



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-excited ultrasonic transients. Radiation from a Nd-YAG laser (pulse duration 7 ns, pulse energy 100 μ J) was absorbed by the surface of the sample. The excited 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.

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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 usu-

ally 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:

$$\frac{V_{SX} - V_{SY}}{V_{S0}} = B(\sigma_{XX} - \sigma_{YY}), \quad (2)$$

$$\frac{V_{SX} + V_{SY} - 2V_{S0}}{2V_{S0}} = C(\sigma_{XX} - \sigma_{YY}), \quad (3)$$

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 $A \approx 10^{-12} \text{Pa}^{-1}$. 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 than 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 than 150 μm) will be the following:

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

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-

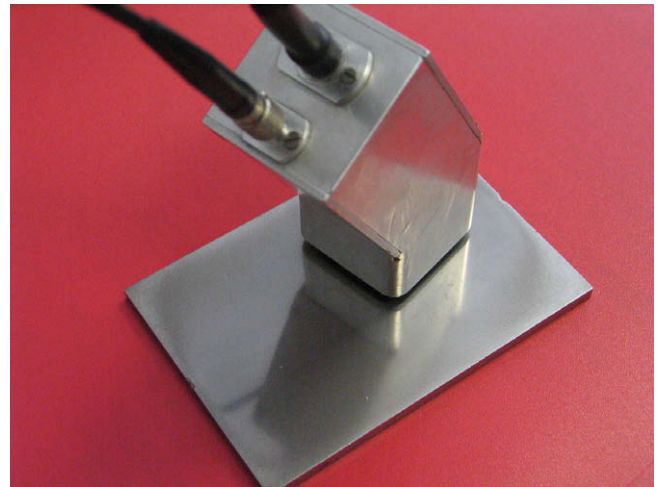


Fig. 2. Optoacoustic transducer.

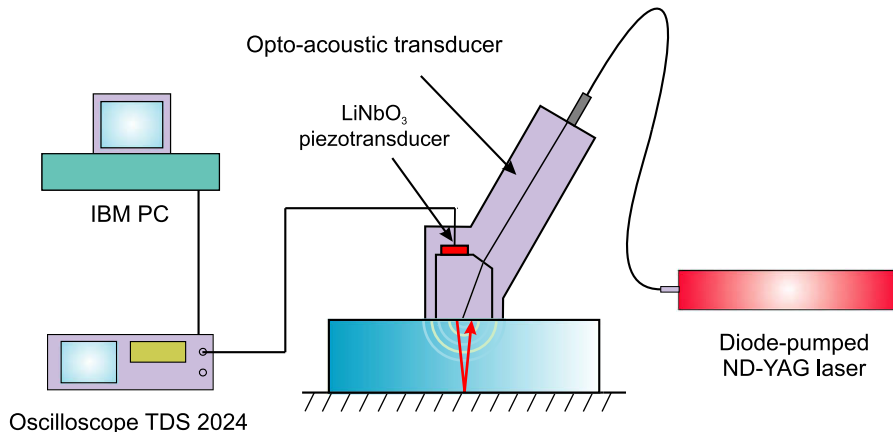


Fig. 1. Experimental setup.

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