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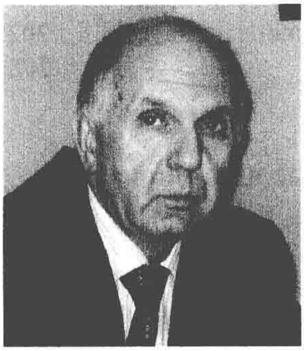
The Authors



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Introduction

Fracture of materials under cyclic loading is due to fatigue which is the gradual accumulation of damage in the material under conditions of variable loads, leading to the nucleation of a fatigue crack, its development and final destruction.

The phenomenon of fatigue is characterized by exceptional complexity and diversity of the processes occurring in materials under the action of variable loads, and also by high sensitivity of these processes to the effects of various technological, operational and structural factors. All this makes it difficult to study the process of fatigue failure and the development of a sufficiently complete theory of fatigue, which could serve as a reliable basis for ensuring the strength of machine parts under the action of variable loadings. Despite the very significant results of the study of material fatigue, the majority of failures, encountered in practice, due to fatigue.

In modern conditions of operation of machines and structures, the number of main tasks include the increase of the strength, service life, endurance and durability. Extreme conditions in terms of mechanical, thermal, electromagnetic, hydraulic and aerodynamic loads cause repeated presence of plastic strains in the loaded zones. The most critical and unique products, machinery and construction are operated in cyclic deformation conditions, defining destruction even at low loads. The durability and reliability of the machines is largely determined by their fatigue resistance, as in most cases the main type of dynamic loading for machine parts are dynamic, repeated and alternating loads, and the main type of fracture – fatigue.

In practice, fatigue failure and premature failure of machine parts and structures are quite common. This is due to the lack of precision of design techniques, including the neglect of the actual regime and the level of forces acting on the parts, insufficient knowledge of the material properties that lay in the calculation, unjustified failure criteria and safety margins; imperfections in materials and processes, resulting in the production of parts to a deviation from the calculated properties of materials and the appearance of defects; deviation from normal operating conditions, expressed in temperatures and other parameters of the working process exceeding the design values, delays and low quality of maintenance and repair [1].

The study of materials resistance to deformation and destruction must be closely linked with the loading conditions (thermal, mechanical and other) of those parts for the manufacture of which they are intended, because only in this case it is possible to obtain reliable information for material selection and to calculate the strength of the parts. This is especially important due to the fact that the loading conditions of parts for various purposes differ greatly in the duration of loading, the loading mode, operating temperature, contact interaction, stress concentrations, exposure and media streams. At the same time, in practice the calculations of the strength of the component are often carried out by a very simple approach, which takes into account only the characteristics of the statistical strength.

Important information for improving the properties of materials, technologies of their processing and design techniques is the analysis of failures of parts and structures encountered in practice. Analysis of these destructions reveals specific reasons for the destruction of equipment and to eliminate them in the future and develop the relevant scientific studies to describe these processes which are very complex.

Questions of fatigue and strength are the subject of the most thorough studied in terms of both scientific research and experimental design and technological developments. Fatigue strength and durability are important measures of the performance, capacity and service life of parts and structures. Their role becomes more important for modern heavily loaded responsible products exposed to cyclic loading in the field of not only multilateral but also low-cycle fatigue. The complexity of evaluating the cyclic strength of structural materials is due to the fact that the fatigue failure is affect by many various factors (the structure, the state of the surface layer, the test environment and temperature, frequency of loading, stress concentration, the stress ratio, the scale factor and others). In general, the fatigue process is associated with the gradual accumulation and interaction of crystal lattice defects (vacancies, interstitials, dislocations and disclinations, twins, grain boundaries and grains, etc.) and, as a consequence, the development of fatigue damage in the form of formation and propagation of micro- and macroscopic cracks.

Although the first fatigue curve was constructed more than 140 years ago and currently the fatigue curves are plotted for all known constructional materials, however, we still unable to completely solve the problem of fatigue strength in the study of the physical nature of the phenomenon or in the engineering approach to this issue. A huge amount of material accumulated and analyzed in monographs and publications of recent years [2–23] highlights the complexity of the behaviour of metals and alloys in fatigue.

The internal logic of the development of the science of fatigue is based on the need to construct a consistent description based on the evolution of the structure and phase composition of the material. Models and approaches used in solid state mechanics reflect usually the external reaction of materials to cyclic loading and do not consider structural changes. They are based on deformation, energy and power parameters of the stress–strain state, the criteria for the development of cracks and the equations of linear and non-linear mechanics of cyclic destruction for the main characteristics of the design – the rate of growth of cracks. However, it is clear that to establish patterns of accumulation of damage in fatigue and physical nature of the phenomenon at different stages the knowledge of the evolution of dislocation substructures and structural-phase state is very important.

Furthermore, it should be taken into account that the fatigue cracks typically originate primarily in the surface layer of the metal. Preliminary hardening of surface layer can lead to increased fatigue strength, durability, endurance limit, high-cycle fatigue [24], etc. One of the promising methods of targeted modification of the structural-phase state of the surface layer of metals and alloys is the high-intensity electron beam surface treatment in micro- and submillisecond ranges of exposure time. It provides extremely high rates of heating (up to 10^6 deg/s) of the surface layer to a predetermined temperature limit, formation largest temperature gradients (up to 107...108°C/m) and cooling of the surface layer due to heat transfer to the bulk material at 10^4...10^9 deg/s. As a result, the surface layer creates suitable conditions for the formation of none-quilibrium structural and phase states – nanocrystalline and amorphous [25–28].

Through a variety of techniques and new methods of nano-technology used for studying the structure and composition the spectrum of polycrystalline materials research bodies has been expanded and changed qualitatively.

This gave the opportunity to deepen existing ideas in the field of basic aspects of nanostructured materials science and identify ways of their application in industry. Nanostructure materials technology currently is a powerful multi- and interdisciplinary scientific direction, partially related to physics, chemistry and other natural sciences [25–28].

Despite the growing use of low-energy high-current electron beams for the intensification of various technological processes of forming, reliable experimental and theoretical understanding of the processes of plastic deformation is very limited, and the physical nature of the effect of electron-beam processing of metals has been studied insufficiently, despite the extensive experimental and theoretical material [29–32].

Low-energy high-current electron beams are a versatile tool to change the physical and mechanical properties, of course, can be effective to restore the fatigue life metal products. However, the development of such an approach to managing fatigue characteristics needs a reliable diagnosis of fatigue damage, knowledge of the evolution of structural and phase states and patterns of interaction of electron beams with them [33].

In this paper we summarize the results of research carried out in recent years at the Siberian State Industrial University and the Institute of High Current Electronics, Siberian Division of the Russian Academy of Sciences.

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1

Methods for increasing the fatigue life of metals and alloys

1.1. Fatigue failure of metals and alloys

The process of gradual accumulation of material damage under the influence of alternating stresses, resulting in changes in the properties, cracking and crack propagation is called fatigue fracture [1]. Currently, there is high-cycle fatigue and low-cycle fatigue [2]. According to the GOST 23.207-78 standard [3], high-cycle fatigue is the fatigue of a material in which fatigue damage or destruction occurs mainly during elastic deformation, and low-cycle fatigue – material fatigue at which fatigue damage or destruction occurs in elastoplastic deformation [4, 5–10].

1.1.1. Periods and stages of fatigue

The periods and stages of fatigue are described most comprehensively in the construction of the Wöhler curve or fatigue curve. Figure 1.1 shows the complete fatigue curve in the stress range from ultimate strength (tensile strength) to the endurance limit (fatigue limit). Construction of complete fatigue curves allows to understand the methods of calculation of the load-carrying capacity in each area of the fatigue curve and improve the methodology of research in non-stationary cyclic loading [4, 11–14].

The limiting state as a material property is characterized by a single fatigue curve for which crack nucleation in all areas of low-cycle, high-cycle fatigue and super high-cycle fatigue is realized under the surface. However, in this case it should be noted that after reaching the surface the crack growth period is short. The main fraction of the crack growth period includes the stage when the crack

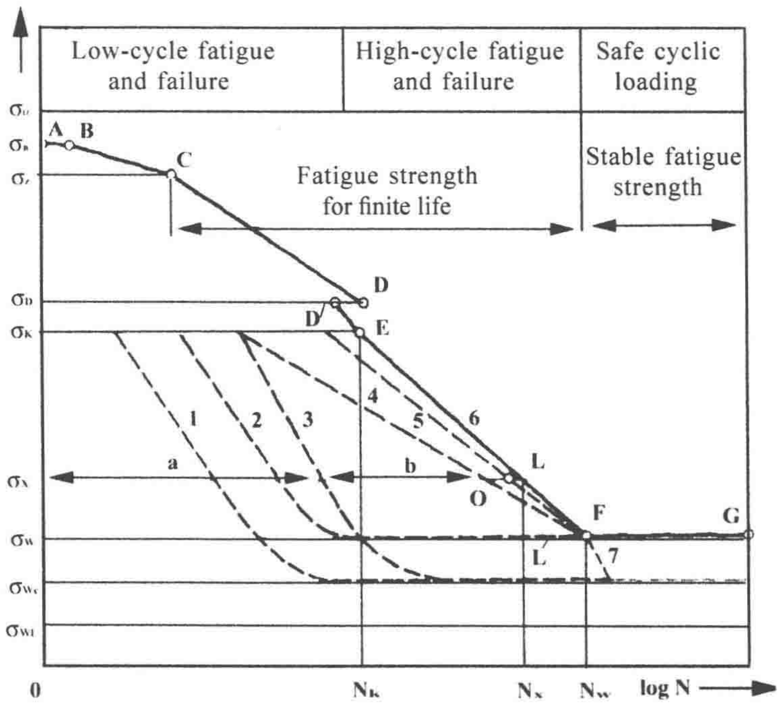

Fig. 1.1. Chart diagram of fatigue fracture. σ_B – tensile strength; σ_z – the stress of the first inflection point of the curve; σ_D – stress corresponding to rupture or fracture; σ_ω – fatigue limit; $\sigma_{\omega c}$ – cyclic sensitivity stress; $\sigma_{\omega e}$ – cyclic elastic limit; N_k – limiting number of cycles; N_ω – base cycles to determine σ_ω; 1–7 – cyclic hardening stages.

is not yet continuous and has not reached the surface. Therefore,the process of tracking crack growth, to implement the principle of operation of the structural elements with safe damage, is problematic with modern means of non-destructive testing, focused on revealing through cracks [15].

The full fatigue curve is divided into two main areas, low-cycle and high-cycle fatigue. Several studies have shown that the conventional boundary between these regions is a stress equal to the dynamic yield strength [16-18].

The low-cycle fatigue region covers a range of stresses from σ_B to σ_K. In this area there are two characteristic regions. In section I (AC), which is sometimes called the cyclic creep section, failure of ductile metallic materials is of a quasi-static nature to form a kink in the inflection area. This area is characterized by the accumulation of plastic deformation. In section II (CE) the fracture surface shows