Experimental study of creep and relaxation of steels at the postcritical stage of deformation

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Abstract. The work is aimed at experimental and theoretical study of the regularities and effects of the behaviour of metallic materials at the stage of postcritical deformation, which is of both applied and fundamental interest from the point of view of understanding preceding of the fracture processes and the possibility of predicting the survivability and kinetics of structural failure processes. An experimental assessment was made of the influence of the strain rate in a wide range on the postcritical behaviour of X15CrNi12-2 steel samples at the temperature of 500 °C. Experimental data of rheological processes of the steel at various levels of achieved postcritical deformation was obtained. It was shown that during creep holding at the postcritical stage of deformation, a transition to the final creep stage and subsequent destruction of the samples almost immediately were occurs. An analysis of the experimental dependences obtained during exposition in the relaxation mode demonstrates the independence of the stress level at the end of exposition on the speed of preliminary deformation and, therefore, on the initial value of the stresses, which reached at the beginning of the exposition. The data obtained are necessary to develop models of softening media, taking into account the rheological processes that occur in metallic materials under conditions of postcritical deformation at high temperatures.

1. Introduction
Currently, considerable attention of researchers is directed to studying the processes of deformation and failure of materials, which is of interest from the point of view of controlling safety, predicting survivability and reducing the catastrophic damage of structures in emergency situations, and the increasing requirements for reliability, resource and long-term strength of critical products determine unconditional relevance of experimental and theoretical research in this area [1-7]. To date, the foundations of a theory of the processes of stability of the postcritical deformation of softening media have been developed: the criteria of postcritical deformation has been formulated, the uniqueness theorem for solutions of elastoplastic problems with contact-type boundary conditions for bodies with destroyed regions has been proved, the necessary conditions for the stability of the postcritical deformation of damaged structural elements of inhomogeneous media have been derived [1-2]. During the experimental study of this stage of deformation, special attention is paid to the processes of inhomogeneous deformation of the sample, which lead to the formation of a neck in the working part [5, 7]. Taking into account the postcritical behavior of materials is of practical interest.
in studying the failure processes of polymer composites [2, 6], as well as in modeling the behavior of specimens with a crack taking into account nonlinear bonds at its tip [8].

Theoretical and experimental study and accounting of the rheological behavior of materials under conditions of the postcritical deformation is a necessary element in the further development of models of softened media, which are necessary when analyzing and predicting the behavior of critical structures during failure. Most structural materials demonstrate the rheological behavior at high temperatures, which manifests itself in the form of creep and relaxation. Metals and alloys demonstrate rheological properties in a certain range of stresses and temperatures. Moreover, neglecting the creep effect can lead to significant errors in the assessment of the mechanical behavior and performance of the studied objects. The creep phenomenon could be divided into three stages: primary creep (hardening stage), secondary creep (stationary) and tertiary creep (softening stage). At high temperatures, the characteristic features of the deformation-strength behavior of materials are the absence of an initial creep stage (hardening stage) and the relatively short duration of the third stage (softening stage) [9].

The aim of this work is to expand experimental research methods and to obtain new data on the processes and regularities of creep and relaxation of steels at the stage of postcritical deformation.

2. Test procedure and discussion of the results

The test procedure was implemented using the Instron 8801 universal servo-hydraulic testing system (± 100 kN, loading frequency up to 30 Hz). The samples were heated and tested in Instron CP103202 three-zone furnace with a maximum operating temperature of 1100 °C. During testing, a sample and traction of cooled grippers are located in the furnace. The tests used an induction type high-temperature extensometer Epsilon 3648-010M with a measurement base of 10 mm and a working range of strain registration of ± 2.5 %. All sensors of the test system and extensometer provide measurements with an error of not more than 0.5 % of the measured value.

The tests are carried out under uniaxial tension at a sample elongation rate of 6 mm/min, 0.6 mm/min, 0.06 mm/min and 0.006 mm/min using the built-in displacement sensor of the testing machine, either until it is completely fractured or to the required level of the postcritical deformation and then exposure is carried out at constant deformation of the sample (relaxation mode) or load level (creep mode) with recording of all test parameters. The tests were carried out at a sample temperature of 500 °C (the temperature difference along the length of the working part does not exceed 5 °C). Heating and exposition of the samples is carried out for at least 3.5 hours, which ensures uniform heating of the sample and equipment, with registration of movements caused by thermal expansion of the sample and high temperature rods. The tests were carried out on solid cylindrical samples (diameter is 6 mm, working part is 38 mm) of heat-resistant high-alloy corrosion-resistant steel of martensitic grade X15CrNi12-2. A sketch of the sample is shown in figure 1. The chemical composition of the steel is given in table 1, a detailed description of the test procedure is discussed in [3].

| Table 1. Chemical composition of steel X15CrNi12-2 |
|---|---|---|---|---|---|---|---|
| C | Cr | Si | Nb | Ni | W | Mo | V |
| 0.13 % | 12.50 % | 0.05 % | 0.20 % | 2.05 % | 0.70 % | 1.50 % | 0.20 % |
In [3, 4] it was noted that at room temperature there is no significant effect of the strain rate on the postcritical behavior of steels (for example, 40Cr), but such an effect is present at high temperatures. In this work, is evaluated the dependence of the postcritical behavior of the considered steel at high temperature (500 °C) on the strain rate. The elongation rates of the samples realized in the tests correspond to the following strain rates: 6 mm/min - 2.6·10^{-3} s^{-1}, 0.6 mm/min - 2.6·10^{-4} s^{-1}, 0.06 mm/min - 2.6·10^{-5} s^{-1} and 0.006 mm/min - 2.6·10^{-6} s^{-1}.

In figure 2 the general view of the fracture surfaces of destroyed samples after testing at various speeds is shown. The destruction occurred on the cup-cone type. A decrease in the strain rate led to an increase in the maximum achieved strain and, accordingly, to an increase in the residual transverse narrowing. It can be seen that not only the minimum diameter of the sample in the neck changes, but also the ratio of the sizes of the central matted part of the fracture and the region of the plastic cut. A decrease in the strain rate leads
to an increase in the area of the central matted part of the fracture surface (figure 2, d). The tensile diagrams, which obtained in the tests are shown in figure 3 in the coordinates "engineering stress - elongation".

Figure 3. Tensile diagrams of samples of steel at temperature of 500 °C at various elongation rates

An increase in the tensile rate is reflected in the form of a known increase in steel resistance, an increase in yield strength and temporary resistance. At the stage of postcritical behavior, a significant decrease in the ultimate strain (a decrease in deformation resources) is observed. At the maximum realized elongation rate (6 mm/min), the tensile diagram differs at a qualitative level (red curve in figure 3): the moment the maximum stress corresponding to the temporary resistance is reached is shifted to the right with respect to the curves obtained at the other considered strain rates, and accordingly, the minimum extent of the postcritical deformation section is characterized. With a decrease in the strain rate, the steel resistance decreases and the diagrams are lower, which indicates the active flow of rheological processes.

To assess the contribution of the rheological behavior of steel at the postcritical stage of defining in accordance with the research methodology, tests were carried out in the creep and relaxation regimes at holdings at various stages of postcritical behavior. In figure 4 shows the creep curves in the coordinates “elongation (∆u) - time” obtained after stops at various degrees of postcritical deformation (tensile rate 0.6 mm/min, values of preliminary elongation (u): u=1 mm (black line), u=2 mm (red line) and u=3 mm (blue line).
According to the data obtained, it can be seen that when holding at the load (creep mode) at the postcritical stage of deformation, the transition to the third creep stage and subsequent destruction of the sample occurs almost immediately. The fact that the postcritical stage corresponds to actively proceeding processes of plastic deformation, which lead to the appearance of an inhomogeneous distribution of deformations in the working part of the sample and the formation of a neck.

In [3], experimental data were obtained on the relaxation processes of the considered steel and the influence on their course of parameters such as: test temperature, the degree of preliminary postcritical deformation achieved by the time the tensile stop and hold at a fixed elongation. In the present work, the influence of the tensile rate on the postcritical behavior of the steel under consideration is noted, which is associated with rheological processes. In this regard, in order to assess the effect of the rate of preliminary deformation on the intensity of relaxation processes occurring at the postcritical stage of deformation, tests were carried out with exposures at different levels of softening, the results of which are shown in figure 5. The solid lines in figure 5 correspond to tensile diagrams at different speeds: 0.6 mm/min (blue), 0.06 mm/min (green), 0.006 mm/min (black). The dashed lines in Figure 5 connect the points corresponding to stress levels to which stresses decrease during relaxation during exposure for one hour.
Figure 6. Relaxation curves with an elongation of 3 mm in the form of dependences of the engineering stress (a) and relative stress (b) on the exposure time obtained at various rates of preliminary tension.

As was shown earlier [3], the magnitude of the stress drop during relaxation depends both on temperature and on the degree of postcritical deformation previously achieved. In figure 6 shows the dependences of engineering (a) stresses and relative stress (b) on the exposure time for a previously achieved elongation of 3 mm. The relative stress is calculated by the ratio of the current value of σ to the value of stress σ₀ corresponding to the beginning of exposure in the relaxation mode.

From the figure 6 (a) it can be seen that the stress reduction curves for tensile velocities of 0.6 mm/min and 0.06 mm/min practically coincide, and the curve for tensile speeds of 0.006 mm/min is close to them and has a qualitative correspondence. As can be seen from the obtained data (figure 5 and figure 6, a), the stress values at the end of the exposure in the relaxation mode are close to each other for the considered tensile velocities, the difference in stress values did not exceed 13 %. The obtained difference in the values of stresses is comparable with the error of the experimental data during such tests, however, it requires clarification, which requires additional tests and statistical processing. The construction of relaxation curves in the form of the dependence of the relative stress on the exposure time (figure 6, b) illustrates the decrease in the intensity (speed of decreasing) of relaxation with a decrease in the strain rate of the samples. At low strain rates under the conditions of postcritical behavior of the considered steel, rheological processes proceed to a greater extent in the process of active loading.

3. Conclusion

As a result of the work, methods were developed for the experimental study of the patterns of rheological behavior of samples of metallic materials at the stage of postcritical deformation, which is a source of information about the ongoing processes of deformation and fracture, and is associated with predicting the kinetics of the processes in assessing the survivability and reserve of the bearing capacity of structural elements. An experimental assessment was made of the influence of the strain rate on the resistance of X15CrNi12-2 steel samples at the stages of elastoplastic and postcritical deformation at a temperature of 500 °C in the speed range from $2.6 \times 10^{-3}$ s⁻¹ to $2.6 \times 10^{-6}$ s⁻¹. Data were obtained on the processes of rheological behavior of steel at various levels of achieved postcritical deformation in the modes of creep (load retention) and relaxation (retention of elongation). It was shown that during creep holdings at the postcritical stage of deformation, almost immediately a transition to the third creep stage and subsequent destruction of the samples occurs. Excerpts in the relaxation regime of the same length in time revealed the independence of...
the level of stresses by the end of the exposure on the speed of preliminary deformation and, therefore, on the initial value of the stresses reached by the beginning of exposure. The data obtained are required for constructing models of softening media that take into account the rheological processes occurring in metallic materials under conditions of postcritical deformation at high temperatures.

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