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On high- and very high cycle fatigue of metals and alloys

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The results of the well-known theoretical and experimental studies of fatigue processes at axial loading and shear are systematized. The existence of the continuous fatigue curve by a certain level of micro-, meso- or macrodefectivity in areas of high- and very high loading at a given frequency, temperature and cycle asymmetry, and, possibly, different fatigue mechanisms, is discussed. The analysis of experimental data was carried out for two groups of metallic materials with fatigue properties dependent and independent of loading frequency.

Keywords: high-cycle and very high cycle fatigue, microfailure, macrofracture, loading frequency.

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Analysis of a representative amount of experimental data on high- (in average, $N_f \in (10^4, 10^6)$ cycles before macrodestruction) and very high (in average, $N_f \in (10^6, 10^{11})$ cycles) metallic materials fatigue [1–23] revealed the presence of different physical mechanisms of the process. Metals and alloys can be divided in two groups depending on the areas of durability where the first or second mechanisms of fracture development are realized. According to the first mechanism, two processes can simultaneously develop in the multi-cycle region at the microlevel: the formation of microcracks on the surface of the body (brittle microfracture) and growing of dislocations along the mechanisms of sliding and twinning with the formation of a mesh substructure and sliding planes (inelastic deformation and failure of plastic materials) [1,6,11,12], which are realized with different probabilities. At the meso level, as a result of the fusion of microdefects, the nucleation, growing and fusion of mesodefects (mesofractures) occur, on average, of grain size (brittle mesofracture). The development of the reticulated substructure leads to the movement of grain ensembles and the evolution of porosity with the formation of a pitted relief with a cascade of steps. At the macro level, mesofractures merge with the formation and development of macrodefects (macrocracks), leading to brittle macrofracture by the mechanisms of transgranular or intergranular cleavage, and the fusion of pores with the formation of a neck or fracture of the calyx structure with fatigue grooves. In this field, the magnitude of inelastic deformations does not exceed the magnitude of elastic deformations, and inelastic deformations inhibit the growth of brittle cracks. At the same time, most of the durability, up to 90%, takes the evolution of micro- and mesofailure before the formation of a macrofracture.

In the very high cyclic region, the second mechanism of fatigue is observed [2–15], which is characterized by the nucleation of microcracks in the volume of the body from the geometric concentrators of the structure: in the matrix, at the grain boundaries, from inclusions and etc., with the formation of a region of finely granular mesostructure „fish eye“ and the formation of facets of the microchip. H. Mayer, T. Sakai, and others [9,13] attribute this mechanism to the accumulation of hydrogen in the microvoids between the inclusion and the matrix (hydrogen embrittlement), to the presence of technological hardening of the surface and additional hardening in the process of loading, with different coefficients of thermal expansion of the inclusions and the matrix. It is observed in iron, as well as low-carbon, stainless, bearing, spring steels (Fig. 1) and titanium alloys. It should be noted that in the very high cyclic region, both at axial loading and torsion, the first mechanism of brittle microfracture from the surface of the body is possible in the case when the surface is ahead of the internal volumes in the accumulation of microdefects, for example, as in cast Al−Si-steels (such materials, as a rule, do not have a limit of endurance). C. Bathias with coworkers [14] in the field of very high cyclic fatigue of some steels, aluminum and magnesium alloys „fish eyes“ not observed. In the second mechanism, the formation of mesodefects takes up to 99% of durability, the rate of their gorwing in the body volume is significantly lower than the rate of development on the surface. H. Mugrabi [15] has given abundant evidence that most of the durability — is the development of fracture to French lines at durability, averaging $N_f > 10^6$ cycles. Fig. 1 shows data from T. Beck, S.A. Kovacs, F. Ritz, L. Singheiser [10] for 9−12% carbon martensitic chromium steel at different asymmetries of the axial loading cycle R. At $N_f > 4 \cdot 10^7$ cycles, the mechanism of brittle failure associated with the occurrence of foci of microfailure in the volume of the body („fish eyes“) is realized, as shown in Fig. 1, *b–d*. With the asymmetries of the tensile cycles $R \geq 0.5$ and high-frequency loading, it is found that the maximum stress of the cycle changes slightly with the increase of the cycle number and is almost equal to the ultimate static strength of steel. At the same time, cyclic creep and inelastic deformation develop in the samples. It is also known that in the multi-cycle region of some materials,

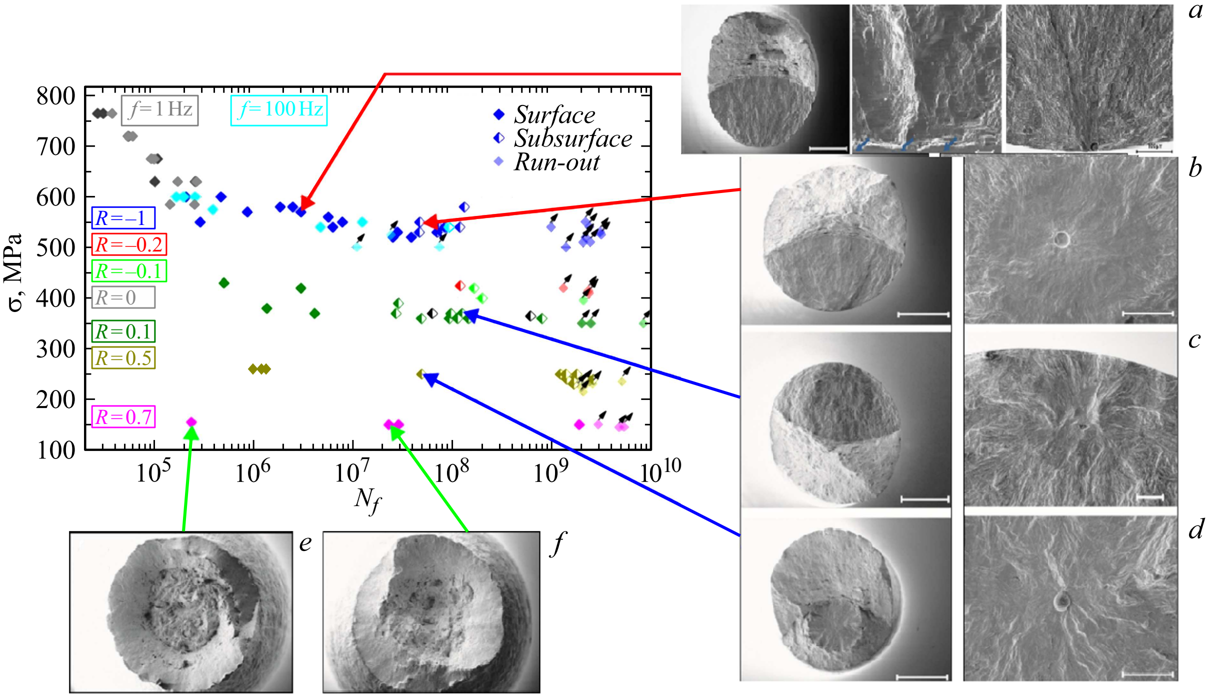

Figure 1. Experimental data for X10CrNiMoV12-2-2 steel in coordinates: stress amplitude (in MPa) as a function of the number of cycles at axial loading and various cycle asymmetries R with a frequency of $\nu = 20\,\text{kHz}$, except for a symmetrical cycle (where for light rhombuses $\nu = 100\,\text{Hz}$, for dark rhombuses — $\nu = 25\,\text{Hz}$); solid rhombuses — microfracture focus on the surface, semi-solid rhombuses — in body volume, arrow icons — unbroken specimens. Fractography: a — $\sigma_a = 570\,\text{MPa}$, $R = -1$, $N_f = 2.97 \cdot 10^6$ cycles; b — $\sigma_a = 550\,\text{MPa}$, $R = -1$, $N_f = 4.66 \cdot 10^7$ cycles; c — $\sigma_a = 370\,\text{MPa}$, $R = 0.1$, $N_f = 1.24 \cdot 10^8$ cycles; d — $\sigma_a = 250\,\text{MPa}$, $R = 0.5$, $N_f = 4.87 \cdot 10^7$ cycles; b–d — with focus from aluminate inclusion in the body volume with an area of finely granular structure „fisheye“; e — $\sigma_a = 155\,\text{MPa}$, $R = 0.7$, $N_f = 2.35 \cdot 10^5$ cycles; f — $\sigma_a = 150\,\text{MPa}$, $R = 0.7$, $N_f = 2.28 \cdot 10^7$ cycles; e,f — steady-state creep failure.

the formation of a fracture center in the volume of the body is observed.

The high- and very high cyclic fatigue curve for micro-, meso- or macrofracture [11,12] at single-frequency uniaxial loading or cycle skewness shear is described by a function of four independent variables in the form: $\sigma^*_{\max} = \sigma^*_{\max}(\nu, N, T, R)$, where $\sigma^*_{\max}$ — maximum stress, ν — loading frequency, N — number of cycles, T — temperature, and R — cycle skewness.

The conducted analysis of a large volume of known results allows us to consider the loading frequency ν as an independent variable by which the materials can be divided into two groups. The effect of frequency (or loading rate) does not appear to be the effect of heating the sample in the general case (in the experimental study, special attention is paid to the (air or water) cooling of the samples, and the dependence on frequency is investigated at cooling conditions). The effect of frequency on fatigue properties is different and depends on the structure of the material [12–16]. The group of materials, the fatigue properties of which practically do not depend on frequency, include some nickel alloys (Udimet U500, MAR-M-246, EI437B, U1612 et al.), high-carbon steels. Materials belonging to a different group (Fig. 2), for example, titanium alloys (VT22, VT22M, OT4-1, VT22), low- and medium-carbon steels (45. 1X17H2Sh, 1X2M and X18H9), aluminum alloys (D16T) demonstrate a stable dependence on frequency (according to the data, the increase in fatigue limits, for example, for low-carbon steels, reaches 40%). At the same time, depending on the different structure obtained in the technological processes of stamping, heat treatment and etc., one and the same alloy, as, for example, the well-known titanium alloy BT6 (Ti-6Al-4V) can demonstrate both independent of frequency (at different mechanisms of the nucleation and development of cracks in the areas of high- and very high cyclic fatigue), and an increase of fatigue strength up to 20% with an increase in frequency at the same durability (Fig. 2, b) [16]. According to some researchers' data, a non-monotonic dependence of fatigue curves on frequency [1,12,16–19] is possible. With the decrease of the grain size is observed by an increase of fatigue strength at high frequency, while there is an intragranular growing of microcracks, in contrast to low-frequency development, where growing of microcracks mainly occurs along the grain boundaries. Both mechanisms of failure can be realized with different probabilities at any frequency and asymmetry of the cycle, depending on the areas of durability. High-frequency test methods, as accelerated test methods, cannot be applied to materials whose fatigue properties are frequency-dependent; Their application can lead to the prediction of the fatigue

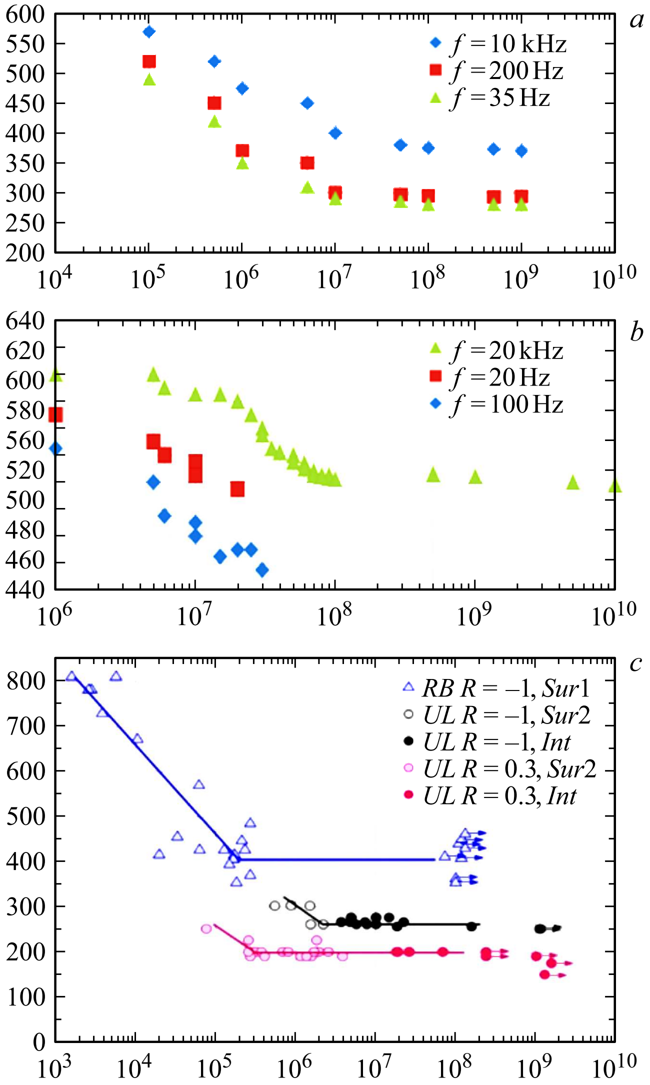

Figure 2. Experimental data in coordinates: stress amplitude (MPa) as a function of the number of cycles before macrofracture for the following materials: *a* — nickel alloy EP202 [14], *b* — titanium alloy Ti-6Al-4V [14], *c* — medium carbon steel [20] (*RB* — data for symmetrical bending with rotation, *UL* — ultrasonic experiments, *Sur* 1 — failure by first mechanism, *Sur* 2 — failure by the first mechanism from MnS inclusions, *Int* — failure by the second mechanism [20].

strength at a given durability above the real one. At the same time, for materials whose fatigue properties do not depend on frequency, it is possible to use ultrasonic methods to assess fatigue strength.

Fatigue curves are uniform continuous curves for each of the four variables, and there are no gaps. If materials have an endurance, then it is one. At a given loading frequency, there are no „bifurcation sections“ of the fatigue curve, where there are two branches of the curve according to two different dependencies in the same range for the number of cycles, the presence of which was assumed and associated with different mechanisms of failure, A.A. Shanyavsky et al. [5,6]; „two branches of longevity“ that considered L.R. Botvina [1] and V.F. Terentyev [21]. The fatigue curve is not a „duplex curve“, as it was presented by T. Sakai [13], K. Shiozawa, S. Ishihara, et al. [22]. In the high- and very high cyclic domain, there is no „effect of the duality of the Woehler curve“, as O.B. Naimark and his colleagues believe [23]. Different fatigue curves occur depending on the loading frequency for materials whose fatigue properties are frequency-dependent. The diagram of H. Mugrabi [15] shows two different fatigue curves at different frequencies for a material with frequency-dependent fatigue properties. Famous experiments by T.P. Zakharova, A.A. Shanyavsky, K. Shiozawa, S. Ishihara, L. Lu and others [3–6,20,22] for nickel and titanium alloys, as well as a number of steels, were carried out at bending with rotation and, apparently, when determining the maximum stress values, the authors did not consider that at bending conditions, a heterogeneous stress state is formed along the cross-section, and if the focus of microfracture is located under the surface, then the failure with the same number of cycles occurs at a lower stress than the maximum stress measured at the surface. Therefore, in particular, the two branches of the fatigue curve are not observed in the tension-compression experiments. The validity of the proposed explanations is proved by the results of the work [16], in which for nickel alloys ZhS6U and EI698 and titanium alloy VT8M-1 at different temperatures, it is shown that axial tension-compression and bending with rotation correspond to different fatigue curves, and the latter lies above.

In the papers [11,12] the process of brittle fatigue failure is considered as a hierarchical random process at six scale-structural levels. Fialure probability distribution functions at each level are introduced, and a recurrent system of determining relations is written for them. Fatigue curves on defect levels are determined when the specified values of the failure probability at each level are reached. An algorithm for finding basic functions based on the data of standard fatigue tests at single-frequency axial loading is given, taking into account the results of physical studies on the development of brittle cracks.

Thus, based on the results of the analysis, it can be concluded that there are uniform continuous fatigue curves on a certain level of micro-, meso- or macrodefects for each of the process variables in the field of multi- and very high cyclic fatigue. Depending on the durability range for different materials, failure can develop by both the first and the second mechanism.

Conflict of interest

The authors declare that they have no conflict of interest.

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