Manifestation of inelasticity in metals during slight deformation

I. A. Bilenko, V. P. Mitrofanov, and O. A. Okhrimenko
M. V. Lomonosov Moscow State University

(Submitted 24 April 1990)
Pis'ma Zh. Eksp. Teor. Fiz. **51**, No. 10, 532–535 (25 May 1990)

Experiments on the static deformation of metal samples reveal an inelastic behavior at stresses well below the yield point, at the level of the resolution in terms of the strain, $\Delta\epsilon \sim 10^{-9}$. An inelastic strain of a relaxation nature arises in samples subjected to a prior plastic deformation, while it disappears upon annealing.

The inelasticity of real solids is usually linked with their structural defects and the motion of these defects in the course of the deformation.[1] This inelasticity may be manifested both in dynamic experiments, as an internal friction during the excitation of vibrations in the solid, and in static experiments, e.g., in the appearance of a time-dependent strain at a constant stress. Static experiments are usually carried out either at a high stress, above the yield point of the material, or temperatures close to the melting point, at which the strain is relatively large, and there is no particular difficulty in measuring it.

In the present letter we are reporting an experimental study of the relaxation of the elastic strain which arises in polycrystalline metals upon the application of low constant stresses ($\sim 0.1\sigma_T$, where σ_T is the yield point) at a temperature near room temperature. We used a highly sensitive method for measuring small displacements.[2] We studied polycrystalline samples of the steel 40KhNYu and the aluminum alloy D16, since these materials have relatively high yield points. The shape of the samples is shown in the inset in Fig. 1a. Also shown there is a schematic diagram of the loading method. In this method, a cantilever (with geometric dimensions $50 \times 10 \times 2$ mm) bends, and a nonuniform tensile and comprssional strain arises in it, distributed over the cross section and along the length of the cantilever. A measure of this strain is the displacement of the free end of the cantilever. This displacement is measured by measuring the change in the capacitance between the cantilever and the conducting surface of a quartz inset. The maximum strain which arises in the sample is shown in the figures. The minimum change in strain which could be detected over a time interval of 3×10^4 s was $\Delta\epsilon \sim 10^{-9}$. The measurements were carried out at a constant temperature of 40 ± 0.02 °C.

In experiments with annealed steel samples ($T_{\rm ann} = 950$ K), the application of a constant load caused only an elastic strain up to the yield point. We observed no aftereffects at the level $\Delta\epsilon \sim 10^{-9}$. After the samples were subjected to a plastic deformation with a strain $\epsilon_p > 1 \times 10^{-3}$, their response to the application of a constant load changed. An elastic aftereffect of a relaxation nature appeared. Figure 1a shows the ratio of the inelastic component of the strain to the elastic component, ϵ_i/ϵ_e, versus the time elapsed since the load was first applied to the sample, for various levels of the preliminary plastic deformation. Within the measurement error, the maximum value

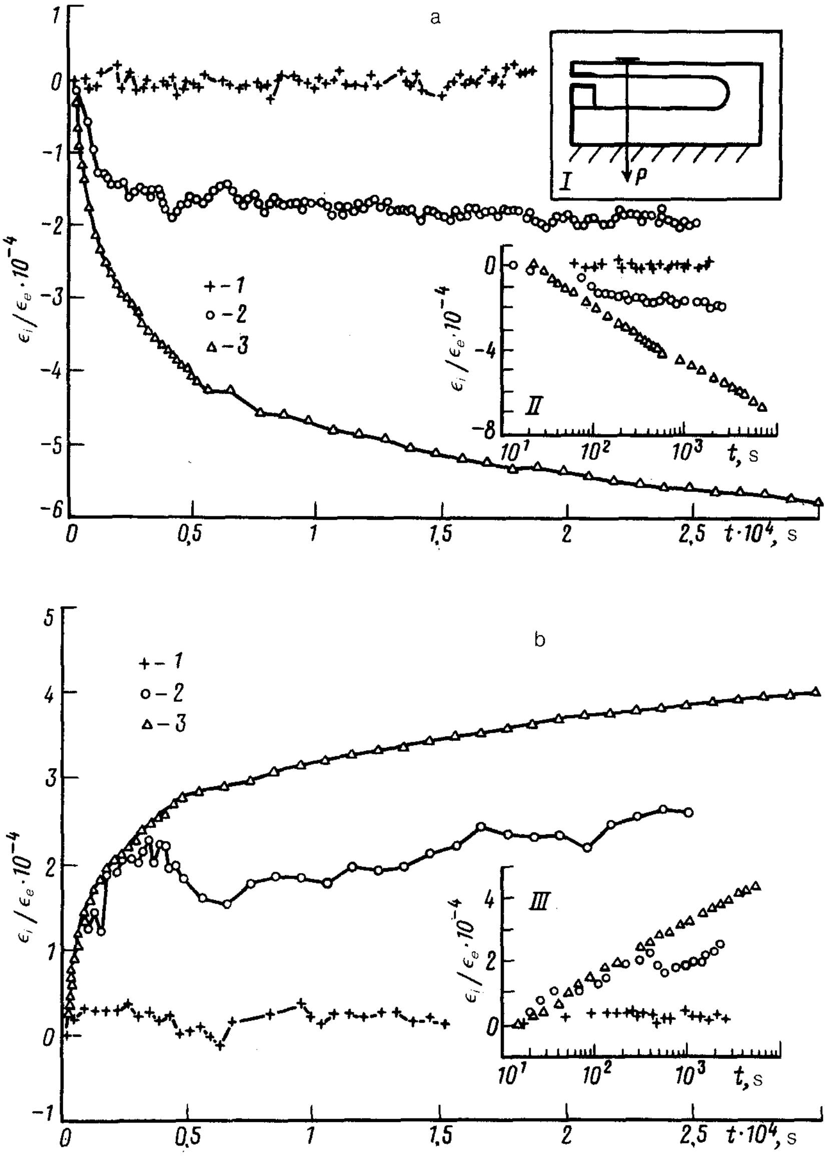

FIG. 1. Time evolution of the ratio of the inelastic component of the strain to the elastic component during (a) the application and (b) the removal of a load for a sample of the steel 40KhNYu (the elastic strain is $\epsilon_0 = 1 \times 10^{-4}$). *1*—Preliminary plastic deformation $\epsilon_p = 0$; *2*—$\epsilon_p = 1 \times 10^{-3}$; *3*—$\epsilon_p = 5 \times 10^{-3}$. Inset I) Loading method; I,III) time dependence in logarithmic scale.

of the ratio ϵ_i/ϵ_e is independent of ϵ_e for ϵ_e from 5×10^{-5} to 5×10^{-4}. In this sense we can say that the inelastic strain is linear. Because of this result, we can draw some quantitative estimates from the bending experiments, in which case the strain is not uniform over the volume of the sample.

When the load was removed, and the stress in the sample decreased sharply to zero and then remained constant, we also observed a relaxation of the strain, but the change in the inelastic component over times ranging from 10 to 3×10^4 s turned out to be smaller than that during the loading (Fig. 1b). Subjecting the sample to several loading-unloading cycles, we observed no buildup of a residual strain due to an asymmetry in the change in the strain during the loading and the withdrawal of the load. When the load is removed, the inelastic component of the strain apparently equalizes at an earlier time ($t<10$ s). The state of the sample after the deformation is thus restored completely, although we do observe a hysteresis in the time dependence of the inelastic strain.

Corresponding results were obtained during deformation of the aluminum alloy D16. Again in this case, a relaxing strain appeared after a preliminary plastic deformation of the sample. This relaxing strain was not observed in annealed samples. The aluminum alloy differs from the steel in the magnitude of the inelastic component of the strain and also in the time evolution.

The time evolution found for the inelastic strain cannot be described by a standard relaxation formula $\epsilon_i \sim [1-\exp(-t/\tau)]$ with single relaxation time τ. The same curves are shown in logarithmic time scale in the inset in Figs. 1a and 1b. We see that the time dependence of the inelastic component of the strain can be described well by a logarithmic law over the interval from 10 to 10^4 s. This result is evidence that the corresponding processes responsible for the relaxation of the strain have a broad spectrum of relaxation times, ranging up to $t\sim3\times10^4$ s. For the aluminum alloy, the curve of $\epsilon_i(t)$ is slightly different from logarithmic, indicating a narrower distribution of relaxation times, near $\tau\sim10^3$ s. The inelastic effects which are observed should also be manifested in dynamic experiments, through an increase in the internal friction during periodic deformation. In that case, however, these effects would be difficult to study since the inelastic strain found in our experiment corresponds to the insertion of an attenuation

$$Q^{-1} \approx \frac{\pi}{2\epsilon_e} \frac{d\epsilon_i}{d\ln(t)} \approx 10^{-4},$$

which would be close to or below the background level for dynamic experiments in measurements at frequencies $\omega \approx \tau^{-1}$ (Ref. 1). The sensitivity to the degree of preliminary plastic deformation and to the annealing indicates that the inelastic phenomena observed in these experiments are of a dislocation nature. Several modes involving the motion of dislocations in the field of point defects have been proposed to describe the plastic deformation and the creep of solids which occur at high stress levels.[3] Those models, however, have been restricted to fairly general representations, since in these cases the defect structure of the sample changes, and these changes are difficult to take into account. The results reported here show that the inelastic deformation at low stress levels has a broad spectrum of relaxation times. The conclusion points to mechanisms involving thermally activated transitions of dislocation segments between metastable states.[4]

We wish to thank V. B. Braginskiĭ for interest in this study and for useful discussions.

[1]S. Nowick and B. S. Berry, *Inelastic Relaxation in Crystalline Solids*, Academic, New York, 1972.
[2]V. B. Braginskiĭ, Usp. Fiz. Nauk **156**, 93 (1988) [Sov. Phys. Usp. **31**, 836 (1988)].
[3]T. Suzuki *et al.*, *Dislocation Dynamics and Plasticity* [Russian translation], Mir, Moscow, 1989.
[4]V. M. Vinokur and S. P. Obukhov, Zh. Eksp. Teor. Fiz. **95**(**1**), 223 (1989) [Sov. Phys. JETP **95**, 126 (1989)].

Translated by Dave Parsons