STATISTICAL ASSESSMENT OF THE RELIABILITY OF PREDICTION OF THE FATIGUE STRENGTH OF ALLOY KhN55MVTs USING A TEMPERATURE-TIME RELATIONSHIP

B. N. Sinaiskii and A. D. Pogrebnyak

A procedure is presented for statistical assessment of the reliability of the prediction of the cyclic longevity of a high-temperature alloy using Fisher's variance ratio and the Student t-test. It is demonstrated on the example of the high-temperature alloy KhN55MVTs that when certain conditions are met, a phenomenological type of temperature-time relationship ensures statistically reliable prediction of cyclic longevity under multicycle fatigue.

Introduction. Extension of the remaining life of power plants and complication of operating conditions are increasing the volumes of experimental investigations and expenditures for these investigations markedly to obtain characteristic features of the endurance of high-temperature materials on bases comparable to the remaining life of the plants (5000-10,000 h). This results in the need to develop methods of predicting the cyclic longevity of materials under high operating temperatures.

At the present time, analytical relationships based on temperature-time approaches are widely used to predict the long-term-strength and creep curves of metallic materials at high temperatures [1-3]. These equations make it possible to obtain a single relationship between stress, time to failure, and test temperature (or their parameters); this enables us to solve prediction problems, having determined the coefficients of a single curve and using experimental data for several temperatures on a limited base. The proposition that in certain temperature-time intervals, the same physical processes that determine the damage sustained by materials take place at higher rates and, correspondingly, in shorter times at higher temperatures is the basis of longevity prediction using the temperature-time approach. Having determined the coefficients of a single temperature-time relationship on a limited base, but with the use of data obtained at higher temperatures, this provides grounds for us to predict longevity up to failure under stresses acting for prolonged periods, but at lower temperature levels. In that case, it is necessary to consider the boundaries of temperature-time intervals with similar damaging processes.

The problem of the temperature-time description of the multicycle-fatigue strength of high-temperature metallic materials at high temperatures is not as well understood. It was established previously [4-8] that the process of fatigue damage and failure of high-temperature nickel alloys in the case of multicycle loading (including a symmetric cycle), which takes place during thermal activation, is carried out with participation of micromechanisms characteristic of creep. Thermally activated processes affect the pattern of microplastic deformation and the initiation and development of fatigue cracking. This makes it possible to describe multicycle-fatigue curves for high temperatures and longevities by temperature-time relationships used to describe long-term strength and creep. The existence of similar temperature-time relationships, which have the same physical nature and which satisfactorily describe experimental data for different types of material tests, including long-term strength, creep, and multicycle-fatigue tests, is also pointed out in [9].

A temperature interval with a correct description of the fatigue-strength curve by temperature-time relationships is selected in [4-6]. It is established on the basis of reduction of a large volume of experimental data that in selecting a temperature interval above the threshold temperature $T_{thr}$ (equal to approximately $(0.55-0.6)T_{mel}$), where thermally activated processes play a principal role, a satisfactory description of the multicycle fatigue strength of high-temperature nickel alloys is provided by temperature-time relationships.


Mathematical processing of experimental data on the multicycle-fatigue strength of high-temperature nickel alloys Éi867, ZhS6U, and VZhL12U in the interval of temperatures above the threshold temperature $T_{th}$ and longevities of $10^4$-$10^9$ cycles suggests that the indicated characteristics are satisfactorily described by Larson—Miller, Sherby—Dorn, and Manson—Sakkop parametric relationships and by an equation of the temperature-time dependence of strength [2, 5, 6]. Preference is given to a phenomenological type of temperature-time equation [2], which does not require preliminary assessment of the feasibility of its use and demonstrates stability in approximating the experimental data under consideration. Based on the indicated temperature-time equation, Sinaiskii [7] proposes a temperature-time relationship, which also makes it possible to approximate and extrapolate curves of the multicycle-fatigue strength of high-temperature alloys in the case of different temperatures and loading frequencies in fulfilling the condition $T_{test} > T_{th}$.

The purpose of the present study is to develop a procedure for statistical assessment of the reliability of the prediction of multicycle-fatigue-strength curves using a temperature-time equation and its testing on a high-temperature nickel alloy.

Subject of Investigation. The nickel-base alloy KhN55MVTs, which is intended for use in high-temperature power plants, served as the subject of investigation [10]. A distinguishing feature of the alloy under investigation is its high ductility—the relative elongation on rupture reaches 50-60% in the temperature range from 293 to 1073 K. Stability of the structural state under long-term high-temperature effects is also characteristic of this alloy. Characteristics of the static strength and ductility of alloy KhN55MVTs at various temperatures are presented in Table 1.

Procedure and Results of Investigations. As has been pointed out, Sinaiskii [5-7] has used a temperature-time relationship satisfactorily to approximate and predict the multicycle-fatigue strength of high-temperature alloys. The equation, which is modified as applies to cyclic loading in a form convenient for processing on a computer, can be written as follows:

$$
\lg N_R = A + M \lg T - N \lg \sigma_a + BT^{-1} - CT^{-1} \sigma_a^3,
$$

where $N_R$ is the number of cycles to failure, $\sigma_a$ is the peak of the variable stress in MPa, $T$ is the temperature in K, and $A$, $M$, $N$, $B$, and $C$ are coefficients subject to determination.

Experimental data on the fatigue strength of alloy KhN55MVTs, which were obtained under tension-compression in the form of fatigue curves for four-six stress levels, four temperatures within the interval from 1023 to 1273 K, and longevities ranging from $10^4$ to $10^8$ cycles (approximately 1-1000 h) and under bending with rotation in the form of fatigue curves for five-eight stress levels, four temperatures within the interval from 1023 to 1273 K, and longevities ranging from $5 \cdot 10^4$ to $2 \cdot 10^7$ cycles (approximately 0.5-100 h) were used as initial data for the calculations. Curves of multicycle fatigue strength were obtained on MIR-ST and UIT machines under tension-compression and bending with rotation, respectively [4].

The coefficients in (1) were determined on a computer by an exhaustive search of the values by the method of least squares based on a minimum of computational dispersion in processing the above-indicated mass of data. Proceeding from preliminary testing [2, 5], the coefficient $M$ was assumed constant ($M = 2$); this facilitated determination of the other coefficients.

The following equations were derived as a result of the calculation:

for tension-compression:

an approximating equation for a test base of $10^8$ cycles

$$
\lg N_R = -8.508 + 2.01 \lg T - 2.964 \lg \sigma_a + 181607^{-1} - 2.415 \cdot 10^{-4} T^{-1} \sigma_a^3;
$$

an equation for prediction using limited results on a test base of $10^7$ cycles

### Table 1. Mechanical Properties of Alloy KhN55MVTs

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Temperature, K</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>293</td>
</tr>
<tr>
<td>$\sigma_s$, MPa</td>
<td>600...700</td>
</tr>
<tr>
<td>$\sigma_{0.2}$, MPa</td>
<td>245...340</td>
</tr>
<tr>
<td>$\delta$, %</td>
<td>40...45</td>
</tr>
<tr>
<td>$\psi$, %</td>
<td>65...75</td>
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