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LASER ULTRASONIC RAYLEIGH WAVES TESTING OF RESIDUAL STRESS IN METALS

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Laser ultrasonic technique for non-destructive subsurface biaxial residual stress testing in metals is developed in the current work. Th method is based on laser pulse excitation of surface acoustical Rayleigh waves (SAWs) with YLF:Nd laser and wideband piezoelectric detection of acoustical signals with especially designed high time-domain resolution wedge-shaped transducer . Developed technique implies measurement of relative variations of the SAWs velocities in two orthogonal directions. An accuracy of such measurements is substantially below 0.1%. Frequency bandwidth is 5-25 MHz, which corresponds to the depths approximately of 120-600 μm. *Measurements were carried out in samples made of stainless steel. The samples were of* 105×76 mm^2 *size and thicknesses were 8 and 4 mm. Samples were welded at the center with electron beams having different intensities. Anisotropy of velocities and attenuation has been also measured. Such anisotropy might be a consequence of manufacturing and treatment procedure. Dispersion of phase velocities of SAWs, that was observed, indicates spatial heterogeneity of the samples.*

The problem of residual stress investigations in different materials has a rather long history and nowadays is still of a great importance, because the knowledge of residual stress magnitude and distribution can be used in resource evaluation or in materials quality control. And the most important thing is searching for the optimal non-destructive method. At the moment there exist several principal methods for non-destructive testing of residual stress such as magnetic memory method (MMM) [1], X-ray method [2], neutron diffraction method [3], various ultrasonic methods [4,5], methods that study residual stress influence on a thermophysical properties of material [6] etc. Each of them has its own advantages and shortages, and that is why the universal method doesn't exist yet. For subsurface residual stress testing the most attractive are the X-ray method and ultrasonic method based on Rayleigh waves. But the first one is restricted to about 20 μm depth, whereas the second one can be applied to the depths in a millimeter range. Another significant disadvantage of the X-ray technique is difficulties of applying in field condition.

In this paper we developed a wideband Rayleigh waves technique for non-destructive testing of biaxial residual stress in metals. Our approach is based on laser pulse excitation of Rayleigh waves [7], and further wideband piezoelectric registration of broadband SAW pulses. Spatial distribution of stress was obtained by scanning the sample by means of a two-dimensional computer-controlled coordinate system.

The SAW velocity in every propagation direction is a function of two components of a stress tensor that are applied along and perpendicular to the wave propagation direction σ_{11} and σ_{22}. Then in linear approximation these components of a stress tensor can be expressed as functions of velocities propagating along and across them and can be expressed as:

$$\begin{cases}\sigma_{11}=\dfrac{1}{A^2-B^2}\left(A\times\dfrac{V_1-V_0}{V_0}-B\times\dfrac{V_2-V_0}{V_0}\right)\\[2ex] \sigma_{22}=\dfrac{1}{A^2-B^2}\left(A\times\dfrac{V_2-V_0}{V_0}-B\times\dfrac{V_1-V_0}{V_0}\right)\end{cases}, \text{ where} \qquad (1)$$

V_0 - velocity in an unstressed media, *A,B* – acoustoelastic constants that are determined by the material properties. These constants were calculated numerically in quadratic approximation by the method similar to that described in [5] or in [8]. In stainless steel their values are: $A=1.1\times10^{-5}\ MPa^{-1}$ and $B=5.2\times10^{-6}\ MPa^{-1}$. So, to determine biaxial residual stress it is enough to measure relative changes of SAW velocities propagating in two orthogonal directions with a rather high accuracy (0.1% or less).

For excitation a Q-switched YLF:Nd laser was used with wavelength $\lambda = 1.047\ \mu m$, pulse duration $\tau_L = 7\ ns$ and pulse energy $E \approx 150\ \mu J$. A cylindrical lens focused the laser radiation into a thin line on a sample surface. Registration realized using a specially designed wedge-shaped piezoelectric transducer. Frequency bandwidth of the setup was limited primarily by a strong attenuation of surface waves in steel, and was within the range $\Delta f = 5 \div 25\ MHz$. The Rayleigh wave penetrates into the sample for about a wavelength, which corresponds to the depths interval of $\Delta x_3 = 120 \div 600\ \mu m$. Residual stress in the stainless steel (12X18H10T) samples was produced by melting with electron beams of different intensities along their center lines. The sizes of samples were: length $X_1 = 105\ mm$, width $X_2 = 76\ mm$ and thicknesses 8 and 4 *mm*. In this work only biaxial stress σ_{11} and σ_{22}, along and across weld, were investigated. Other components of stress tensor were considered as $\sigma_{ij} = 0\ (i \neq j\ or\ i = j = 3)$.

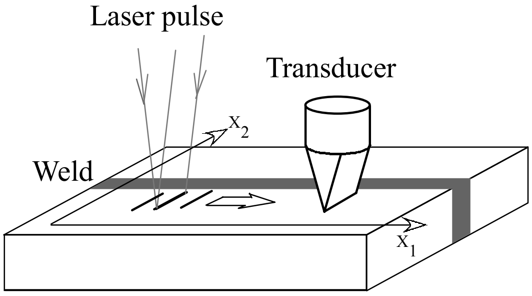


Fig.1. Arrangement of the measurements.

The schematic diagram of the velocity measurement is shown in Fig.1. Here V_1 component is measured, which is defined as parallel to the weld. The same scheme was used to measure the V_2 component, but with a sample turned at 90°. In the vicinity of the weld stress changes very fast along the X_2 axis, so that main changes take place within the 5 mm region around the weld frontier. This dictates the spatial resolution, which should not exceed 1 mm. Taking this into account a differential method was developed with spatial resolution of $\Delta l = 125\ \mu m$. SAW pulses were generated at different positions l_i on the sample surface, spaced by Δl and located along the direction of propagation, see Fig.1. For each l_i corresponding time-of-flight $t = t(l_i)$ was measured, using either correlation or phase method. Then, the velocity at each location is given by:

$$V(l_i) = \left(\frac{\partial}{\partial l_i} t(l_i) \right)^{-1} \tag{2}$$

To calculate the velocity at l_i, 5 points were taken, centered at l_i. These 5 points were fitted by a quadratic polynomial, and its derivative was used as an estimate for the partial derivative in Eq.2. Described approach allows us to calculate not only relative change of velocity, but its absolute value in each point on the sample as well. In that case localization accuracy equals to spatial resolution. For transverse to weld velocity measurement spacing was chosen equal to $\Delta l = 125\ \mu m$, and for longitudinal velocity measurement - $\Delta l = 500\ \mu m$, because the gradient of stress along the weld is not so big compared to the gradient across the weld . In addition, the same measured data can be used for phase and group velocities calculation as well. In Fig.2 the dispersion of phase velocity at different distances from the weld is presented. The same figure shows dispersion of velocity in an unstressed sample in the same direction. As can be seen in this figure, in the whole experimental frequency range dispersion of velocity remains linear. For such a character of dispersion, group velocity appears to be slightly more sensitive to stress than the phase one, so henceforth the group velocity was used for stress evaluation.

All samples were scanned by means of a two-dimensional coordinate system powered by two stepping motors controlled from a computer. V_1 was measured with a 0.5 mm step along the X_2-axis and 10 mm along the X_2. For the V_2 these steps were 0.125 mm and 10 mm respectively.

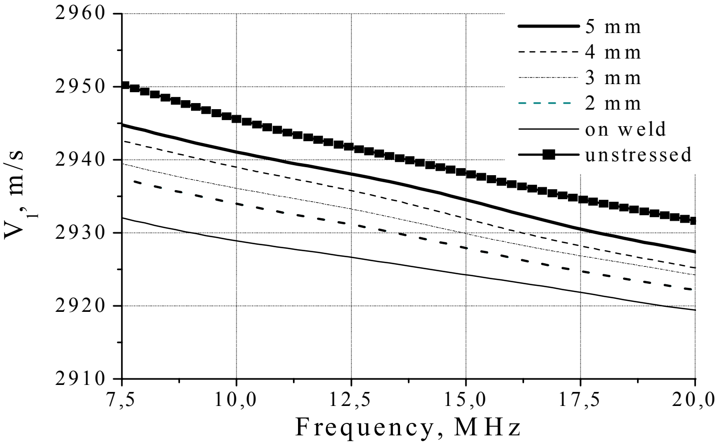
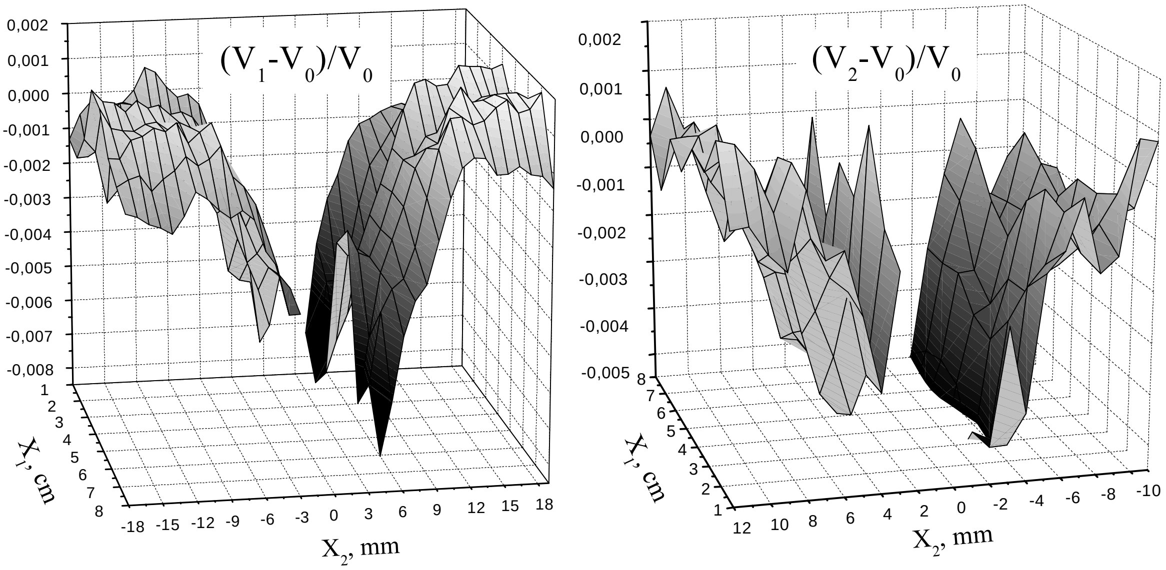


Fig.2. Dispersion of phase velocity V_1 at different distances from the weld.

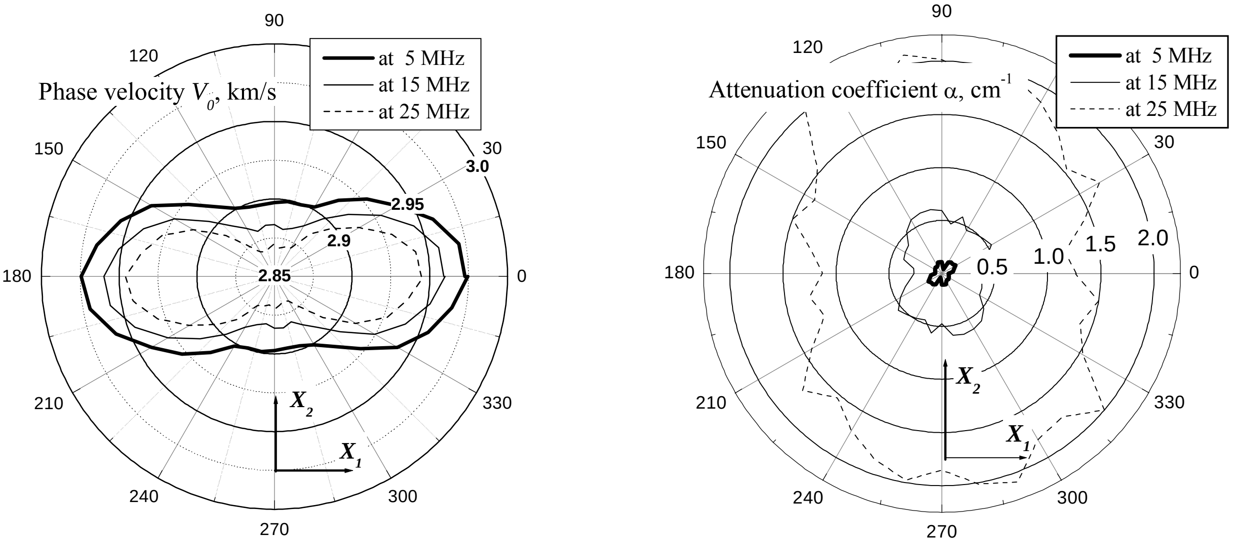
Typical distributions of velocities relative changes in one of *h*=8 mm thickness sample are presented on a Fig.3a,b. The scanning area is $X_1 = 8$ cm along the weld and $X_2 = 22$ mm for V_2 and $X_2 = 36$ mm for V_1 across the weld. Value $X_2 = 0$ is related to the center of the weld. Making use of the known acoustoelastic constants *A*, *B* and measured relative variations of SAW velocities, one can calculate the residual stress components σ_{11} and σ_{22} according to the Eq.2, and their distribution across the sample surface, with spatial resolution of $\Delta l = 125\ \mu m$.



(a) (b)

Fig.3. Spatial distribution of relative change of velocities V_1 (a) и V_2 (b) in near-weld region in one of the samples with *h*=8 mm thickness.

In order to reach the needed accuracy of velocity measurements as high as 0.1%, one must know the unperturbed velocity V_0 in an unstressed medium with maximal possible precision. Due to technological processes during manufacturing and treatment, V_0 depends on the propagation direction and frequency. Thus in Eq.(1) the reference velocities V_0 should be related to a specific direction and frequency. In view of the aforesaid there was measured anisotropy of velocity in unstressed sample without weld. Fig.4a. exhibits the SAW phase velocity dependence on the direction of propagation. The parameter of anisotropy attains 3%, which exceeds the stress-induced velocity variations significantly. Anisotropy grows with frequency, indicating that the near to the surface areas are more anisotropic.



(a) (b)

Fig.4. (a) - anisotropy of SAW phase velocity at different frequencies; (b) – anisotropy of attenuation of SAW at different frequencies.

Moreover, the same data acquired in velocity anisotropy measurement was used for attenuation coefficient calculation (Fig.4b). SAW attenuation is conditioned by scattering on grains. Anisotropy of velocity and attenuation most likely conditioned with rolling and, as consequence, grains elongation in the X_1 direction.

In summary, a technique for non-destructive testing of subsurface biaxial residual stress in metals is developed in the current work. Spatial resolution of this technique is $\Delta x \sim 125\ \mu m$ and depth of stress determination is $\Delta x_3 = 120 \div 600\ \mu m$. There also measured anisotropy of SAW velocity and attenuation that give us information about technological process of material producing and treatment.

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