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ACOUSTIC EVALUATION OF THE ENDURANCE OF STEEL SPECIMENS AND RECOVERY OF THEIR SERVICEABILITY

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A study is made of the possibility for evaluation of damage accumulation during fatigue loading by measuring the ultrasound velocity. It is shown that the dependence of the ultrasonic velocity on the number of loading cycles is represented by a three-stage curve and that the ultrasonic velocity decreases at each stage. The most rapid decrease occurs during the final stage of the test, immediately before fracture. It is also shown that the transition to the critical state can be observed on the basis of ultrasonic-velocity measurements. A method of increasing the service life of a specimen that has neared the critical state is proposed. The method involves exposure of the specimen to a series of high-energy pulses of electric current. The treatment increases the service life by 30–40% compared to the initial value.

1. Formulation of the Problem. Predicting the residual service life of parts subjected to fatigue loading is a complex problem. For example, fatigue-limit data obtained by construction of the so-called Weller curve [1] only allow estimation of averaged characteristics of the material and provide no information on such an important indicator of product reliability as service life (fatigue life) [2]. Fatigue fracture usually occurs suddenly, without any noticeable outward signs of its impending occurrence. Microscopic studies [1, 3] show that microscopic damages gradually accumulate during fatigue. Then the fatigue crack undergoes slow latent growth that ends with the catastrophic growth of the main fracture crack. The existence of a long preparatory stage in the fatigue process suggests that it might be possible to find some suitable method of delaying the transition to the final stage. To do this, two problems must be solved:

- Selection and substantiation of a reliable and sufficiently informative indicator of the transition to the dangerous stage of structural changes for a specific product;
- Creation of methods of delaying the development of dangerous defects whose growth could lead to fracture in a short period of time (these methods must be suited for use directly on machine parts or products).

2. Informative Indicator of Fatigue Fracture. A convenient quantity that provides reliable information on the structure of metals and alloys and its changes is the ultrasound velocity (USV) in metals and alloys [4]. The fact that this quantity is determined by the elasticity modulus G (for transverse waves) and the density of the material ρ, i.e., $V_R = (G/\rho)^{1/2}$, does not fully reflect the depth of the problem [5]. It was found in [4] that nearly all of the structural changes caused by heat treatment, alloying, or deformation lead to small but measurable changes in the USV. The measurement of USV has proved promising for diagnosing materials under fatigue loading. Measurements made by a method involving the automatic circulation of pulses of ultrasonic surface waves at a carrier frequency of 2.5 MHz with the use of an ISP-11 device [4] have shown that the dependence of the ultrasonic velocity on the number of loading cycles N is qualitatively the same for all specimens. Figure 1 shows data from the use of bending vibrations for the fatigue testing of specimens of steel St. 45 with a mean stress. Similar relations have been obtained also for specimens of rail steel M76. In all the cases, the curve of $\Delta V/V_R(N)$ (ΔV is the decrease in the USV compared to the initial value of this quantity, i.e., V_R) includes three successive stages. However, the level and rate of the quantitative

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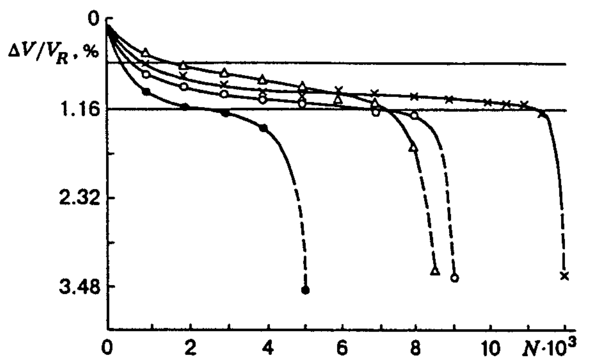

Fig. 1

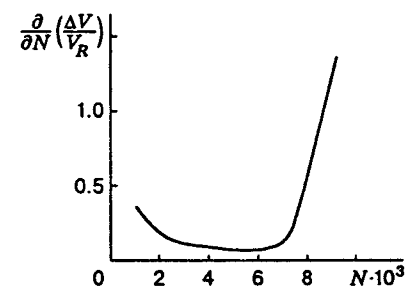

Fig. 2

changes differ for each specimen. The three-stage kinetics of the change in certain properties of metals in fatigue tests was noted earlier in measurements of the Young modulus of steel [6], the fractal dimensions of sources of fatigue corrosion [7], electrical resistivity [8], and the amplitude of deflection of specimens during bending vibrations [9, 10]. Studies of the metal subjected to fatigue tests in [4] showed that no significant changes occur in the microstructure in stages 1 and 2. However, traces of plastic deformation appear with the approach of stage 3, and signs of fracture in the form of microcracks of the size $\geqslant 0.01$ mm are seen immediately after the beginning of the steep drop on the $\Delta V/V_R(N)$ curve.

Thus, there are sound reasons for assuming that the transition to stage 3 is an indication of approach of the catastrophic stage of fatigue and exhaustion of the safe life of the product. Since measurements of the USV made on an ISP-11 device or a similar instrument [4] are fairly simple, they can be performed almost without restriction on structures and machines operating under alternating loads. This provides sufficient time to catch signs of the onset of the critical state in the materials of products during their service.

The character of the curves in Fig. 1 is consistent with the dependence of the failure rate (the number of failures per unit time) on the time of service t, which is described by a U-shaped function [11]. In fact, the curve in Fig. 2 that illustrates the dependence of the derivative $\partial/\partial N(\Delta V/V_R)$ on the number of cycles N (obviously, $N \sim t$) and was constructed on the basis of the data in Fig. 1 is U-shaped: in terms of the theory of reliability [2, 11], its initial stage corresponds to failures during the run-in period, the stage during which the USV decreases slowly corresponds to the period in which sudden failures occur (during the normal operating period), and the stage in which the USV decreases rapidly signals the advent of the most dangerous period, namely, the period of wear-related failures. Microscopic studies have shown that fatigue cracks of critical size have already formed by the time the last-mentioned period begins.

3. Recovery of Serviceability of Parts after Fatigue Tests. Timely detection of the beginning of the critical stage of failure might make it possible to recover the serviceability of parts by closing microcracks through the action of specific external factors [12]. The use of powerful pulses of electric current is promising in this regard. For example, it was suggested in [13–15] that the plasticization of alloys due to the electroplastic effect is related to the closing of microcracks as a result of the passage of a train of pulses of electric current with the density $j \geqslant 1$ GA/m^2. In this paper, we report the results of an attempt to use this method on steel specimens that were in the condition corresponding to stage 3 after fatigue tests.

The experiment was performed in accordance with the following scheme. Specimens of steel St. 45 and rail steel M76 were subjected to fatigue tests with a mean stress. The amplitude of the load was 1.6 MPa. We simultaneously measured the USV on an ISP-11 device. The ultrasonic velocity in the initial state was 2910 m/sec. Specimens under such conditions fractured after ~3150 loading cycles (the average for 8 specimens), while a substantial decrease in the USV (to 2890 m/sec) began after 3000 cycles. Specimens that reached this state were treated by exposing them to current pulses with a frequency of 20 Hz and an amplitude ~20 kA over a period of 30 min. Continuation of the fatigue tests showed that such treatment not only nearly restored the USV to its original value, which indicates a restoration of the initial structure of the material, but also allowed the specimens to withstand additional 1000–1500 loading cycles before fracturing, i.e., the effect obtained from the treatment was quite noticeable.

Thus, electrical treatment of materials after beginning of the critical stage of fatigue damage accumulation can appreciably increase the life of specimens and prolong the service life of actual products. The most likely reason for the increased durability is the closing of nucleated microcracks as a result of local heating of the material near the ends of current lines, blunting of those ends due to stress relaxation, and a corresponding reduction in the level of stress concentration in these zones. Similar effects have been widely discussed in the literature in regard to the problem of fatigue [12–14].

The electrical treatment plays a large role in these changes. A similar attempt was made by Stepanov and Babutskii [16] to improve the fatigue strength of steel through its preliminary treatment with electrical pulses. However, the treatment did not improve the durability of the specimens in which cracks had already grown to different lengths (1.5–2.0 mm). The treatment only decreased the scatter of the data from one specimen to the next. This result might be related to the form of the electrical pulses that were used. The pulses were in the form of rapidly decaying sine waves characteristic of the discharge of a capacitor onto a low-inductance circuit. It is known [15, 17] that the maximum electroplastic effect is achieved by using unipolar pulses from a special generator.

Thus, by combining direct monitoring of the state of metal in fatigue tests with the measurement of the ultrasonic velocity and treatment by electrical pulses, it is possible to increase the service life of products that are subject to fatigue loading and to improve the reliability of machines and mechanisms.

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