Correlation of acoustoelasticity with hydrogen saturation during destruction

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Abstract. The surface effect of acoustic anisotropy in steel and aluminum industrial alloys was experimentally detected. Changes in the integral value of acoustic anisotropy in 10–15 times were observed after removing the surface layer with a thickness of 100 microns in steel specimens and 250 microns in aluminum specimens. The correlation between distributions of acoustic anisotropy and hydrogen concentrations in surface layer of specimens was found. It was suggested that the surface effect of acoustic anisotropy occurs due to the influence of microcrack systems localized in a surface layer of metal. This result can be used to improve existing approaches to estimating of corrosion damage, fatigue, mechanical stresses and plastic deformations of technical structures by using acoustic anisotropy.

1 Introduction

Acoustic anisotropy is the relative difference between velocities of bulk shear waves of mutually orthogonal polarization. It is one of the main characteristics of the acoustoelastic effect [1]. The idea of using velocities of shear waves to measure principal stresses in case of uniaxial and biaxial stress-strain state was proposed in 1950s [2, 3]. Several ultrasonic methods of non-destructive testing are based on investigation of acoustic anisotropy.

The acoustoelasticity method is the first industrial certified method with the use of acoustic anisotropy for measuring mechanical stresses in structures subject to elastic deformations. It was developed in Russia [4,5]. Today it is used to estimate stress-strain state of the carriage wheels and rails [6], pipelines [7], steam generators [8, 9], and other structures.

The acoustoplasticity method [10–12] is based on investigation of acoustic anisotropy in case of inelastic deformations. It is based on the use of Murnaghan nonlinear elastic model [13]. In this model, deformation components of third order of smallness are included in the equations for the potential energy. The verification of this theory was carried out only for specially prepared specimens subjected to small plastic deformations [14]. The articles published during the last thirty years [15–17] were mainly devoted to development of this approach.

However, recent experimental [18–21] and theoretical [22–24] results cast doubt on the universality of the approach proposed in [10]. In particular, the non-monotonic dependence of acoustic anisotropy on plastic deformations [25, 26], the influence of damage due to cyclic loading [27] and hydrogen cracking [28] of metals on the integral value of acoustic anisotropy were observed. These results impose limitations on application of the acoustoelasticity method according to the standard [4]. Moreover, the contribution of inelastic factors to the value of acoustic anisotropy can be orders of magnitude greater than influence of elastic stresses.

We found that damage accumulation in a surface layer [21, 26–28] occurs during plastic deformation, corrosion and fatigue. It is necessary to investigate its influence on the value of acoustic anisotropy.

2 Experimental investigation of the surface effect of acoustic anisotropy in industrial alloys

At the first stage, the investigation of acoustic anisotropy was carried out for corset specimens with thickness of 17 mm made of weather resistant steel 14HGNDC destroyed after fatigue tests. The specimens were subjected to cyclic loading with a pulsating sign-constant load below the yield strength. The minimum load was equal to 10% of the maximum value.

The measurement points of acoustic anisotropy were selected on one of destroyed specimens according to the scheme in Fig.1. Three points n in each row were selected.

The acoustic sensor with three piezoelectric transducers was used to measure acoustic anisotropy. Transducers were responsible for emission and reception of longitudinal waves and two shear waves with orthogonal polarization. Shear waves were oriented along and across the specimen axis. Calculation of acoustic anisotropy was carried out by using an IN-5101A certified acoustic anisotropy analyzer. It is based

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on the high-precision measurement of time delays between multiply reflected pulses according to Eqn. (1).

$$a = \frac{2(t_2 - t_1)}{(t_1 + t_2)}$$  \hspace{1cm} (1)

where $t_1$ and $t_2$ are time delays between reflected pulses of orthogonally polarized waves.

At the second stage, each surface of specimen was subjected to mechanical grinding to a depth of 1.5 mm.

At the third stage, measurements of acoustic anisotropy measurement at the same points as before grinding were carried out (in Fig. 1).

The distributions of acoustic anisotropy in specimen before and after removal of surface layer are shown in Fig. 2.

Similar investigations were carried out for flat corset aluminum specimens cut along the rolling direction. Specimens with a size of 500x70x20 mm were subjected to uniaxial monotonic stretching until destruction. The total axial deformation of one of the specimens was equal to 17.7%. Deformations were measured by using a high-precision strain gauge sensor with a base length of 10 mm and an accuracy of $10^{-4}$ mm.

Measurements of acoustic anisotropy after mechanical tests were carried out at $n = 10$ points located along the working part of the specimen (in Fig. 3).

Grinding of the aluminum specimen was carried out manually due to the curved surface of the specimen after plastic deformation. There were two stages of grinding on one side of the specimen. At the first stage a surface layer of $\Delta h = 250 \div 330 \mu m$ thick was removed. The average value of the removed surface layer was equal to $\Delta h_{\text{average}} = 310 \mu m$. The thickness of the removed layer exceeded 300 microns at points 4-7 (see Fig. 4). At the second stage, surface layer of $\Delta h = 500 \div 650 \mu m$ thick was removed. The thickness of the removed layer exceeded 590 microns at points 4-6 (see Fig. 4). The average value was equal to $\Delta h_{\text{average}} = 580 \mu m$ after two stages of grinding. Acoustic anisotropy was measured at each stage of grinding at the points indicated in Fig. 3.

The obtained distributions of acoustic anisotropy are shown in Fig. 4.

**Fig. 3.** The location of the measurement points of acoustic anisotropy $a, \%$ in aluminum specimen.

**Fig. 4.** The distribution of acoustic anisotropy $a, \%$ in specimen before loading, after mechanical tests and after two stages of grinding.

### 3 Discussion

Distributions presented in Fig. 2 and Fig. 4 indicate the surface effect of acoustic anisotropy in industrial alloys. The uneven distribution of the value of acoustic anisotropy in the range of -0.1501 to 0.6751% is observed before grinding steel specimens (see Fig. 2). It becomes close to a uniform distribution in the range of -0.0642 to -0.0999% after removal of surface layer. Thus, the change in the integral value of acoustic anisotropy is equal to 10–15 times after removal of surface layer in steel specimens.

The surface effect of acoustic anisotropy also appears in the aluminum specimen (in Fig. 4). The value of integral acoustic anisotropy tends to the initial level measured before uniaxial tension tests after each grinding step. At the same time, the weakening of the surface effect is observed after the removal of surface layer of metal over a certain thickness. For example, the integral acoustic anisotropy at point 5 changes by the...
value of $\Delta a_I = 0.26\%$ after removing $\Delta h_I = 330 \, \mu m$ of thickness at the first stage. However, the change in acoustic anisotropy after removing another $\Delta h_{II} = 650 \, \mu m$ in the second stage is 3.4 times smaller and equals to $\Delta a_{II} = 0.077\%$.

The cases presented in Fig. 2 and Fig. 4 are different. Grinding in the steel specimen was carried out from two sides (in Fig. 1). However, the influence of damaged surface layer on non-polished side is retained in the aluminum sample (in Fig. 3).

Thus, the damage of thin surface layer of specimens occurs during fatigue destruction and plastic deformations. Removal of this layer leads to recovery of the value of acoustic anisotropy to initial state before deformation and fatigue. This experimental result allows to develop methods for estimating damage of surface layer. It correlates with the value of plastic deformation and degree of metal fatigue.

All specimens had a significant thickness about 2 cm. Removing a thin surface layer with a thickness from 50 to 300 μm is possible at the measurement site during the preparation of the surface of diagnosed construction. In this case, it does not affect bearing ability of structures. However, there is a very strong change in the value of acoustic anisotropy after removing only 50 μm in case of existence of damaged layer. This change may be a diagnostic feature for technical control of structures.

It was shown that the destruction of metals due to friction is correlated with hydrogen absorption [29]. It occurs due to dissociation of hydrogen-containing compounds on surface irregularities. These compounds include water vapor in atmosphere. Therefore, the accumulation of hydrogen in specimens under external mechanical load may be an indicator of damage zones.

We carried out additional measurements of distribution of hydrogen concentrations in aluminum specimens after destruction by the method of vacuum heating [30–34]. The results of measurements and distribution of acoustic anisotropy are shown in Fig. 5 and Fig. 6. The measurement points were chosen as in case presented in Fig. 3. The abscissa axis in Fig. 5 and Fig. 6 shows the distance to destruction area of the aluminum specimen. Hydrogen concentrations were measured in metal columns cut around points of acoustic anisotropy measurement. They had a height equal to thickness of specimen and a base of 6x6 mm².

The qualitative coincidence of the distributions presented in Fig. 5 and Fig. 6 suggests that structural changes in metal localized in a thin surface layer cause a surface effect.

In addition, the obtained result can be used to control concentration of dissolved hydrogen and corrosion damage in metal by using acoustic anisotropy. It is important that the value of acoustic anisotropy correlates with structural changes in surface layer of metal. It allows to consider the process of accumulation of hydrogen with high binding energy in internal traps regardless the situation when the dissolved hydrogen accumulates and destroys the metal. Similarly, changes in acoustic anisotropy will be correlated with corrosion damage of metal structure.

4 Conclusion

The results of acoustic measurements in specimens made of steel and aluminum industrial alloys indicate the surface effect of acoustic anisotropy.

The change in the integral value of acoustic anisotropy by 10–15 times was observed after removal of surface layer in steel specimens after fatigue destruction. The surface effect also appeared after removal of 300 microns of surface layer in aluminum specimens destroyed after uniaxial tension. Rapid attenuation of surface effect was observed when the metal layer was removed above the thickness correlated with the average grain size of metal.

The correlation between the distributions of acoustic anisotropy and hydrogen concentrations is an indirect confirmation of surface effect.

The obtained results allow to formulate diagnostic feature for fatigue destruction, large plastic deformations, corrosion damage and hydrogen degradation of structure of metals. These features are based on measurements of acoustic anisotropy before and after removal of a thin surface layer in zones of installation of ultrasonic sensors with an area of about 1.5 cm². It means that nondestructive testing of all the listed cases of destruction and accumulation of damage
is possible for a large range of structures and machine parts with a metal thickness of about 1-3 cm.

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