

Ultrasonic Sensing Method for Evaluating the Limit State of Metal Structures Associated with the Onset of Plastic Deformation

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Abstract—The deformation behavior of St3 steel was studied to show that the stress-strain state of a structure can be estimated using Rayleigh surface waves in both the elastic and plastic region. The most informative parameters in the analysis of the limit state associated with the onset of plastic deformation are the dispersion and shape of the probing signal. If the processes governing the effect of the medium on the elastic wave parameters are represented by a statistical model in the form of the Dirichlet distribution, it is possible to single out a new diagnostic feature of acoustic anisotropy in a structure which describes ultrasonic wave propagation in a material under elastic-plastic deformation. These data can be used for a preliminary assessment of the degree of structural deformation, before assessing its state from wave velocity measurement results.

Keywords: ultrasonic sensing, Rayleigh wave, Dirichlet distribution, entropy, nonlinearity, self-organization

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1. INTRODUCTION

One of the promising methods for solving the problem of operational monitoring and diagnostics of the stress-strain state of metal structures is an acoustic method based on the assessment of acoustic anisotropy in a medium under acting stresses [1, 2]. In the case of elastic strains and variation in elastic wave velocity, the anisotropy is proportional to the difference in principal stresses [3–7]. In so doing, the expression for potential strain energy includes the nonlinear elastic Murnaghan model with regard to the third-order strain components [3].

In the inelastic region, the dependence of acoustic anisotropy on plastic strain becomes nonlinear, which makes it difficult to interpret the monitoring results for the stress-strain state determined by velocity measurement [7–11].

However, when studying a real structure, the stage of deformation (elastic or elastic-plastic) is unknown prior to diagnostics.

In this work, we propose an ultrasonic sensing method to identify the material state and to class a

structure to be diagnosed as the structure in the state associated with the onset of plastic deformations.

2. EXPERIMENTAL PROCEDURE

The investigation is performed on hot-rolled sheet St3ps steel intended for variable-load operation in the temperature range from -40 to $+425^{\circ}\text{C}$ and characterized by the ultimate strength $\sigma_B = 470$ MPa and yield strength $\sigma_{0.2} = 300$ MPa.

A uniaxial stress-strain state is achieved in the material by tension of proportional bar specimens 8 mm in thickness with the gauge width 20 mm and of non-standard strips 200 mm wide with the gauge length 400 mm. The tensile test is carried out in accordance with GOST 1497 on a universal testing machine manufactured by Tinius Oilsen Ltd (model H100KU) and a TsDMU-30 machine with a maximum load of 30 tons. The effect of the stress-strain state on the sensing elastic wave parameters is studied using Rayleigh surface waves. The latter are chosen on account of their universal application for ultrasonic testing of parts and billets of any shape [12].

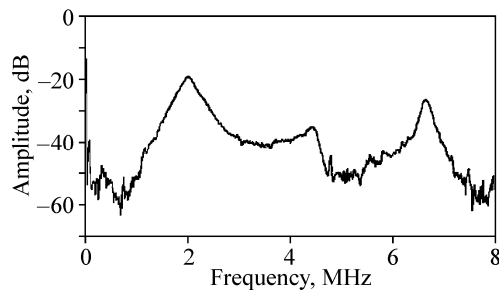


Fig. 1. Fourier transform of the probing signal.

A surface wave is generated by piezoelectric transducers at the vibration frequency of 2, 5, and 10 MHz. The transmitting and receiving piezoelectric transducers are installed in the same block and spaced at 50 mm. The transmitting piezoelectric transducer is excited using an A1214 flaw detector, the probing pulse is recorded using a Tektronix TDS2022 oscilloscope with a maximum time resolution of 2 ns. The delay of the received signal relative to the informative point (when the pulse crosses zero) is taken as a numerical indicator of the strain-induced change in the elastic wave velocity. A longer delay, as compared to the initial position, at the constant distance between the transmitting and receiving transducers points to a decrease in the probing pulse velocity, and vice versa.

The problem of analyzing the probing pulse shape is solved using a special measuring circuit with wide frequency capabilities: sensing wave excitation by a transmitter with a resonant frequency of 2 MHz, and probing signal recording by a receiver with a resonant frequency of 5 MHz. The Fourier transform of the probing signal recorded by the receiving transducer is shown in Fig. 1.

3. EXPERIMENTAL RESULTS AND DISCUSSION

Figure 2 shows the stress and elastic Rayleigh wave delay (velocity) as a function of strain during tensile testing of proportional specimens. The Rayleigh wave propagates parallel to the applied stress.

With reference to the figure, in the elastic region the delay decreases linearly (the elastic wave velocity increases) with growing strain. In the plastic region, the elastic Rayleigh wave velocity demonstrates a complex nonlinear behavior and decreases with strain. The delay variation in the elastic region is independent of the probing pulse frequency. In the plastic region, the velocity-frequency dependence is apparent. Note that, since the Rayleigh wave propagates to the depth approximating the wavelength, these dependences and velocity variations are related to the thickness

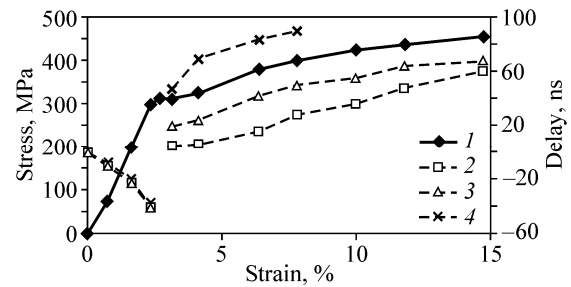


Fig. 2. Strain dependence of stress (1) and the delay of probing pulses with the frequency 2(2), 5(3), and 10 MHz (4).

of the diagnosed material. The latter, in the absence of phase-velocity dispersion of the Rayleigh wave [12] (classical theory), is indicative of a nonuniform thickness distribution of structural transformation during plastic deformation [13].

Figure 3 exhibits the 2-MHz pulse delay (velocity of the sensing Rayleigh wave) as a function of stress in tensile testing of a 200-mm-wide strip. The wave propagates both parallel and perpendicular to the acting stress.

As stresses grow in the elastic region ($\sigma < 300$ MPa), the delay decreases (the pulse velocity increases) for the probing pulse parallel to the acting stress, and it increases (the pulse velocity decreases) for the probing pulse perpendicular to the acting stress. In so doing, the velocity increase for a parallel probing pulse is asymmetrical, as compared to a decrease for a perpendicular pulse. As stresses grow in the plastic region ($\sigma_{0.2} < \sigma < \sigma_B$), the probing pulse velocity decreases (the delay increases) for both probing pulses—parallel and perpendicular to the acting stress.

For purely elastic strains ($\sigma < \sigma_{0.2}$), the delay (velocity) variation for waves parallel and perpendicular to the stress direction in the loaded material is proportional to the acting stress. For plastic strains ($\sigma > \sigma_{0.2}$), the dependence of acoustic anisotropy (delay variation) on the applied stress is nonlinear and decreases with stress. This makes it difficult to evaluate plastic strain by measuring acoustic anisotropy.

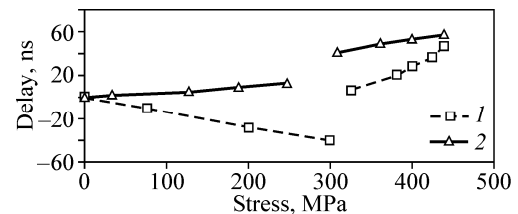


Fig. 3. Dependence of the pulse delay on the acting stress for the parallel (1) and perpendicular direction of the probing pulse (2).

4. CALCULATION OF THE DIAGNOSTIC PARAMETER OF SELF-ORGANIZATION BASED ON THE STATISTICAL MODEL OF THE DIRICHLET DISTRIBUTION

In recent decades, a deformable solid has been widely considered as a multilevel hierarchically organized system, which should be described within nonlinear mechanics and nonequilibrium thermodynamics [13–19]. According to this methodology, a deformable solid is an open system highly nonequilibrium in local stress concentration zones, with nonequilibrium local structural transformations occurring during loading. Their self-organization under the given boundary conditions of loading is responsible for the formation of dissipative structures, whose evolution determines the nature of plastic flow and fracture of the material. Along with a number of factors caused, in each specific case, by the above deformation processes, each can be represented as a process of formation-disappearance of free volume elements with the aid of a statistical model of the Dirichlet distribution [20] defined on a k -dimensional simplex by a probability density function

$$D(x_1, \dots, x_k) = \frac{\Gamma(a_n)}{\prod_{i=1}^k \Gamma(v_i)} \prod_{i=1}^k x_i^{v_i-1} (1 - \sum_{i=1}^k x_i)^{v_n-1}, \quad (1)$$

$$0 \leq \sum x_i \leq 1, v_i \geq 0, \dots, v_n \geq 0, \sum_{i=1}^n v_i = a_n, n = k + 1,$$

where x_i is the relative concentration of free volume elements, v_i is the rate of opposite independent processes of formation or disappearance of free volume elements (strain-induced defects). Such a representation, according to the thermodynamic concept proposed by Shannon [21], enables a study of processes occurring in the analyzed system in terms of thermodynamics and one of its most important concepts—entropy. For further discussion, it is important that entropy as a universal function of the state of matter includes production and flow [22]. The Dirichlet distribution entropy defined as

$$H = - \int_x \varphi(x) \log_{\alpha} \varphi(x) dx \quad (2)$$

is taken to the logarithmic base

$$H(v_1, \dots, v_n) = \prod_{i=1}^n \Gamma(v_i) - \ln \Gamma(\alpha_n) + (\alpha_n - n) \psi(\alpha_n) - \sum_{i=1}^n (v_i - 1) \psi(v_i) \quad (3)$$

and can be represented as the sum [7]

$$H(D) = H_i(v_i, \dots, v_n) + H_e(a_n). \quad (4)$$

In expression (4) the always positive term

$$H_i(v_1, \dots, v_n) = \ln \prod_{i=1}^n \Gamma(v_i) - \sum_{i=1}^n (v_i - 1) \psi(v_i) \quad (5)$$

represents the entropy production due to irreversible processes, and the term

$$H_e(a_n) = -\ln \Gamma(a_n) + (a_n - n) \psi(a_n) \quad (6)$$

characterizes the entropy flow responsible for the interaction with the environment by exchange of matter or energy. Here $\Gamma(x)$ is the γ -function, $\psi(x) = d/dx \ln \Gamma(x)$ is the logarithmic derivative of the γ -function. Since distribution (1) is completely determined by the rates of independent processes v_i , the presented statistical model is invariant not only to the type of the stress-strain state but also to the type of processes associated with plastic deformation. At $n \geq 3$, entropy flux (5) can take both positive and negative values, which, in terms of the Dirichlet distribution model, makes $H_e(a_n) < 0$ one of the conditions of self-organization [22] and, as was shown in [13–15], can point to ordering processes in the local crystal distortion zone caused by the formed metastable defective phases. The representation of the Dirichlet distribution entropy as the sum of production and a sign-changing flow compares favorably with the widely used models based, for example, on normal distribution, γ -distribution, and Poisson distribution, in which such a representation is impossible [20, 23].

To calculate the diagnostic parameter of pulse shape self-organization K_c within the statistical model of the Dirichlet distribution (1), the digitized probing signal with the number of values N is divided, by the sliding window method, into a sequence of samples m_i , where $i = 1, \dots, N - m$ (the sample size is $m = 24$ values, and the sliding step is a value). For each sample sequence m_i , we choose skewness β_1 and kurtosis β_2 , which are used to find shape parameters v_i of the sequence of β -distributions (one-dimensional Dirichlet distributions) [24]. Given the Dirichlet distribution, if (x_1, \dots, x_k) is a random vector variable having a k -dimensional Dirichlet distribution $D(v_1, \dots, v_k; v_{k+1})$, then the sum $x_1 + \dots + x_k$ has a β -distribution $Be(v_1 + \dots + v_k; v_{k+1})$ [25]. Successive β -distributions are convoluted to a sequence of Dirichlet distributions. In accordance with the rules of the statistical theory of information [23] and within a ten-dimensional model, the parameters α_i of Dirichlet distributions for each i th dimension are determined as

$$\alpha_i = \frac{6(\beta_{2(i)} - \beta_{1(i)} - 1)}{6 + 3\beta_{1(i)} - 2\beta_{2(i)}}, \quad (7)$$

and used to calculate external entropy (3).

The number of Dirichlet distributions in the analyzed sample N , with positive and negative external entropy, provides a way of estimating the self-organization parameter of the pulse shape:

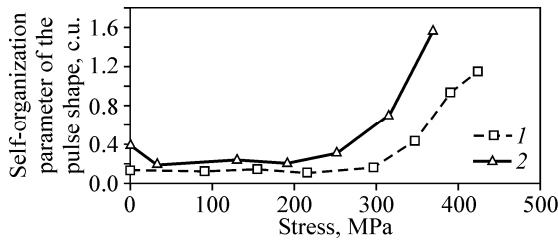


Fig. 4. Dependence of the self-organization parameter of the probing pulse shape on the acting stress. The direction of wave propagation is parallel (1) and perpendicular to the stress (2).

$$K_c = \frac{\sum i Q_{D-}^i}{\sum i Q_{D+}^i}, \quad (8)$$

where $\sum i Q_{D-}^i$ is the number of i -dimensional Dirichlet models with the negative external entropy (flux) in the analyzed numerical series of the signal, and $\sum i Q_{D+}^i$ is the number of Dirichlet models with the positive external entropy.

The structure of the self-organization parameter is measured via the contribution K_{ci} to the parameter of Dirichlet models of each dimension:

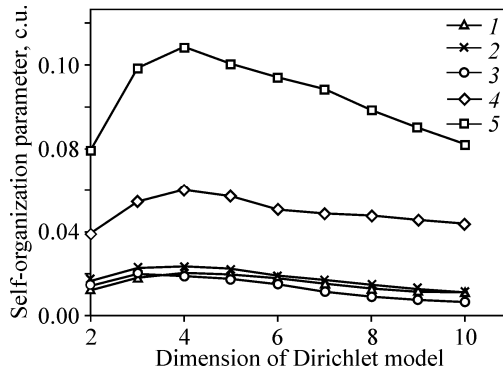


Fig. 5. Structure of the shape self-organization parameter of the probing pulse propagating parallel to the acting stress: 0 (1), 155 (2), 215 (3), 347 (4), and 390 MPa (5).

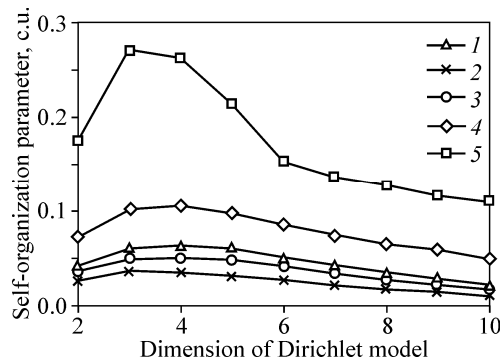


Fig. 6. Structure of the shape self-organization parameter of the probing pulse propagating perpendicular to the acting stress: 0 (1), 191 (2), 252 (3), 315 (4), and 369 MPa (5).

$$K_{ci} = \frac{i Q_{D-}^i}{\sum i Q_{D+}^i}. \quad (9)$$

Figure 4 shows the dependence of the self-organization parameter of the pulse shape K_c on the acting stress for the parallel and perpendicular probing pulse.

In the elastic region ($\sigma < \sigma_{0.2}$), the shape self-organization parameter K_c for the parallel and perpendicular probing pulse is independent of the acting stress. In the plastic region, the parameter K_c increases nonlinearly with stress regardless of the probing pulse direction. This points to local (the 2-MHz probing pulse penetrates to the depth ~ 2 mm) transformations of the defective structure associated with plastic flow of the material.

Figures 5 and 6 plot the parameter K_{ci} as a function of the acting stress for the parallel and perpendicular pulse.

With reference to Figs. 5 and 6, it is seen that the self-organization parameter structure changes significantly at the stress above the yield stress. Plastic deformation increases the contribution of higher-order models, which is indicative of a changed mechanism of self-organization of processes associated with plastic deformation. This change is most pronounced for the probing pulse normal to the acting stress.

5. CONCLUSIONS

It was shown that Rayleigh surface waves can be used for evaluating the stress-strain state of a structure both in elastic and plastic regions. In the plastic region, the interaction of the probing pulse with the medium changes due to nonlinear dissipative processes, which makes the acoustoelastic method based on the nonlinear elastic Murnaghan model inapplicable. The obtained results give reason to propose new diagnostic features of a material under elastic-plastic deformation—the self-organization parameter of the probing pulse shape and the frequency dependence of Rayleigh surface wave velocity. These parameters can be used to assess the state of metal structures associated with plastic deformation.

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