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INFLUENCE OF CYCLIC LOADING PARAMETERS ON FATIGUE CHARACTERISTICS OF DIE STEEL

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Abstract

Studying the fatigue characteristics of structural materials is a time-consuming process. The possibility of using high loading frequencies on the example of 5CrNiMn steel is presented in this paper.

The results of studies of structurally sensitive characteristics are microhardness, electrical resistance and dislocation density. It is established that the nature of their change does not change with increasing loading frequency.

Based on the obtained results the common nature of the accumulation of fatigue damage is assumed.

Keywords: steel, microhardness, electrical resistance, testing, fatigue.

ВЛИЯНИЕ ПАРАМЕТРОВ ЦИКЛИЧЕСКОГО НАГРУЖЕНИЯ НА УСТАЛОСТНЫЕ ХАРАКТЕРИСТИКИ ШТАМПОВОЙ СТАЛИ

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Реферат

Исследование характеристик усталости конструкционных материалов – длительный и трудоемкий процесс. В данной работе на примере стали 5 CrNiMn показана возможность использования высоких частот нагружения для таких исследований.

Приведены результаты исследований структурно-чувствительных характеристик: микротведость, электросопротивление и плотность дислокаций. Установлено, что характер их изменения не меняется с ростом частоты нагружения.

На основе полученных результатов выдвинуто предположение о единой природе накопления усталостной повреждаемости.

Ключевые слова: сталь, микротвердость, электросопротивление, испытания, усталость.

Introduction

For the manufacture of products operating under conditions of cyclic loads as well as thermal changes die steels of the 5CrNiMn type are usually used. The durability of such equipment is largely determined by a complex of mechanical properties especially the fatigue characteristics of the material. The determination of such characteristics is also necessary for the selection of rational parameters for thermal and chemical-thermal treatment of such products. However, the methods of low-frequency testing currently used are very time-consuming and energy-intensive especially when a large number of loading cycles (10^6–10^7 cycles) have been run. Therefore, in this paper, we consider the possibility of using high loading frequencies (18.0 kHz) for the implementation of fatigue tests of die steel [1-4].

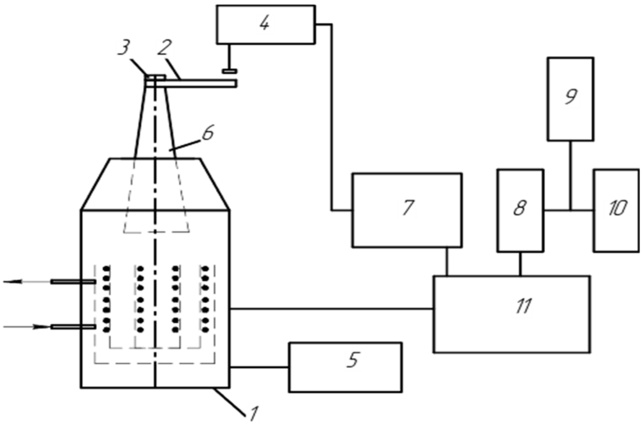
Materials and research methods

Difficulties with fatigue testing are caused by a limited list of equipment that allows loading model samples according to various schemes in a wide frequency range. The most accessible for the implementation of loading in the frequency range of 3-44 kHz are test facilities with excitation of vibrations by magnetostrictive packages. They can be used to implement various loading schemes: tension-compression; symmetrical (asymmetric) cycles of alternating bending and torsion. A further increase in the loading frequency is limited by a significant heating of the test specimens which can lead to a significant effect on the research results [1-4].

To determine the effect of frequency loading on the fatigue characteristics of materials, as well as the nature of changes in their physical and mechanical properties we used test equipment that allows loading test specimens with the following frequencies: 0.15; 3.0; 9.0; 18.0 kHz [5,6] (Figures 1, 2).

To load test specimens at high (more than 0.3 kHz) frequencies, magnetostrictive stands operating in self-oscillatory mode were used. The schematic diagram of the stands is shown in Figure 1. Magnetostrictive transducers served as active elements of these installations. They convert electrical vibrations into mechanical ones.

The parameters describing the micro structure of the elements of the oscillating systems of the test installations were selected in such way as to obtain a single oscillatory circuit with the same natural frequency, which made it possible to obtain the maximum values of the amplitude of the cyclic stresses in the sample for oscillation with minimal energy consumption when working at the selected resonance frequency. The test complexes operated in auto-oscillating mode.



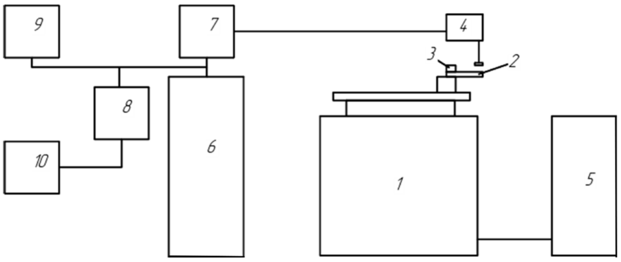
1 – magnetostrictive transducer; 2 – sample; 3 – fastening device;
4 – vibrometer MRTI; 5 – bias module; 6 – concentrator-waveguide;
7 – amplitude stabilization device (PSA); 8 – frequency meter;
9 – oscilloscope; 10 – output to a computer;
11 – amplifier and signal generator

Figure 1 – Schematic diagram of the complex carrying out loading in a wide range of frequencies and temperatures

To increase the amplitude of sample oscillations, conical, stepped cylindrical and ampoule-stage concentrators were used. The mounting geometry of the samples was chosen to achieve a reduction in resonantly oscillating masses. To improve the reliability of sample fixing, a fixing device was used (patent RB No. 12601). The proposed design made it possible to increase the accuracy of sample positioning and ensure the stability of the friction coefficient.

The test complexes operated in a self-oscillating mode, and the required amplitude of the sample oscillations was maintained using a special device for stabilizing the amplitude of the PSA [5,6].

To carry out fatigue tests at a low frequency of bending vibrations a test setup based on an electrodynamic vibration stand of type B3 was used (Figure 2).



1 – vibrator VE; 2 – sample; 3 – fastening device; 4 – vibrometer MRTI; 5 – bias module; 6 – amplifier; 7 – amplitude stabilization device (PSA); 8 – frequency meter; 9 – oscilloscope; 10 – output to the computer

Figure 2 – Schematic diagram of a low-frequency test stand for kinematic excitation of bending vibrations

Fatigue testing of cyclic samples for cyclic tension-compression of low frequency (150 Hz) was carried out by force excitation on the same electrodynamic shaker with some of its modernization. To control the level of cyclic stresses, the shaker was additionally equipped with a multi-channel strain gauge of the Spider type. The values of cyclic stresses acting both in the dangerous section of the sample and in other sections with a lower level of stresses were determined using strain gauges glued in different parts. The use of 3 to 5 strain gauges made it possible to determine the stress state of the sample with a higher accuracy at various amplitudes of its oscillations.

Studies on the effect of amplitude-frequency and temporal loading parameters on the course of fatigue damage processes in the materials under study were carried out by tracking the kinetics of the following properties: microhardness, fine structure, electrical resistivity, magnetic characteristics and microstructure.

To study the effect of frequency on the kinetics of hardening-softening processes of the studied materials, we observed the change in microhardness during cyclic loading at various bending stresses. For this reason the value of the initial microhardness (Hμ) was preliminarily determined before testing, and then measurements of Hμ were carried out in the zone of action of cyclic stresses of the selected value after the aging time.

The microhardness of the materials was measured using a PMT-3M and Duramin 5 device, which made it possible to conduct studies for the entire range of materials with the same relative measurement errors due to approximately the same dimensions of the imprint diagonals.

To study the processes of fatigue damage to materials at the microlevel during cyclic deformation in a wide frequency range we used a Bruker X-ray diffractometer in order to study the kinetics of structure-sensitive characteristics were studied using.

Structural changes caused by static and cyclic stresses affect both the mechanical and electrophysical properties of materials. Studies of changes in electrical resistance (electrical conductivity) make it possible to trace not only the kinetics of damage accumulation in weak and most favorably oriented in relation to the applied stress microvolumes of the material, but also allow us to identify the periods of the fatigue process, their duration in relation to the total durability. So, on the basis of the E7-20 immittance meter, a setup was created [7] which makes it possible to determine the change in the electrical resistance of the materials under study. The schematic diagram of the installation is shown in Figure 3.

The objects of research were samples made of 5CrNiMn steel.

Research results

Analyzing the whole complex of the results obtained in the context of the influence of the amplitude-frequency and time parameters of loading of test specimens on the kinetics of the physical and mechanical properties of the studied material, proved that the most intensive changes in the structural-sensitive characteristics for the selected levels of alternating stresses occur under cyclic loading up to 10^7 cycles. Therefore, for example, an increase in the microhardness of die steel 5CrNiMn was noted already after 10^5 loading cycles (Figure 4).

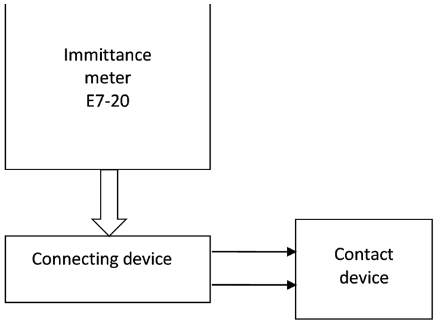
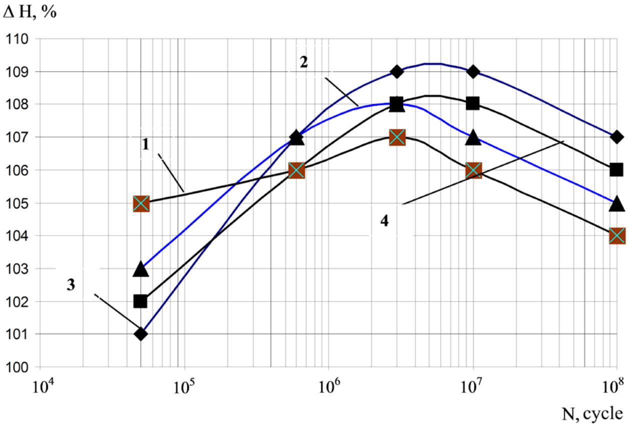


Figure 3 – Block diagram of the installation for measuring electrical resistance

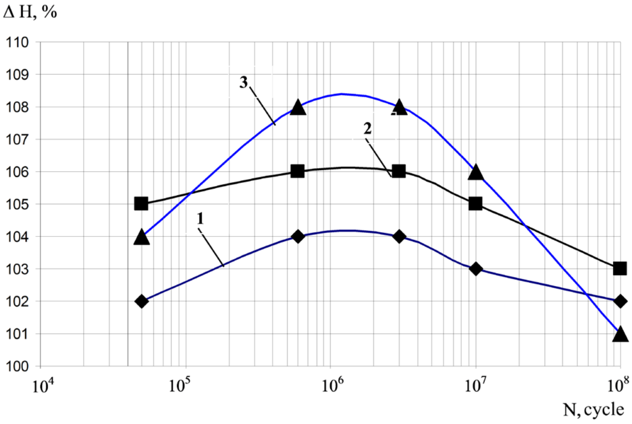
The fine structure of the studied materials is also characterized by the most significant change in the relative density of dislocations during the first loading cycles. Later on, with the cycles running saturation occurs which is replaced at the stage of microcrack development by a gradual transition through the extremum (Figure 5).

It should be noted that due to the high sensitivity of the dislocation density to the action of cyclic stresses, the hardening process proceeds with a pronounced intensity on the basis of up to 10^6 cycles, and subsequently, after $2{\times}10^6$ cycles predominantly softening processes are observed.



1 – 0.3 кHz; 2 – 3.0 kHz; 3 – 9.0 kHz; 4 – 18.0 kHz

Figure 4 – Influence of the frequency of alternating bending on the kinetics of microhardness of steel 5CrNiMn



1 – 346 MPa; 2 – 254 MPa; 3 – 135 MPa

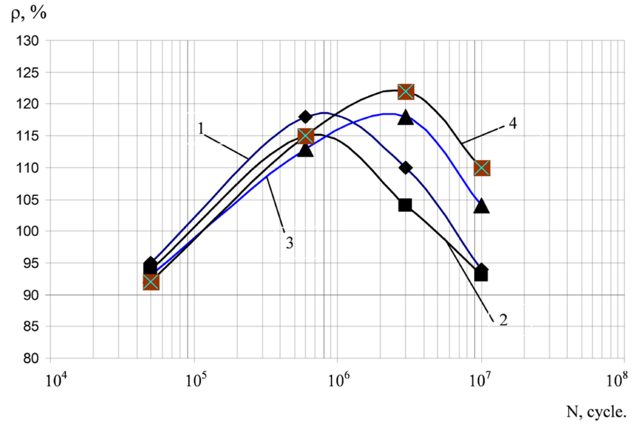
Figure 5 – Influence of the magnitude of cyclic stresses of alternating bending on the kinetics of microhardness of steel 5CrNiMn

Certain regularities can be seen in the transformation of the physical and mechanical characteristics of materials. During cyclic deformation, hardening of materials occurs at the initial stages of loading which is reflected in an increase in microhardness, an increase in the density of dislocations and microstresses. Then, it's the stage of saturation, replaced on large test bases by the stage of softening, characterized by a drop in the values of the above characteristics.

The observed effects of the kinetics of a number of structurally sensitive properties depend on the amplitude-frequency and are determined mainly by the nature of the distribution and interaction of defects in the crystal lattice. The dislocation density at the first stage of testing increases at all studied frequencies, which indicates the beginning of the process of material hardening. In the initial stage of loading, only oscillatory movement of segments of pinned dislocations around the equilibrium position takes place. The subsequent imposition of alternating stresses with a high frequency of the half-cycle of oscillations leads to the activation of dislocations present in the material, it helps them overcome potential barriers and move through obstacles, thereby causing plastic deformation. The continuation of cyclic loading causes the appearance of new defects due to the action of dislocation sources activated in the first loading cycles, as well as sources arising due to the interaction of dislocations located in adjacent parallel slip planes. As a result, the density of dislocations and point defects (interstitial atoms and vacancies) increases significantly. At a certain concentration of defects, both dislocations and vacancies, their mass breakdown from obstacles occurs that causes a violation of interatomic bonds. The determining factor in this case is an increase in the dislocation density with an increase in the number of loading cycles, which is confirmed by X-ray diffraction studies (Figure 6).

An increase in the density of dislocations is explained not only by the translational motion of decoupled dislocations, but also by their multiplication mainly through the operation of Frank-Read sources.

The cessation of the increase in the density of dislocations occurs due to the deceleration of the action of the source of their multiplication by stresses from previously emitted dislocations. The process of annihilation of dislocations of the opposite sign emitted during cyclic loading by sources located in parallel atomic planes is also possible. Along with an increase in the density of dislocations at the initial stage of loading, an increase in the concentration of point defects is also observed, which is also confirmed by a decrease in electrical conductivity. An increase in the number of vacancies can be associated with an increased mobility of dislocations under alternating loading, since excess vacancies appear as a result of the nonconservative movement of thresholds on dislocations. When a certain number of loading cycles is reached, the material is saturated with vacancies, which, effectively interacting with moving dislocations, cause their pinning and disappearance. With a further increase in the number of loading cycles, a group of vacancies with a high activation energy is formed. In addition, an increase in microhardness occurs due to intense plastic deformation of microvolumes of the material. In this case, the nucleation and development of submicrocracks takes place in the walls of dislocation cells. A softening process develops when the plastic deformation of the material increases. This process is characterized by a decrease in the density of dislocations, a decrease in the level of microstresses and microhardness. The absence of significant qualitative differences in the nature of the development of the dislocation structure at high and low loading frequencies leads to an analogy in the kinetics of changes in the considered quantities in the studied frequency range.



1 – 0.3 kHz; 2 – 3.0 kHz; 3 – 9.0 kHz; 4 – 18.0 kHz

Figure 6 – Influence of the frequency of alternating bending on the kinetics of the dislocation density of steel 5CrNiMn

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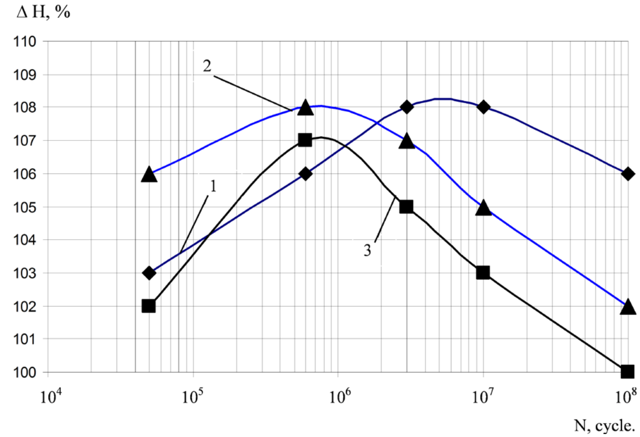
Obviously, with an increase in frequency an increase in the rate of deformation of metals occurs at the same number of loading cycles. Thus, relaxation processes which play a significant role under static loading slow down with increasing loading frequency. In proportion to the loading frequency, the number of cycles before the start of the softening process also increases. An increase in frequency leading to an increase in the rate of elastic deformation, also contributes to an increase in the rate of dislocation motion; this increases the efficiency of their reproduction. In addition, with increasing frequency, the number of vacancies also increases, and their extremely high concentration arises, as a result of which they condense into disks parallel to the most densely packed planes. When a certain critical disk size is reached, its sides are flattened and connected together. It forms a dislocation loop. All this leads to hardening, resulting in an increase in the density of dislocations and microhardness.

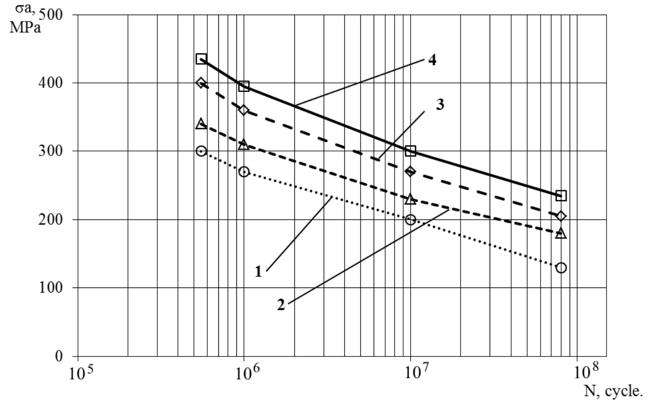
It should be noted that similar processes are also typical for elevated test temperatures of 5CrNiMn die steel (Figure 7). An increase in temperature contributes to an earlier occurrence of hardening-softening processes due to the activation of the interaction of dislocations and point defects, as well as the movement of dislocations.

The test results also showed that the shape of the fatigue curves does not change with increasing frequency (Figure 8). The fatigue curves for different frequencies are almost equidistant. One can note a monotonic increase in fatigue life with increasing loading frequency. Similar results were obtained at different temperatures (Figure 9).



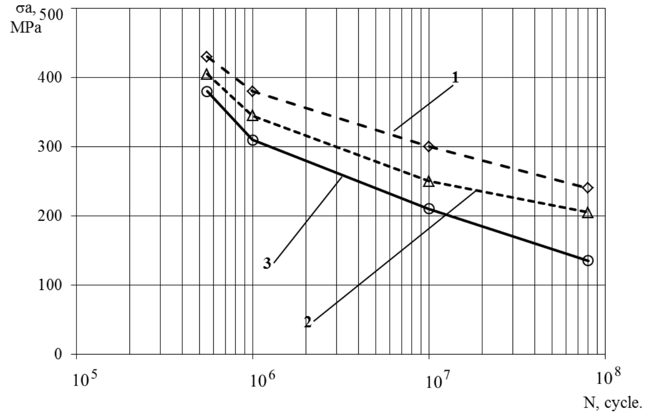
1 – 20°C; 2 – 200°C; 3 – 250°C

Figure 7 – Change in the microhardness of steel 5CrNiMn at different test temperatures (loading frequency 18.0 kHz)



1 – 0.3 kHz; 2 – 3.0 kHz; 3 – 9.0 kHz; 4 – 18.0 kHz

Figure 8 – Fatigue curves for steel 5CrNiMn when tested at different loading frequencies



1 – 20°C; 2 – 200°C; 3 – 250°C

Figure 9 – Fatigue curves for steel 5CrNiMn at different test temperatures (loading frequency 18.0 kHz)

Conclusions

The above studies have shown that despite certain quantitative differences in the kinetics of the physical and mechanical characteristics of the materials the process of fatigue failure develops according to the same patterns that are characterized by a combination of hardening-softening processes. This confirms the unified physical nature of the development of fatigue damage in the considered range of frequencies and temperatures and, therefore, the fundamental possibility of implementing accelerated fatigue tests using high loading frequencies.

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