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Evolution of Discrete Phenomena of Inelasticity in Aluminum Alloy under Cyclic Loading

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An approach has been developed that allows assessing inelastic phenomena in a material based on the parameter of the phase shift angle distribution between the stress and strain, which is measured in local zones on the surface of the investigated material. The distribution of the phase shift angle variance in the service life range investigated allows tracing the kinetics of the discrete phenomena of inelasticity in the material studied.

Keywords: inelasticity, high-cycle fatigue, damageability, hardening, softening.

Introduction. Investigations on the dynamics of the discrete phenomena of structure evolution in local volumes of the material under cyclic deformation are aimed at determining the relationship between these phenomena and changes in the material mechanical properties, and describing the laws of damageability within its lifetime range prior to the initiation of the main crack. Contemporary works on physical metallurgy consider the process of material deformation and fracture as a dynamically non-linear system, which is connected with the environment by means of the information exchange [1]. In order to describe the changes in the material structure in quantitative terms with a view to assess its system characteristics at various stages of damage accumulation, mathematical approaches are used, which include multifractal parameterization of the structure [2, 3]. Special attention is paid to the near-surface layer of the metal as the place of fracture initiation, with the emphasis in most cases [4] on the difference in the rates of self-organization of micro- and mesostructures (self-similarity and hierarchical nature of the processes) in the near-surface layers and internal volumes.

It is shown in [5, 6] that the process of plastic deformation taking place at a microlevel under cyclic loading is characterized by regular stage-like nature. The results of the investigations of inelasticity variation within the high-cycle fatigue region [7–9] show that traditional concepts of the scattered damage progressing in stages in metals and alloys at a macrolevel can be extended by taking into account the scale level of the analysis of inelastic processes of material deformation which reveal stochastic peculiarities at the microstructural level. This approach is of current importance considering the fact that the characteristics of inelastic processes in the material that were obtained on the basis of the integral assessment do not reflect the discrete character of the material damageability under cyclic deformation [10].

The aim of this work is to investigate the kinetics of the discrete phenomena of inelasticity in the aluminum alloy under cyclic deformation in the high-cycle fatigue region.

Experimental Methods. Changes in inelasticity were investigated during fatigue tests of cylindrical specimens with 7.5 mm diameter under axial tension–compression on a magnetostrictive setup with the loading frequency of 20 kHz and a symmetrical cycle. Cyclic loading of up to $5 \cdot 10^8$ cycles was applied at that enabling to assess the kinetics of discrete manifestations of inelasticity in the studied alloy before the initiation of the main crack. This paper presents the results of investigations of the kinetics of inelasticity in the aluminum alloy with due account of the frequency characteristics of the phase shift distribution between the stress and strain which is measured in local volumes of the material (for grain clusters) on the working surface of the specimen using the method described in [9].

The kinetics of the material inelasticity was evaluated taking into account the changes in the value of the generalized energy dissipation parameter at a steady stress state initiated in the zone of contact interaction between the gauge and the specimen surface. The changes in the generalized parameter were attributed to the evolution of the material microstructure in the specimen surface zone studied. Upon termination of certain stages of the fatigue tests, statistically representative samples of the values of the energy dissipation parameter corresponding to a certain specimen loading time were obtained for each stage individually. Kinetic dependencies of the measured parameter were analyzed taking into account relative variance of the parameter values reflecting the discrete character of the inelasticity changes in the process of cyclic loading.

Experimental Results. The kinetics of the material inelasticity was investigated on the specimens made of aluminum alloy. For each of the three cyclic stress levels applied, the kinetic damage accumulation curves were plotted in the coordinate system, where the X-axis shows the number of the load cycles and the Y-axis shows the relative variance of the generalized inelasticity parameter (Fig. 1). The non-monotonous character of the curves with irregular alternation of the maxima and minima demonstrates the stochastic regularity representative of a stationary random process of structural evolution of a non-uniform dissipative system which is the material under study. These regularities include:

(i) a decrease in the frequency of the maxima and minima occurrence on the kinetic damage accumulation curves plotted for low amplitudes of cyclic stresses;

(ii) an increase in the amplitude values of the generalized inelasticity parameter as the material exhausts its plasticity at the stages of specimen nonlocalized damage.

As seen from the curves in Fig. 1, the energy dissipation decreases during the initial period of loading which is evidenced by the material hardening [5] resulting from the ordering of microstructure, redistribution of local overstressed zones throughout the specimen volume, and homogenization of the material [6]. During local assessment, this process is characterized by a decrease in the normalized value of the variance, as compared to that for the material in the initial state, and corresponds to the cyclic hardening of the alloy on the initial part of the generalized fatigue curve during the integral assessment of the material inelasticity characteristic [11].

At the initial stage of loading, the presented curves show lowering of the kinetic characteristic to some minimum value that may be connected with the material hardening (the aluminum alloy studied belongs to the cyclically hardening materials). On the curves given in Fig. 1, the point corresponding to such an extremum is designated by digit 1. With an increase in the cyclic stress amplitude in the course of fatigue tests, a more intensive accumulation of damages takes place in the alloy structure within one load cycle, which is evidenced by the displacement of the first extremum point towards the smaller number of the operating cycles.

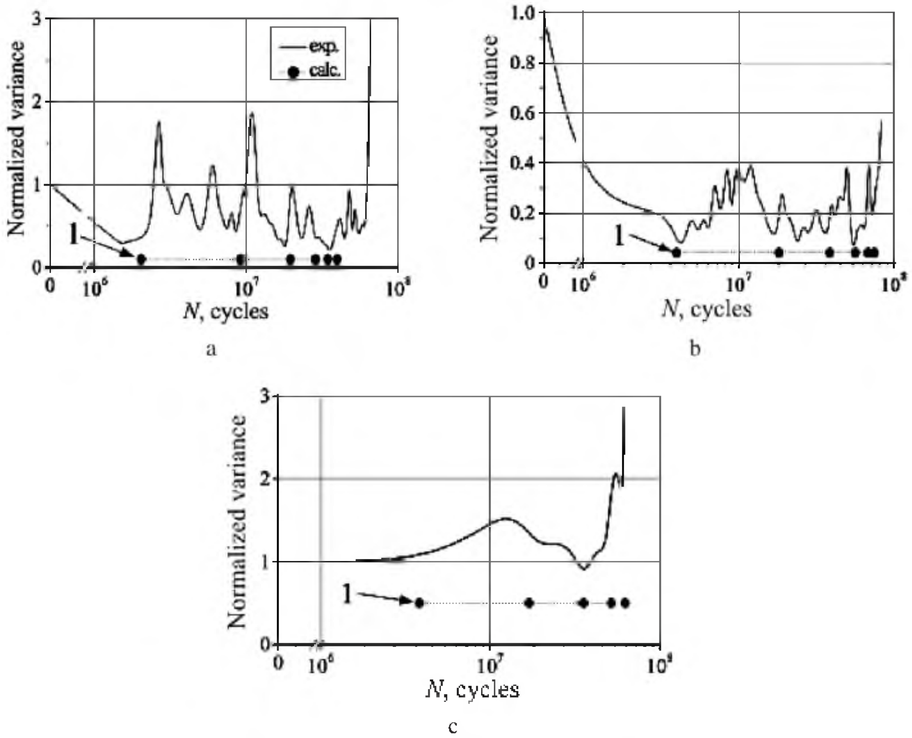

Fig. 1. Kinetic diagrams of the generalized parameter of local inelasticity for different cyclic stress amplitudes [(a) $\sigma_a = 83.4$ MPa; (b) $\sigma_a = 73$ MPa; (c) $\sigma_a = 65.3$ MPa].

The authors of [10] present their interpretation of the discrete events of structural evolution of a fatigued polycrystalline material similar to those considered in this paper, and revealed by the kinetic characteristics of microhardness of alloy D16T subjected to cyclic deformation at a stress of 159 MPa. The experimental results summarized there account for the complexity of the revealed dependence of the series of macrohardness peaks on the number of operating cycles characterizing this complexity by different level of stability against the influence of cyclic deformation regimes shown by certain alloy components (Al, Cu, Mg). The kinetic characteristics presented in Fig. 1 are their analogues expressed by changes in the dissipative properties.

According to the conclusions concerning the behavior of a dissipative system in fatigue as presented in [11], the material hardening process is governed by certain laws. First of all, this process is characterized by the discreteness of the material hardening events with subsequent softening that occur periodically and whose behavior is close to that described in [10]. According to the aforementioned, the first event of significant manifestation of the changes in the properties of the fatigued polycrystalline material (bifurcation of dissipative structure) occurs when the material reaches the state of ultimate plasticity [7] and is a random quantity. Its position on the lifetime scale corresponds to the periodicity of the series of the material hardening-softening events succeeding each other to fracture. Their position corresponds to the material capacity to resist fatigue in accordance with the law described using the series of Ivanova [11]:

$$\frac{N_i}{N_{i+1}} = \Delta^{1/n},$$

where Δ is a dimensionless universal constant of fracture, N_i is the number of cycles corresponding to the ith extremum, and $n = 1, 2, 4, 8, \ldots$. According to [11], the constant Δ characterizes the energy state of the material local volume by analogy with the process of melting. This constant is believed to be practically independent of the modifications in the metal chemical composition at room temperature and, therefore, its value was taken to be $\Delta \approx 0.22$ for aluminum alloys.

On the diagrams in Fig. 1, the calculated series is shown on a conventional horizontal line by solid symbols and is compared to the experimental values of the minima on the curves. The results of comparison are listed in Table 1.

Table 1

Comparison of the Recurrent Series Value with the Experimental Values of the First Extremum on the Kinetic Curves of Damageability

σ_a, MPa	83.4	73.0	65.3
N_{1calc}, cycles	$2.01 \cdot 10^6$	$4.50 \cdot 10^6$	$3.81 \cdot 10^6$
N_{1exp}, cycles	$1.51 \cdot 10^6$	$4.00 \cdot 10^6$	$5.60 \cdot 10^6$
δ, %	26.0	7.1	31.9

In Table 1: σ_a is the amplitude of cyclic stresses, N_{1calc} is the number of cycles corresponding to the first calculated member of the recurrent series, N_{1exp} is the number of cycles corresponding to the first extremum on the curve, and δ is the conformity error between the first extremum on the curve and the calculated number of cycles.

The task of the calculation was to find the first value of the number of operating cycles which corresponds to the first point of bifurcation. To do so, the number of cycles corresponding to the first minimum on the curve was taken as such in the first approximation. Next, the whole series was calculated for this value. By comparing the obtained estimated life values of the series and the experimental ones, a standard error was determined which was used to specify the accuracy of the estimated life value. The calculation continued until the minimal generalized error δ between the estimated and experimental values was reached. Comparison of the number of cycles corresponding to the hardening extrema on the kinetic diagram (Fig. 1) in the service life range to macrocrack initiation and the members of the recurrent series calculated from the above formula is shown in Fig. 2.

The graphs show a good agreement between the experimental data and the calculated results. Therefore, the appearance of the extrema on the kinetic curves, which are similar to those shown in Fig. 1, may adequately reflect the kinetics of structural changes in the material of an elastic-plastic body under conditions of non-localized fatigue damage.

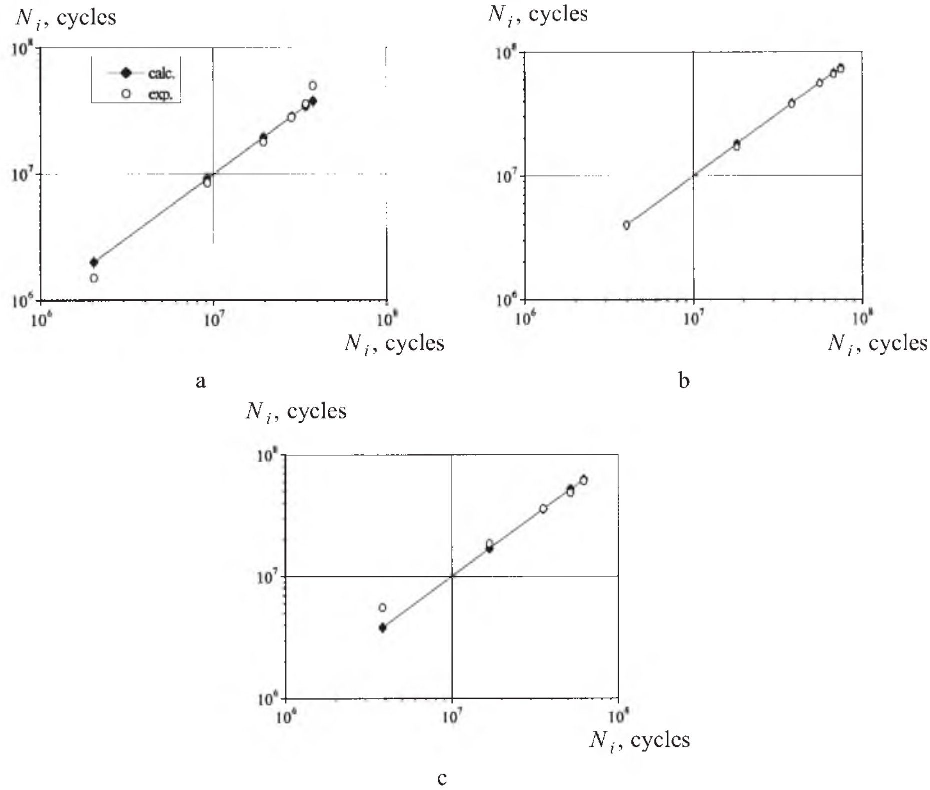

Fig. 2. Correspondence of the experimental values of the extrema to the members of the calculated recurrent series [(a) σ_a = 83.4 MPa; (b) σ_a = 73 MPa; (c) σ_a = 65.3 MPa].

The developed methodology allows assessing the kinetics of changes in the material properties under conditions of cyclic deformation by the parameters of distribution of the generalized parameter of inelasticity measured locally on the surface of the material under study.

Conclusions

1. Local nonuniformity of the material inelastic properties is a structure-dependent characteristic of damageability of a structural material in fatigue.

2. A satisfactory agreement between the estimated values in the series of bifurcation points under cyclic loading and the hardening extrema on the curves of inelasticity distribution in the service life range from 10^6 to 10^8 cycles has been obtained for an aluminum alloy.

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