

Effect of Pressure on the Lifetime and the Creep of Metals and the Kinetic Equation Parameters

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Abstract—The effect of uniform pressure on the activation parameters of the kinetic equation that describes the exponential dependence of the steady-state creep rate and the lifetime of polycrystalline metals on stress and temperature is estimated. It is shown that, under pressure, the parameters that determine the behavior of a metal under load are the activation energy and the internal stresses. The dependence of these parameters on the applied pressure is revealed.

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According to [1], steady-state creep rate $\dot{\varepsilon}$ and lifetime t_f of pure metals as functions of shear stress τ and temperature kT in the test temperature range $(0.3\text{--}0.5)T_m$ are described by the expressions

$$\dot{\varepsilon} = \dot{\varepsilon}_0 \exp\left(-\frac{H_0 - V(\tau - \tau_\mu)}{kT}\right), \quad (1)$$

$$\dot{\varepsilon} t_f = \dot{\varepsilon}_0 t_{f_0} = 10^{-1} - 10^{-2}, \quad (2)$$

where $\dot{\varepsilon}_0 = 10^7 \text{ s}^{-1}$ is a constant; H_0 is the activation energy, which is equal to the self-diffusion energy [2]; $\tau - \tau_\mu$ is the effective stress at the sites of thermofluctuation restructuring; τ_μ is the long-range internal stress induced by dislocations; and V is the activation volume, which is determined by the dislocation network size in block boundaries [3].

As was shown for a number of pure metals [4, 5], Eq. (1) holds true when all parameters entering into Eq. (1) are constant over wide temperature and stress ranges and when τ_μ decreases significantly with increasing test temperature at other constant equation parameters.

It was shown that, during tests under uniform pressure conditions, the time to failure increases, the steady-state creep rate decreases, and the relation between them remains identical to that under conventional test conditions (i.e., it obeys Eq. (2)) [6, 7]. However, it is still unclear what parameters in Eq. (1) affect lifetime and creep under pressure conditions. To elucidate this problem, in this work we measure the lifetime and the creep rate over wide shear stress and uniform compression ranges. The measurements were carried out when samples were loaded after the creation of pressure and under cyclic application–removal of pressure at the steady stage of creep.

Mechanical tests, i.e., the determination of the fatigue life and the steady-state creep rate as functions of the applied stress, were performed during uniaxial tension at room temperature and a pressure of 0.1–1450 MPa. The experimental technique was described in detail in [8]. We studied Al (99.96%) cold-worked at a reduction of 96%, rolled zinc (99.9%), and copper (99.9%) preliminarily annealed at 250°C for 1 h. The samples were dumbbell test pieces with a gauge length of $22 \times 10^{-3} \text{ m}$, a gauge width of $3 \times 10^{-3} \text{ m}$, and a gauge thickness of $1 \times 10^{-4} \text{ m}$ (Al, Zn). The copper sample sizes were $(1 \times 10^{-2}) \times (1 \times 10^{-3}) \times (4.5 \times 10^{-5} \text{ m})$.

Let us consider the obtained data. Figures 1–3 show the time to failure and lifetime as functions of the applied shear stress during tension under uniform pressure conditions. According to Eq. (1), the increase in the fatigue life with the pressure can be related to an increase in activation energy H_0 under pressure or to a change in internal pressure τ_μ . Activation volume V weakly depends on pressure, since the slope of the $\log t_f - \tau$ curves is almost the same at different pressures.

The change of the creep activation energy under uniform pressure conditions can be written in the form

$$H_0(P) = H_0 + \Delta V P, \quad (3)$$

where activation volume ΔV is determined as

$$\Delta V = kT \Delta \ln \dot{\varepsilon} / \Delta P \quad (4)$$

and is calculated in experiments on cyclic application–removal of pressure at the steady stage of creep.

Note that the experiments on cyclic application–removal of pressure that were carried out under high-temperature creep conditions at $T \geq 0.5T_m$, which is known to be controlled by a diffusion mechanism, showed that activation volume ΔV and the creep energy coincide with the activation volume and the

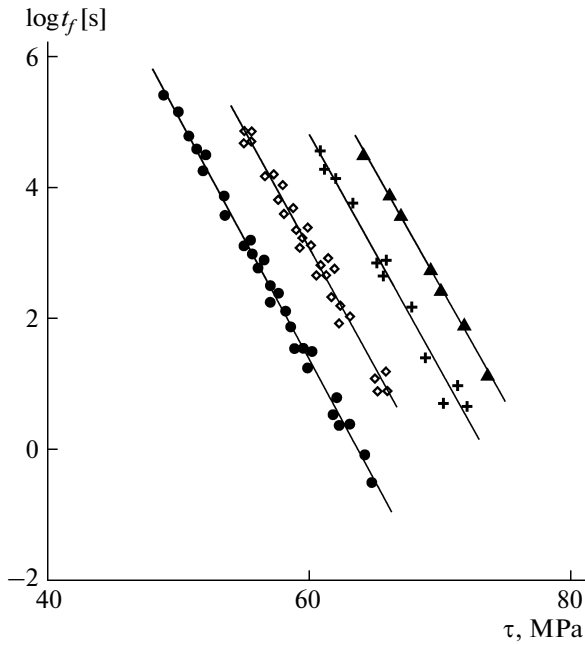


Fig. 1. Lifetime of Al on the shear stress at a pressure of (●) 0.1, (◇) 270, (+) 540, and (▲) 1150 MPa.

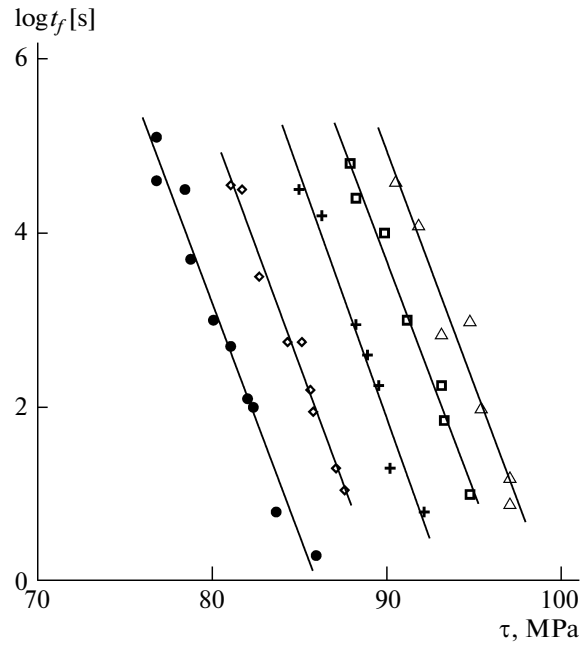


Fig. 2. Lifetime of Cu on the shear stress at a pressure of (●) 0.1, (◇) 270, (+) 540, (□) 1000, and (△) 1450 MPa.

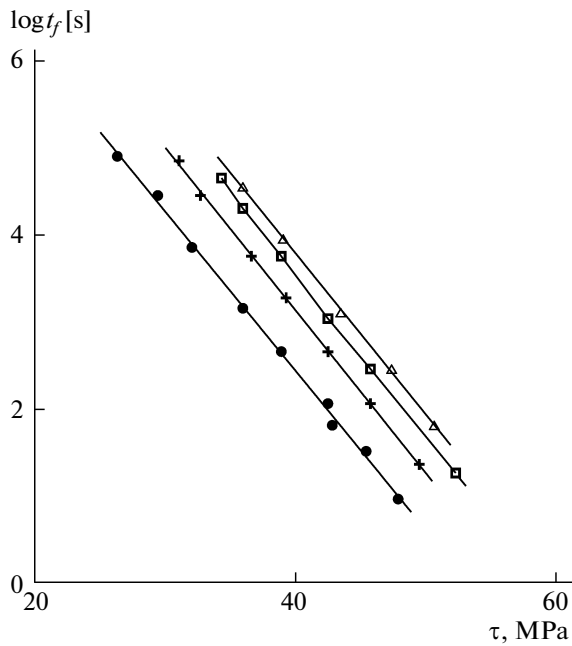


Fig. 3. Lifetime of Zn on the shear stress at a pressure of (●) 0.1, (+) 540, (□) 1000, and (△) 1450 MPa.

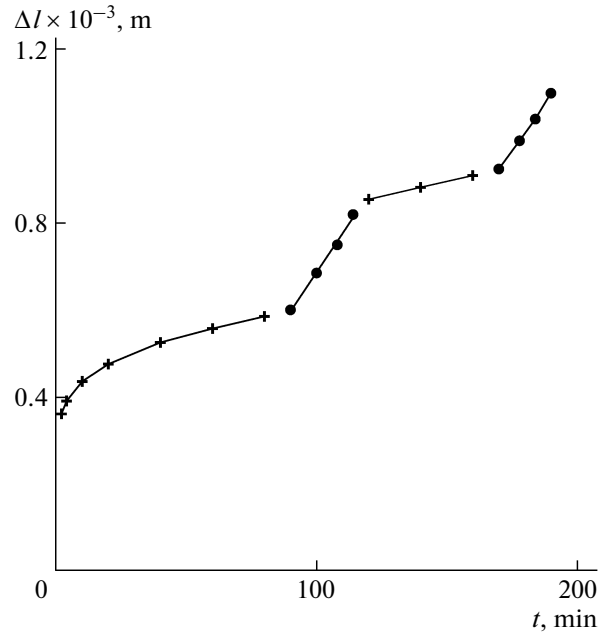


Fig. 4. Effect of a cyclic change of pressure on the steady-state creep rate in Al. The designations are identical to those in Fig. 1.

energy of self-diffusion [9]. For close-packed metals, ΔV is $(2/3-3/4)$ of their atomic volume V_a ; for metals without close packing, it is $(1/3-1/2)V_a$ [10].

As an example, Fig. 4 depicts the strain versus the test time under cyclic application—removal of pressure

at the steady stage of testing Al. The calculations according to Eq. (4) show that the activation volume in Al is 0.85 ± 0.08 of the atomic volume. For copper, we have $\Delta V = (0.9 \pm 0.1)V_a$. For zinc, the activation volume is $\Delta V = (0.5 \pm 0.1)V_a$. This value is close to the

Table

Material	$\Delta \log t_f$, s	$\Delta \log t_f(p\Delta V)$, s	$\Delta \log t_f(\tau_\mu)$, s
Cu	4.2	0.6	3.6
Al	3.6	0.85	2.75
Zn	0.8	0.45	0.35

self-diffusion activation volume in zinc along the basal plane ($0.59V_a$) [11]. Note that activation volume ΔV in all metals in the pressure range under study is almost independent of the applied uniform pressure.

We now estimate the contribution of the creep activation energy to the increase in the lifetime under load and pressure. The table gives the total increase in the lifetime $\Delta \log t_f$ at a pressure of 540 MPa for the metals under study in comparison with the test at $P = 0.1$ MPa and the increase in the lifetime due to the activation energy [$\Delta \log t_f(p\Delta V)$]. As follows from these data, the increase in the lifetime caused by an increase in the energy is a low fraction of the total increase in the lifetime. According to Eq. (1), this means that, apart from energy, the decrease in effective stress $\tau - \tau_\mu$ due to an increase in internal stress τ_μ can contribute to the increase in the fatigue life under pressure. This part of strengthening is designated as [$\Delta \log t_f(\tau_\mu)$] in the table.

It is known [1] that τ_μ is related to total dislocation density ρ as

$$\tau_\mu = \tau_0 + \alpha m G b \rho^{1/2}, \quad (5)$$

where τ_0 is the lattice friction stress, $\alpha = 0.2-0.4$ is a coefficient affected by the mechanism of dislocation

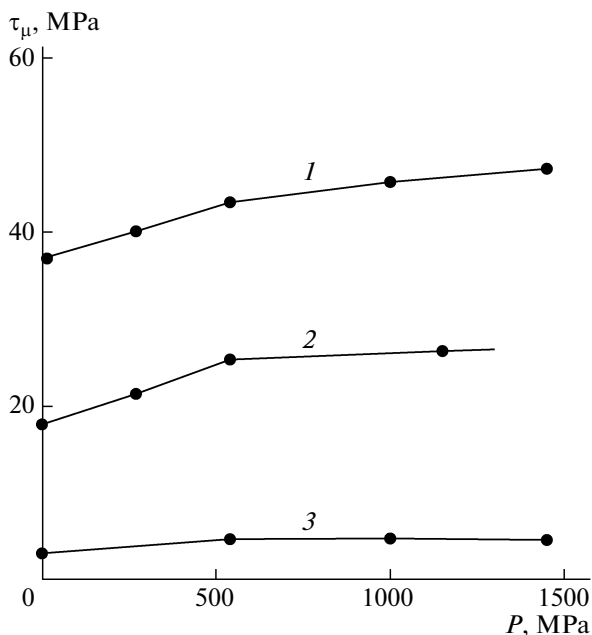


Fig. 5. Internal stress vs. pressure for (1) Cu, (2) Al, and (3) Zn.

interaction, $m = 3.06$ is the Taylor factor, G is the shear modulus, and b is the Burgers vector of dislocations.

An increase in the dislocation density in copper and aluminum during creep at a pressure $P = 1050$ MPa was detected in [12]. It was found that ρ increased due to a decrease in the cell size and an increase in the dislocation density inside cells. This circumstance supports the conclusion about an increase in internal stress τ_μ under pressure.

We now estimate the change of τ_μ with pressure. Figure 5 shows stress τ_μ versus the applied stress for the metals under study. It is seen that τ_μ increases most intensely in the pressure range 0.1–540 MPa for all metals. At higher pressures, τ_μ increases insignificantly or remains constant.

Equation (5) is valid for any dislocation distribution in a metal, which makes it possible to estimate the increase in the dislocation density with pressure. Since $\tau_0 = 0$ for copper [13], we have $\rho_{P_2} \approx \rho_{P_1} (\tau_{\mu_{P_1}} / \tau_{\mu_{P_2}})^2$, and the dislocation density increases by a factor of 1.4 when pressure changes from $P_1 = 0.1$ MPa to $P_2 = 540$ MPa.

Note that the weak change of τ_μ detected for aluminum and zinc at a pressure higher than 540 MPa means that the increase in the lifetime in aluminum and zinc at a high pressure is almost completely caused by an increase in the creep activation energy and is not related to additional strain hardening. However, for copper at $P > 540$ MPa, the increase of t_f is still induced by an increase in the activation energy and a decrease in effective stress $-(\tau - \tau_\mu)$.

The possible causes of metal hardening during tension under uniform compression conditions were considered earlier. For example, the hardening detected in [14] was related to retarded development of microporosity under pressure. However, pressure influences the formation and development of pores only at the third stage of creep in the neck of a specimen, and the time of this stage is short as compared to the lifetime of the entire specimen [15]. Therefore, retarded development of pores in the neck under pressure cannot affect the lifetime and the steady-state creep rate.

Another cause (in addition to an increase in the activation energy) was associated with an increase in activation volume V under pressure [12]. As noted above, energy increment $p\Delta V$ explains only a relatively small part of the pressure-induced increase in the lifetime. As follows from Eq. (1), an increase in activation volume V can lead to a decrease in the activation energy and an additional decrease in the pressure-induced hardening. The effect of pressure on the effective stress was not considered in [12].

Thus, the increase in the lifetime and, correspondingly, the decrease in the steady-state creep rate at a high pressure are caused by an increase in the creep activation energy and an increase in the internal stress due to an increase in the dislocation density. The con-

tributions of these factors to the detected hardening change with pressure.

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