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PHYSICAL ACOUSTICS

Measurement of Velocity Distribution for Longitudinal Acoustic Waves in Welds by a Laser Optoacoustic Technique

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Abstract—An optoacoustic technique for diagnostics of residual stress in metals is proposed. The theoretical part of the technique employs acoustoelastic relations establishing a linear relationship between the biaxial residual stress and the relative variation of the velocity of longitudinal ultrasonic waves. The experimental technique is based on laser excitation of nanosecond ultrasonic pulses at the surface of samples under investigation and their detection with a high time resolution. Distributions of the relative variation of longitudinal wave velocities due to the presence of residual stress in the samples are obtained.

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Fulfilling the task of increasing the service life of metal structures and their strengthening simultaneously leads to the development of methods for material hardening and to the development of techniques for measuring the residual stress arising as a result of thermal or mechanical action on a material. The destructive techniques are different versions of the method of hole drilling [1] as applied to metals, rocks, and composites, and also the method of layer-by-layer removal of the material [2]. Together with these, nondestructive methods are developed, i.e., ultrasonic techniques [3], an X-ray method [4], and the neutron diffraction method [5].

The method of hole drilling [6] is based on measuring the stress (or strain) variation caused by drilling a hole in a part with mechanical stress. As applied to testing welds, it is possible to single out the method by Cordiano and Salerno [7]. It is necessary to note that its use is based on the assumptions that the stress does not vary with depth, the major stresses are parallel and perpendicular to the direction of welding, and the residual stress tends to zero at a certain distance from the weld and increases according to a linear law as the distance becomes smaller.

The X-ray method [8] provides an opportunity to conduct direct measurements of loaded parts. The interatomic spacing (and its measurement) is used as the basis for certain planes of the crystal lattice. The resolution is 20–30 MPa. The application of the method is possible for testing the stress at depths from 2 to 20 μm.

The stress present in a material leads to microstructure changes in it, i.e., the rise of preferential directions in the orientation of polycrystallites. At the macroscopic level, this manifests itself in the change of the elastic moduli, attenuation, and ultrasonic wave velocity in the substance. The inverse problem of acoustoelasticity is the basis for ultrasonic techniques, i.e., the reconstruction of the residual stress distribution in a medium according to the variation of ultrasonic velocities. To solve it successfully, it is necessary, first, to develop a theoretical model for elastic wave propagation in a medium in the presence of stress. Second, to obtain ultrasonic data in an experiment, a high precision of measurements is necessary.

Let us consider in more detail the theoretical part of the problem. The microstructure changes that occur in a medium under the effect of stress evidently influence the spectrum of ultrasonic wave attenuation in the substance. However, it is not yet possible to apply this fact to the determination of stress values because of the absence of a theoretical model (even an empirical one) capable of establishing an unambiguous relationship between the frequency spectrum of ultrasonic attenuation and the stress distribution in a medium (see papers on ultrasonic scattering in polycrystallites).

On the other hand, there are many papers devoted to the determination of the relation between the values of residual stress and the phase velocities of bulk [10] and surface [11] acoustic waves. The approximation of geometrical acoustics is used in [12] to determine the velocities of surface acoustic waves in a stressed solid, and the necessity to conduct precision measurements is also indicated. Therefore, to estimate the level of residual stress, it seems to be reasonable to measure the variation of the elastic wave velocities that is caused by the presence of residual stress in the medium.

Many experimental techniques for measuring the velocities of longitudinal, transverse [12, 13], and surface [14] acoustic waves have been developed up to now. Nevertheless, the problem of determining the residual stress level in metals still remains relevant. For example, in the case of the typical value of residual stress equal to 100 MPa, the relative variation of elastic wave velocities is very small and lies within the range of 10^{-3}–10^{-4}. To improve the precision of measurements, it seems promising to use the optoacoustic effect [15]. Since thermooptically excited acoustic pulses are broadband and short, a high precision of measurements of ultrasonic velocity can be attained with samples of relatively small dimensions with a thickness of several millimeters.

In this paper, we propose an optoacoustic technique for measuring the relative variation of the velocities of longitudinal acoustic waves in metals that is caused by the presence of the stress produced in them by welding. The purpose of this work is to demonstrate the feasibility of the determination of residual stress in welds with samples whose thickness is about several millimeters and to estimate the error of the optoacoustic technique.

Writing down the equation of motion for the medium, it is necessary to take into account the presence of a nonzero displacement caused by residual deformation of the medium. Thus, all the equations must be written down in the Lagrangian coordinates $\{X_i\}$ of a deformed solid. To return to the initial coordinate system $\{x_i\}$, it is necessary to use certain transformations, which will be briefly represented below.

The generalized Kristoffel's equation for a medium with residual stress is commonly written down in the form [16]

$$[\bar{C}_{ijkl}p_ip_l + (\sigma_{il}p_ip_l - \rho V^2)\delta_{jk}]d_k = 0, \quad (1)$$

where

$$\bar{C}_{ijkl} = \frac{\rho}{\rho_0}(C_{mnpq} + C_{mnpqrs}E_{rs})\frac{\partial X_i}{\partial x_m}\frac{\partial X_j}{\partial x_n}\frac{\partial X_k}{\partial x_p}\frac{\partial X_l}{\partial x_q}; \quad (2)$$

ρ_0 and ρ are the densities of the undeformed medium and the medium subjected to static deformation; V, p_i, and d_k are the velocity, the component of the polarization vector, and the component of the wave vector of the elastic wave, respectively; and σ_{il} is the tensor of residual stress present in the medium. The expression for $\bar{C}_{ijkl}$ takes into account both the physical transformation of the elastic moduli due to nonlinearity and the geometrical transformation on account of the transformation of coordinates.

We assume that a biaxial uniform stress

$$\sigma_{ik} = \begin{pmatrix} 0 & & 0 \\ & \sigma_{22} & \\ 0 & & \sigma_{33} \end{pmatrix} \quad (3)$$

is present in a solid.

Let a wave propagate along the $\mathbf{x}_1$ axis: $p_1 = 1, p_2 = 0$, and $p_3 = 0$. In this case, expressions for the velocities of the elastic waves propagating in this direction can be obtained from the solution to the characteristic equation

$$\left|\bar{C}_{1jk1} + \rho V^2\delta_{jk}\right| = 0. \quad (4)$$

The coefficients with $j \neq k$ are $\bar{C}_{1jk1} = 0$, because the matrix is diagonal. Its determinant is equal to the product of the diagonal elements, and the modes are pure. Thus, we have

$$(\bar{C}_{1111} - \rho V^2_{lx_1})(\bar{C}_{1221} - \rho V^2_{Sx_2})(\bar{C}_{1331} - \rho V^2_{Sx_3}) = 0. \quad (5)$$

The first root corresponds to a longitudinal acoustic wave, and two other roots correspond to the transverse waves polarized in the directions $\mathbf{x}_2$ and $\mathbf{x}_3$, respectively. In addition, we use an abridged form [17] for the tensor $\bar{C}_{ijkl}$. Then, we write

$$V^2_{lx_1} = \frac{1}{\rho}\bar{C}_{11}, \quad V^2_{Sx_2} = \frac{1}{\rho}\bar{C}_{66}, \quad V^2_{Sx_3} = \frac{1}{\rho}\bar{C}_{55}. \quad (6)$$

The matrix $\bar{C}_{ijkl}$ is written down using the Lagrangian coordinates, and it must be represented in terms of the elastic constants of an undeformed solid. In our case of axial stress [4],

$$\frac{\partial X_i}{\partial x_j} = \delta_{ij}(1 + E_{ii}). \quad (7)$$

In this case, for example,

$$\begin{aligned}\bar{C}_{1111} &= \frac{\rho}{\rho_0}(C_{1111} + C_{1111rs}E_{rs})(1 + E_{11})^4 \\ &\approx \frac{\rho}{\rho_0}[C_{1111}(1 + 4E_{11}) + C_{1111rs}E_{rs}].\end{aligned} \quad (8)$$

We assume that, in the stressed state, the Hooke law is also valid:

$$E_{rs} = S_{rsij}\sigma_{ij}, \quad (9)$$

where S_{rsij} is the compliance tensor.

If only σ_{22} and σ_{33} are present in the medium and $\sigma_{11} = 0$, then, at $\mathbf{k} = \{1,0,0\}$, with allowance for Eq. (6),

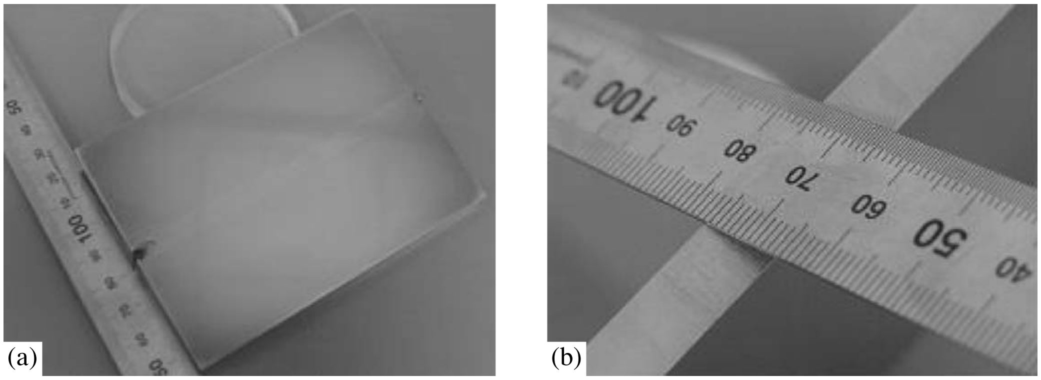

Fig. 1. Samples under study.

the expressions for the relative variation of the velocities of longitudinal acoustic waves take on the form [12, 18]

$$\frac{V_{lx_1}-V_{l0}}{V_{l0}} \approx \frac{\rho V_{lx_1}^2-\rho V_{l0}^2}{2\rho V_{l0}^2} = A(\sigma_{22}+\sigma_{33})+D(\sigma_{22}-\sigma_{33}), \tag{10}$$

where

$$V_{l0}^2 = \frac{C_{11}}{\rho_0}, \tag{11}$$

$$A = \frac{1}{2}\left[\left(2+\frac{C_{111}}{2C_{11}}\right)(S_{12}+S_{13})+\frac{C_{112}}{2C_{11}}(S_{22}+S_{23}) + \frac{C_{113}}{2C_{12}}(S_{32}+S_{33})\right] = \frac{2\mu(a+b)-\lambda(2\lambda+4\mu+2b+c)}{6\mu K(\lambda+2\mu)}, \tag{12}$$

$$D = \frac{1}{2}\left[\left(2+\frac{C_{111}}{2C_{11}}\right)(S_{12}-S_{13})+\frac{C_{112}}{2C_{11}}(S_{22}-S_{23}) + \frac{C_{113}}{2C_{12}}(S_{32}-S_{33})\right] = 0. \tag{13}$$

Analogous relations are valid for the transverse waves (for example, see [12, 13, 18]):

$$\frac{V_{Sx_2}-V_{Sx_3}}{V_{S_0}} = B(\sigma_{22}-\sigma_{33})+E(\sigma_{22}+\sigma_{33}), \tag{14}$$

where

$$V_{S0_2}^2 = \frac{C_{66}}{\rho_0}, \quad V_{S0_3}^2 = \frac{C_{55}}{\rho_0}, \tag{15}$$

$$B = \frac{4\mu+c}{8\mu^2}, \tag{16}$$

$$E = 0. \tag{17}$$

It is also possible to demonstrate that

$$\frac{V_{Sx_2}+V_{Sx_3}-2V_{S_0}}{2V_{S_0}} = C(\sigma_{22}-\sigma_{33})+F(\sigma_{22}+\sigma_{33}), \tag{18}$$

where

$$C = \frac{b-\frac{1}{2}(\lambda-2\mu)\left(1+\frac{c}{4\mu}\right)}{6K\mu}, \tag{19}$$

$$F = 0. \tag{20}$$

Equations (10)–(20) show that, to determine the residual stress, one has to measure the relative variations of the elastic wave velocities rather than their absolute values. When measuring with the use of longitudinal acoustic waves, it is possible to measure only the sums of stresses. The use of transverse waves with mutually orthogonal polarizations provides an opportunity to determine the anisotropy of residual stress.

It is necessary to note that the proposed technique needs calibration. The calibration consists of measuring the relative velocity variation by using the samples with a known applied load, which makes it possible to determine the weighting coefficients in Eqs. (10)–(20). This method is described in [12], for example.

Within this study, we conducted experiments with samples made of stainless steel of the 12Kh18N10T type, which were welded at the center by an electron beam with different intensities (see Fig. 1). The sample parameters are listed in the table. The weld width was determined by the beam diameter. Before measuring, the samples were polished to eliminate roughness and to provide a flatness to their surfaces. We also deter-

Table

Marking	Dimensions (length × width × height, mm)	Width of the weld region, mm	Power of the electron beam, W
A1	106.5 × 78 × 8.51	5	3200
A2	106.5 × 78 × 8.87	6	3200
A3	106.5 × 78 × 8.73	7	3200
C1	80 × 50 × 1.91	2	800
C2	80 × 50 × 1.67	3	800
C3	80 × 50 × 1.97	4	800

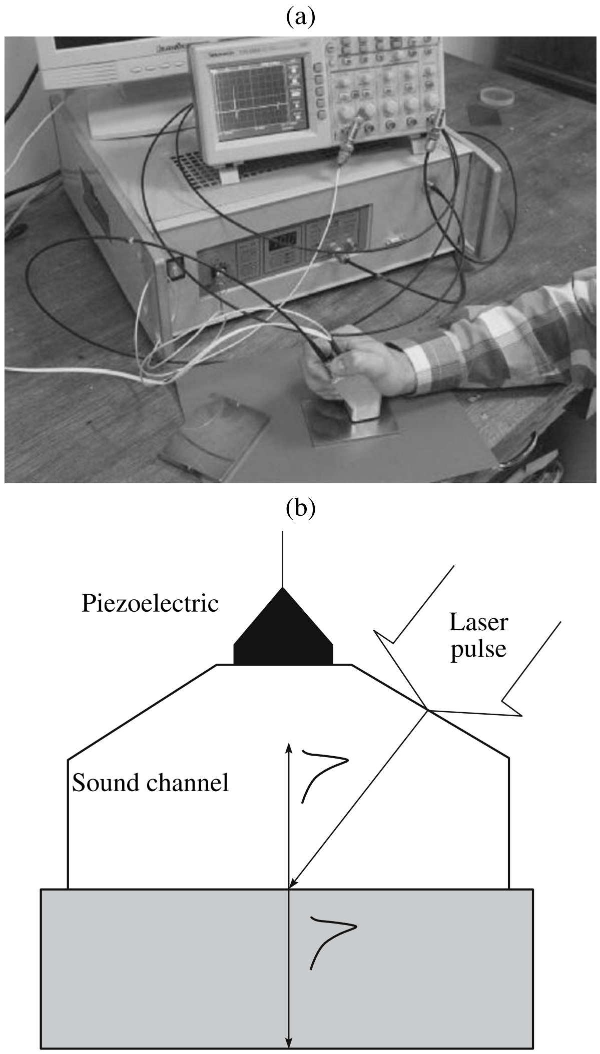

Fig. 2. (a) Experimental setup and (b) the operation principle of the optoacoustic converter.

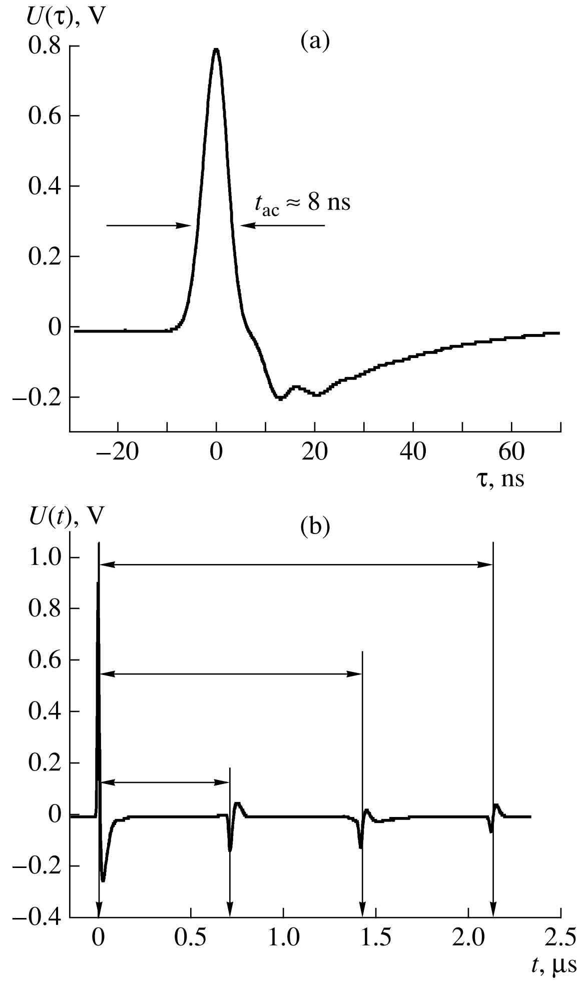

Fig. 3. (a) Probing optoacoustic pulse excited at the face surface of a metal sample and detected by the broadband piezoelectric receiver and (b) a characteristic reverberation pattern of the probing pulse in the sample.

mined their thickness by a micrometer at each point where the sound velocity was measured. The error in thickness measurements was 1–2 μm.

To test for residual stress in samples with welds, we used an optoacoustic converter with indirect detection of ultrasonic signals [18] (see Fig. 2a). From the theory of thermooptical sound excitation, it is well known that any light-absorbing object can be a source of acoustic waves. The waveform, amplitude, and spectrum of optoacoustic signals depend on the mechanical and thermophysical properties of the medium, the parameters of laser radiation, and the geometry of object irradiation. The optoacoustic conversion has a doubtless advantage over the standard piezoelectric excitation of sound, since it provides an opportunity to obtain short (up to several nanoseconds) intense ultrasonic pulses with a smooth time envelope and a broad frequency spectrum. The advantage of the use of indirect detection is its one-sided access and also the convenience of the measuring process.

The operation principle of the optoacostic converter is given schematically in Fig. 2b. A laser pulse is transmitted by an optical fiber through a transparent prism to the face surface of the sample. The acoustic contact between them is provided by a thin water layer. Being absorbed in metal, laser radiation heats a thin surface layer of the sample and the liquid layer next to it. The subsequent thermal expansion leads to the excitation of ultrasonic pulses, i.e., optoacoustic signals, whose time profile repeats the shape of the envelope of the laser pulse intensity [15]. To excite optoacoustic signals, we used the fundamental frequency radiation of a diode-pumped Nd:YAG laser (with a pulse length of 7–8 ns, a pulse energy of 100 μJ, and a pulse repetition rate of 500 Hz). The sensitive element of the optoacoustic converter was a lithium niobate crystal. The low-frequency sensitivity of the receiving channel was about 3 μV/Pa.

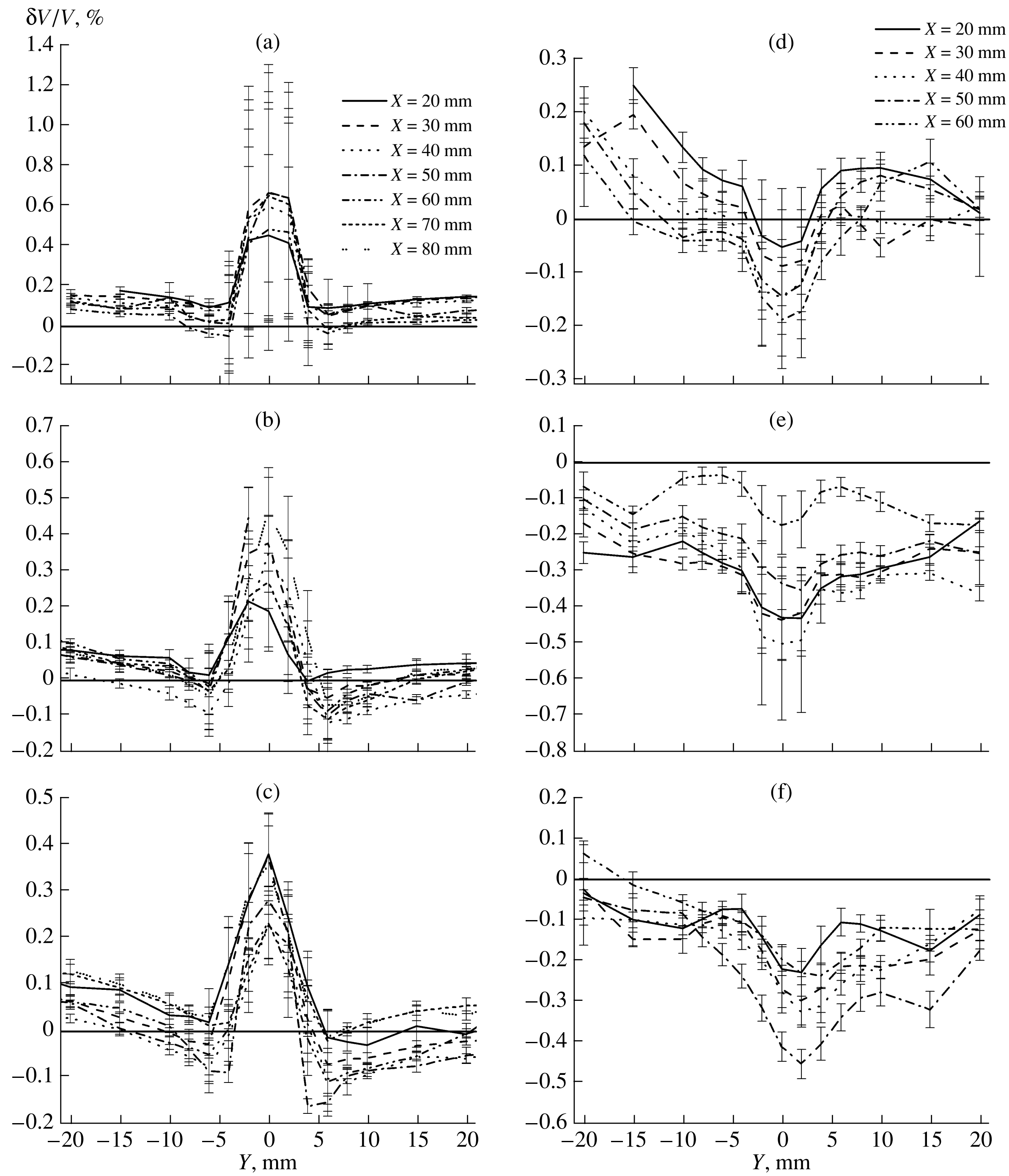

Fig. 4. Dependence of the longitudinal acoustic wave velocity on the distance from the weld center in samples with welds: (a) A1, (b) A2, (c) A3, (d) C1, (e) C2, and (f) C3.

Figure 3a presents the characteristic time profile of a probing optoacoustic signal. The length of its positive part is determined by the length of the intensity envelope of the laser pulse. The negative low-frequency "tail" is caused by the diffraction of the ultrasonic signal in the acoustic channel of the converter, and some oscillations in the pulse "tail" are caused by the nonuniformity of the sensor's transient characteristic at frequencies higher than 70 MHz.

While propagating in the sample, the probing pulse is subjected to multiple reverberation (see Fig. 3b). The first large-amplitude signal is the probing pulse excited at the face surface of the sample. The second signal is its first reverberation in the sample. The amplitude of

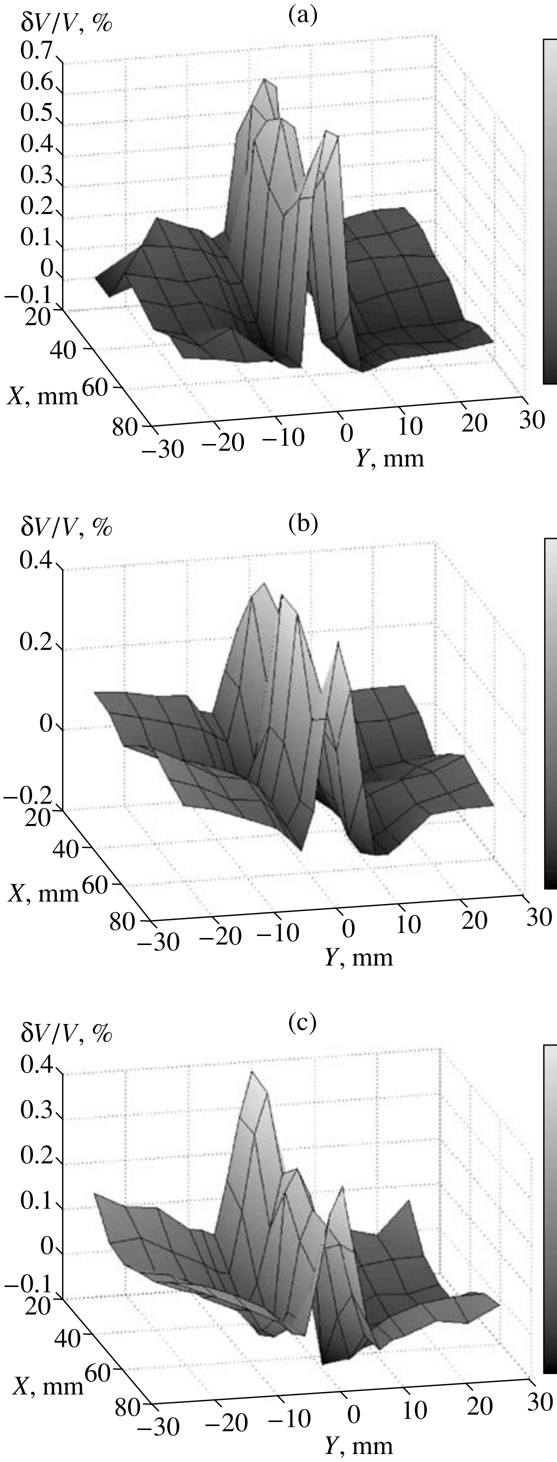

Fig. 5. Lateral distribution of the longitudinal wave velocity in samples with welds: (a) A1, (b) A2, and (c) A3.

this pulse is considerably smaller than that of the initial one because of the losses during the course of acoustic wave transmission from the metal to the quartz sound duct and also ultrasonic attenuation in the metal. Measuring the time delay between reverberations, it is possible to determine the sound velocity in the sample. The optoacoustic technique provides an opportunity to measure the time delays between signals with a precision not worse than 0.5 ns. With such an error, the determination of the relative variation of sound velocity with a precision of 10^{-4} is possible only in the case of a sample thickness greater than 10 mm. Therefore, the velocity measurements with the samples of group C were conducted using a multipass scheme; i.e., we determined the delay between the probing pulse and its third reverberation in the sample. To acquire data on the relative velocity variations, we measured the sound velocities in reference samples. Their values were $V_{l0A} = 5657 \pm 2$ m/s and $V_{l0C} = 5752 \pm 3$ m/s for the samples of groups A and C, respectively.

The measurements were conducted at approximately 100 points in each sample to obtain information on the residual stress distribution. The measurements were conducted along the weld (the X axis) at a step of 10 mm and across the weld (the Y axis) at a step of 2 mm near the weld and 5 mm away from it.

Figure 4 shows the results of measuring the relative variation of the longitudinal acoustic wave velocities. The measurements were conducted several times at each point to determine the statistical error of the method. Taking into account the fact that the acoustic beam diameter in our experiments was 4 mm, in the near-weld region (–10 mm < Y < 10 mm) at each point, we calculated the "floating average" over three points; i.e., for example, at the point with the coordinate $Y = 0$, $Y = 0$, $\langle V_{X,0}\rangle = \dfrac{V_{X,-2} + V_{X,0} + V_{X,2}}{3}$. The large error in the velocity plots for the weld area is associated precisely with this averaging. The measuring error in the region $Y > 10$ mm is determined by the errors of the thickness measurements $\delta h = 1$ μm, the measurements of the time interval between reverberations $\delta t = 0.5$ ns, and the statistical scatter of experimental data.

Figures 4a–4c demonstrate that compression stress exists near the weld and tensile stress exists away from it. One can see that the zone of material compression changes for different welding modes: it is narrowest for sample A1 and widest for sample A3. The velocity variation in the weld itself may occur not only because of the presence of stress, but also because of the change in the material structure. Figures 4a–4c also show that the plots of $\delta V/V$ "go down" from the section $X = 20$ mm (the sample edge) to the section $X = 50$–60 mm (the sample center) and then, again, "climb" up to the section $X = 80$ mm (another edge of the sample). This trend may be explained by the presence of not only the longitudinal stress σ_{11}, but also the transverse stress σ_{22} at the sample edges.

In the samples of group C (Figs. 4d–4f), the situation is similar to that in group A. The zone of material compression varies for different welding modes. It is narrowest in sample C1 and widest in sample C3. However, in thin samples, the compression stress prevails over the rarefaction stress. This may be explained by the fact that the same welding conditions affect thinner samples more strongly. It is also necessary to note that, in the weld zone, the ratio $\delta V/V$ is negative, while it is positive for the samples of group A.

Figures 5a–5c present the three-dimensional dependences of the relative velocity variation in the samples of group A that are plotted according to the data given in Figs. 4a–4c.

Let us make some conclusions. The use of laser thermooptical excitation of sound for testing metals for residual stress is proposed. A laser optoacoustic converter with indirect detection of ultrasonic pulses is used in the experiments. The relative variation of the velocities of longitudinal acoustic waves was measured in samples made of stainless steel of the 12Kh18N10T type, which had a thickness from 1.67 to 8.87 mm and contained residual stress generated by their heating with an electron beam of different intensities. It is demonstrated that the error in the determination of the relative velocity variation is about 2×10^{-4} for "thick" samples and 6×10^{-4} for "thin" ones.

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