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EFFECT OF LOADING PREHISTORY ON MECHANICAL PROPERTIES OF STEEL IN SINGLE-AXIS EXTENSION

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Rational design of structures operating under intense dynamic loads requires a detailed study of material properties in various modes of high speed deformation. Maximum exploitation of the material's strength properties requires a knowledge of the parameters of the equation of state in the deep plasticity region with significant shifts in deformation rate. In such cases [1, 2] the material's loading prehistory can have a significant effect on the properties [3]. For example, it is known that hardening is greater with high speed deformation than with deformation at lower rates [4, 5].

The goal of the present study is an experimental investigation of the effect of loading prehistory on the mechanical properties of stainless steel. The literature is lacking in data from such studies on important structural materials such as steels.

The studies were performed at a temperature of 293 ± 3°K on specimens of 12Kh18N10T sheet steel, quenched in air ($\sigma_{0.2}$ = 0.33 GPa, σ_B = 0.63 GPa, δ = 61.5%). In the experiments

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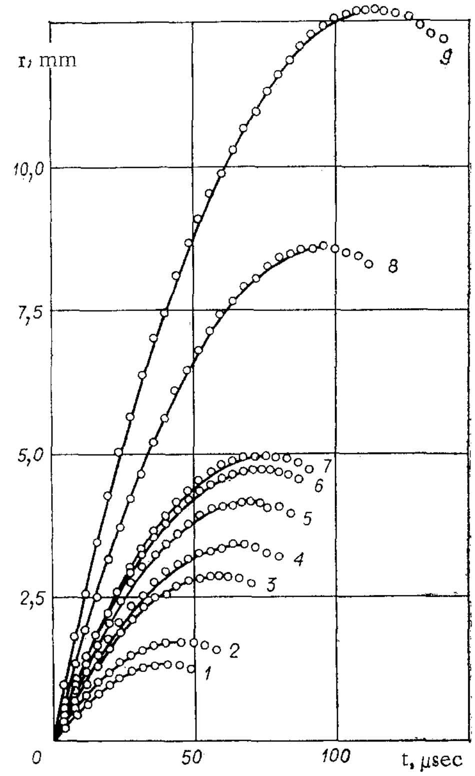

Fig. 1

TABLE 1

Experiment No.	w_0, m/sec	ε_0, sec^{-1}	ε_1, %	t_1, μsec	ε_2, %	A
1	65	1300	2,62	41,0	—	1,0175
2	75	1509	3,38	46,0	—	1,0266
3	97	1948	5,54	59,0	—	1,0371
4	108	2161	6,62	64,0	—	1,0444
5	120	2402	7,98	70,0	7,64	1,0536
6	130	2595	9,05	74,0	8,70	1,0608
7	133	2665	9,46	75,5	—	1,0636
8	183	3656	15,85	96,0	—	1,1071
9	229	4572	22,60	114,0	—	1,1532

the specimens were placed under single axis tension at variable (decreasing from a maximum value to zero) and constant deformation rates ε, as a result of which true stress σ was obtained as a function of true (logarithmic) deformation ε.

Dynamic tests in the varying deformation rate modes were performed by pulsed expansion of toroidal specimens [6, 7] (outer radius R_0 = 50 mm, thickness 1 mm, height 5 mm), using an explosive device providing a brief pulse from within the ring (over ~0.2 μsec) to impart various initial velocities w_0. The ring then continued to expand symmetrically due to inertia, being halted by the radial components of the peripheral stress:

$$\sigma = -\rho R(dw/dt), \quad (1)$$

where ρ is the density of the material, R and $w = dR/dt$ are the current value of the outer radius and the radial velocity of the expanding ring, and t is time. In the experiments the function $r(t) = R(t) - R_0$ was recorded, as shown by the points of Fig. 1. The point numbers in Figs. 1, 2, 4, 5 correspond to the experiment numbers of Table 1, where $\varepsilon_0 = w_0/R_0$ is the initial peripheral deformation rate, ε_1, t_1 are the maximum peripheral deformation and the time at which that value is reached, and ε_2 is the residual deformation. A is an integration constant for Eq. (1) (see below).

Using the function r(t), Eq. (1) can be employed to find the dynamic function $\sigma(\varepsilon)$, where $\varepsilon = \ln(R/R_0)$. However, Eq. (1) is very sensitive to scattering of experimental values of r(t), so those values must be approximated by a smooth function. The approximation method used differed from that of [6, 7]. Equation (1) was first integrated with the assumption that

$$\sigma(\varepsilon) = \sigma = \text{const} \text{ for } 0 \leqslant t \leqslant t_1 \tag{2}$$

(the greatest velocity change is realized in the interval $0 \leqslant t \leqslant t_1$). In the well-known model of a rigid-viscoplastic body with linear hardening

$$\sigma = \sigma_0 + k\varepsilon + \eta\dot{\varepsilon} \tag{3}$$

where σ_0 is the static yield point, k is the hardening constant, and η is the dynamic viscosity) the condition $\sigma(\varepsilon)$ implies that during the ring expansion process there is a mutual compensation between hardening with increase in ε and reduction in hardness due to decrease in $\dot{\varepsilon}$ upon ring braking.

The solution of Eq. (1) given assumption (2) has the form*

$$Y(x) = AT(t), \tag{4}$$

where

$$Y(x) = ax - bx^3/3 + cx^5/5 - dx^7/7,\ T(t) = 1 - t/t_1; \tag{5}$$

$$x = \sqrt{1 - \frac{\varepsilon}{\varepsilon_1}},\quad \varepsilon = \ln\left(1 + \frac{r}{R_0}\right), \tag{6}$$

$$a = 1 + \varepsilon_1 + \frac{\varepsilon_1^2}{2} + \frac{\varepsilon_1^3}{6},\quad b = \left(1 + \varepsilon_1 + \frac{\varepsilon_1^2}{2}\right)\varepsilon_1,$$

$$c = (1 + \varepsilon_1)\frac{\varepsilon_1^2}{2},\quad d = \frac{\varepsilon_1^3}{6};$$

$$\varepsilon_1 = \rho(R_0\dot{\varepsilon}_0)^2/2\sigma,\ A = \dot{\varepsilon}_0 t_1/2\varepsilon_1. \tag{7}$$

If Eq. (2) is valid, then Eq. (4) must be linear. In the opposite case it is necessary to search for a correction function empirically, for example $\Phi(t) = Y(x)/T(t)$, which will be an indicator of how much the real stress state differs from that of Eq. (2).

Equation (4) as obtained from the experimental points proved to be very close to linear. Thus we conclude that within the limits of experimental uncertainty, during the interval $0 \leqslant t \leqslant t_1$ the stressed state of Eq. (2) did exist.

The integration constants A, found empirically with Eq. (4) for each experiment, are presented in Table 1.

Approximating functions r(t) obtained from expressions following from Eqs. (4)-(6) (at $0 \leqslant x \leqslant 1$), are shown in Fig. 1 (solid lines) and agree satisfactorily with experiment.

Finally, Eqs. (6), (7), and the first integral of Eq. (1) give the desired functions $\sigma(\varepsilon)$ and $\dot{\varepsilon}(\varepsilon) = \dot{\varepsilon}_0 e^{-\varepsilon}\sqrt{1 - \varepsilon/\varepsilon_1}$, shown in Fig. 2. The error of the functions $\dot{\varepsilon}(\varepsilon)$ and $\sigma(\varepsilon)$ does not exceed 5 and 10%, respectively.

Using Fig. 2 as a nomogram, one can transform from the functions $\sigma(\varepsilon)$ at variable $\dot{\varepsilon}$ to $\sigma(\varepsilon)$ at $\dot{\varepsilon}$ = const† (see, for example, curves *a*-d of Fig. 3).

Dynamic tests of the specimens in constant rate tension were performed with a pendulum impact machine using the technique of [8] (cylindrical specimens were extended at $\dot{\varepsilon} = 840\ \text{sec}^{-1}$), and by a modified Kol'skii method [9] using an explosive device, in which a bell-shaped specimen was placed between striker and reference bars of identical cross section and extended at $\dot{\varepsilon} = 1200\ \text{sec}^{-1}$. In both cases the functions $\sigma(\varepsilon)$ and $\varepsilon(t)$ were determined tensometrically. The uncertainty in $\sigma(\varepsilon)$ determination was in the range 10-14%. The functions $\sigma(\varepsilon)$ obtained by the two methods proved very close to each other (Fig. 3, curve e).

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*Equation (1) does not have an exact solution because the exponential e^{ε} appears in its first integral. Solution (4) was obtained by replacing the exponent by the first four terms of its expansion in a Taylor series (error of less than 0.01%).

†A horizontal line must be drawn in Fig. 2 through the required value $\dot{\varepsilon}$ = const, and the point at which it intersects with the curve $\dot{\varepsilon}(\varepsilon)$ for each experiment must be projected on the corresponding $\sigma(\varepsilon)$ and the abscissa. These projections are the coordinates of ε, σ desired.

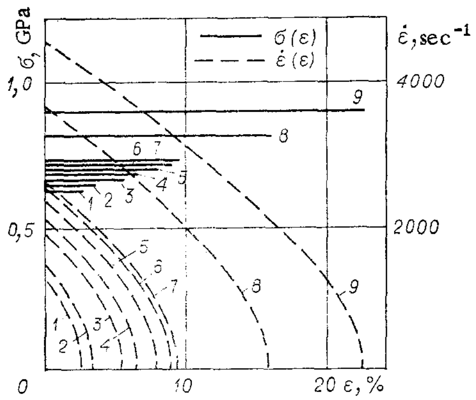

Fig. 2

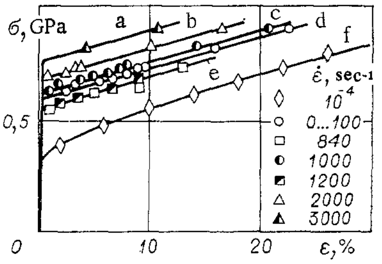

Fig. 3

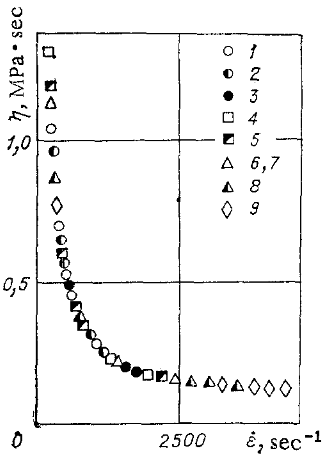

Fig. 4

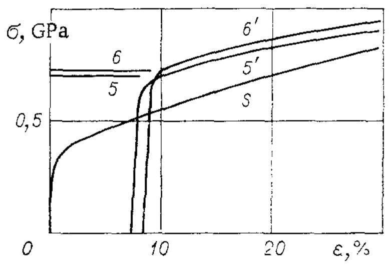

Fig. 5

Static tests of the material were performed with planar specimens by the standard method at $\dot{\varepsilon} \approx 10^{-4}$ sec^{-1}. The static $\sigma(\varepsilon)$ (Fig. 3, curve f) was obtained by processing machine diagrams using the principle of conservation of volume upon deformation [10].

Comparison in Fig. 3 of dynamic (curves *a*-e) and static (curve f) $\sigma(\varepsilon)$ shows that at $\varepsilon > 1\%$ the slopes of the curves are similar, so that it can be assumed that the modulus of hardening of the steel is practically independent of loading prehistory and comprises $k = d\sigma/d\varepsilon \approx 1.4$ GPa.

A more abrupt dynamic hardening of the steel with increase in $\dot{\varepsilon}_0$ occurred at small (~0.3-0.5%) deformations during the process of transition into the plastic state, a result of which is an increase in the yield point* — a phenomenon generally found in steels.

The dynamic viscosity of the steel can be evaluated from the experimental results, using $\dot{\varepsilon}$ and σ values for specified values of ε in Fig. 2. and the model of Eq. (3):

$$\eta = (\sigma - \sigma_0 - k\varepsilon)/\dot{\varepsilon}. \tag{8}$$

Equation (8), obtained for $\sigma_0 = \sigma_{0.2}$, $\dot{\varepsilon} \leqslant 5 \cdot 10^3$ sec^{-1} and $\varepsilon = 1\text{-}22\%$, is shown in Fig. 4 and may be written as

$$\eta = 5.7 \cdot 10^4 + 2.5 \cdot 10^8 \, \dot{\varepsilon}^{-1}, \ \text{Pa} \cdot \text{sec} \, . \tag{9}$$

It is obvious that the viscosity decreases with increase in deformation rate, which agrees qualitatively with results of other studies (see, for example, [11]). We note that the values of $\eta(\dot{\varepsilon})$ shown in Fig. 4 are practically independent of ε over the interval studied.

With consideration of Eq. (9), the equation of state of the steel, Eq. (3), for fall in $\dot{\varepsilon}$ from some maximum to zero takes on the form

$$\sigma = 0.58 + 1.4\varepsilon + 5.7 \cdot 10^{-5} \, \dot{\varepsilon}, \ \text{GPa} \, . \tag{10}$$

*By yield point we understand here the resistance to deformation at the beginning of plastic deformation (at $\varepsilon \approx 0.3$).

It follows from Eq. (10) and Fig. 3 that when the dynamic functions $\sigma(\varepsilon, \dot{\varepsilon})$ are extrapolated to $\dot{\varepsilon} = 0$ the yield point ($\sigma_1 \simeq 0.6$ GPa) is practically twice the value obtained in static tests ($\sigma_{0.2} = 0.33$ GPa). This effect, which is apparently a consequence of the differences in loading prehistory of the specimens, can be explained by stress relaxation.

In fact, the dynamic stress $\sigma_1 \simeq 0.6$ GPa ($\varepsilon_0 = 0$, $\varepsilon \simeq 0.3\%$) is reached over a time period equal to a fourth of the ring elastic oscillation period ($t_1 \simeq 15$ μsec) at the limiting initial deformation rate $\dot{\varepsilon}_* \simeq 300$ sec^{-1} which does not put the ring into the plastic state. On the other hand, the yield point value of $\sigma_{0.2} = 0.33$ GPa at a constant deformation rate of $\dot{\varepsilon} = 10^{-4}$ sec^{-1} was obtained over ~40 sec. Therefore relaxation processes with a characteristic time τ lying between $15 \cdot 10^{-6}$ sec and 40 sec cannot be completed in the ring experiments as opposed to the static case.

The marked difference in relative location in Fig. 3 of curves $\sigma(\varepsilon)$ with similar $\dot{\varepsilon}$ values (compare 3 and 5, 4 and 6), but differing loading prehistory, can be explained by the combined effects of stress relaxation and dynamic hardening. An example of the latter is the results of static extension of specimens prepared from the rings used in experiments 5, 6 (see Table 1). Figure 5 shows static $\sigma(\varepsilon)$ curves obtained for these specimens (curves 5', 6') which appear to continue the dynamic curves 5, 6,* but in the plasticity region are located significantly above the static curve $\sigma(\varepsilon)$ obtained for the same material in its original state (Fig. 5, curve S).

Thus, the experimental data obtained on the mechanical properties of 12Kh18N10T steel reveals the following: 1) Above the elastic limit the modulus of hardening of the material is practically independent of loading regime and deformation rate; 2) effects connected with loading prehistory (in particular, relaxation processes and dynamic hardening) have a significant influence in extension of steel in various velocity regimes. Thus, in extension at a rate which falls from some maximum, due to relaxation the yield point of the steel exceeds the static value by two or more times; 3) considering these effects of loading prehistory, the study of mechanical properties of materials sensitive to such effects, intended for operation under intense dynamic loads, should be performed with deformation not only at constant rates, but also with variable rates in regimes closely approximating real operating conditions. For example, the method used to test the toroidal specimens here is close to a regime of cylindrical shell operation with pulsed (explosive) loading from within.

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*This is confirmed by the correspondence of the $\sigma(\varepsilon)$ curves of Fig. 2 to the real state of the material in the experiments with rings.