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EXPERIMENTAL INVESTIGATION BY ULTRASOUND OF ENGINEERING MATERIALS BEHAVIOR UNDER THE CYCLIC LOADING

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Abstract. The results of experimental investigations of the influence of plastic deformation and cyclic loading on the structural state and strength properties of samples of steel and duralumin are given. The value of the acoustic anisotropy of the material, that is, the relative difference of velocities (delays) mutually perpendicular polarized shear waves propagating perpendicular to the line of loading, was used as an informative parameter of ultrasonic testing. The ability to use echo-method of nondestructive testing, by means of shear waves, for the study of elastic-plastic properties and damage of engineering material in the process of fatigue failure, is proved.

1. Introduction

The fatigue of metal is the main type of fracture at a variable (including harmonic) loading [1]. If the cause of the destruction from fatigue of material is macro-stresses, primarily in the surface layers of the metal the nucleation of fatigue micro-cracks occurs due to process of micro-yielding. Often, metals and alloys are not destroyed perfectly brittle, i.e., without the previous plastic deformation [2]. The process of failure takes place at stresses much lower than the strength limit, often even below the elastic limit. In areas where are violations of the structure, micro-cracks are developed. They become stress concentrators, causing the appearance of new micro-cracks and then - the main crack, which breaks material.

Metal fatigue covers two areas of cyclic loading and deformation, which greatly differ from each other. Unlike the region of high-cyclic fatigue (number of cycles up to 10^7 – 10^8) [3] in area of low-cycle fatigue which characterized by high amplitudes of loading and the number of cycles to $5x10^4$ - 10^5 [3], the significant plastic deformation appears in a material.

The most important informative characteristics of acoustic methods of testing and diagnostics of engineering materials are the attenuation and velocity of propagation of ultrasound [4, 5]. The most widespread method of non-destructive testing of items for different purposes is pulse-echo method.

Very informative in the study of engineering materials are shear elastic waves. Shear wave velocity is much more sensitive to discontinuities, laminations, micro-cracks that are transverse to the direction of its polarization than to ones disposed in the same direction. If the stresses, plastic deformation are appear along some direction in the material, the velocities of shear waves polarized along and across it, will change in different ways. Parameter characterizing this difference is the value of the acoustic anisotropy of the material *a*, which was experimentally determined by us in accordance with the results of precision measurement of propagation time of shear wave pulses:

$$a = \frac{V_1 - V_2}{V_{cp}} = \frac{t_2 - t_1}{t_{cp}}, \qquad (1)$$

where V_1, V_2 - velocities of shear waves; t_1, t_2 - delays in the material of pulses of shear waves, which are traveling normal to material's surface and are polarized along and across the direction of loading.

As noted earlier (see, for example, [6]), plastic deformation along the direction of the loading increases the parameter of acoustic anisotropy of the material. We found quite essential parameters of acoustic anisotropy in steel of compressor blades after prolonged exploitation (apparently associated with the processes of creep under the influence of inertial loads). After heat treatment a value of acoustic anisotropy of material is considerably reduced [7].

The aim is to carry out an experimental study of the behavior of the parameter of acoustic anisotropy during the action of cyclic loading on the engineering materials steel 38HN3MA and aluminum alloy D16.

2. Arrangement which used to fulfill the ultrasonic measurements

Experimental investigations of samples of engineering materials subjected to various force actions were performed by ultrasonic echo-method using a laboratory acoustic stand (Fig. 1).

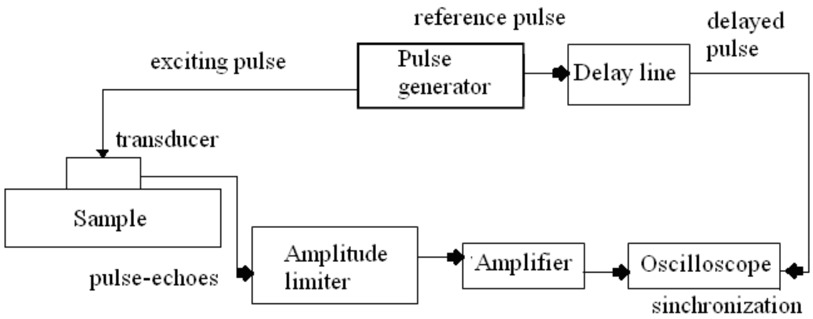

Fig. 1. Block-scheme of measuring stand.

It consists of: measurer of time intervals I2-26, block for formation and amplification of pulses (BFA), exciting and receiving (united) piezoelectric transducers (PET) of original design to excite and receive pulses of longitudinal and shear waves. We used the PET of shear oscillations at frequency of 4 MHz. Functions of generator of reference pulse and a calibrated delay line performs the source of time shifts (STS) of device I2-26. Display unit of I2-26 device serves as an oscilloscope. BFA device creates from a weak signal of STS a powerful pulse for excitation of piezoelectric transducer, amplifies the weak echo-pulses and acts as a limiter of amplitude of powerful "shock" pulse on the oscilloscope screen. Power supply of device provides standard power supply unit.

Electrical signals corresponding to the ultrasonic pulses feed to the input of the oscilloscope. A reference pulse from generator is also fed to the delay line, and then to the clock input of the oscilloscope, and so sweep is run whenever the reference delayed pulse occurs. By changing, the scanning speed of the indicator and testimonies of the delay line one can observe as the whole picture of the reflected pulses, and "examine" individual echo-pulses delayed in the material precisely to the same time as the reference pulse in the delay line. According to the indication of its scale, one can accurately measure as the time interval between the coherent points of pulse-echoes and phase and frequency distortion in pulse passing one or another way in the material.

The changes of elastic wave velocities in a wide range of different structural states and technological treatments of engineering materials usually do not exceed a few percents [8], so for their using as informative parameters of nondestructive testing the adequate accuracy of measurement of time intervals must be ensured. Required accuracy is enforced by precision ultrasonic equipment, qualified acoustical measurements and correct interpretation of their results.

3. Ultrasonic testing of steel samples

The samples No 1 and No 2 of constructive alloy steel 38HN3MA were exposed to acoustic investigations. Parameters of acoustic anisotropy were calculated on the basis of our precise measurements of the intervals between the coherent points of ultrasonic pulses reflected 1, 2, 3 and 4 times from the surface of the sample. PET was set at five points on the working part of the sample 3 times.

The sample No 1 was subjected to a static loading for the occurrence of plastic strain ε = 0.2 % and ε = 1.2 %. After each stage of loading, including initial sample, acoustic measurements of propagation time of pulses of shear waves polarized along and across the line loading and propagating along the normal to the sample surface were made.

Four pulses can be clearly seen on the oscilloscope screen. The delay time of the fourth pulse relative to the first was about 51 microseconds. Measurement error of delay of elastic wave pulses in the material is 0.01 microseconds, and the base of measuring 50 microseconds. Hence, the error of the calculating of the parameter of the acoustic anisotropy of the material according to the formula (1) is 0.04 %. Figure 2 shows the results of the acoustic measurements on each loading step.

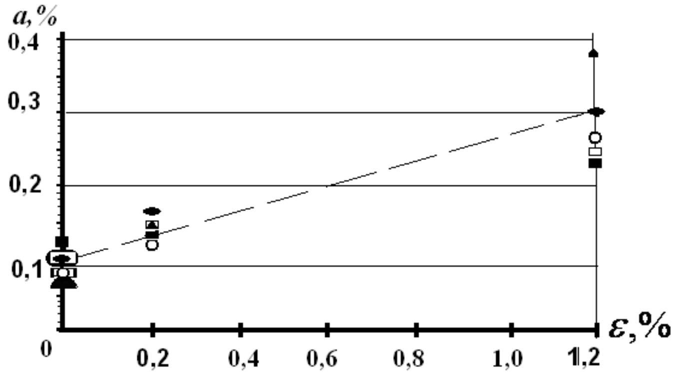

Fig. 2. Dependence of the parameter of acoustic anisotropy from the value of plastic deformation of the sample.

Indeed, the parameter of acoustic anisotropy increases with increasing of plastic deformation of the sample, which confirms the experimental results described, for example, in [6].

The influence on the material of sample No 2 the cyclic regime of loading, with a symmetrical cycle with an amplitude of deformation of 0.5 % and the number of cycles of 0, 1000, 2000, 3000, was studied. The sample was fractured after 3017 cycles of loading. Figure 3 shows the dependence between parameters of the acoustic anisotropy of the material and the number of loading cycles.

Figure 3 shows that at the beginning stage of testing the parameter of acoustic anisotropy of the material increases with increasing number of cycles of loading, apparently in accordance with the increase in plastic deformation. In the area of 1000 cycles it begins to decrease sharply, and then this decrease slowed down. Non-monotonic dependence between the informative acoustic parameter and the degree of fatigue of engineering material, we explain by the existence of two competing physical mechanisms affecting the value of the acoustic anisotropy, namely:

a) increase in the degree of plastic deformation - the growth of value of anisotropy;

b) emergence of micro-cracks (micro-defects) arranged perpendicular to the line of loading. Reducing of the speed of waves polarized along the line of loading -decreasing of the anisotropy parameter.

c) formation of macro-cracks leading to breakage. The influence of one or more macro-cracks on the wave velocity is much less than a plurality of micro-cracks. Therefore, the decrease of the anisotropy parameter becomes slower.

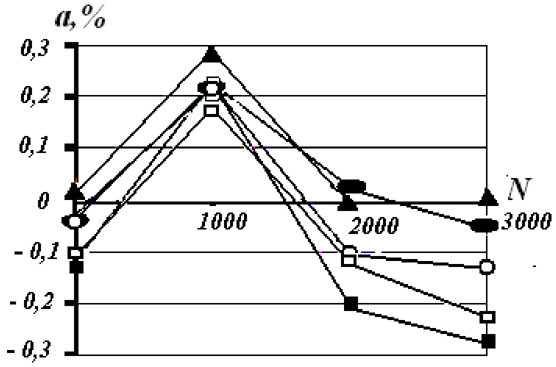

Fig. 3. Dependence of the parameter of acoustic anisotropy from the number of cycles of loading of steel sample.

Our experimental investigations have shown that the first of these factors is most important at the initial stage of low-cycle loading, the second - at the next, and the third - at it final stage.

4. Ultrasonic testing of duralumin samples

The effects of the harmonic loading on the acoustic characteristics of the samples of the alloy D16 have been studied. Duralumin samples No 1 and No 2 were subjected to harmonic loading at frequency 30 Hz and amplitude σ_a = 3 MPa in steps of 30,000 periods. Every 30,000 cycles of load samples were removed from the test machine, and then acoustic measurements were conducted at several points of each sample until its destruction. Sample No 1 withstood 190,000 load cycles, and the sample No 2 was destructed after 210,000 cycles. Test results are presented in Fig. 4 (the number of cycles is specified in the thousands).

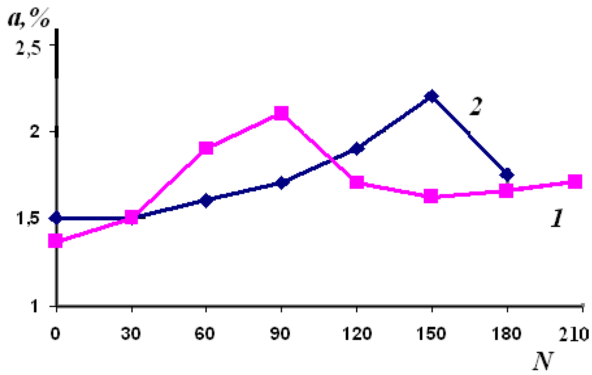

Fig. 4. Connection between the numbers of cycles of loading of duralumin samples and their acoustic anisotropy.

In the region of high-cycle fatigue at small amplitude of load deformation during each cycle largely elastic [3, 4] and the plastic deformation does not accumulate. In our case, we come to the boundary between the low-cycle and high-cycle fatigue. However, the growth of parameters of acoustic anisotropy observed here, it means that the plastic deformation of the samples under harmonic loading with a frequency of tens of hertz is going on.

Experiments have shown a relation between the degree of fatigue of the material of sample, characterized by an increase of plastic deformation and an accumulation of micro-cracks, which lead to the development of macro-crack, and its acoustic properties. Laws of change of acoustic anisotropy parameter which were revealed at low-cycle fatigue of steel specimens are conserved for duralumin specimens subjected to harmonic loading. It is possible to identify by non-destructive acoustic method as the moment of beginning of an intense failure (the beginning of decreasing of acoustic anisotropy parameter) so and the start of intensive destruction (occurrence of macro-cracks) (the ending of decreasing of the measuring parameter).

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