The assessment of damage and resource of vessel and apparatus elements, taking into account the adaptation of the material to long-term quasistatic loading

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Abstract. The research of influence of long quasistatic loading on characteristics of resistance to deformations and destruction of elements of vessels and devices, is of great interest to the solution of problems of control and forecasting of their technical condition. In order to detect changes in the mechanical characteristics of 09G2S steel and changes in the structure of the material under the influence of quasistatic loading, destructive tests of the studied samples in an initial state and after establishment of extrema of tension of constant magnetic field have been carried out. It is established that long influence of quasistatic loading in the considered conditions leads to change of a condition of steel 09G2S which causes reduction of characteristics of plasticity ($\delta$) and energy of destruction and increase in resistance to plastic deformations ($\sigma_y, \sigma_{TS}$) what, in turn, can lead to a reduction temporary resource. The received results have allowed to develop the equation of assessment of a resource of the shell designs operated in the conditions of quasistatic loading, based on settlement and experimental dependence of a ratio of mechanical characteristics ($\sigma_y/\sigma_{TS}$) of steel 09G2S from duration of quasistatic loading.

1. Introduction
The reaction of the material to the influence of various kinds of factors which are associated with the features of technological processes determines the reliability and resource of safe operation of the elements of vessels and apparatuses. Fluctuations in the operating parameters of the process (such as pressure, temperature and flow rate) lead to the occurrence of low-frequency alternating voltages in the structural elements, which makes the loading mode of this equipment quasistatic.

Preliminary studies [1] of flat specimens of 09G2S steel, subjected to static and quasistatic loading under conditions of longitudinal bending in elastic deformations (figure 1), showed that constant magnetic field strength changes as a result of long-term loading. It was noted that with an increase in the level of relative deformation of ($\varepsilon$) of the sample, the normal component of the magnetic field strength decreases (figure 2a), reaching a minimum value when $\varepsilon=0.28$ % (relative deformation at which the samples were held). At the same time, there is a tendency of a gradual decrease in the normal component ($H_n$) of the constant magnetic field intensity with increasing loading time (figure 2b).
Figure 1. Device for static bending of plane samples and device for measuring bend with indicating gage (a) and the sample measurement schematic diagram (b) [1].

Figure 2. The dependence of the change in the normal component of the vector of constant magnetic field intensity on the level of relative deformation of the sample (a) and on the duration of loading when measuring at different levels of deformation in the zone of maximum bending (b) [1].

The established patterns indicate the occurrence of complex processes of changing the material structure during prolonged exposure of quasistatic load.

There is a question: with what can the established changes be connected?

The works of Ivanova V.S. And Panin V.E. have shown that a solid deformable body is a multi-level hierarchical system that can adapt to external influences by self-organization at various scale levels of the material structure [2-5]. Already at the stage of elastic deformation of a solid, the excess energy of external action is accumulated in localized nonequilibrium areas, which form an open, self-organizing subsystem, and the greater the effect on it then the deeper the deformation level the mechanisms of adaptation of the system are implemented [2, 5].

The works of Demchenko A.A. showed the influence of scale levels of the structure on the dynamics of the formation of the strain relief of St3sp5 steel under low-cycle loading [6, 7]. As an indicator of the change in the structure of the material with the accumulation of fatigue damage ($N/N_p$), the author evaluated the parameter of the fractal dimension ($D$) of the deformation relief of steel at the micro, submicro, and nanoscale.

At the initial stage of low-cycle loading (in the range of accumulated damage $N/N_p = 0.0 \div 0.4$), an inhomogeneous formation of shear defects was established for stress concentrators at all scale levels, especially pronounced at the nanoscale. In the range $N/N_p=0.4+0.8$, simultaneous propagation of defects at all scale levels is observed, and self-organization of shear defects that originated at an early stage occurs. When the level of accumulated damage reaches $N/N_p=0.8$ and until complete destruction at
$N/N_p=1$, a sharp increase in the fractal dimension that prevails at the submicro level is recorded, which is a consequence of the relaxation of critical tensions as a result of the formation of large defects [6, 7].

Analysis of the presented studies shows that the adaptation of the material to the loading begins with the levels of the nanoscale and gradually covers the structures of larger scale levels. This means that a property gradient is created in the material as a result of changes at different scale levels. Energy is transferred from one area to another. This fact can explain control breaks and staging in the dependence (figure 2, b) of magnetic characteristics in time.

The question of the influence of changes occurring at a certain scale level of the structure on the physical and mechanical properties of the material is of great interest for solving problems of monitoring and forecasting the technical condition of structures.

2. Experimental research

The destructive testing of samples in the initial state and after the establishment of the extrema change of the magnetic field, described in study [1] were carried out in order to identify changes of the mechanical properties of steel 09G2S, and changes in the structure of a material under quasistatic loading.

The mechanical properties of the samples were monitored after 100, 190, 288, and 373 days of loading. Mechanical characteristics of steel in the initial state and after 100 days of exposure under load were determined by testing samples for static tension, and then by calculating the hardness method according to the method described in works [8, 9, 10]. The hardness was measured using the Rockwell method. To assess the tendency of the steel to brittle fracture, the samples were subjected to a Sharpie impact bending test in the initial state and after 190, 288, and 373 days, the results of which were used to determine the value of the impact strength (KCV).

Figures 3 and 4 show the dependences of strength characteristics ($\sigma_y$, $\sigma_{TS}$), relative elongation ($\delta$), and impact strength (KCV) on the duration of quasistatic loading obtained from the test results.

Figure 3. Dependence of the yield strength (a) and strength limit (b) of steel 09G2S on the duration of quasistatic loading.

Figure 4. Dependence of the relative elongation (a) and the impact strength (b) of steel 09G2S on the duration of quasistatic loading.
It was found that the long-term impact of the quasi-static load in the considered conditions leads to a change in the state of the steel 09G2S, which causes an increase in the resistance to plastic deformation (σ\text{y}, σ\text{TS}) (figure 3, a, b), reduction of plasticity (δ) (figure 4, a, b) and impact strength (KCV), which, in turn, can lead to an increase in the probability of brittle material destruction and to a decrease of the time resource of structural elements.

Metallographic studies of the microstructure in the cross-sectional area of the samples, in the initial state and after 242 days of quasistatic loading, have shown that heterogeneity of the structure and microdamage are observed in the stretch zone and in the middle cross-sectional area of the sample. The method of multifractal parameterization of microstructure images revealed a decrease in the \( f_q \) parameter - the degree of uniformity of the structure, and the analysis of the microhardness distribution in ferrite, perlite and intergrain boundaries showed a General trend of increasing microhardness compared to samples in the initial state.

The established results correlate with the dependencies presented in works [11, 12], devoted to the study of the properties of 09G2C pipe steel subjected to long exposures under constant load. The authors [11, 12] indicate that exposure under constant load is accompanied by deformation aging of 09G2S steel. The most noticeable development of deformation aging is in the first 5 years. At the same time, there is a shift in the temperature of the visco-brittle transition towards higher temperatures, and a brittle component appears in the fractures [12].

The decrease in the impact strength of low-alloy steel and the shift of the visco-brittle transition towards higher temperatures after long-term operation in pipelines (about 25 years) was also noted in the work [13]. It is shown that for the considered time, the plasticity of the material (δ) decreased about 1.5 times, and the total value of fracture A decreased almost 2 times (mostly due to the reduction of the work of crack initiation). The authors show that when the service life increases, the strength properties (especially the yield strength) increase slightly, and the plasticity and energy intensity characteristics decrease, due to the processes of microplastic deformation and deformation aging that occur in low-alloy and low-carbon steels at stresses significantly less than the static yield point [13].

The ratio (\( \sigma_y/\sigma_{\text{TS}} \)) along with the fracture work is one of the most important characteristics for evaluating the material’s tendency to brittle fracture, since the higher (\( \sigma_y/\sigma_{\text{TS}} \)), the less ductility of the steel. The established changes in the yield strength and tensile strength formed the basis of a computational and experimental relationship linking the changing ratio of mechanical characteristics (\( \sigma_y/\sigma_{\text{TS}} \)) and the operating conditions of 09G2S steel under quasistatic loading (figure 5). The criterion for the onset of the limit state is the achievement of the value (\( \sigma_y/\sigma_{\text{TS}} \))\text{crit} =0.96, since it is known that when (\( \sigma_y/\sigma_{\text{TS}} \))\text{crit} =0.95+0.98 the metal loses its ability to deform plastically and behaves as a brittle material [14, 15].

![Figure 5](image_url)

**Figure 5.** Dependence of the ratio (\( \sigma_y/\sigma_{\text{TS}} \)) on the duration of exposure under quasistatic load.

The projection of the intersection point of the dependence (\( \sigma_y/\sigma_{\text{TS}} \)) on the loading duration with the level of the critical value of this magnitude (\( \sigma_y/\sigma_{\text{TS}} \))\text{crit} =0.96 on the abscissa axis (loading duration)
shows the time of the onset of the limit state—the formation of microcracks in the material, after which the design resource should be evaluated according to the survivability criteria.

Using power equations for changes in mechanical characteristics, taking into account the temperature-time factor, developed by Makhutov N.A. [16, 17, 18], an equation for estimating the resource realized by the construction material $\tau$, and determining the moment of occurrence of the limit state of the material of shell structures during the operation of steel 09G2C under quasi-static loading was obtained for the established dependence $(\sigma_0/\sigma_{TS})=f(\tau)$:

$$\tau = \tau_o \cdot \left( \frac{\sigma^T \cdot \sigma_{TS}}{\sigma^T_{TS} \cdot \sigma^T_{y_o}} \right)^{m_\tau},$$

(1)

where $\tau_o$ is the test time to failure under short-term static loading (for plastic steels $\tau_o \approx 0.05$ h);

$\sigma^T, \sigma^T_{TS}$ - tensile strength and yield strength at the time of evaluating the resource of the object;

$\sigma^T_{TS}, \sigma^T_{y_o}$ - is the tensile strength and yield strength for short-term standard mechanical tensile tests;

$m_\tau$ - is the material characteristic, depending on the loading time and process parameters; for the test samples made of steel 09G2S.

It was found that $m_\tau$ varies from 0.0002 to 0.01 depending on the duration of operation, while the value $m_\tau = 0.01$ corresponds to the onset of the material limit state, which is a diagnostic sign when evaluating the resource of shell structures.

3. Conclusion

Thus, the studies on the example of steel 09G2S showed that the structural material under quasistatic loading, changes of mechanisms of adaptation of the structure of the material to the current load, which lead to the accumulation of damage and increase the likelihood of brittle fracture of elements of shell structures, and the proposed calculation-experimental dependence gives the possibility to evaluate the technical condition of the structure taking into account the influence of quasi-static loads and to improve the accuracy of establishing the time of transition of a material in the ultimate state.

The described results allow making a refined assessment of the residual life of 09G2S steel shell structures operated under quasi-static loading conditions.

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