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MECHANICAL PROPERTIES, PHYSICS OF STRENGTH, AND PLASTICITY

Mechanical Properties of Steel 20 at Small Deformations

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Abstract—The elastic hysteresis and residual deflections of samples made of steel 20, which correspond to the model of a thin rigid round plate pinched over the contour, have been investigated. It has been shown that annealing of the samples at 470 and 670 K weakly affects these characteristics, while after complete annealing (1170 K), the aging of steel 20 for three days is accompanied by a decrease in amplitude ω_h of the elastic hysteresis by ~20%. A postulate that there is no elasticity limit of metals, below which residual deformation would be absent, has been confirmed experimentally. It has been shown that, based on the values of ω_h, the ultimate strength of metals can be estimated acting on the samples by stresses smaller than the yield stress by an order of magnitude. A giant increase (by a factor of ~2.5) in ω_h has been found after a prolonged (for 2 months) aging of steel 20 after the diffusion of hydrogen from it, which indicates the corresponding decrease in its cyclic longevity.

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1. INTRODUCTION

In [1, 2], we described the procedure of investigating the mechanical properties of materials under the effect of small stresses $\sigma \sim 0.1\sigma_y$ (σ_y is the yield stress). It was shown using the example of aluminum alloy D16 [1] that the procedure is very sensitive to the states of the material, which are caused by heat treatment (complete annealing, quenching, and overburning). Namely, the amplitudes of elastic hysteresis ω_h and relative residual deflections β_{res} substantially (by several times) change after heat treatments by different methods. It was shown that, based on these results, one can estimate the standard mechanical characteristics of the materials (the ultimate strength σ_u and the yield stress σ_y) and evaluate their cyclic longevity.

In this study, the efficiency of the procedure was shown for steel 20 (international analog is steel 1020), which has been widely used in industry, belongs to high-quality steels [3], and is a good material for operation at high (~670 K) temperatures [4]. Therefore, the main purpose of our study was to investigate the parameters ω_h and β_{res} after exposure of the samples at high temperatures.

2. EXPERIMENTAL TECHNIQUE

The amplitude ω_h of elastic hysteresis and relative residual deformations (relative deflections) $\beta_{res} = \omega_{res}/\omega$ (ω_{res} are absolute residual deflections and ω is the sample deflection under the effect of mechanical stress σ) are investigated for the samples corresponding to the model of a thin rigid round plate pinched over the contour. The model was described in detail in [1, 5–7]. Samples were prepared in the form of a cylinder 5 mm in height with inner and outer diameters of 60 and 70 mm, respectively, and a thin (~1 mm) bottom.

When the pneumatic pressure P affects the internal cavity of the sample, its bottom is deflected by magnitude $\omega = 0.17PR^4/(Eh^3)$ (it is the displacement of the sample center), while maximal mechanical stresses in the plate (cylinder bottom) are determined as $\sigma = 0.775PR^2/h^2$ [5–7], where R is the plate radius, h is its thickness, and E is the Young modulus. The coefficient of 0.775 is found based on the vector summation of radial and tangential stresses [1, 7], which appear in the plate under the effect of P, and with the use of the Poisson ratio $\nu = 0.26$, which is characteristic of low-carbon steels, such as steel 20 (carbon content of ~0.20%).

The dependences ω–σ used to determine ω_h and β_{res} were investigated with a high (~0.01%) accuracy. This accuracy was ensured by the use of a remote deformometer (for determining deflections ω) and a meter of pressure P (stresses σ were calculated based on P, see the relationship above), which provided the relative error in determining ω and P no larger than 0.01%. It is seen from Fig. 1 that the spread of experimental points does not exceed 0.01%.

The samples were thermally treated at 470 ± 2 K (4 h), 670 ± 2 K (4 h), and 1170 ± 5 K (20 min; this annealing was performed in vacuum). Annealing at 470 K is interesting in that, by not varying the

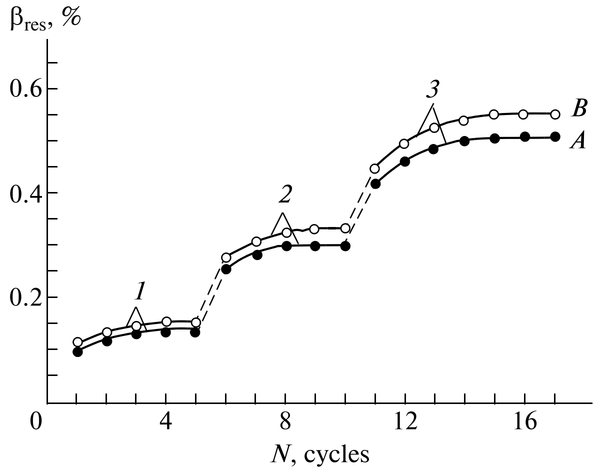

Fig. 1. Examples of dependences of residual deflections β_{res} on the number N of loading cycles: A is the primary sample and B is the sample after annealing at 670 K for 4 h; segments *1*, *2*, and *3* are found at cyclic loads $\sigma = 25.4$ $(0.08\sigma_y)$, 50.8, and 76.2 MPa, respectively.

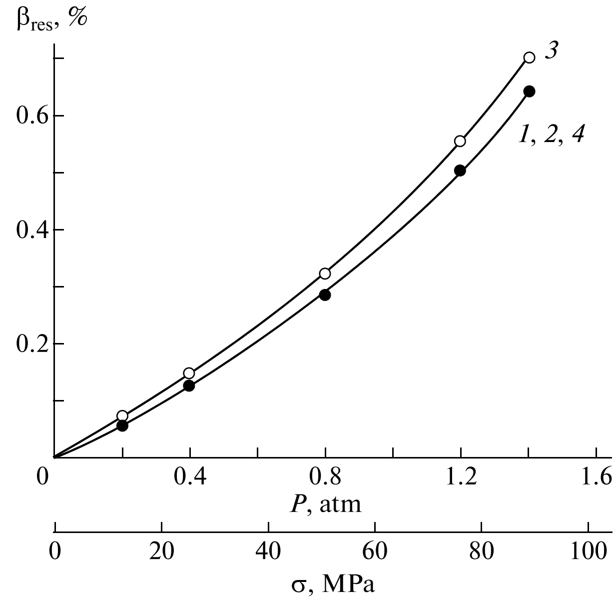

Fig. 2. Dependences of residual deflections β_{res} (in the saturation region, see Fig. 1) on cyclic load σ: (*1*) primary sample, (*2*) after annealing at 470 K (4 h), (*3*) at 670 K (4 h), and (*4*) at 1170 K (20 min).

mechanical characteristics of steel 20 [8], it promotes the return of structural defects, which are the source of residual deformations and inflections, to the primary equilibrium state. Consequently, such annealing can exclude the errors in determining β_{res} associated with the prehistory of samples. A temperature of 670 K is the maximal operational temperature of steel 20 [4]. Therefore, we should be convinced that ω_h and β_{res} change insignificantly after the effect of mentioned temperatures. Annealing at 1170 K (complete annealing of steel 20 [9, 10]) is used in order to refine the granular structure of the samples [9–11], to increase their microplasticity [10], and, correspondingly, to increase the amount (concentration) of defects, which are the source of the elastic hysteresis and residual deformations.

3. RESULTS AND DISCUSSION

3.1. Residual Deformations

Figure 1 shows dependences of residual deflections β_{res} on the number N of cycles of like-sign load σ. It is seen that after 5–7 loading cycles, dependences $\beta_{res}(N) \longrightarrow$ const, i.e., during the further loading cycles, the sample behaves as an elastic body. Effect $\beta_{res}(N) \longrightarrow$ const is called in [1] as microhardening. This effect in steel 20 is valid both at minimal loads used in the experiment ($\sigma = 12.7$ MPa $= 0.04\sigma_y$) and at maximal loads ($\sigma = 89$ MPa $= 0.28\sigma_y$); $\sigma_y = 320$ MPa is the yield stress of normalized steel 20 [8]. We emphasize that microhardening occurs after all heat treatment modes, including after complete annealing. Thus, microhardening of steel 20 by several cycles of the quasi-static load both after the normalization (primary samples) and after annealing (Fig. 1), including the complete annealing, as well as small distinctions in corresponding quantities β_{res} (curves A and B in Fig. 1) indicate a weak dependence of the operational quality of steel 20 on the heat treatment. For comparison: after the complete annealing (670 K) of the known construction material D16 (aluminum alloy), the value of β_{res} varies by a factor of ~4 compared with quantity β_{res} after quenching preceding such annealing [1].

Based on maxima of dependences $\beta_{res}(N)$, which are determined in their saturation region (see examples in Fig. 1), dependences of residual deflections on the magnitude (amplitude) of cyclical load σ are constructed (Fig. 2). Below, we will generalize the results of analysis of dependences presented in Figs. 1 and 2, namely:

(i) dependences $\beta_{res}(\sigma)$ for the primary sample and the sample after annealing at 470 K (4 h) in error limits of 0.01% of determining the residual deflections are identical (Fig. 2, curves *1* and *2*), i.e., such annealing determines the complete return of defects, which are the source of residual deformations to the equilibrium position characteristic of the primary sample. The conclusion follows from here: if the sample prehistory is unknown, then in order to construct more objective dependences $\beta_{res}(\sigma)$, the sample should be annealed under mentioned conditions;

(ii) it follows from the comparison of curves *1* and *3* in Fig. 2 that annealing the sample at $T = 670$ K (4 h) very weakly (only by ~9% at $\sigma = 89$ MPa) increases residual deflections and, correspondingly, the concen-

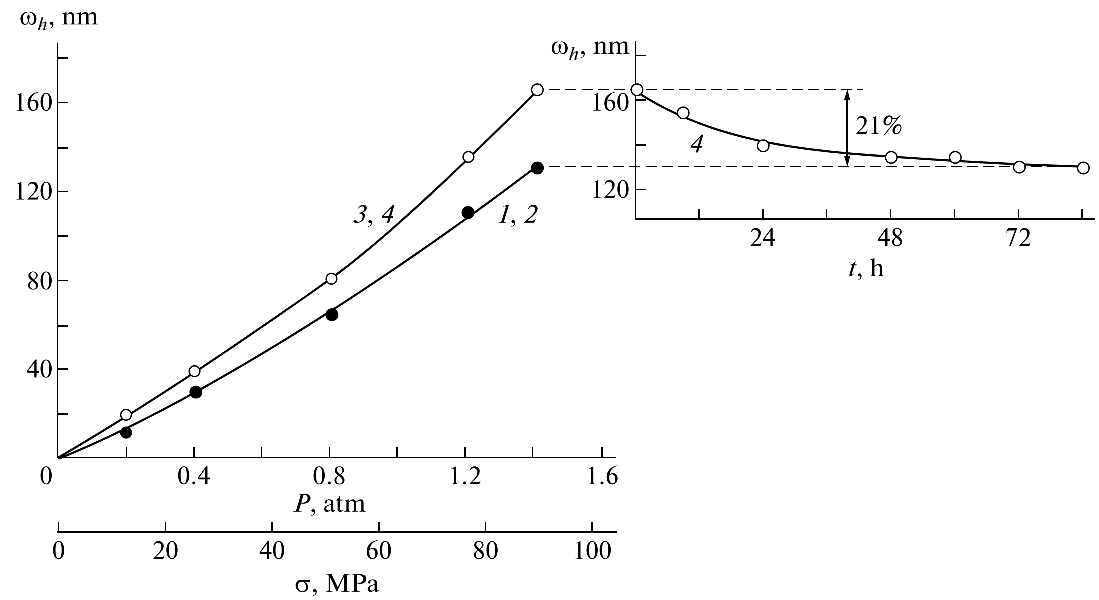

Fig. 3. Dependence $\omega_h(\sigma)$ after heat treatment of the sample: (*1*) primary sample, (*2*) after annealing at 470 K (4 h), (*3*) at 670 K (4 h), and (*4*) at 1170 K (20 min). Evolution in time (at T_{room}) of quantity ω_h, which corresponds to curve *4* at $\sigma = 89$ MPa ($0.28\sigma_y$), is in inset.

tration of microstructural defects, which are the source of such deformations. This result is confirmed by the known fact [4] that steel 20 is a good material for the operation at ~670 K;

(iii) complete annealing does not change the number of defects, which is evidenced by identity of curves *1* and *4* in Fig. 2 in the limits of the experimental error of 0.01% over the entire range of used loads $\sigma \leq$ 90 MPa. Thus, steel 20 is suitable for the operation under the effect of quasi-static mechanical stresses $\sigma \sim$ 90 MPa even after the complete annealing;

(iv) it is noteworthy that all dependences in Fig. 2 have tendency $\beta_{res} \longrightarrow \infty$ for $\sigma > 90$ MPa, i.e., $\sigma \sim$ 90 MPa can be considered the optimal mechanical stress for the operation in acting conditions of quasi-static cyclic loads. We can assume that the effect of hardening $\beta_{res}(N) \longrightarrow$ const will be also observed for cyclic loads $\sigma > 90$ MPa. However, we specially did not use such loads in order to avoid large plastic deformations, at which the further investigation of the samples would be impossible since the convexity of plastically deformed samples distorts the model (plane plate pinched over the contour), in terms of which the investigations are performed;

(v) it follows from Fig. 2 that the following regularity is valid for all states of the sample (curves *1*–*4*): residual deflections occur even at $\sigma \longrightarrow 0$ since dependences $\beta_{res}(\sigma)$ are extrapolated into the origin of coordinates. This fact for steel 20 experimentally confirms the foresight by Hodkinson and Wertheim made one and half centuries ago that there is no the elasticity limit of metals, below which the residual deformation would absent [12].

3.2. Elastic Hysteresis

Figure 3 shows the dependences of amplitudes ω_h of elastic hysteresis on mechanical stress σ. Measurements of ω_h are performed after microhardening when the sample behaves as an elastic body, i.e., when $\beta_{res}(N)$ = const (Fig. 1). For the primary sample (Fig. 3, curve *1*), the magnitude of ω_h is relatively small being 100 nm for $\sigma = 72$ MPa, i.e., the parameter introduced in [1] $\sigma^h_{100\text{ nm}} = 72$ MPa. By this parameter, steel 20 is somewhat worse than alloyed steel 40Kh [2]

Comparison of steel 40Kh, steel 20, and alloy D16 by the parameters $\sigma^h_{100\text{ nm}}$ and σ_u

Material	$\sigma^h_{100\text{ nm}}$	σ_u
	MPa	
Steel 40Kh [2]	76	850
Steel 20:		
(i) normalized	72	510
(ii) after complete annealing	61	480
Alloy D16 [1]:		
(i) after first quenching	60	440
(ii) after second quenching	31	310

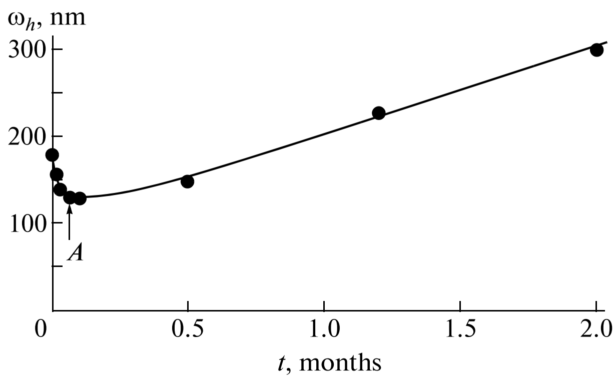

Fig. 4. Dependence of ω_h (for σ = 89 MPa) on time t of sample aging (at T_{room} = 290 K) after the effect of hydrogen: point A corresponds to finishing the diffusion of hydrogen from the sample for ~2.5 days, while the further increase in $\omega_h(t)$ evidences the nucleation of new defects after the diffusion of hydrogen.

and substantially surpasses aluminum alloy D16 [1] (see table). It also follows from the table that parameter $\sigma^h_{100\ \mathrm{nm}}$ for materials listed in it correlates with their strength σ_u. Moreover, the correlation of parameters $\sigma^h_{100\ \mathrm{nm}}$ and σ_u for these materials is also observed after their heat treatment. From here, the conclusion follows that we can evaluate the strength of materials affecting the sample small mechanical stresses ~$0.1\sigma_u$ based on parameter $\sigma^h_{100\ \mathrm{nm}}$, which is preferentially smaller than ultimate strength σ_u by an order of magnitude (table).

It is seen from Fig. 3 that all dependences $\omega_h(\sigma)$ are extrapolated into the origin of coordinates, i.e., hysteresis amplitude $\omega_h \neq 0$ even at $\sigma \longrightarrow 0$. This is a qualitative distinction of steel 20 from alloyed steel 40Kh and aluminum alloy D16, for which threshold values $\sigma = \sigma_0$ occur, at which the hysteresis starts: σ_0 for steel 40Kh is 23 MPa (according to the data [2]), and for D16 alloy—18 MPa [1].

Let us pay attention to main regularities that characterize the influence of heat treatment on the elastic hysteresis of steel 20.

Curves *1* and *2* (Fig. 3) are identical in the limits of determination accuracy of amplitudes ω_h of the elastic hysteresis (the measurement error of ω_h is 10 nm including the error of remounting the samples; measurement discreteness of ω_h is 5 nm). From here, we can conclude that annealing of the samples at 470 K (4 h) does not change the concentration of defects being the source of the elastic hysteresis (similar identity of curves *1* and *2* in Fig. 2, which describe residual deflections, was discussed above). Moreover, even annealing at 670 K (4 h) weakly varies the microstructure imperfection since the hysteresis amplitude after such annealing increased only by ~20% (Fig. 3, curve *3*). This fact indicates that the cyclic longevity of steel 20, which is in general inversely proportional to the hysteresis amplitude of materials [3, 13], changes insignificantly after such annealing.

Complete annealing also weakly affects the elastic hysteresis (curves *3* and *4* in Fig. 3 are identical). However, hysteresis amplitude ω_h noticeably decreases after such annealing for ~3 days of aging (inset in Fig. 3) and reaches 130 nm (at σ = 89 MPa), which is characteristic of normalized steel 20 (Fig. 3, curve *1*). This fact evidences that the sample microstructure during its aging after complete annealing varies towards decreasing the number of defects being the source of the elastic hysteresis. Since complete annealing refines the microstructure of steel 20 [9–11], we can assume that its microstructure becomes more coarse-grained during the subsequent aging. The concentration of defects, the reversible motion of which (upon increasing and decreasing the load) is the cause of elastic hysteresis, decreases correspondingly.

We emphasize that the evolution of ω_h in time for the samples annealed at 470 K (4 h) and 670 K (4 h) is not revealed, i.e., annealing of steel 20 under mentioned conditions does not worsen its microstructure and, correspondingly, mechanical properties, which is also evidenced by small variations in β_{res} and ω_h after annealing at 670 K and the absence of variations in these characteristics after annealing at 470 K (Figs. 2, 3).

We can also practically conclude from Fig. 3 that since the hysteresis after annealing at 470, 670, and 1170 K varies weakly, the cyclic longevity for such states of steel 20 is almost invariable. However, the limiting temperature, at which the prolonged operation of steel 20 is possible, is T = 670 K since graphitization of steel 20 (isolation of free carbon over the grain boundaries), which causes a decrease in its strength, occurs at higher temperatures.

Thus, exactly temperatures up to 670 K are probable operational temperatures, at which the cyclic longevity of steel 20 worsens insignificantly. In this connection, an important question appears on stability of cyclic longevity of steel 20 at such temperatures in hydrogen-containing media, when hydrogen is actively incorporated into metal, which is accompanied by substantial worsening of its mechanical characteristics (the influence of such media on metals is intensely studied in the recent time, see, for example, [14–17]). Let us list first results on the influence of hydrogen on steel 20.

The hydrogen pressure of 120 atm at T = 620 K for 4 h noticeably (by ~40%) increases amplitude ω_h of the elastic hysteresis. The value of ω_h decreases during the diffusion of hydrogen from the sample (for three days at T_{room} = 290 K) to the primary value (130 nm for σ = 89 MPa, see Fig. 4, point *A*). The qualitatively another result was obtained for the prolonged sample observation after the diffusion of hydrogen (Fig. 4, to the right of point *A*): the value of ω_h after 2-month aging at T_{room} increases by a factor of ~2.5. It follows from this "giant" rise of quantity ω_h that the defects being the source of elastic hysteresis intensely multiply during the prolonged aging of the sample and its cyclic longevity N_d correspondingly decreases since $N_d \sim 1/\omega_h$ [3, 13]. The mechanisms of the prolonged evolution of ω_h and intense multiplication of structural defects after the diffusion of hydrogen from the sample is still unclear.

4. CONCLUSIONS

The influence of annealing at 470, 670, and 1170 K on residual deformations (deflections) and elastic hysteresis amplitudes of steel 20 under the effect of small mechanical stresses $\sigma \sim 0.1\sigma_y$ was investigated for the samples corresponding to the model of a thin rigid round plate pinched over the contour. It was shown that annealing at mentioned temperatures weakly affects relative residual deflections and elastic hysteresis of the samples, while their microhardening, after which the material behaves as the elastic body, is attained already after the effect of 5–7 quasi-static load cycles with the magnitude up to 90 MPa. It was found that 3-day aging of the samples after complete annealing is accompanied by a decrease in hysteresis amplitude ω_h by ~20%, which evidences coarsening the grains structure of steel 20 and increasing its cyclic longevity.

It was shown that parameter $\sigma^h_{100\ \mathrm{nm}}$ (mechanical stress at which $\omega_h = 100$ nm) correlates with ultimate strength σ_u ($\sigma^h_{100\ \mathrm{nm}}$ is smaller than σ_u by approximately an order of magnitude), i.e., based on this parameter, we can evaluate the ultimate strength for different states of constructional materials by a nondestructive method.

After hydrogen diffused from the sample, aging processes prolonged for months continue in it. They are accompanied by a considerable increase in the elastic hysteresis amplitude and corresponding decrease in cyclic longevity. Thus, steel 20 is a good material for operation at temperatures up to 670 K (the material graphitizes at larger *T*), but only in media containing no hydrogen.

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