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UltraMARS SYSTEM FOR NON-DESTRUCTIVE MEASUREMENT OF RESIDUAL STRESSES: NEW DEVELOPMENTS

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ABSTRACT

One of the effective methods for non-destructive testing of residual and operating stresses is the acoustic method that is based on the propagation of elastic ultrasonic vibrations inside a solid body. A portable complex for measurement of applied and residual stresses in solid materials using an acoustic non-destructive stress control method was developed in the early 2000 by a team of scientists from Integrity Testing Laboratory, Sintec and E.O. Paton Electric Welding Institute (PWI). An advanced complex UltraMARS was developed based on the early prototype that allows measuring the magnitude and the sign of operating and residual stresses in laboratory and field conditions, either averaged through thickness, or in surface and subsurface layers, as well as monitoring stresses in metal structural elements during their manufacture, repair and operation. It is effective in assessing the quality of welded joints, after post-weld treatments carried out in order to redistribute residual stresses. It has been successfully used in various applications in marine, aerospace, construction and other industries. A four-pole transducer has been developed to improve the operational characteristics of the UltraMARS complex in monitoring stresses on the surface and in the near-surface layers of the material. It differs from the used two-pole transducers of the surface wave (Surface-Rayleigh Wave — Transducer RF12) and subsurface wave (Subsurface — Transducer SF12) in having two transmitter-receiver pairs located at 90° to each other. This change allowed measuring the velocity of ultrasonic waves simultaneously in both orthogonal directions without rotating the transmitterreceiver by 90°. To use these transducers with the UltraMARS complex, a transmitter-receiver switching program has been developed. A transducer with a variable pole distance was also developed for measurement of residual stresses in the near-surface layers of materials, making it possible to determine the uniaxial induced stresses to a depth from 0 to 8–10 mm by changing the base distance between the emitter and receiver. At the moment, a stress control technique is being developed. 22 Ref., 10 Figures.

KEYWORDS: residual stresses, non-destructive ultrasonic measurement of residual stresses, UltraMARS, variable base transducer, 4-pole transducer

INTRODUCTION

Residual stresses (RS) play a very important role in the integrity of structural members, as they can significantly change the mechanical properties of materials and thus affect fatigue life, deformation, dimensional stability, corrosion resistance, etc. The control of operating (acting) and residual stresses (RS) is becoming top priority in many industries [1–3].

In the last few decades, more and more research has been carried out on use of ultrasound to measure residual stresses in materials of various designs and to measure the elastic-acoustic constants of materials. Numerous examples of stress measurements in bulk (average in thickness) and surface layers have shown that ultrasonic methods can be used for non-destructive evaluation of stresses in various materials, being especially suitable for measuring stress profiles and evaluation of stress distributions at the same point after different treatment conditions [4–9].

In recent years we made significant progress in modernizing the UltraMARS complex that makes it possible to measure operating and residual stresses not only in bulk (average through thickness), but also in surface and near-surface layers of materials. Using the method for determining stresses, developed by PWI [5], we designed the hardware and developed the software, making it possible to measure all three types of reflected ultrasonic signals at the same point using a non-destructive method [6, 10].

Generally, the change in the speed of an ultrasonic wave in materials under the action of stresses amounts only to tenths of a percent. Therefore, the equipment for the practical application of the ultrasonic method for measuring residual stresses must be of high resolution and fully computerized. The developed UltraMARS complex, shown in Figure 1, includes a measurement unit; a preamplifier for excitation and

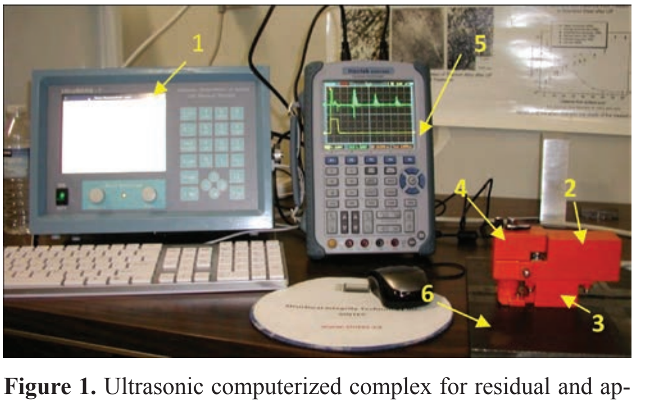

Figure 1. Ultrasonic computerized complex for residual and applied stress measurement: 1 — measurement unit with supporting software; 2 — preamplifier (REW component); 3 — magnetic holder; 4 — transducer; 5 — oscilloscope (20 MHz); 6 — sample

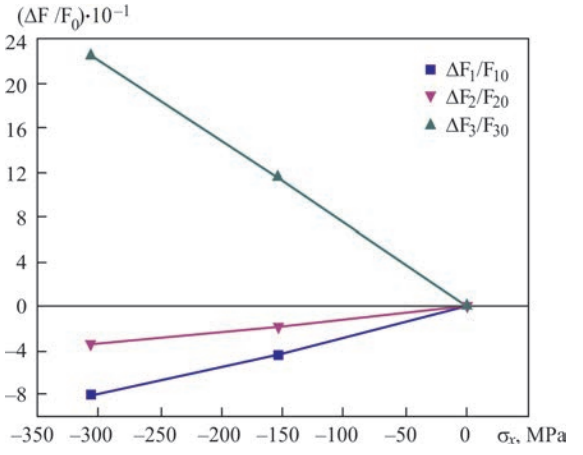

Figure 2. Changes of ultrasonic wave velocities in a sample of a material under the action of applied stresses

reception of reflected ultrasonic signals (REW) before they are sent to the measurement unit for further processing; a transducer holder that can be either magnetic or electromagnetic or mechanical; a set of replaceable ultrasonic transducers that are used for excitation and reception of longitudinal (XF3) and shear (YF12) waves; as well as for excitation and reception of surface waves (RF12) and subsurface waves (SF12). An oscilloscope is usually used for visual control of the received reflected signals. Typically, the oscilloscope is needed to select and tune to a reflected waveform when using the manual method.

The developed UltraMARS complex makes it possible to determine single- and biaxial working (applied) and residual stresses in various materials and structures. This article will, firstly, review the latest advances in the development and application of the non-destructive ultrasonic method for measuring of residual stresses in materials and structures and present examples of stress measurement in various materials and structures and introduce the new transducers that are at different stages of development, i.e. the four-pole transducer and the variable base transducer for measuring stresses at different depths of materials.

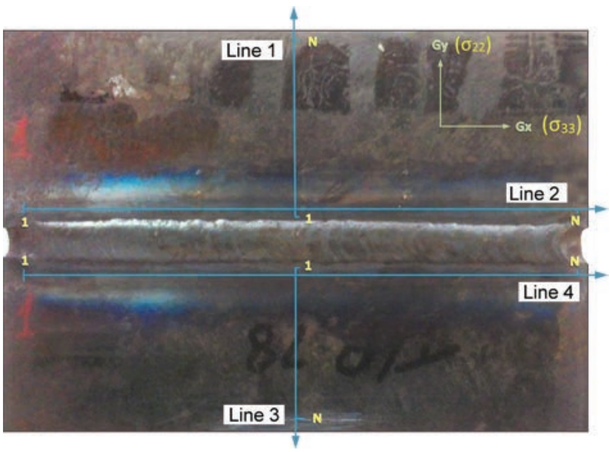

Figure 3. Welded sample (low carbon steel) with marked lines 1–4 indicating the locations of RS measurements

MEASUREMENT OF RESIDUAL STRESSES BY ULTRASONIC METHOD

The measurements of residual stresses (RS) using ultrasound are based on solid theory [11–13] and original technique and use of precise instrumentation [5, 10, 12]. It is possible to use ultrasound for measurement of stresses in materials, because, according to the acoustic-elastic theory of interaction of ultrasound with materials, the changes in travel velocities (or frequencies) of ultrasound in a material depend linearly on the stresses in the materials over a certain range of stresses (Figure 2). The intensity and nature of such changes may vary depending on the physical and mechanical properties of the material. With known acoustic-elastic properties of the material, the determination of stresses is reduced to measuring the velocities (proportional to frequency) of longitudinal and shear waves, when they propagate in the main directions of stress action. The acoustic-elastic properties of the material are included in the equations relating the propagation velocities of ultrasonic waves to the stresses in the material in the form of proportionality coefficients. They are determined by the elasticity constants of the second and third orders and can be calculated or measured [13, 18].

For determination of the elasticity constants, control samples are used, in which, under uniaxial or biaxial loading, changes in the velocities of longitudinal and shear ultrasonic waves are measured and the calculation of acoustic-elastic coefficients based on these measurements is performed.

The UltraMARS complex performs these measurements, and the calculated values of the acoustic-elastic coefficients are stored in memory for further stress calculation [3 and references therein]. The measurement error of operating stresses in the elastic region is ~15 MPa, and for residual stresses is ± 0.1 σ_t, where σ_t is the ultimate tensile stress of the material.

Figure 3 through Figure 5 are presented as examples of the type of residual stress information that can be achieved using the UltraMARS system with different transducers. A butt-welded sample shown in Figure 3, measuring 200×150 mm and 12 mm thick, was used for residual stress measurements. The distribution of the longitudinal and transverse residual stresses (respectively, parallel and perpendicular to the weld direction) were measured along lines 1 and line 2, as marked in Figure 3. The stresses were measured starting from point 1 (as marked in Figure 3) and advancing towards point marked as N. Measurement point 1, on line 1, was located at a distance of ~ 3 mm from the weld toe. All measurements along lines 2 were made at a distance of ~5 mm from the

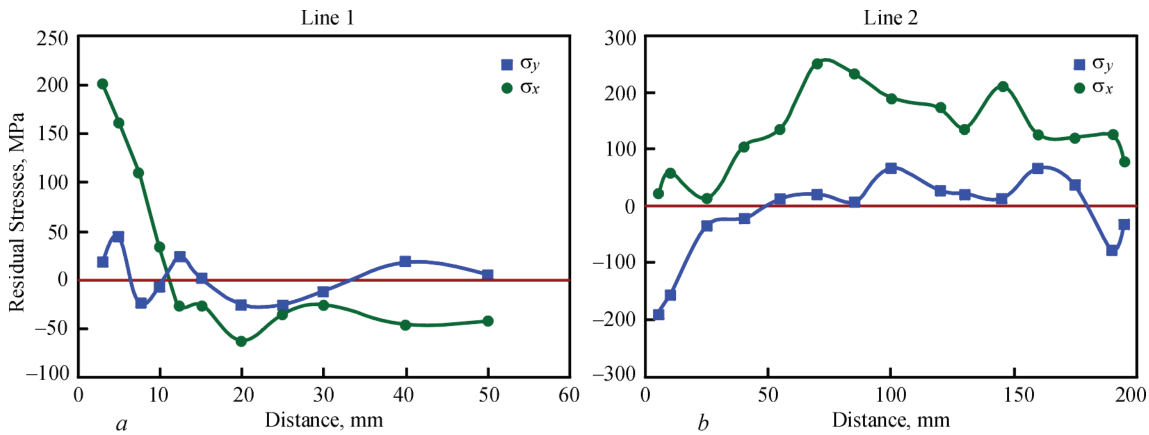

Figure 4. The distribution of average through thickness (bulk ultrasonic waves) residual stresses in the sample along line 1 (*a*) (normal to the weld direction) and along line 2 (*b*) (along the weld direction)

weld toe. To measure the residual stresses even closer to the weld/bead or in the weld require special preparation of the surface of the weld/bead or removing of the weld reinforcement.

Figure 4. presents the measurement results of average through thickness residual stresses along lines 1 and 2 obtained with the bulk transducers. In all cases, two components of the residual stress, σ_{22} and σ_{33} were measured (marked in the figures as σ_x and σ_y, respectively).

In technical literature, different symbols are used to mark the distribution of residual stresses and propagation velocities of ultrasonic waves [13, 18]. Among the most common used, one can mention the following:

- symbol σ_{33} (or σ_x) — marks the longitudinal principal stress that is acting along the application of external force or along the weld (see Figures 3 and 4);
- symbol σ_{22} (or σ_y) — marks the transverse principal stress that is acting perpendicular to the applied external force or in the direction perpendicular to the weld (see Figures 3 and 4);
- symbol F3 (or F1) — denotes the frequency (propagation velocity V_{Sx3}) of the reflected (bottom) shear ultrasonic wave, excited and received back by a Y-cut piezoelectric transducer. The polarization vector of the piezoelectric transducer is directed along the action of the stress σ_{33} (σ_x), and the plane in which the particles oscillate in the element is directed perpendicular to the wave propagation (along the thickness of the material);
- symbol F2 — denotes the frequency (propagation velocity V_{Sx2}) of the reflected (bottom) shear ultrasonic wave. The polarization vector of the piezoelectric transducer is directed along the action of the stress σ_{22} (or σ_y) or perpendicular to the action of the stress σ_{33} (or σ_x), and the plane in which the particles in the element oscillate is directed perpendicular to the propagation of the wave (along the thickness of the material);
- symbol F1 (or F3) — frequency (propagation velocity V_{Lx1}) of the reflected (bottom) longitudinal ultrasonic wave, excited and received by a X-cut piezoelectric transducer.

The polarization vector of the piezoelectric transducer can be at any angle to the direction of the stress σ_{33} (or σ_x), and the particles in the element oscillate in the direction of wave propagation (along the thickness of the material).

Figure 5 shows the distribution of surface (*a*) and subsurface (*b*) residual stresses in the sample as mea-

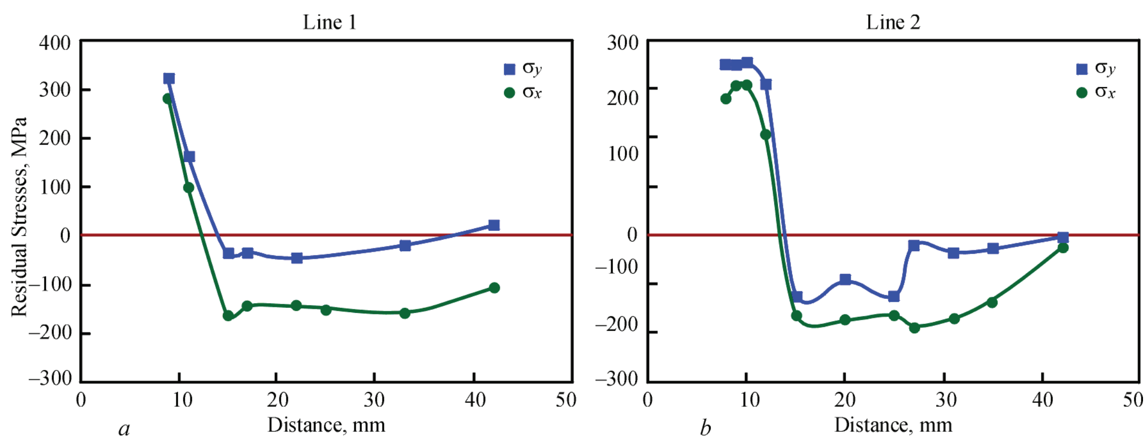

Figure 5. The distribution of surface residual in the sample as measured along Linne 1 using the surface (*a*) and subsurface (*b*) ultrasonic wave transducers (in both cases the stresses normal to the weld direction were measured)

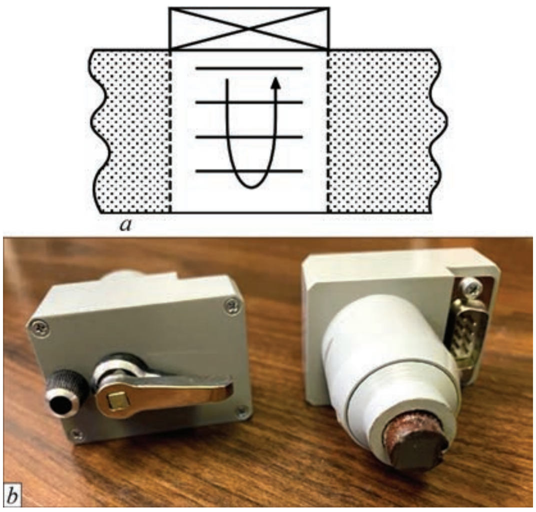

Figure 6. Principle of measurement of average through thickness (bulk) stresses (pulse-echo) and the transducers for measurement of the longitudinal and the transversal components of average through thickness (bulk) stresses

sured along Line 1 using the surface (RF12) and subsurface (SF12) ultrasonic wave transducers (in both cases the stresses normal to the weld direction were measured). Using the surface ultrasonic transducer allows to measure residual stresses in surface layers of material, with a penetration depth for this application being ~ 0.7 mm (determined experimentally). By using subsurface transducers, it is possible to measure stresses to a depth of ~ 6 mm. The 9×4 mm standard transducer was selected for this application.

The obtained RS profiles were analyzed and the obtained data had shown that the results of ultrasonic RS measurements in the sample are in accordance with existing understanding of the distribution of RS in welded elements and structures [14, 15]. In a study of residual stresses in a large-scale welded panel, designed to represent structural elements of a ship, good coincidence between the measured stresses and calculations using the FEA method was demonstrated [16, 17].

Recently, the UltraMARS complex was modified further, including a number of new technical solutions, making the operation of the complex more stable and user-friendly. The symbols denoting the major stresses and frequencies have been replaced. Thus, σ_1 determines the vector of the main stress acting along the applied force to the structure or weld; σ_2 determines the vector of the main stress acting perpendicular to the force applied to the structure or weld. The frequency designation symbols have been also changed, tying them to the new stress symbols. The use of new electronic elements made it possible to improve the tuning to the wave in automatic mode and increase the accuracy of identification of received reflected signals. Changes have been also made to the calculation of stresses when using surface and subsurface wave transducers.

ULTRASONIC TRANSDUCERS

Presently, the measurement of average through thickness longitudinal and transverse residual stresses in the sample are performed (respectively, parallel and perpendicular to the welding direction) at each point by two types of ultrasonic transducers (Figure 6). To excite bulk ultrasonic waves, quartz plates with a polarization vector Y-cut (cut along the optical Y axis) and X-cut (cut along the optical X axis) with a 5 MHz resonant frequency of quartz piezoelectric plates were used. This is the optimal frequency of quartz oscillation, at which mechanical ultrasonic oscillations respond to changes in the crystals of the material from stresses and do not attenuate when reflected from the lower surface of the sample.

Piezoelectric PZT plates with a resonant frequency of 4 MHz are used to excite and receive the Rayleigh surface ultrasonic wave (Figure 7, *a*–*c*). The plates are glued to a damper made of a solid polyamide material

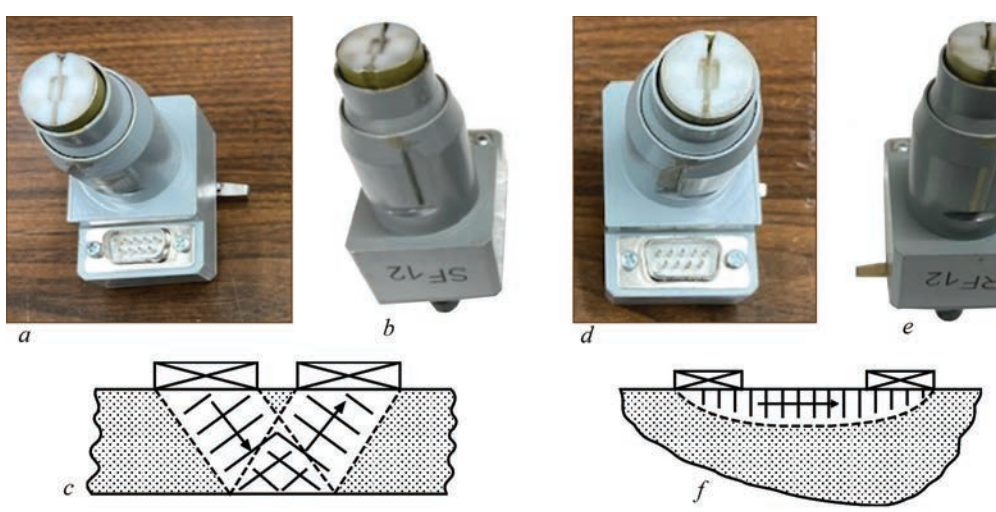

Figure 7. Principle of measurement of sub-surface (*a*–*c*) and surface (*d*–*f*) stresses (pitch-catch) and the transducers for measurement of two transversal components of stresses

Figure 8. Images of the four-pole transducers for measurements of surface and subsurface stresses

with good wear resistance [20, 21]. The wedge angles of the emitter and receiver for the surface wave are 70° [20–22]. The damper with glued piezoceramic plates is protected by a metal cap.

For excitation and reception in the near-surface layers of the material, piezoelectric PZT plates with a resonant frequency of 4 MHz are used. The plates are glued to a damper with the emitter and receiver wedge angles at 29° (Figure 7, *d–f*) [20–22] that makes it possible to obtain the maximum amplitude of received ultrasonic waves for various metals. The damper with glued piezoceramic plates is protected by a metal cap.

To simplify the measurements of surface and subsurface stresses, four-pole transducers were developed that, unlike two-pole transducers, allow measurements in two directions without turning the transducer head 90°. The transducer dampers are made by milling them from a solid polyamide block that has good abrasion strength. The PZT plates with a resonant frequency of 4 MHz were then attached to transmitters and receivers. The wedge angles of the transmitter and receiver for the surface wave is 70°, and for the subsurface 29° that allows to obtain the maximum amplitude of the received waves for different metals. The transmitter and the receiver are placed opposite each other at a constant base distance. The second transmitter-receiver set is placed at 90° to the first one. To reduce interference between the transmitter and the receiver, a square recess is made in the damper housing, which does not allow interference from the transmitter to the receiver. The damper housing with piezoceramic plates is protected by a metal cap. The whole damper assembly is inserted into the transducer housing (Figure 8). To conduct a measurement, the four-pole transducer is inserted into the REW device (item 3 in Figure 1) of the UltraMARS-8 instrument.

To check the penetration depth of the ultrasound waves for the two-pole and four-pole transducers,

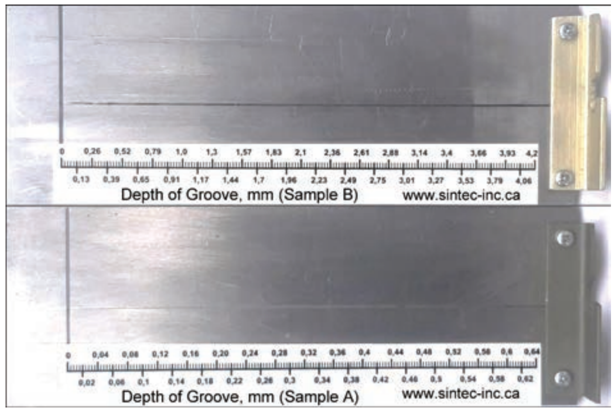

Figure 9. Images of the plates with a slot cut in them for evaluating the propagation depth of the ultrasonic wave in materials. The rulers with marked slot depth are attached to the plates

plates were made from various metals with a grove cut into them. The depth of the grove was made with an increasing slope of a few degrees, and a ruler was attached to the plate, showing the change in depth of the grove with distance, starting from 0 mm and continued, to reach the thickness of the metal (Figure 9).

A study is now in progress to evaluate the depth penetration of the surface (RW) and subsurface (SW) waves in 2-pole and 4-pole transducers in steel and aluminum plates prepared as described above with increasing slope groves.

A transducer with a variable base between the emitter and the receiver was developed recently. Figure 10 shows the developed transducer with a variable base that emits and receives longitudinal critically refracted (LCR) waves. In this transducer, the receiver and transmitter can move relative to each other. The distance between them (base) can be changed either

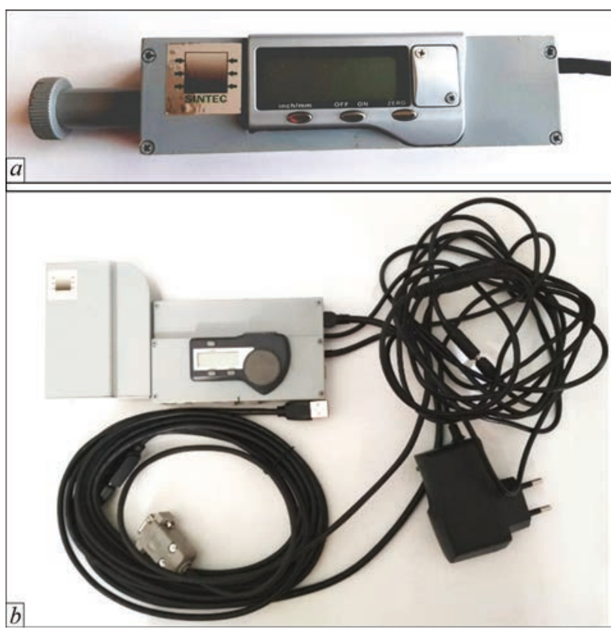

Figure 10. Images of the variable base LCR transducers with a manual (*a*) and a mechanized (*b*) change of distance between the emitter and the receiver (top view)

manually by turning the handle on the side of the transducer (Figure 10, *a*) or by a command from the UltraMARS system (Figure 10, *b*). Presently, work is underway to develop programs to acquire and process the stresses and for controlling the movements of the emitter and the receiver in the transducer. The transducer is attached to the sample with permanent magnets that ensures good contact between the transducer and the sample. A coupling lubricant is used to ensure efficient signal transmission from the PZT crystals to the sample. In this design the base distance between the transmitter and the receiver varies from 10 mm to 50 mm.

By changing the base distance, one can change the propagation depth of the LCR wave that allows to probe different layers of the sample. The wedge angle of the transmitter and receiver was chosen to be 29° [20–22]. This angle was chosen based on the maximum amplitude of the received signal for different metals. The developed prototypes are currently undergoing various tests, the results of which will be published elsewhere.

CONCLUSIONS

Through selected examples, it has been shown that an acoustic method that is based on the propagation of elastic ultrasonic vibrations inside a solid body can be effectively used for nondestructive testing of residual stresses in materials. An UltraMARS complex was developed and recently modernized for measurement of the magnitude and the sign of operating and residual stresses, either averaged through thickness, or in surface or sub-surface layers of materials, in laboratory and field conditions. The developed technology allows monitoring stresses in metal structural elements during their manufacture, repair and operation. It is also effective in assessing the quality of welded joints, after post-weld treatments carried out in order to redistribute residual stresses.

A four-pole transducer has been developed to improve the operational characteristics of the UltraMARS complex in monitoring stresses on the surface and in the near-surface layers of the material, allowing measuring the velocity of ultrasonic waves simultaneously in both orthogonal directions without rotating the transmitter-receiver in the transducer by 90°.

A variable-base transducer was designed and manufactured that allows measuring uniaxial induced residual stresses in the near-surface layers of materials to a depth up to ~10 mm by changing the base distance between the emitter and receiver.

Work is now in progress on extensive evaluation of the new transducers and developing a stress control technique for the variable-base transducer.

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