. The tests were performed under constant loads; however, since the strain of the specimens usually amounted to less than 1%, the change in the stress was neglected.

Constant-Stress Creep. We shall determine the dependence of the plastic strain ε on the stress σ and the time t.

Figure 1a shows typical creep curves for films in a log–log plot. The numbers in Fig. 1a and b correspond to the following values of σ (kg/mm²):

	1	2	3	4	5	6	7	8
σ =	25.8	24.5	23.9	23.1	20.8	19.9	19.0	17.0

It is obvious that the dependence of ε on t can be described by a step function. The exponent m, determined with respect to the slope of the straight lines in Fig. 1, can be assumed to be independent of σ in the first approximation. For certain batches, the values of σ close to the ultimate strength, for which a sharp increase in m from 0.40-0.45 to 0.70-0.80 was sometimes observed, constituted an exception.

After writing the relationship ε = ε(σ, t) as

$$\varepsilon = [f(\sigma)/m]^m t^m$$

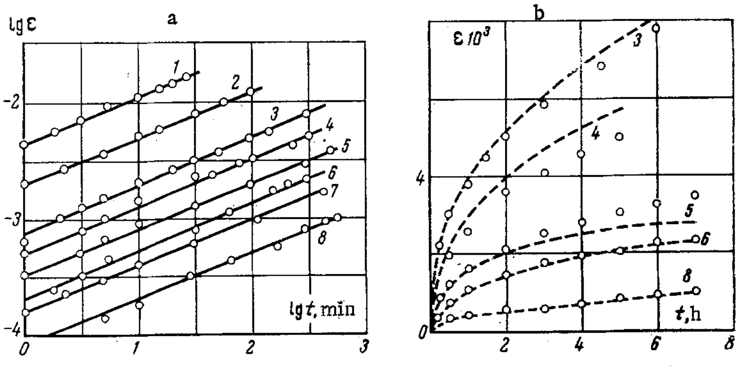

Fig. 1

Novosibirsk. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 3, pp. 110-112, May-June, 1971. Original article submitted June 29, 1970.

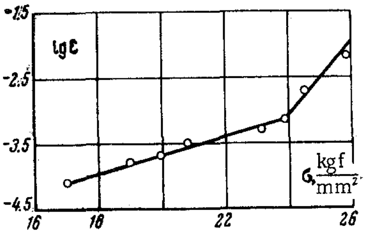

Fig. 2

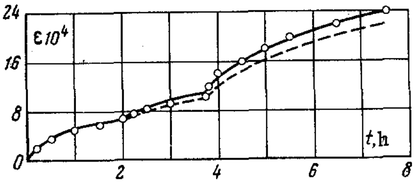

Fig. 3

we find the form of $f(\sigma)$. By analogy with solid materials, we assume that

$$f(\sigma) = ke^{\sigma/A}$$

where A and k are the constants of the material. Then,

$$\varepsilon = (kt/m)^m e^{m\sigma/A} \tag{1}$$

For t = 1, relationship (1) in a log ε vs σ plot describes a straight line whose slope is determined by the value of A, while the distance from the coordinate origin is determined by k. The experimental results for m = 0.40 lie on a broken curve whose salient point corresponds to $\sigma_* = 23.9$ kg/mm² for the batch in question (Fig. 2). In this case, different values of A and k must be used for $\sigma \geq \sigma_*$ and $\sigma \leq \sigma_*$, namely

$$k = 7.53.\times 10^{-18}\ \text{min}^{-1},\quad A = 1.15\ \text{kg/mm}^2\ \text{for}\quad \sigma \leqslant 23.9$$
$$k = 1.26\times 10^{-33}\ \text{min}^{-1},\quad A = 0.37\ \text{kg/mm}^2\ \text{for}\quad \sigma \geqslant 23.9$$

The accuracy with which expression (1) describes the experimental results for the given m, k, and A is illustrated in Fig. 1b. The theoretical curves are given by dashed lines. For all curves $\sigma \leq \sigma_*$. Considering that, for the same value of σ, the scatter between individual specimens attains 15-20% even for solid materials, we find the above accuracy quite satisfactory.

Variable-Stress Creep. We shall discuss the possibility of applying to thin films certain hypotheses used in creep mechanics for describing the behavior of solid metals. According to [3, 4], the creep rate $\dot{\varepsilon}$ at constant temperature is a function of the present value of σ and a certain set n of parameters q_i, while

$$dq_i = a_i d\varepsilon + b_i d\sigma + c_i dt$$

where a_i, b_i, and c_i are generally functions of σ, ε, t, and q_k. Since the films were deposited on a backing heated to a high temperature, it is not very likely that their structure changed appreciably in time at room temperatures. Therefore, we checked the hardening hypothesis for the usual case where

$$n = 1, \qquad dq = d\varepsilon \tag{2}$$

and the case where the following quantity is used as the hardening parameter for n = 1:

$$dq = \sigma d\varepsilon, \qquad q = \int \sigma d\varepsilon \tag{3}$$

In order to obtain contrasting results, the tests were performed with stepwise increases in stress. Figure 3 shows typical test results under such conditions. The points denote the experimental values of ε. The dashed curve was obtained on the basis of hypothesis (2), while the solid curve pertains to hypothesis (3). The time intervals $\Delta t = 120, 100, 260$ min correspond to effective stresses $\sigma = 17.6, 19.0, 24.2$.

It is evident that, for slight increases in stress, both hypotheses yield results that are close to experimental data. For larger increases in σ, the hardening parameter (3) yields better results, as it apparently does for solid materials [5].

We shall now calculate the relaxation curves by using the above two hypotheses. Passing to the dimensionless variables

$$\sigma' = \sigma / A, \quad \varepsilon' = \varepsilon E / A, \quad t' = k(E/A)^{1+\alpha} t$$

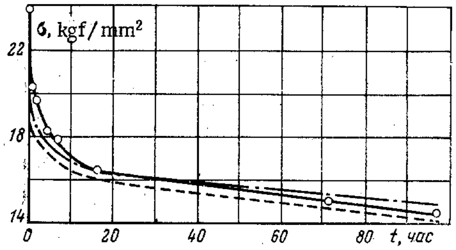

Fig. 4

and differentiating (1) we obtain

$$\varepsilon''\varepsilon'^{\alpha} = e^{\sigma'} \qquad (\alpha = m^{-1} - 1) \tag{4}$$

Here, E is the Young modulus.

In the case of pure relaxation, $\sigma' + \varepsilon' = \text{const}$; however, in our experiments, the length of the specimens varied somewhat due to the displacement of the stiff dynamometric spring. In this case,

$$M\sigma' + \varepsilon' = \text{const} \left(M = 1 + \frac{csE}{L}\right)$$

Here, c is the pliancy of the spring, L is the specimen's length, and s is its transverse cross section. For the investigated specimens, the value of M varied from 1.5 to 1.6.

For $\varepsilon = 0$ and $t = 0$, the function $\sigma' = \sigma'(\sigma_0', t)$ can be obtained from (4) and (5) in the following form:

$$\sigma' = \sigma_0' - \varphi_* \left(t' \frac{e^{\sigma_0'}}{M^{\alpha+1}}\right) \tag{6}$$

Here, φ_* is the inverse function of φ, where

$$\varphi(x) = \int_0^x z^{\alpha} e^z dz$$

If expression (3) is used as the hardening parameter, Eq. (4) can be written thus:

$$q''q'^{\alpha} = \sigma'^{\alpha+1} e^{\sigma'} \tag{7}$$

In the case of relaxation,

$$q' = {}^1/_2 (\sigma_0'^2 - \sigma'^2) \tag{8}$$

By taking into account the correction for the displacement of the spring, we obtain the following from (7) and (8) for the same initial conditions:

$$t' = \frac{M^{\alpha+1}}{2^{\alpha}} \int_{\sigma'}^{\sigma_0} \left(\frac{\sigma_0'^2 - \sigma'^2}{\sigma'}\right)^{\alpha} e^{-\sigma'} d\sigma' \tag{9}$$

Figure 4 provides a comparison between the experimental data (circles and solid curve) and the results of calculations by means of (6) and (9) for a specimen with a Young modulus of 9600 kg/mm² and an initial stress $\sigma_0 = 23.9$ kg/mm². The values of the constants A and k are given above. The dashed curve pertains to calculations based on (6), while the dot-dash curve pertains to calculations based on (9). Although expression (9) yields a lower relaxation rate, which was to be expected, it is obvious that both hypotheses produce results that are very close to each other and in good agreement with the experimental data.

Thus, it has been shown that, in spite of the differences in dimensions and structures, the creep behavior is qualitatively similar for the investigated films and for solid materials. The mechanical models used for describing the creep of structurally stable solid metals can also be used for films with equal success.

LITERATURE CITED

1. K. K. Ziling, L. D. Pokrovskii, and V. Yu. Pchelkin, "Relationship between the mechanical characteristics and the structure of copper films deposited by vaporization," Fiz. Met. i Metallov., No. 5 (1970).
2. V. G. Kostyuk, K. K. Ziling, and A. V. Serebryakov, "Strength characteristics of filamentary metal crystals with impurities," Fiz. Tverd. Tela, 5, No. 11 (1963).
3. Y. N. Rabotnov, "The equation of state of creep," Proc. J. Internat. Conf. on Creep (1963).
4. Y. N. Rabotnov, "The equation of state for creep," Progr. Appl. Mech., Macmillan (1963).
5. N. S. Vilesova and V. S. Namestnikov, "A hardening parameter," Zh. Prikl. Mekhan. i Tekh. Fiz., No. 3 (1964).