It is necessary to quantitatively consider the changes in structure during long-term use at high temperatures in order to evaluate and control the strength parameters of the structurally unstable heat-resisting nickel alloys widely used in transportation gas turbines.

The main methods of improving the stability of these complex nickel alloys and of evaluating the strength parameters are based on examining the aging kinetics, particularly with regard to the strength characteristics [1, 2]. Much attention has recently been given to the experimental and theoretical aspects of evaluating the effects of temperature and time on the structure parameters and the strength.

Here we examine experimental data on the structure and strength of a heat-resisting alloy to establish correlations between these, and we consider evaluation and forecasting of structure characteristics, short-term static strength, and fatigue resistance for heat-resisting nickel alloys in relation to the temperatures and times of use in gas-turbine engines. We used deformed nickel alloy Е1867, in which the hardening phase is indicated by x-ray structure analysis as being based on the intermetallide Na3Al, which has a small structural discrepancy (ε = -0.25) and constitutes a large fraction of the volume (about 60%) [3].

The effects of the aging on the strength parameters were examined under long-term isothermal cyclic loading in the range 600-950°C.

X-ray structural analysis and electron microscopy showed that the structural discrepancy and volume proportion of the primary grains of the γ' phase hardly altered during long-term aging and cyclic loading, while the basic variable characteristic of the hardening phase was the degree of dispersion, which was estimated from the change in mean particle size at high temperatures. The structural characteristics of the dispersed phase were examined with a UEMV-100K electron microscope. Statistical processing of the electron micrographs gave the arithmetic mean particle size, the standard deviation, the coefficient of variation, and histograms, from which the theoretical size distribution was derived.

There are three stages in the change in the short-term static strength and fatigue resistance, which are related to the dispersion of the hardening phase [3, 4]. When the material is exposed to temperatures below 0.6T_{mp} (600-800°C) for up to 4000 h, the material hardens, with increases of 15% in the ultimate strength, yield point, and fatigue resistance, while the plasticity falls by 70-80%; the hardening effect is associated with further deposition of the γ' phase and slight change in the size of the primary particles. The coherent particles of the hardening phase are still capable of producing a system of resistance points to the movement of dislocations, which form largely immobile nets in the solid solution (Fig. 1a and b).

The region of high working temperatures extends above 0.6T_{mp} (900-950°C) and is characterized by softening of the material and reduction in the above strength characteristics by 20-25%, with a simultaneous increase in the plasticity. In this temperature range, the reduction in the strength and increase in the plasticity are typical of a dispersion-hardened system, since they are due to coagulation of the hardening phase and a marked increase in the mean particle size.

The increase in mean particle size at high temperatures is accompanied by a reduction in the number of particles per unit area (Fig. 1c). A difference from temperatures below 0.6T_{mp} is that the size distribution deviates from the normal distribution (Fig. 2), which is characteristic of the diffusion-coalescence mechanism [1, 2, 5]. In particular, the γ' phase coalesces in Е1867 by the diffusion absorption of one particle by another.
Fig. 1. Microstructure of EI867 alloy after typical heat treatment (a), typical heat treatment and fatigue testing at 800°C, N = 10^8 cycles (b), and at 950°C, N = 2 \times 10^7 cycles (c).

One can obtain quantitative data on the enlargement of the dispersed phase in relation to temperature by examining the structure. In the softening stage, a linear relationship applies with the power of 1/3 (Fig. 3) for the change in size of the γ' phase when the coordinate system is the mean linear dimension versus time, in accordance with the general theories of diffusion growth [5-7]. This approximation is characteristic for the aging-time dependence of the grain size and also of the fatigue resistance, since it has been found that the nature of the aging in heat-resisting nickel alloys does not alter during prolonged high-temperature cyclic loading. The coalescence of the γ'-phase particles under these conditions is also controlled by diffusion, but it occurs at a higher rate when there are alternating stresses. The following equations [5] give the particle size in relation to temperature and time:

\[ \bar{a}^2 - \bar{a}_0^2 = K_T, \]  
\[ K = K_0 e^{-\frac{Q}{R_T}}, \]  

where K is the diffusion-growth constant; \( K_0 \), preexponential factor; Q, activation energy for coalescence; and \( R_T \), gas constant.

These functional relationships allow one to calculate the diffusion-growth constant and the activation energy. The first is determined from the slope of the observed relationship against aging or cyclic-loading time (Fig. 3).

The activation energy for the coalescence of the γ' phase was calculated from the observed temperature dependence of the time required to attain a certain particle size [8] in accordance with

\[ Q = R \ln \frac{\tau_n - \tau_{n-1}}{\tau_n^2 - \tau_{n-1}^2}. \]  

Values found for the activation energy for the γ' phase and isothermal cyclic loading are in agreement with published data: for nickel-aluminum alloy the energy is close to the activation energy for diffusion of aluminum in nickel (Q is 64.4 kcal/g-mole [6]). EI867 is an alloy with elements such as molybdenum, tungsten, and cobalt, which retard the diffusion and increase the activation energy.

The diffusion-growth constant and the activation energy (Table 1) are initial data for evaluating and forecasting the structure parameters, and therefore for evaluating the strength properties in relation to temperature and time.

Variations in the strength characteristics were examined from the viewpoint of the main hardening mechanisms for dispersion-hardening systems on the basis of the principal structural factors.

The strength change in a dispersion-hardened system at high temperatures is determined mainly by the changes in the elastic constants of the alloy and in the microstructure: the size and distribution of the dispersed-phase particles.

On high-temperature short-term static loading of EI867 in the initial structural state, where the γ' phase has a particle size of 110-130 Å, the yield point varies with temperature in accordance with the Ansell-Lenel equation [9]:

\[ \sigma_T = \frac{\mu a_d}{4\varepsilon}, \]