THE LIMITING STATE OF STRUCTURE-STABLE STEEL
UNDER CREEP CONDITIONS FOR INTENSE IRRADIATION
I. STUDY OF THE APPLICABILITY OF LIMITING-STATE FUNCTIONS
TO Kh16N15M3B STEEL UNDER REACTOR IRRADIATION CONDITIONS

V. N. Kiselevskii, V. K. Lukashev, B. D. Kosov, and G. P. Khristov

UDC 539.4:535.23

The experimental data obtained in [1] on the long-term strength of Kh16N15M3B steel for various forms of stressed state enabled the existing criteria of long-term strength to be compared in order to determine the extent to which they are applicable to describing the fracture of irradiated steel.

When estimating the long-term strength of complex-stressed structural elements (the criteria of long-term strength) the number of limiting-state functions is relatively small at present. In particular, a function of the maximum principal stress [2-6], the octahedral tangential stress (stress intensity) [7-10], the half sum of the stress intensities and the maximum principal stress [11, 12] are used, each of which has been confirmed experimentally for certain types of materials and load conditions.

In [13-15] the concept of a generalized criterion of long-term strength is introduced, according to which

\[ \sigma_{eq} = \chi \sigma_i + (1 - \chi) \sigma_A \lambda^{-j}; \]

\[ j = -\frac{3(\sigma_1 + \sigma_2 + \sigma_3)}{\sigma_1}, \]

where \( \sigma_{eq} \) is the stress which for uniaxial loading leads to fracture over the same time as a given three-dimensional combination of stresses having an intensity \( \sigma_i \) and a maximum principal stress \( \sigma_i \) (\( \sigma_1 > \sigma_2 > \sigma_3 \)).

The constant \( A \), which depends on the nature of the defects present in the materials, and the constant \( \chi \), which reflects the rate of the shear processes in the development of fracture, are determined experimentally.

The results of many experimental tests showed good agreement between Eq. (1) and the test data, both for short-term and long-term static and dynamic loads, for various types of materials under various conditions of the action of temperature [14].

However, when processing certain data on the long-term strength of stainless steels and alloys for the complex stressed state it has been established that the constant \( \chi \) depends on the time to fracture [16]. A tendency has been noted towards both an increase and a decrease in the quantity \( \chi \) with an increase in lifetime. This allows us to suggest that the constant \( \chi \) reflects not only the role of one or other of the mechanisms in the preparation of a microfracture but is also a certain quantitative criterion, in which a variation reflects the kinetics of structural transformations in the material. If this point of view is taken as valid then it may be concluded that neutron irradiation, which has a drastic effect on the kinetics of structural transformations, should appear as a variation in the constants cited.

Under normal deformation conditions a variation in the constant \( \chi \) is relatively small so that averaging it does not lead to substantial errors in determining the lifetime of the material on the basis of...
Fig. 1. Dependence of $\chi$ on time to fracture: 1) $\sigma_1/\sigma_3 = -1$ and $\infty$; 2) $\sigma_1/\sigma_3 = -3.3$ and $\infty$.

10^3 - 10^4 h. The intensity of the variation in $\chi$ under irradiation should vary sharply, which may increase the error cited or make it necessary to introduce into Eq. (1) instead of the constants certain functions which reflect the action of irradiation on the kinetics of the structural transformations. However, as was shown in [1], the effect of irradiation on the strength and deformation properties of steel, and consequently on its structure, is not unique and is caused by a form of stressed state. Therefore, for complex-stressed materials irradiated during loading, the definition of the quantity $\chi$ as a constant of the material independent of the type of stressed state may be found to be either impossible or leading to large errors in the calculation of $\sigma_{eq}$. Since applicable functions of the limiting state are a particular case of the generalized criterion (1), their use in calculations of the lifetime of irradiated structures definitely requires caution and an experimental justification.

From the experimental data presented in [1] the values of $\chi$ for Kh16N15M3B steel were calculated, which confirmed the proposed suppositions.

Figure 1 shows the dependence of $\chi$ on time to fracture for normal and radiation loading conditions. The constant $A$ is taken as 0.75 [17]. For normal loading conditions, irrespective of the pair of stressed states selected, the values of $\chi$ can be assigned to a single function $\chi(t)$ with a definite degree of error. This indicates, on the one hand, a slight divergence in the kinetics of structural transformations for various types of stressed state. On the other hand, it predetermines a satisfactory agreement between Eq. (1) and the experimental data. Figure 2 shows the results from studying the long-term strength of Kh16-N15M3B steel for the complex stressed state under normal loading conditions, processed according to Eq. (1) and other criteria applicable to long-term strength. The extent to which the experimental points corresponding to tests on complex-stressed specimens deviate from the long-term strength curve obtained for uniaxial extension (continuous line) indicates the degree to which the various long-term strength criteria are valid. The comparison showed that Eq. (1) has the highest degree of invariance relative to the type of stressed state.

By analyzing the relative position of the points corresponding to the values of $\chi$ determined when the data from radiation experiments are used (see Fig. 1) for $\sigma_1/\sigma_3 = \infty$ and $\sigma_1/\sigma_3 = -3.3$, and also of points corresponding to the variant $\sigma_1/\sigma_3 = \infty$ and $\sigma_1/\sigma_3 = -1$, it can be verified that reactor irradiation alters the kinetics of the structural state as a function of the type of stressed state. In contrast to the results obtained under normal loading conditions, for irradiation the values of $\chi$ found experimentally for two of the variants cited above in the choice of ratio of the principal stresses cannot be approximated to a single function. Consequently, Eq. (1) cannot be used because the constant $\chi$ lost the invariance of a relative form of stressed state.

Figure 3 presents a comparison of the criteria of long-term strength for irradiated Kh16N15M3B steel [1]. The degree of stratification in the experimental points corresponding to various $\sigma_1/\sigma_3$ ratios showed that not one of the criteria considered can be applied to calculating the equivalent stress with sufficient accuracy. The rather better agreement of the criterion in the form of stress intensity would seem to be fortuitous since this criterion is a particular case of Eq. (1) for $\chi = 1$. However, such a conclusion requires further testing because it may be found that the ambiguous connection between the constant $\chi$ and the kinetics of substantial structural transformations caused by irradiation, impairs the invariance of Eq. (1) compared with the criterion in the form of stress intensity.

Furthermore, if we turn to well-known literature data on the creep of steels in the complex stressed state under normal conditions [2-6, 18, 19], then an anomalous deformation is generally noted in them for torsion ($\sigma_1/\sigma_3 = -1$). Taking the natural connection between creep and long-term fracture into account, it can be suggested that the action of radiation amplifies this anomaly in the long-term torsion strength of the investigated steel which, in turn, makes it impossible to determine the constant $\chi$ in Eq. (1) uniquely.

Therefore an additional investigation was conducted into the long-term strength of Kh16N15M3B steel under reactor irradiation conditions for a ratio $\sigma_1/\sigma_3 = -1.5$, so that account was not taken of the experimental data obtained for torsion when calculating the value of $\sigma_{eq}$. 

1471