High temperature creep of steel 09G2S under non-stationary loading

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Abstract. Experimental analysis of deformation of steel 09G2S under creep conditions has been carried out to determine the optimal modes of high temperature forming of steel shells. The efficient temperature range in terms of saving of the plasticity resource was defined. The material parameters including scalar damage parameters have been determined by taking into account the description of the deformation of a material under non-stationary loading conditions. A satisfactory description of the unsteady creep processes of the material 09G2S in the temperature range from 700 to 800°C has been received.

1. Introduction

The work of structural elements under non-stationary loading conditions under long-term temperature influence is one of the major issues appearing in the material rupture time analysis. This is a relevant question in the field of shipbuilding and aircraft building industries, engineering and other industries. Non-stationary processes have a significant impact on the deformation processes, strength and component life of structural elements. The study takes into consideration in these processes changes of remaining life time.

To describe the materials creep processes, we used the determined relations characterizing considered non-stationary state [1-9].

2. Theory

2.1. Experimental data on the deformation of a material in the creep mode

Tensile tests were carried out under the slow mode of deformation in order to determine the optimal modes for forming of steel 09G2S. The experiments were carried out on cylindrical specimens. The strain was determined by the logarithmic dependence \( \varepsilon = \ln \left( \frac{L}{L_0} \right) \), where \( L \) is the current and \( L_0 \) is the initial length of the specimens. Three-four experiments were carried out for each fixed temperature level: 700, 730, 750, 770 and 800°C, both at constant stress and with an overload to other stress levels at a constant temperature. The external load of the axial tension \( P \) is corrected during experiment taking into account cross section area of the specimens so as the true stress \( \sigma = \frac{P}{S} \) has remained constant. This correction is based on the assumption that the material is an incompressible medium, i.e. its volume is not changed \( V = S_0 L_0 = SL \), where \( S_0 \) and \( S \) are cross-sectional area at initial time...
and at current time, respectively). All experiments were brought to the destruction of the specimens in order to determine the limiting value of the strain $\varepsilon^*$.

An analysis of the experimental data showed that up to deformation value $\varepsilon \approx 10\%$, the strain rate is a function of only the stress and temperature $\dot{\varepsilon} = \varphi(\sigma, T)$, i.e. the material acts like a viscous medium and strain rate is not dependent on any hardening or softening parameters. The material softening is observed when $\varepsilon > 10\%$.

Diagram of the change in the limiting strains as a function of temperature are shown in Figure 1. From the graphic, it is concluded that the most efficient temperature range from the point of view of the magnitude of the "plastic reserve" should be seen as $T \approx 730^\circ C$.

3. The determination of the material constants of creep taking into account damage material

The experimental data on the creep at constant stress are analyzed to determine the constants of the material. A mathematical description of the forming process is based on the kinetic equations with the parameter of damage by Rabotnov [1, 3–5, 11]. The constitutive equations describing of the creep processes and long-term strength are used with the same softening coefficient $m$ in both equations [1, 4, 5, 8–11]:

$$
\begin{align*}
\frac{d\varepsilon}{dt} &= \frac{\varphi(\sigma)}{(1-\omega)^m}, \\
\frac{d\omega}{dt} &= \frac{\psi(\sigma)}{(1-\omega)^m}.
\end{align*}
$$

(1)

For plotting the approximation curves were used functional dependences such as

$$
\varphi(\sigma, T) = B_\varepsilon (T)\sigma^{k(T)} \quad \text{and} \quad \psi(\sigma, T) = B_\omega (T)\sigma^{n(T)}.
$$

(2)

The scalar parameter of damage $\omega$ is determined by the ratio of the strain during the creep process of the material to its corresponding value at the moment of destruction time in the experiments, i.e. $\omega = \varepsilon^x / \varepsilon^*$.  

We integrate (1) under $\sigma = \text{const}$ to determine constants $B_\varepsilon, n$

$$
\varepsilon = \frac{B_\varepsilon}{B_\omega} \sigma^{n-k} \left( (1-(1+m)B_\omega \sigma^{k} t)^{1/(m+1)} -1 \right).
$$

(3)

and after taking the logarithm of the equation at the steady-state creep stage, we obtain the equation of a straight line in the $\ln(\sigma) - \ln(\dot{\varepsilon})$ plane:

$$
\ln \dot{\varepsilon} = \ln B + n \ln \sigma.
$$

(4)

Figure 2 presents the experimental data that are denoted by dots in the coordinates $\ln \sigma - \ln \dot{\varepsilon}$.
Figure 2. Experimental data 1-5 on the logarithmic plane correspond to fixed temperatures 700, 730, 750, 770 and 800°C respectively.

Having a group of experimental points (1-5) corresponding to fixed temperatures (700, 730, 750, 770 and 800°C respectively in Figure 2), can approximate experimental data of direct line in the plane \( \ln \sigma - \ln \varepsilon \) which integrally reflects the strain-strength behavior of the material corresponding to the temperatures. We believe that all the lines are parallel, i.e. the exponent \( n \) reflecting the slope of the lines, is temperature independent.

The softening coefficient \( m \) is determined after the experimental curves are reduced to a single curve by scaling of the strain and time to \( \varepsilon_* \) and \( t_* \) \([5–8]\). Similarly to the second equation (2), the constants \( B_\varepsilon \) and \( k \) are determined. All the creep constants of the material obtained using the system of equations (1) are indicated in Table 1.

| \( T_1, ^\circ \text{C} \) | \( B_\varepsilon, (\text{MPa}^{-n} \cdot \text{s}^{-1}) \) | \( B_\sigma, (\text{MPa}^{-k} \cdot \text{s}^{-1}) \) | \( n \) | \( k \) | \( m \) |
|---|---|---|---|---|---|
| 700 | \( 3.12 \cdot 10^{-15} \) | \( 2.09 \cdot 10^{-11} \) | 5.5 | 3.5 | 1.105 |
| 730 | \( 1.97 \cdot 10^{-14} \) | \( 3.97 \cdot 10^{-14} \) | 5.5 | 5.4 | 0.65 |
| 750 | \( 2.97 \cdot 10^{-14} \) | \( 6.04 \cdot 10^{-13} \) | 5.5 | 4.82 | 1.054 |
| 770 | \( 5.8 \cdot 10^{-14} \) | \( 1.39 \cdot 10^{-13} \) | 5.5 | 5.4 | 0.89 |
| 800 | \( 1.12 \cdot 10^{-13} \) | \( 2.39 \cdot 10^{-11} \) | 5.5 | 4.2 | 0.44 |

Figure 3 shows diagrams of the constants of creep in the form of strain versus the time when specimens are stretched under 700, 730, 750, 770 and 800°C. The dots denote experimental data, and the curves are obtained using the system of equations (1). It shows that with the use of the system (1) a satisfactory agreement of numerical and experimental data was obtained.

4. Analysis of an unsteady creep process of steel 09G2S
The experiments carried out confirmed that with deformations not exceeding 10%, the softening is insignificant. Comparison of the experiments carried out under a constant stress and piecewise constant stress indicates that the overload has a slight effect on the strain rate towards the rate increase.

Figure 4 presents the experiments under the constants stress (solid line) and the experiments with one stage–overload at the same values of the stress and temperatures (dash line) for different strain values at the time of the overload. It can be seen that the rate after the overload in comparison with the
stationary experiment increased insignificantly. This fact demonstrates that time is a weak softening factor.

![Creep diagrams for st. 09G2S at different temperatures](image)

**Figure 3.** Creep diagrams for st. 09G2S at different temperatures.

![Kinetic equations of creep and damage](image)

**Figure 4.** The influence of the overloading on strain rate: (a) under $\varepsilon \approx 2\%$; (b) under $\varepsilon \approx 5\%$.

Kinetic equations of creep and damage were applied to the description of the non-stationary process of the strain. To describe the non-stationary creep process [1, 2, 4, 6, 8, 12, 13] at the moments in time of overload with the stress $\sigma_1$ to the stress of $\sigma_2$, the parameter of damage $\omega_1 = 1 - (1 - \tau)^{\psi(m+1)}$ is determined by the constants of the softening material $m$ and the duration of experiment $\tau = t (m + 1) \psi(\omega)$. The deformation $\varepsilon = \omega_0 B_e(T)/B_e(T) \sigma^{\alpha_1} \varepsilon$ is calculated. When the overloading to the next level of loading $\sigma_2$, the process starts with the accumulated damage level $\omega_1$ and the corresponding time. The considered models are isotropic. The use of isotropic models to finite-strain transient creep was discussed in [14].

The results of 5 experiments and comparison of experimental (points) and numerical (solid curves) creep data with the overloads to other stress levels as temperatures range from 700 to 800°C are shown in Figure 5. Moments of overload are marked by vertical arrows.
The non-stationary experiments were carried out according to the following schemes:

a) starting with $\sigma_1 = 53.955$ MPa for $t < t_1$, $t_1 = 80$ min; at $t = t_1$ the overload up to $\sigma_2 = 58.86$ MPa with a holding time $t_2 = 30$ min; then after overload up to $\sigma_3 = 63.765$ MPa, the stresses are kept constant to destruction, total long-term experiment time $t_{e_1} \approx 4$ h;

b) starting with $\sigma_1 = 39.24$ MPa for $t < t_1$, $t_1 = 112$ min; at $t = t_1$ the overload up to $\sigma_2 = 58.86$ MPa, the stresses are kept constant to destruction, total long-term experiment time $t_{e_2} \approx 2.8$ h;

c) starting with $\sigma_1 = 34.335$ MPa for $t < t_1$, $t_1 = 120$ min; at $t = t_1$ the overload up to $\sigma_2 = 49.05$ MPa, the stresses are kept constant to destruction, total long-term experiment time $t_{e_3} \approx 3.13$ h;

d) starting with $\sigma_1 = 29.43$ MPa for $t < t_1$, $t_1 = 64$ min; at $t = t_1$ the overload up to $\sigma_2 = 34.335$ MPa with a holding time $t_2 = 51$ min, after the overload up to $\sigma_3 = 39.24$ MPa and during $t_3 = 8$ min then after overload up to $\sigma_4 = 42.183$ MPa the creep occurred to destruction, total long-term experiment time $t_{e_4} \approx 2.89$ h;

e) starting with $\sigma_1 = 24.525$ MPa for $t < t_1$, $t_1 = 115$ min; after the overload up to $\sigma_2 = 29.43$ MPa and during $t_2 = 46$ min, after the overload up to $\sigma_3 = 34.335$ MPa and during $t_3 = 30$ min, then after overload up to $\sigma_4 = 39.24$ MPa the creep occurred to destruction, total long-term experiment time $t_{e_5} \approx 3.79$ h.

Figure 5. Experimental (points) and approximation (curves) diagrams under non-stationary stress: (a) $T=700^\circ C$; (b) $T=730^\circ C$; (c) $T=750^\circ C$; (d) $T=770^\circ C$; (e) $T=800^\circ C$.

From the analysis of the primary creep curves obtained for all the tested specimens, it is observed that failure of material under steady-state conditions occurs when the creep strain $\varepsilon_c$ range of 55 to 75% is reached (Figure 3). The same limiting values $\varepsilon_c$ are observed under conditions of non-stationary regimes.
5. Conclusion
The material constants under steady-state loading conditions were identified to describe the unsteady creep process. Simulation of stationary and nonstationary creep processes with damage was carried out. A satisfactory agreement between numerical and experimental data was obtained.

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