Mater.Phys.Mech. 7 (2004) 72-78

# LONG-TERM STRENGTH PREDICTION FOR CHROMIUM-NICKEL AUSTENITIC STEELS BASED ON SHORT-TERM EXPERIMENTAL RESULTS

**S. A. Shesterikov [1], T. A. Beliakova [2], B. M. Voshedchenko [3], V. V. Kashelkin [3], I. A. Kuznetsova [3] and V. A. Yakovlev [4]**

[1] – Institute of Mechanics, Moscow State Lomonosov University, Michurinsky prospect, 1, 117234 Moscow Russia
[2] — Moscow State Lomonosov University, Vorobievy Gory, 119992 Moscow, Russia
[3] — Federal State United Organization "Krasnaiya Zvezda", Elektrolitnyi proezd, 1, 115230 Moscow, Russia
[4] — Federal State United Organization, Central Scientific Investigation Institute "Prometei", Shpalernaya str., 49, 193015 St. Petersburg, Russia

*Received: June 10, 2003*

**Abstract.** A method is proposed for the long-term strength predictions for chromium-nickel austenitic steels based on short-term experimental tests. The experimental data consists of a series of creep diagrams for various applied stresses and temperatures, as well as of the tentative values of the failure time. The long-term strength and creep experiments are illustrated by the results for the steel 08X16H11M3. The metallographical studies of the samples tested in long-term strength and creep experiments are carried out. The microstructure of the deformed sample metal and the failure nature are analysed for various temperature regimes.

Prevention of the creep failure for constructions exploited for a long time at extreme temperature and loading conditions is one of the actual problems of the fracture mechanics. Since carrying out the construction lifetime creep experiments is expensive and almost impossible technically, then long-term strength predictions, based on short experimental tests, become especially important.

The given method is based on the results of the paper [1], where general approaches to the long-term creep data analysis were developed using an entirely new description of the long-term strength diagram,

$$\lg t_r = D + 17\lg\sigma_b - n\lg\left[\frac{\sigma}{\sigma_b - \sigma}\right], \qquad (1)$$

where $t_r$ is the creep failure time (h), $\sigma_b$ is the conditional short-term ultimate strength (MPa), $\sigma$ is the applied stress during the loading (MPa), while $D$ and $n$ are constant parameters. The relation (1) is assumed to be applicable to long-term strength predictions based on short-term experimental tests.

Consideration of numerous experimental data shows [1] that the best description of a number of austenitic steels is achieved for $n = 4$ and $D = -39$. Thus the unknown parameter $\sigma_b$ is determined from Eq. (1) using the experimental tentative failure time $t_r$.

This method was tested for the four classes of austenitic stainless steels and the calculations demonstrated that the parameters of the basic relation (1) had been determined with a significant error, as a consequence of the limited experimental data as well as of the strongly dispersed values of the failure time for the samples under the same stress and temperature conditions.

Corresponding author: V. V. Kashelkin, e-mail: re.entry@g23.relcom.ru

Thus, in this paper, in order to validate the relation (1) up to 100000 h, it is proposed to determine the values of the parameters $D$, $n$, and $\sigma_b$ using the experimental data on the steady strain rate based on the results of the experiments with the duration of 1000 h. The data include a series of creep diagrams for different applied stresses at the temperatures 600, 650, and 700°, as well as the tentative values of the failure time.

The process of creep deformation under a fixed temperature can be described by the following relation [1]:

$$\dot{\varepsilon} = A\left(\frac{\sigma}{\sigma_b - \sigma}\right)^n, \tag{2}$$

where $A$ and $n$ are constants, $\dot{\varepsilon}$ being the steady creep strain rate. The range of the steady creep strain rates, $\dot{\varepsilon}_1$, $\dot{\varepsilon}_2$, $\dot{\varepsilon}_3$, for the three stress levels $\sigma_1$, $\sigma_2$ and $\sigma_3$ is defined from the initial part of the experimental creep curves, where the deformations do not exceed 10%. Applying Eq. (2) to the stress levels , and and excluding, by a suitable transformation, the constants and , one arrives at the relation:

$$\frac{\lg\left(\dfrac{\dot{\varepsilon}_1}{\dot{\varepsilon}_2}\right)}{\lg\left(\dfrac{\dot{\varepsilon}_2}{\dot{\varepsilon}_3}\right)} \cdot \frac{\lg\left(\dfrac{\sigma_2}{\sigma_1}\cdot\dfrac{\sigma_b - \sigma_3}{\sigma_b - \sigma_2}\right)}{\lg\left(\dfrac{\sigma_1}{\sigma_2}\cdot\dfrac{\sigma_b - \sigma_2}{\sigma_b - \sigma_1}\right)} = 1. \tag{3}$$

The constant $\sigma_b$ follows from Eq. (3) after substitution of the known stresses $\sigma_1$, $\sigma_2$ and $\sigma_3$ as well as of the steady strain rates $\dot{\varepsilon}_1$, $\dot{\varepsilon}_2$, $\dot{\varepsilon}_3$ determined from the experimental creep curves.

According to the relation (2), the parameter $n$ can be determined as

$$n = \frac{\lg\left(\dfrac{\dot{\varepsilon}_1}{\dot{\varepsilon}_2}\right)}{\lg\left(\dfrac{\sigma_1}{\sigma_2}\cdot\dfrac{\sigma_b - \sigma_2}{\sigma_b - \sigma_1}\right)}. \tag{4}$$

The relation (4) can be used to determine the parameter $n$ for a given value of $\sigma_b$. Then the parameter $D$ can be found from the Eq. (1) using the experimental failure times and the previously obtained values of $\sigma_b$ and $n$.

Eqs. (3)–(4) contain the creep strain rates $\dot{\varepsilon}_i$, $i = 1, 2, 3$. Because of the experimental creep data dispersion, only the allowed range for the evaluated strain rates can be determined. The explicit values used in further calculations should lie within this range. In the meantime, the following conditions are met: 1) the values of the parameter $\sigma_b$, defined from the Eq. (3), are actually permitted (according to the experimental stress data for short (less then 300 h) failure times); 2) such values of $\sigma_b$ depend monotonously on the temperature for the given material (the conditional short-term ultimate strength decreases with the increase of temperature); 3) the calculated creep rates $\dot{\varepsilon}_i$, $i = 1, 2, 3$, defined from the experimentally observed range, depend monotonously on the applied stress at fixed temperature (the strain rate increases with the decrease of the applied stress); 4) the values of the parameter $n$ obtained from Eq. (4) exceed or equal to 1; 5) the theoretical failure times $t_r^{teor}$, defined from Eq. (1) with the help of the determined values of the parameters $\sigma_b$, $D$, and $n$, are close to the experimental values $t_r$.

The relation (1) allows one to give theoretical predictions for creep failure times up to 100000 h.

The experimental and calculated data are presented in Tables 1–3. One can estimate the accuracy of the predictions comparing the theoretical and experimental values of the failure time for low applied stresses – the data which were not used to determine the constants $\sigma_b$, $D$, and $n$ ($\sigma$=135 MPa at the temperature 600°C, $\sigma$=100 MPa and $\sigma$=90 MPa at the temperature 650°C, and $\sigma$=55 MPa at the temperature 700°C). The significant deviation of the predicted times versus the experimental values at the temperature 650°C can be explained by strongly crossing intervals of the experimental failure times for the stress levels of 150 and 170 MPa. In case when the experimental diagrams include more than three levels of the applied stress,

**Table 1.** Long-term strength and creep test results for the steel 08X16H11M3.

| Temperature, ℃ | Applied stress σ, MPa | Failure time $t_r$, h | Relative extension, % | Relative contraction, % |
|---|---|---|---|---|
| 600 | 180 | 5680 | 38.6 | 62.1 |
| | | 5593* | 21.5 | 75.2 |
| | | 2918 | 67.0 | 79.7 |
| | | 2035 | 50.6 | 76.6 |
| | 200 | 2716* | 30.5 | 85.4 |
| | | 1879 | 50.6 | 76.6 |
| | | 1584* | 24.2 | 68.1 |
| | | 798 | 39.3 | 81.2 |
| | | 433 | 42.6 | 78.2 |
| | 250 | 458* | 54.3 | 68.3 |
| | | 266 | 48.3 | 75.0 |
| | | 187 | 41.0 | 71.6 |
| | | 178* | 32.6 | 60.1 |
| | | 88 | 38.0 | 74.9 |
| | 135 | 24937* | 61.8 | 56.3 |
| | 130 | 6255* | experiment in progress | |
| | | 5117 | experiment in progress | |
| 650 | 170 | 821* | 34.0 | 78.2 |
| | | 646* | 31.6 | 75.2 |
| | | 321 | 88.3 | 82.6 |
| | | 113 | 46.0 | 85.2 |
| | | 105 | 60.6 | 78.1 |
| | 150 | 1325* | 29.6 | 85.2 |
| | | 528* | 40.0 | 76.8 |
| | | 362 | 91.3 | 85.5 |
| | | 353 | 61.6 | 87.6 |
| | | 58 | 92.3 | 92.8 |
| | 140 | 2688* | 48.5 | 73.5 |
| | | 1727* | 36.5 | 80.1 |
| | | 1169* | 27.5 | 78.1 |
| | 110 | 6465 | experiment in progress | |
| | | 5253 | experiment in progress | |
| | 100 | 9525 | 41.3 | 55.9 |
| | 90 | 13466 | 19.3 | 19.3 |
| 700 | 120 | 432 | 105.3 | 85.4 |
| | | 399* | 58.5 | 83.3 |
| | | 254* | 24.5 | 83.3 |
| | | 188 | 108.6 | 88.8 |
| | | 174 | 89.3 | 85.3 |
| | 90 | 1774* | 64.0 | 70.8 |
| | | 1487* | 65.7 | 78.7 |
| | | 1133 | 60.6 | 78.2 |
| | 80 | 4797* | 59.0 | 48.1 |
| | | 3108* | 55.2 | 47.3 |
| | | 2985 | 47.0 | 62.0 |
| | 55 | 16256 | 29.7 | 46.4 |
| | | 13495* | 8.7 | 15.0 |

* — creep tests. The other results are from the long-term strength tests.

**Table 2.** Long-term strength and creep data processing for the steel 08X16H11M3.

| Tempera-ture, °C | Applied stress σ, MPa | Calculated value of the steady creep strain rate $\dot{\varepsilon} \cdot 10^{-2}$, $h^{-1}$ | $\sigma_b$ | *n* | *D* | Experimental failure time $t_r$, h | Predicted failure time $t_r^{teor}$, h |
|---|---|---|---|---|---|---|---|
| 600 | 180 | 0.0017 | 316 | 3.54 | -38.393 | 5680 | 4685.4 |
| | | | | | | 5593 | |
| | | | | | | 2918 | |
| | | | | | | 2035 | |
| | 200 | 0.004333 | | | | 2716 | 1837.5 |
| | | | | | | 1879 | |
| | | | | | | 1584 | |
| | | | | | | 798 | |
| | | | | | | 433 | |
| | 250 | 0.07 | | | | 458 | 113.3 |
| | | | | | | 266 | |
| | | | | | | 187 | |
| | | | | | | 178 | |
| | | | | | | 88 | |
| | 135 | – | | | | 24937 | 35684.6 |
| | 130 | – | | | | >6255** | 44915.6 |
| | | | | | | >5117** | |
| 650 | 170 | 0.02008 | 295 | 2.91 | -39.177 | 1821 | 263.8 |
| | | | | | | 646 | |
| | | | | | | 321 | |
| | | | | | | 113 | |
| | | | | | | 105 | |
| | 150 | 0.009055 | | | | 1325 | 584.8 |
| | | | | | | 528 | |
| | | | | | | 362 | |
| | | | | | | 353 | |
| | | | | | | 58 | |
| | 140 | 0.0061 | | | | 2688 | 868.0 |
| | | | | | | 1727 | |
| | | | | | | 1169 | |
| | 110 | – | | | | >6465** | 2930.2 |
| | | | | | | >5253** | |
| | 100 | – | | | | 9525 | 4506.9 |
| | 90 | – | | | | 13466 | 7083.3 |
| 700 | 120 | 0.085 | 195 | 3.27 | -35.8928 | 432 | 234.6 |
| | | | | | | | 399 |
| | | | | | | | 254 |
| | | | | | | | 188 |
| | | | | | | | 174 |
| | 90 | 0.011 | | | | 1774 | 1805.9 |
| | | | | | | 1487 | |
| | | | | | | 1133 | |
| | 80 | 0.005556 | | | | 4797 | 3574.1 |
| | | | | | | 3108 | |
| | | | | | | 2985 | |
| | 55 | – | | | | 16256 | 23154.8 |
| | | | | | | 13495 | |

** — experiment in progress

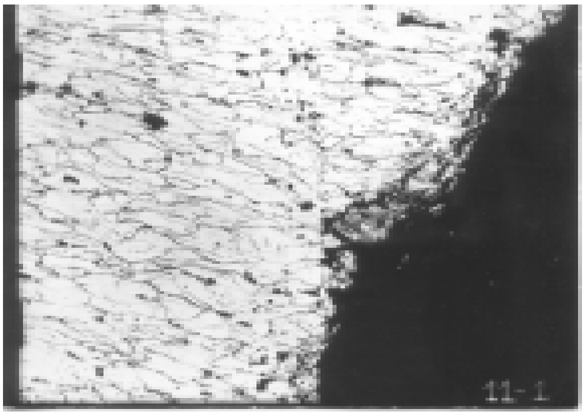
**Table 3**. Predicted values of applied stress at the fixed failure time for the steel 08X16H11M3.

| Temperature, °C | $\sigma_b$ | *n* | *D* | Failure time, h | Applied stress $\sigma$, MPa |
|---|---|---|---|---|---|
| 600 | 316 | 3.54 | -38.393 | 1000 | 212 |
| | | | | 10000 | 163 |
| | | | | 100000 | 113 |
| 650 | 295 | 2.91 | -39.1771 | 1000 | 136 |
| | | | | 10000 | 83 |
| | | | | 100000 | 44 |
| 700 | 195 | 3.27 | -35.8928 | 1000 | 99 |
| | | | | 10000 | 66 |
| | | | | 100000 | 39 |

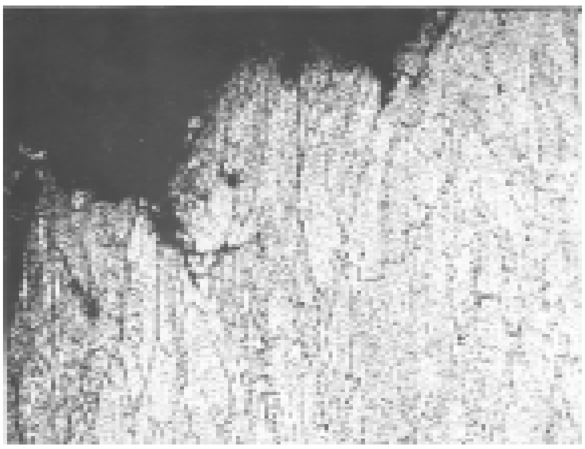
the parameters $\sigma_b$, *n*, and *D*, as well as the predicted failure times, can be determined with a higher precision using the whole set of experimental data.

The long-term strength prediction for a material is known to be most precise when its failure nature is the same for various failure times. It is observed in [2–5] that there are four types of failure for the austenitic chromium-nickel steels:

– the trans-crystallite failure;
– the triple-point crack initiation failure (junctions of three crystallite boundaries);
– the crystallite boundary pores failure;



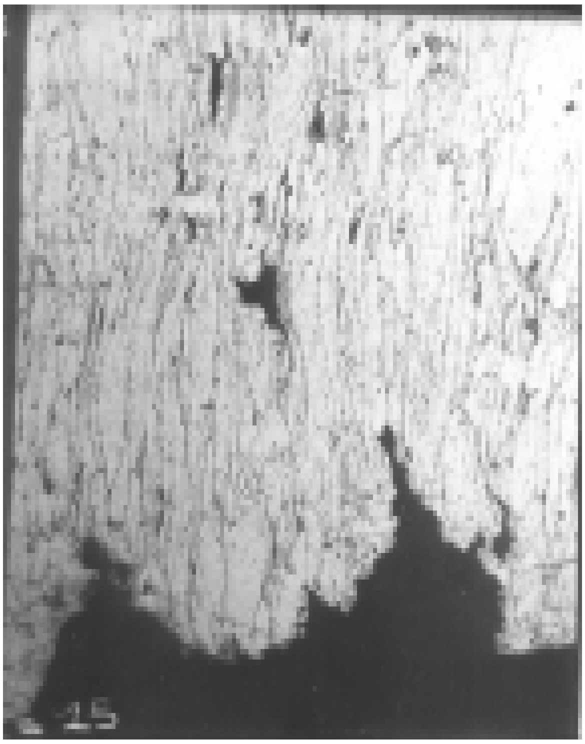

a)



c)

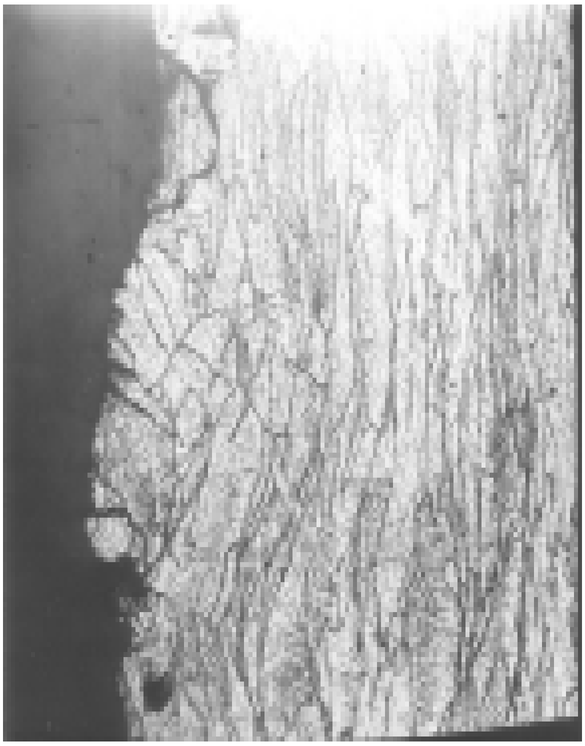

b)

**Fig. 1.** The microstructure of the failure areas of the samples tested at $T$ = 600 °C for 187 h (a), 5593 h (b), 24937 h (c).



a)

b)



c)

**Fig. 1.** The microstructure of the samples tested at *T* = 650 °C for 113 h (a), 1727 h (b), 1727 h (c; lateral surface).

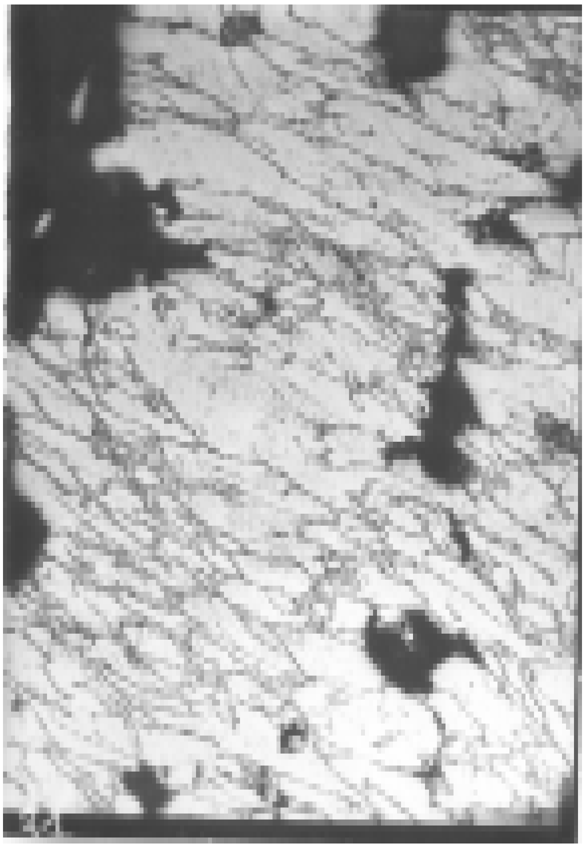


**Fig. 3.** The microstructure of the samples tested at *T* = 700 °C during 2985 h.

– the inter-crystallites failure (the failure through the interface surfaces of intermetallide – σ or λ and austenitic matrix).

The metallographical studies of the samples, tested in long-term strength and creep experiments, demonstrated that the microstructure of the undeformed sample metal (the head part), which had been tested under various temperature regimes, was the austenitic structure with the emission, at the boundaries and inside the crystallite, of chromium carbide, mainly and intermetallide combinations.

The viscous failure is observed in all aforementioned cases, the austenitic crystallites are deformed in the direction of the applied stress and with stronger deformations for larger rupture times and higher test temperatures, with the exception of the experiment with the applied load of 55 MPa and at temperature of 700°C. The failure has a transcrystallytic nature above the temperature of 600°C, pores appear in the failure area after a short test time (187 h) (Fig. 1). Above the temperature of 650°C, the failure nature is also transcrystallytic and, after a shorter experiment (113 h), the discontinuities are observed at the crystallite boundaries (Fig. 2). Failure occurs along the crystallite boundaries and through highly extended austenitic crystallites at temperature above 700°C (fig. 3). According to Fig. 3, there must be intermetallide combinations, as nearly continuous lines, along the crystallite boundaries.

## ACKNOWLEDGEMENTS

The work was supported by the Russian Foundation for Basic Research (grant N 03–1–06042).

## REFERENCES

[1] A. P. Arshakuni and S. A. Shesterikov // *Mechanics of Solids.* N 3 (1994) 224.
[2] Le May // *Theoretical grounds of engineering calculations.* **101**, N 4 (1979) 19.
[3] I. Chadek, *Creep in metal materials* (M.: Mir, 1987).
[4] N. Shinya, H. Tanaka, M. J. Murata // *Iron and Steel Inst. of Japan.* **71,** N 1 (1985) 114.
[5] H. J. Frost and M. F. Ashby, *Deformation mechanism maps.* (Pergamon Press, Oxford-New York-Toronto-Sydney-Paris-Frankfurt, 1982).