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Laser ultrasonic diagnostics of residual stress ☆

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ABSTRACT

Ultrasonic NDE is one of the most promising methods for non-destructive diagnostics of residual stresses. However the relative change of sound velocity, which is directly proportional to applied stress, is extremely small. An initial stress of 100 MPa produces the result of $\delta V/V \sim 10^{-4}$. Therefore measurements must be performed with high precision.

The required accuracy can be achieved with laser-exited ultrasonic transients. Radiation from a Nd-YAG laser (pulse duration 7 ns, pulse energy 100 μJ) was absorbed by the surface of the sample. The exited ultrasonic transients resembled the form of laser pulses. A specially designed optoacoustic transducer was used both for the excitation and detecting of the ultrasonic pulses. The wide frequency band of the piezodetector made it possible to achieve the time-of-flight measurements with an accuracy of about 0.5 ns.

This technique was used for measuring of plane residual stress in welds and for in-depth testing of subsurface residual stresses in metals. Plane stress distribution for welded metallic plates of different thicknesses (2–8 mm) and the subsurface stress distribution for titanium and nickel alloys were obtained. The results of conventional testing are in good agreement with the laser ultrasonic method.

1. Introduction

Development of non-destructive methods for residual stresses evaluation is a very important problem, which has not been solved up to now. Mechanical methods, such as the drilling technique [1] along with measuring of strains modification produced by drilling, are widely utilized. However, they are destructive. There are several non-destructive methods of residual stress evaluation: X-ray [2], neutronographic [3], magnetic [4], thermal [5] and ultrasonic ones [6].

Ultrasonic methods are not limited by the types of material under study and can be utilized for residual stress measurements on thick samples. Thus ultrasonic methods are very promising. Most ultrasonic methods are based on the effect of acoustoelasticity [6–10] – the dependency of the acoustic wave velocity on the value of applied stresses. There are many examples of experimental work that demonstrate the possibility of residual stress reconstruction with using of longitudinal [11], shear [12–13] and Rayleigh waves [14]. The main difficulty with such methods is that the relative deviations of ultrasonic velocities produced by the presence of stress are extremely small. Time-of-flight measurements are usually carried out to determine the velocity difference. The accuracy of such measurements obviously depends on the time duration of a probe pulse. On the other hand the duration of a probe pulse can not be reduced indefinitely, because the attenuation of ultrasound in metals is usually proportional to the second or even fourth degree of frequency. A compromise can be achieved with the application of wide-band ultrasonic pulses. However traditional piezoelectric techniques are inefficient for excitation over a very wide frequency range.

The optoacoustic (OA) phenomenon [15] can be employed for producing a large frequency band. The ultrasonic transients excited by the absorption of laser radiation in a metal follow the time envelope of the laser pulse intensity. This makes it possible to obtain nanosecond ultrasonic pulses with an aperiodic temporal profile, a wide frequency spectrum, and pressure amplitudes up to a few hundreds of MPa [16].

2. Theory

The dependency of the acoustic wave velocity on the value of applied stresses can be obtained from the nonlinear theory of acoustoelasticity. It can be shown [17] that for isotropic solid the relative deviation of longitudinal ultrasound velocity is proportional to the sum of principle stress $\sigma_{XX} + \sigma_{YY}$:

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$$\frac{(V_{lZ}-V_{l0})}{V_{l0}}=A(\sigma_{XX}+\sigma_{YY}). \quad (1)$$

And for shear ultrasonic velocities:

$$\frac{V_{SX}-V_{SY}}{V_{S_0}}=B(\sigma_{XX}-\sigma_{YY}), \quad (2)$$

$$\frac{V_{SX}+V_{SY}-2V_{S_0}}{2V_{S_0}}=C(\sigma_{XX}-\sigma_{YY}), \quad (3)$$

where V is ultrasound wave velocity; σ_{ij} is the stress tensor; *A,B,C* are constants, determined by mechanical properties of material [17]; subscript *l* denotes longitudinal wave; subscripts *SX*, *SY* denote shear waves of different polarization; subscript *0* denotes unstressed medium.

Eqs. (1)–(3) show, that to reconstruct residual stresses in welds the relative deviations of ultrasound phase velocities should be determined. Moreover use of longitudinal waves enables only the sum of principle stress $\sigma_{XX}+\sigma_{YY}$ to be reconstructed. The use of shear waves with mutually orthogonal polarizations make it possible to determine also their anisotropy $\sigma_{XX}-\sigma_{YY}$.

Residual stress states in welds can be near the yield stress ($\sigma \approx 600$ MPa). As shown in Eq. (1) the relative deviation of longitudinal wave velocities is directly proportional to stress: $\frac{\Delta V}{V}=A\cdot\sigma$. The coefficient A can be calculated if the second and third order elastic constants are known. A typical value of $A\approx 10^{-12}\mathrm{Pa}^{-1}$. Therefore, the maximum $\frac{\Delta V}{V}\approx 10^{-3}$. This introduces an additional time delay of the order of only a few nanoseconds for a sample of 1 cm thickness. Thus time intervals between signals must be measured with better then 1 ns resolution.

If there is a depth distribution of stress the relation between the reflectivity coefficient of ultrasound and amplitude of stress when material attenuation can be neglected (due to short distance – less then 150 μm) will be the following:

$$\sigma_{XX}(Z)+\sigma_{YY}(Z)=M\times\int_0^Z R(z)\mathrm{d}z. \quad (4)$$

The constant M can be obtained from the calibration of method. So the distribution of stress can be found using the amplitude dependence of the reflection coefficient.

3. Experiment

Wide-band laser excited nanosecond ultrasonic transients [15–16] were employed to determine relative deviations of phase velocities of ultrasound with the accuracy being suitable for reconstruction of residual stresses in welds and distribution of ultrasound reflection coefficient in hardened metal plates with subsurface stress.

3.1. Experimental setup

Diode pumped Nd-YAG laser operating at the fundamental mode (the pulse energy – 100 μJ, the time duration – 7 ns) was employed for irradiation of metal samples. Laser radiation was delivered to the OA transducer (see Fig. 1), where it was focused onto the front surface of a sample. The photo of the OA transducer is shown in Fig. 2.

The diameter of the probe acoustic beam was equal to the laser beam spotsize, which was 4 mm. The laser pulse is absorbed in the skin layer of metal with the thickness of the order of 10^{-6} cm. Due to transient heating, subsequent thermal expansion of the medium takes place and excites the ultrasonic transients – OA pulses. These are launched in mutually opposite directions. The first signal – the probe pulse – propagates through the clear quartz prism and is detected by wide-band piezoelectric transducer. The second one propagates into a sample, reflects from its rear surface and then returns the way of the probe pulse. In the case of welded samples the time delay between the probe OA pulse and the pulse, reflected from the rear surface is measured. When the sample thickness was smaller than 5 mm, the multiple echoes scheme was used. This measuring scheme allows one to achieve the required accu-

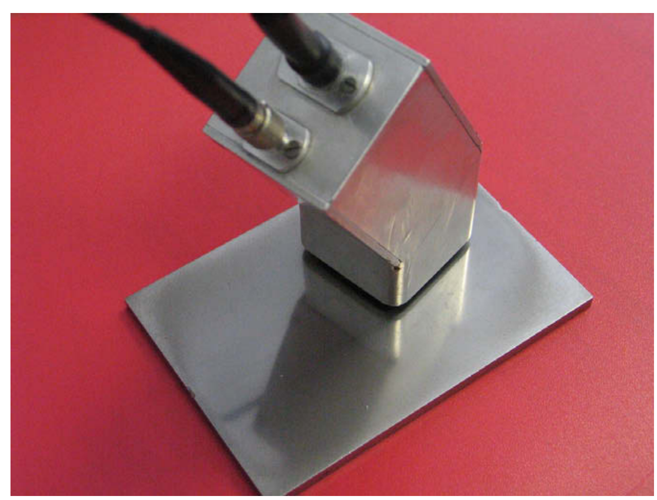

Fig. 2. Optoacoustic transducer.

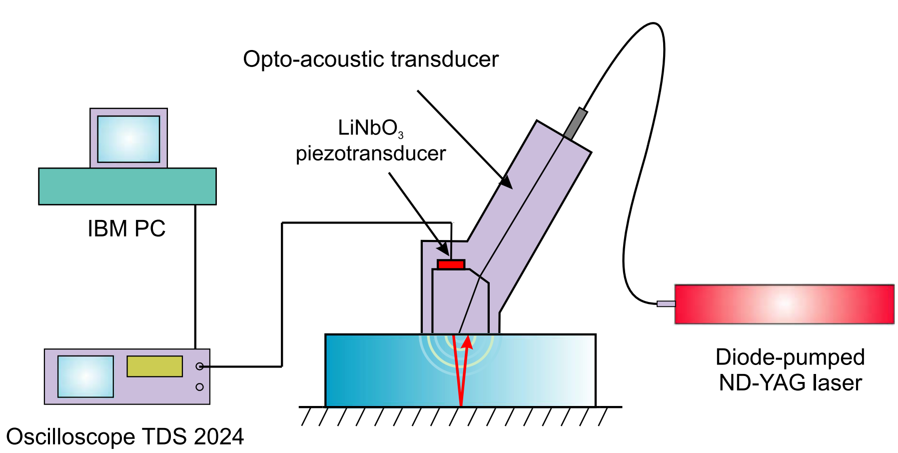

Fig. 1. Experimental setup.

racy of ultrasound velocity measurement and has the one-sided access to an object under study.

Wide-band piezoelectric transducer was operated in the open-circuit regime (lower the half-wave resonance). The thickness of the lithium–niobate piezoelement was approximately 130 μm. In the frequency range up to 70 MHz the spectral sensitivity of the transducer was close to a constant. Digital oscilloscope Tektronix TDS 2024 was employed for recording the ultrasonic data. Data analysis was carried out on a computer workstation.

3.2. Samples

Samples of stainless steel with thicknesses from 1.67 mm to 8.97 mm containing welds over their center produced by the electronic beam of different intensities were studied with the developed method. The photo of sample under study and the designed coordinate system are shown in Fig. 3. Before OA measurements, the surfaces of the welded samples were polished and made to be plane-parallel. Thicknesses of samples were measured by a micrometer with an inaccuracy of 2 μm at each point, where the velocity of ultrasound had been measured. Such accuracy is essential in order to carry out precise velocity measurements – 2 μm distance corresponds to a 0.4 ns time delay which is comparable to the OA method time resolution (0.5 ns). For subsurface stress measurements samples of nickel and titanium alloys with different mechanical treatment: hardening and buffing were used.

3.3. Measurements

Time-of-flight measurements of relative deviations of phase velocities of longitudinal ultrasonic waves were carried out. First the ultrasound velocity was measured in the un-welded reference samples of each group. Then, measurements were conducted on the welded samples. In both cases the phase velocities were determined by the same scheme.

Fig. 4. shows a typical process of reverberations of ultrasonic pulses in a sample. The first pulse (see Fig. 5) is the probe ultrasonic signal. It is excited on the front surface of a sample under study by optoacoustic transformation. As it follows from the theory of the optoacoustic phenomenon, the temporal profile of the laser excited ultrasonic transient in metals should be same as the time envelope of laser pulse intensity, which can be described by the Gaussian function. Definite differences of the probe pulse temporal profile from Gaussian form are explained by both the diffraction of ultrasound in the acoustic line of the transducer and non-uniformity of the spectral sensitivity of the transducer on high frequencies.

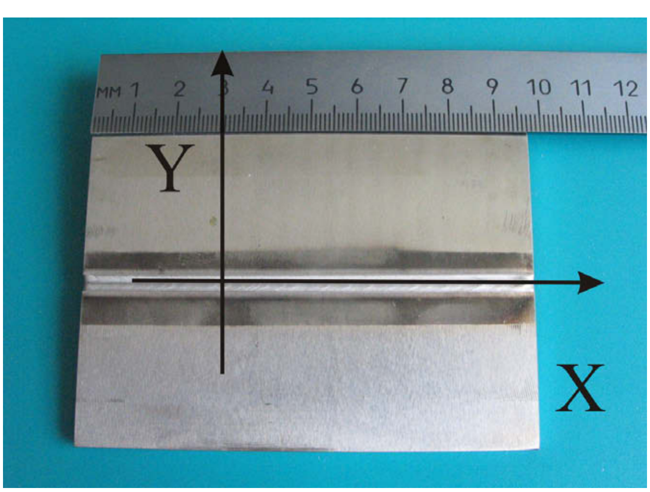

Fig. 3. Welded sample and coordinate system attached with it.

Echo signals reflected from the rear surface of a sample come after the probe ultrasonic pulse in the equidistant intervals, which are the time of the ultrasonic wave round trip through a sample. A typical temporal profile of the echo signal is shown in Fig. 6. It is

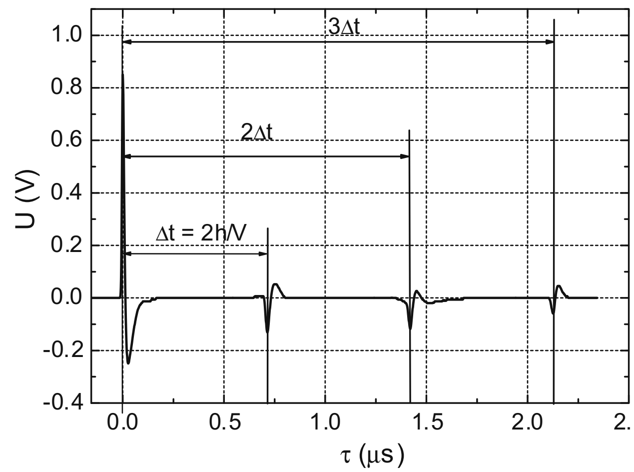

Fig. 4. Reverberations of the probe OA pulse in the welded sample.

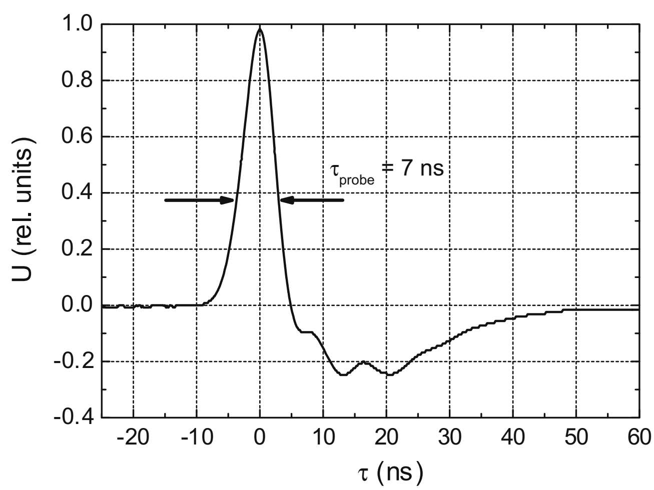

Fig. 5. Probe OA pulse.

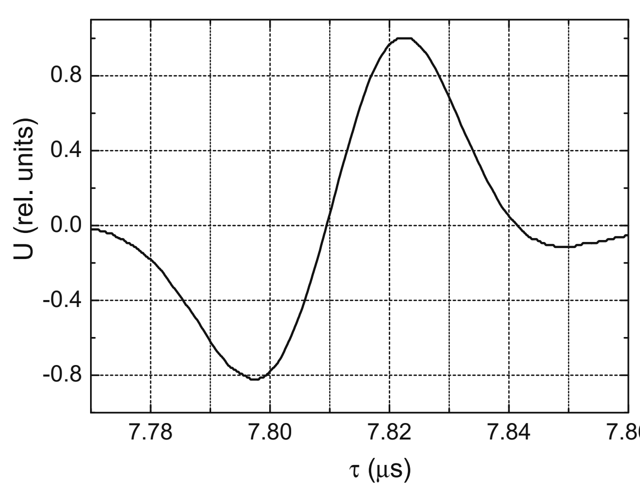

Fig. 6. Echo signal.

close to a bipolar form due to the attenuation and diffraction of ultrasonic waves during their propagation in a metal. The time delay between probe and echo signals determines the sound velocity, which, as it was noted previously, should be measured very precisely. In our experimental scheme, a time delay between any signals can be measured with the accuracy of 0.5 ns. To achieve the required accuracy, the second or even third echo pulse detected can be used to increase acoustical path length when the samples had the thickness less than 5 mm.

The time of the probe pulse arrival on the piezoelectric transducer is characterized by the point of the maximum of this signal, whereas the temporal profile of the echo pulse is changing during its propagation through the sample due to beam spreading [15]. Therefore the zero point of an echo pulse corresponds to its arrival time. The time delay between the specific points of these pulses allows one to determine the group velocity of ultrasound in welded samples.

In the case of subsurface stress the in-depth distribution of ultrasound reflection coefficient was obtained using deconvolution procedure of registered ultrasonic signals from sample with subsurface stress and from reference sample without them. After that, using Eq. (4) the in-depth distribution of the sum of principal stress $\sigma_{XX}(Z) + \sigma_{YY}(Z)$ was obtained.

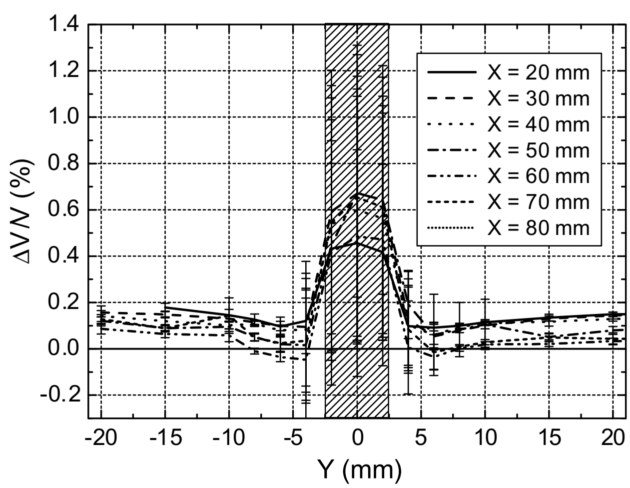

Fig. 7. Dependency of the relative deviations of velocities of longitudinal ultrasonic waves vs. coordinate *Y* across the weld at the different values of coordinate *X* along the weld for samples of the 8 mm thickness.

3.4. Results

The phase velocities of longitudinal acoustic waves in reference samples without weld are measured first. The obtained value of phase velocity for the samples of 8 mm thickness was $V_{l0} = 5657 \pm 2$ m/s. For determination of the spatial distribution of residual stresses the phase velocities of ultrasound were measured in 120–150 points of the sample. Along *X*-axis measurements were carried out in 10 mm step one from another, along *Y*-axis – in 2 mm nearby the weld and in 5 mm far of the weld. Such step of measurements is explained by the strong transverse gradient of the residual stress distribution nearby the weld and relatively smooth stress changing along the weld direction and far of the weld. Measurements are performed five times in each point, then their average value and dispersion are calculated. Due to the diameter of probe acoustic beam was 4 mm, nearby the weld ultrasonic data are averaged over three points.

Fig. 7 shows the experimentally obtained distribution of relative deviations of the phase velocity $\delta V/V$ of ultrasound for the samples of 8 mm thickness. Different plot lines in the figure characterize each measured cross-section of the residual stress state in the samples under study. The crosshatched region correspond to the welding area. In this region the change of grain size due to melting and recrystallization process can influence the ultrasonic velocity that can lead to an error in the residual stress determination but outside the heat affected zone the grain size and orientation remain unchanged. The 3D surface of the residual stress distribution built with respect of the data represented in Fig. 7 is shown in Fig. 8.

Fig. 9 presents distribution of residual stress with respect to depth in titanium alloy samples with different treatment: buffing (solid line) and hardening (dotted line).

4. Discussion

Figs. 7 and 8 show that tensile stresses are presented in the weld area of the samples, nearby the weld residual stresses change the sign and turn into compressing ones. Tensile stresses appear

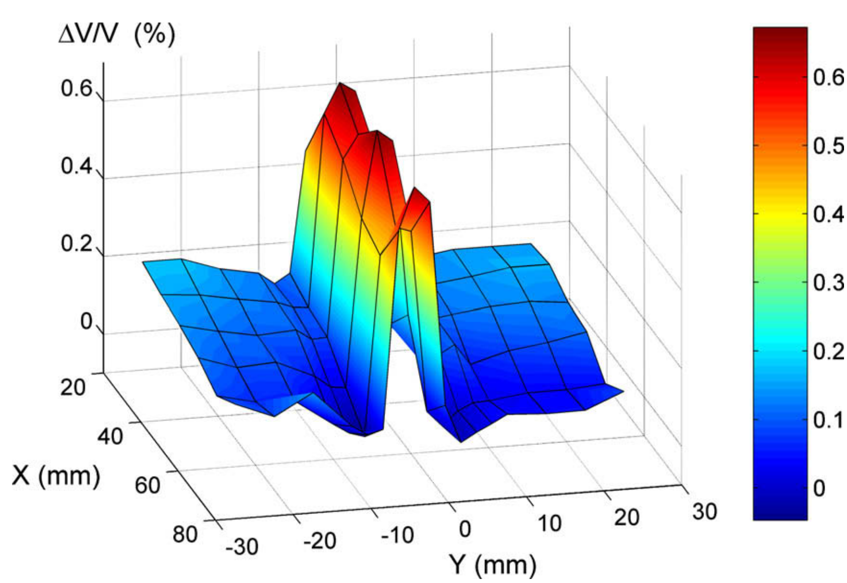

Fig. 8. 3D surfaces of the distribution of relative deviations of velocities of longitudinal ultrasonic waves for samples of the 8 mm thickness.

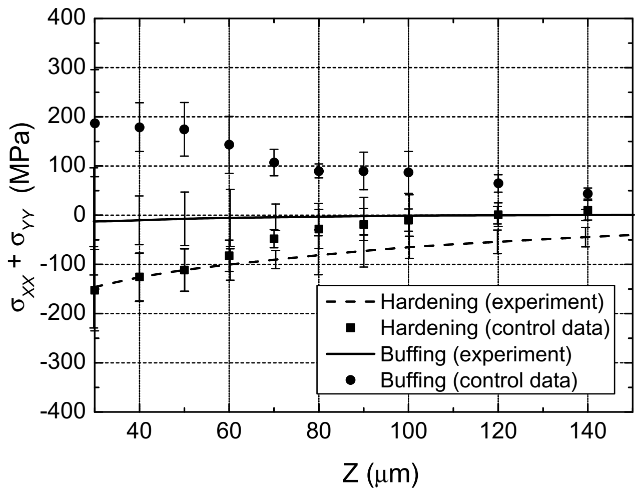

Fig. 9. Subsurface stress distribution for titanium alloy samples with different treatment. Laser ultrasonic method: solid line – buffing, dotted line – hardening; conventional testing: ● – buffing, ■ – hardening.

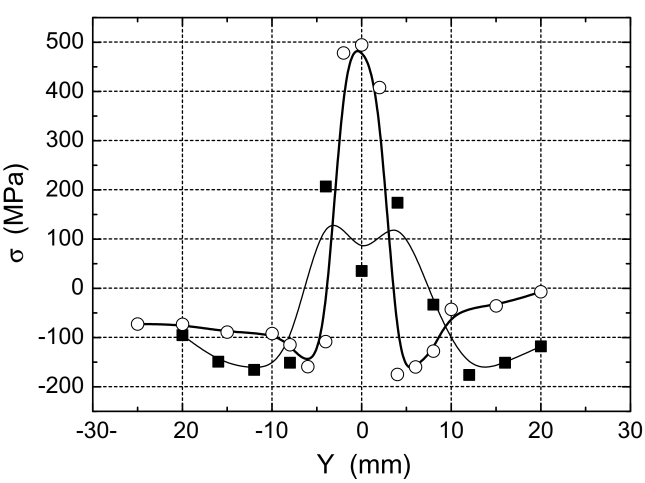

Fig. 10. The comparison of results of laser ultrasonic method (bold line) and conventional testing.

ones again far of the weld. This tendency is explained by the process of welding. Welding is accompanied with non-uniform thermal heating of a material. Subsequent cooling leads to volume decreasing of contiguous layers of a metal, producing the compressing stress. We can see in Fig. 8 also that the dependencies of $\delta V/V$ "go down" from the one edge of the samples ($X = 20$ mm) to the center ($X = 50$–60 mm) of theirs and then "go up" to another edge ($X = 80$ mm). It means that not only σ_{XX} stresses (which are parallel to the weld direction) are presented in these samples – σ_{YY} stresses (which are perpendicular to the weld direction) are presented as well.

For welded samples the conventional mechanical testing has been performed. The sample was cut into strips $\delta X = 35$ mm $\delta Y = 4$ mm. The elongation of each strip due to stress relaxation was measured and the value of σ_{YY} was obtained [18]. It was impossible to obtain σ_{YY} component of stress tensor due to a great gradient of stress in the Y direction (there was no way to measure relative elongation on the spatial scale of few millimeters). The comparison of laser ultrasonic method with conventional testing is presented in Fig. 10. The results of conventional testing are in a rather good agreement with laser ultrasonic method. In the case of subsurface stress the continuous etching method [19–20] was used. The results of conventional testing of subsurface stress are presented in Fig. 9. There is a good coincidence between laser ultrasonic and conventional testing for hardened samples; for buffing treatment only qualitive agreement was obtained.

5. Conclusions

A new laser ultrasonic method for residual stress measurements in welds has been developed. This method is based on the laser excitation of a wide-band nanosecond probe ultrasonic pulses on the front surface of a sample and backward mode detection of signals reflected from the rear surface of a sample with temporal resolution not worse than 0.5 ns. The design of the laser optoacoustic transducer is demonstrated. The spatial distribution of relative deviations of the phase velocity of longitudinal ultrasonic waves in stainless steel samples produced by welding is obtained for the samples with thicknesses of more than 1.67 mm. The subsurface stress distribution for titanium and nickel alloys with different treatment were obtained. The results are in a qualitive agreement with results of conventional testing.

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