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Investigation of the correlation between acoustic anisotropy, damage and measures of the stress-strain state

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Abstract

Investigation of the correlation between measure of damage tensor and acoustic anisotropy of specimens from commercial alloy was carried out. The relationship between the principal values of damage tensor and the velocities of ultrasonic waves was established. The formula for acoustic anisotropy based on the principal values of damage tensor was proposed. It allows to describe the anisotropy of the accumulation of damages, which have a significant influence on acoustic anisotropy. The nonlinear dependence of acoustic anisotropy on local deformations and axial stresses in the region of large plastic deformations was observed. The results of the investigation indicate the possibility of estimating of damage based on measurements of acoustic anisotropy. It has a great importance for an objective estimating the state of engineering structures by acoustic methods.

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Keywords: acoustic anisotropy, damage tensor, plastic deformations, longitudinal and transverse waves, ultrasonic inspection

1. Introduction

The investigation of the anisotropy of the acoustoelastic properties of engineering structures in the nuclear, oil and gas and automotive industries is important for the development of acoustic methods of nondestructive testing. The method of acoustoelasticity is a method of nondestructive testing, based on the measurement of acoustic anisotropy. Measuring of the stresses averaged over the thickness of the material is an advantage of the acoustoelasticity method in comparison with tensometry methods.

Acoustic anisotropy Δa is defined as the relative difference in the velocities of transverse ultrasonic waves v_1 , v_2 of mutually orthogonal polarization:

$$\Delta a = 2(v_1 - v_2)/(v_1 + v_2) \tag{1}$$

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Acoustic anisotropy is related with the acoustoelastic effect discovered by Benson and Raelson (1959). Hughes and Kelly (1953) established a linear dependence of the velocities of transverse waves on the stresses for a linearly elastic isotropic homogeneous medium in the case of uniaxial loading. The general theory of acoustoelasticity was developed by Toupin and Bernstein (1961) and Thurston and Brugger (1964). It was based on the nonlinear elastic Murnaghan (1937) model that accounts for the third-order components. Crecraft (1967) discovered the significant influence of texture on acoustic anisotropy by measuring residual stresses. The texture occurs in the existence of a predominant orientation of the grains in the polycrystalline material. Several theories were developed by Tokuoka and Saito (1969), King and Fortunko (1983), Pao and Gamer (1985) to take into account the influence of the texture on acoustic anisotropy.

The generally accepted equation for acoustic anisotropy was obtained by Pao and Gamer (1985) on the basis of investigations of acoustic anisotropy in the region of small plastic deformations carried out by Johnson (1981), Toda et al. (1982) and Hirao and Pao (1985):

$$\Delta a = a_0 + a_1(\varepsilon_1^P - \varepsilon_2^P) + C_A(\sigma_1 - \sigma_2) \tag{2}$$

where a_0 is the initial acoustic anisotropy, $a_1(\varepsilon_1^P - \varepsilon_2^P)$ is the term related with plastic deformations, $C_A(\sigma_1 - \sigma_2)$ is the term related with the principal stresses, a_1, C_A are the material constants that are independent of plastic deformations. The term $a_0 + a_1(\varepsilon_1^P - \varepsilon_2^P)$ is the contribution of the texture to acoustic anisotropyΔa.

Formula (2) was theoretically and experimentally confirmed for the case of elastic and small plastic deformations King (1981), King (1982), Kobayashi (1987), Kobayashi (1992), Kamyshev (2017).

We have experimentally found that acoustic anisotropy is nonlinearly depends on deformations in the case of elasto-plastic deformation of specimens from commercial alloy (Belyaev et al. (2016a)). This phenomenon was confirmed during mechanical tests of corset specimens (Belyaev et al. (2016b)) and specimens with a stress concentrator in the form of a central circular hole (Grishchenko et al. (2017)). The nonlinear nature of the distribution of acoustic anisotropy cannot be explained by the generally accepted formula (2). The proposed model of propagation of sound wave in stressed elasto-plastic material (Belyaev et al. (2016c)) allows to describe the nonlinear character of acoustic anisotropy in the first approximation.

The significant increase in acoustic anisotropy was observed in experiments on hydrogen cracking of specimens from weatherproof steel without external loading (Alekseeva et al. (2016)). Investigations of the microstructure of the sections of the specimens revealed that the effect is due to the influence of microcracks on acoustic anisotropy.

The relationship between acoustic anisotropy and microcracking has not been studied previously in the scientific literature. We developed a model of a medium with anisotropic damage (Semenov (2017)), which allows relate the components of damage tensor to the velocities of ultrasonic waves measured during nondestructive testing. Thus, the acoustoelastic effect was described in terms of fracture mechanics.

The aim of this work is to establish the relationship between damage and acoustic anisotropy by using various schemes of symmetrization of damage tensor. The motivation is due to the fact that there are no methods for estimating the state of engineering structures in the case of large plastic deformations by acoustic methods of nondestructive testing.

2. Model

We used a model of a continuous medium with anisotropic continual damages to describe the acoustoelastic effect. The concept of local continual damage was proposed by Kachanov (1958) and Rabotnov (1959) and developed later by Lemaitre (1986), Lemaitre (1987), Chow (1987), Chandrakanth (1995) and others. The concept is based on the use of damage tensor $\mathbf{D}$, which allows to take into account the anisotropy of the process of accumulation of damages. The tensor of effective stresses $\bar{\boldsymbol{\sigma}}$ (Murakami et al. (1981)) is used instead of the Cauchy stress tensor $\boldsymbol{\sigma}$ for the formulation of the defining equations:

$$\bar{\sigma} = \sigma \cdot (\mathbf{1} - \mathbf{D})^{-1} . \tag{3}$$

The tensor of effective stresses $\bar{\boldsymbol{\sigma}}$ is asymmetric in the general case. We proposed a unified form of symmetrization of the tensor of effective stresses $\bar{\boldsymbol{\sigma}}$ (Semenov (2017)), which contained explicit additive scheme, implicit additive