Ultrasonic Measurement of Residual Stresses in Welded Elements and Structures

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Abstract. Residual stresses (RS) may change considerably the engineering properties of materials and structural components by affecting their fatigue life, distortion, dimensional stability, corrosion resistance, etc. Although certain progress has been achieved in the development of different experimental techniques, a considerable effort is still required to develop efficient and cost-effective methods of RS analysis. The application of an ultrasonic non-destructive method for RS measurements had shown that, in many cases, this technique is very efficient and allows measuring the RS both in laboratory conditions and in real structures in field for a wide range of materials. Using this technique, one can measure the RS in the same points many times, studying, for instance, the changes of RS under the action of service loading or effectiveness of stress-relieving techniques.

An ultrasonic computerized complex UltraMARS for non-destructive measurement of residual and applied stresses was developed recently. The complex includes a measurement unit with transducers and basic supporting software and an advanced database and an expert system, housed in a laptop, for analysis of the influence of RS on the fatigue life of welded elements. In general, the ultrasonic method allows one to measure the RS in both cases: averaged through thickness or in surface/subsurface layers. The present version of complex allows measuring the averaged through thickness RS in plates 2 - 200 mm thick.

The results of RS measurement in standard and large scale welded specimens are also presented in this paper. A number of examples of RS measurement in real structures are also discussed.

1. Introduction

Fatigue life, distortion, dimensional stability, corrosion resistance, brittle fracture and other engineering properties of materials and structural components may be affected strongly by residual stresses (RS) [1, 2]. Such effects usually lead to considerable expenditures in repairs and restoration of parts, equipment and structures and, for that reason, the knowledge of residual stresses and their behaviour are necessary in the design of parts and structural elements and in the estimation of their reliability under real service conditions.

Systematic studies had shown that, for instance, welding RS might lead to a drastic reduction in fatigue strength of welded elements [2]. In high-cycle fatigue ($N>10^6$ cycles of loading), the effect of RS can be compared with the effect of stress concentration. Fig. 1 illustrates one of the results of these studies. The butt joints in low-carbon steel were tested at symmetric cycle of loading (stress ratio R=-1). There were three types of welded specimens: A, B and C. The relatively small specimens (420x80x10 mm) were cut from a large welded plate. Measurements of RS after cutting revealed that in this case the specimens (type A) had a minimum level of RS. Additional longitudinal weld beads on both sides in specimens of type B created in the central part of these specimens tensile RS close to the yield strength of material. These beads did not change the stress concentration of the considered butt weld in the direction of loading. In the specimens of type C longitudinal beads were deposited and then the specimens were bisected and welded again. Due to the small length of this butt weld the RS in these specimens were very small and approximately the same as those within the specimens of type A.

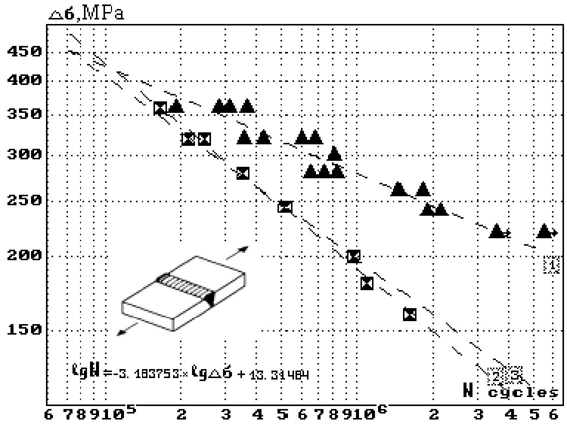

Fig.1. Fatigue curves of butt welded joint in low-carbon steel: 1 - specimens of type A and C without residual stresses; 2, 3 - specimens of type B with high tensile residual stresses (2 - fatigue testing, 3 - computation)

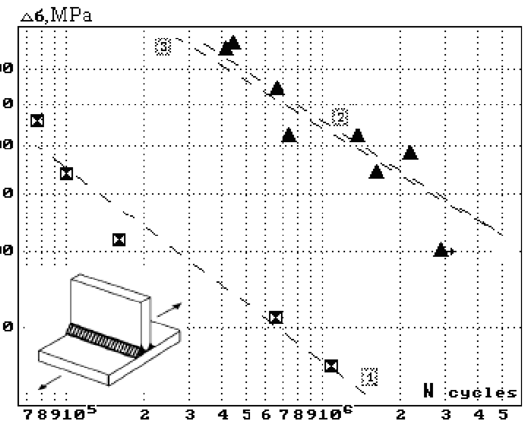

Fig. 2. Fatigue curves of non-load caring fillet welded joint in high strength steel: 1 - in as-welded condition; 2, 3 - after application of ultrasonic peening (2 -fatigue testing, 3 - computation)

Tests showed that the fatigue strength of specimens of types A and C (without RS) is practically the same with the limit stress range 240 MPa at $N=2\cdot10^6$ cycles of loading. The limit stress range of specimens with high tensile RS (type B) was only 150 MPa. In all specimens the fatigue cracks originated near the transverse butt joint. The reduction of the fatigue strength in this case can be explained only by the effect of welding RS. These experimental studies showed also that at the level of maximum cyclic stresses close to the yield strength of base material the fatigue life of specimens with and without high tensile RS was practically identical. With the decrease of the stress range there is corresponding increase of the influence of the welding RS on the fatigue life of welded joint.

The effect of RS on the fatigue life of welded elements is more significant in the case of relieving of harmful tensile RS and introducing of beneficial compressive RS in the weld toe zones. The beneficial compressive RS with the level close to the yield strength of material could be introduced at the weld toe zones by, for instance, the ultrasonic peening (UIT/UP) [1, 3]. The results of fatigue testing of welded specimens in as-welded condition and after application of UIT/UP are presented in Fig. 2. The fatigue curve of welded element in as-welded condition (with high tensile RS) was used also as initial fatigue data for computation of the effect of the UIT/UP. In case of non-load caring fillet welded joint in high strength steel (σ_y = 864 MPa, σ_u = 897 MPa), the redistribution of RS resulted in approximately two times increase in limit stress range and over 10 times increase in the fatigue life of the welded elements.

The RS, therefore, are one of the main factors determining the engineering properties of materials, parts and welded elements and this factor should be taken into account during the design and manufacturing of different products. Although certain progress has been achieved in the development of different experimental techniques, a considerable effort is still required to develop efficient and cost-effective methods of residual stress analysis [1, 3]. The application of an ultrasonic non-destructive method for RS measurements had shown that, in many cases, this technique is very efficient and allows measuring the residual stresses both in laboratory conditions and in real structures in field for a wide range of materials [3-8].

2. Ultrasonic Method of Residual Stress Measurement

Ultrasonic stress measurement techniques are based on the acoustic-elasticity effect, according to which the velocity of elastic wave propagation in solids is dependent on the mechanical stress [3, 4]. The relationships between the changes of the velocities of longitudinal ultrasonic waves and shear waves of orthogonal polarization under the action of tensile and compressive external loads in steel and aluminium alloys are presented in Fig. 3. As can be seen from Fig. 3, the intensity and character of such changes could be different, depending on material properties.

Different configurations of ultrasonic equipment can be used for residual stress measurements. In each case, waves are launched by a transmitting transducer, propagate through a region of the material and are detected by a receiving transducer. The technique when the same transducer is used for excitation and receiving of ultrasonic waves is often called pulse-echo method. This method is effective for analysis of residual stresses in the interior of material. In this case the averaged through thickness RS are measured. The RS could also be determined by using of ultrasound in surface/subsurface layers of a material.

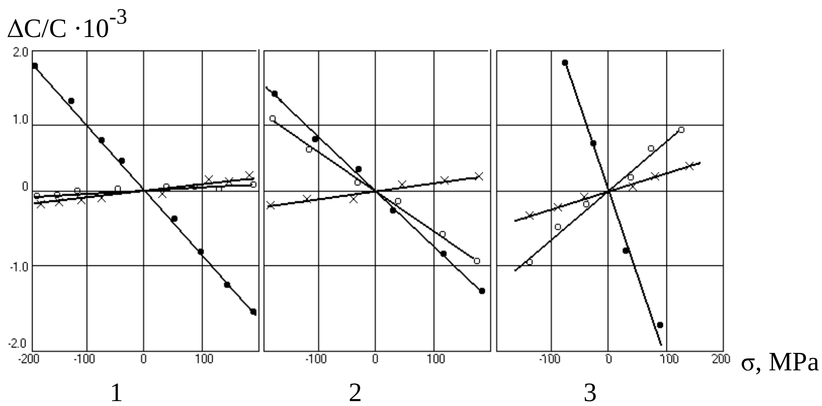

Fig.3. Change of ultrasonic longitudinal wave velocity (C_L) and shear waves velocities of orthogonal polarization (C_{SX3}; C_{SX2}) depending on the mechanical stress σ in steel A (1), steel B (2) and aluminium alloy (3): ● - C_{SX3}; ○ - C_{SX2}; x - C_L

The acoustic-elastic theory was developed that quantify the interaction of mechanical stresses and ultrasonic wave propagation in materials. The acoustic-elastic relationships are the theoretical grounds for the development of methods of ultrasonic stress measurement and in investigations of physical and mechanical properties of materials by means of ultrasound waves. The basic acoustic-elastic relationships (1)-(3) that relate mechanical stresses and ultrasonic wave velocities for bulk waves are presented below [4]:

(1) $$C_{lx1}^2 = C_{lx10}^2 + C_{lx1o}^2\left[2\frac{(a+b)\sigma_{kk}^2}{3K_0(<\lambda>+2<\mu>)} + \left(\frac{2(<\lambda.+<\mu>)\sigma_{11}^0}{<\mu>3K_0(<\lambda>+2<\mu>)} - \frac{<\lambda>(\sigma_{22}^0+\sigma_{33}^0)}{3K_0(<\lambda>+2<\mu>)}\right)(2b+c+4<\mu>+\frac{\sigma_{11}^0}{<\lambda>+2<\mu>}\right]$$

(2) $$C_{Sx2}^2 = C_{Sx20}^2 + C_{Sx20}^2\left\{b\frac{\sigma_{kk}^0}{3K_0<\mu>} + \left[\frac{<\lambda>+2<\mu>}{3K_0<\mu>}\left(\sigma_{11}^0+\sigma_{22}^0\right) - \frac{2<\lambda>}{3K_0<\mu>}\sigma_{33}^0\right]\left(1+\frac{c}{4<\mu>}\right)+\sigma_{11}^0\right\}$$

(3) $$C_{Sx3}^2 = C_{Sx30}^2 + C_{Sx30}^2\left\{b\frac{\sigma_{kk}^0}{3K_0<\mu>} + \left[\frac{<\lambda>+2<\mu>}{3K_0<\mu>}\left(\sigma_{11}^0+\sigma_{33}^0\right) - \frac{2<\mu>}{3K_0<\mu>}\sigma_{22}^0\right]\left(1+\frac{c}{4<\mu>}\right)+\sigma_{11}^0\right\}$$

where: C_{lx1} – is the longitudinal wave propagation velocity, C_{Sx2} and C_{Sx3} – are the polarized shear wave propagation velocities, σ^0_{11}, σ^0_{22} and σ^0_{33} – are the residual stresses in the corresponding directions, and ρ, λ, μ, a, b, c and K_0 – are material constants. Similar equations are developed also for determination of residual stresses based on using surface/subsurface ultrasonic waves.

In general, the change in the ultrasonic wave velocity in structural materials under mechanical stress amounts only to tenths of a percentage point. Therefore the equipment for practical application of ultrasonic technique for residual stress measurement should be of high resolution, reliable and fully computerized.

3. Ultrasonic Equipment and Software for Residual Stress Measurement

The Ultrasonic Computerized Complex (UCC) for residual stress measurement was developed recently based on an improved ultrasonic methodology [5, 6]. The UCC includes a measurement unit with supporting software and a laptop (optional item) with an advanced database and an Expert System (ES) for analysis of the influence of residual stresses on the fatigue life of welded components. The developed device with gages/transducers for ultrasonic residual stress measurement is presented in Fig. 4. The UCC allows determining uni- and biaxial applied and residual stresses for a wide range of materials and structures. In addition, the developed ES can be used for calculation of the effect of measured residual stresses on the fatigue life of welded elements, depending on the mechanical properties of the materials, type of welded element, parameters of cyclic loading and other factors.

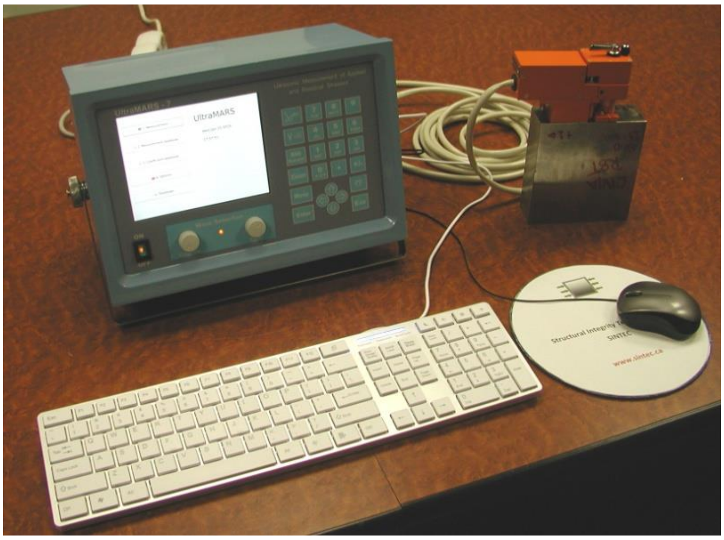

Fig. 4. Ultrasonic Computerized Complex for residual and applied stress measurement.

The basic package for residual stress measurement includes the measurement unit UltraMARS with basic supporting software and transducers, which is enough to perform measurement and computation of stresses in lab and industrial conditions.

The UltraMARS®-7 system provides the following measurements:

a) Magnitude and sign of uni- and biaxial stresses in samples and real structural elements.
b) Uniaxial stresses and forces in pins and bolts.
c) Parameters of the acoustic-elastic characteristics of materials.
d) Young Modulus and Poison Ratio.
e) The thickness of parts and structural elements.

The ultrasonic transducers for bulk or surface and subsurface measurements are held in contact with the object of investigation by a magnetic or electromagnetic holder for ferrous materials or by special clamping straps for non-ferrous materials.

Using the developed equipment, stresses can be measured in materials with thickness 2 - 200 mm. The stress, strain and force measurements can be done in fasteners (pins) 25 to 1000 mm long. The error of stress determination (from external load) is estimated at 5 - 10 MPa and the error of residual stress determination is estimated at 20-40 MPa. The overall dimensions of the measurement unit are 300x200x150 mm and the weight of the unit with sensors is ~ 7 kg.

The supporting software allows controlling the measurement process, storing the measured and other data and calculating and plotting the distribution of residual stresses on the screen of the unit. The measurement unit is equipped with a number of USB ports allowing for easy transfer of data. In addition, provisions are made to connect a PC computer to the unit.

3.1 Ultrasonic Transducers

Sending and receiving of the ultrasonic waves in the material/part for residual stress measurement are performed by ultrasonic transducers (UT). The UTs are the most important elements of the ultrasonic system UltraMARS®. The UTs that are supplied as a part of UltraMARS® system were developed particularly for residual stress measurement and improved during the 30+ years period [4-6] to provide stable and repeatable measurements in lab and field conditions. Standard ultrasonic transducers that are readily available on the market and that are used for other purposes, like detection and location of defects, etc., for a number of reasons could not be effectively used for residual stress measurement.

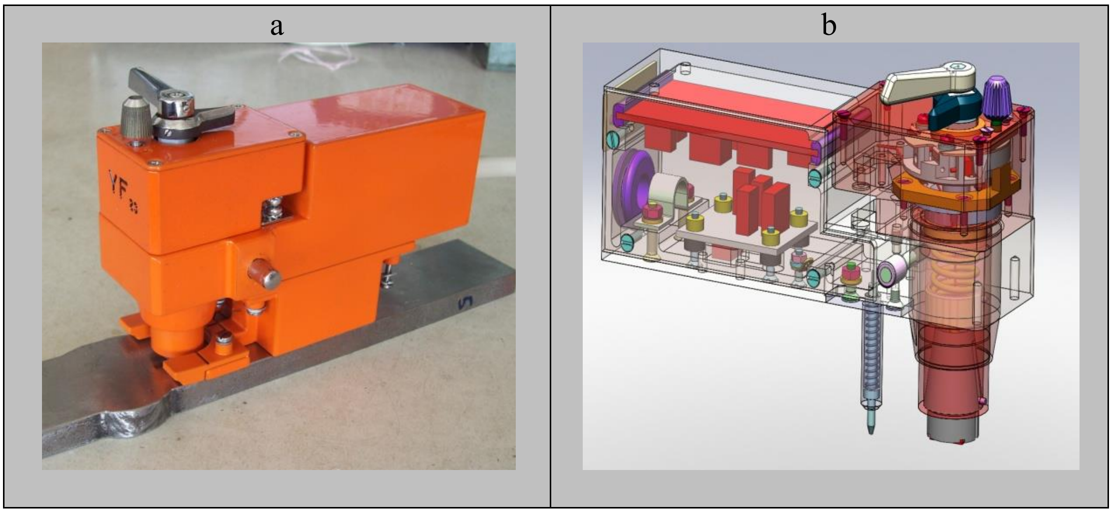

Fig. 5. General view (a) and 3-D expanded schematic view (b) of one of the transducers mounted on the transducer holder and attached to the pre-amplifier

The UTs are installed and fixed at a point of stress measurement on the sample, part or structural element using a special holder that also houses a pre-amplifier. The holder could be attached to the sample/part by a clamping strap, magnet or an electromagnet. Fig. 5a shows the general view of one of the UTs mounted on a magnetic holder. Fig. 5b shows a 3D schematic assembly view of a UT and the pre-amplifier.

Four UTs are supplied with the standard UltraMARS® system: two UTs for measurement of averaged through-thickness residual stresses and two UTs for measurement of surface/subsurface residual stresses.

The two UTs are used to determine the stresses averaged over the thickness of the investigated elements. In this approach, first UT is used to determine two velocities of shear waves of orthogonal polarization. Then, second UT is used to determine the velocity of longitudinal (compression) wave in the same location. Fig. 6 shows the UTs for measurement of averaged through-thickness residual stresses and scheme of this type of measurement.

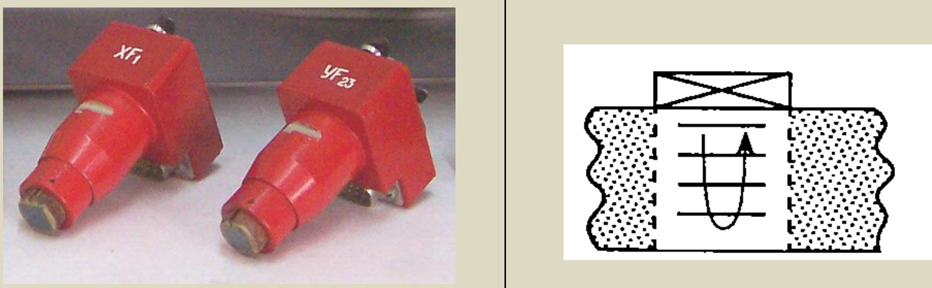

Fig. 6. The ultrasonic transducers for bulk ultrasonic waves (a): color of UTs: red or orange, size of sender/receiver: 7x7mm or 10x10mm and the schematic view of ultrasonic through-thickness pulse-echo measurement principle (b)

The other two UTs are used to determine the stresses in surface/subsurface layers of investigated elements. In this approach first UT is used to determine the velocities of surface waves in orthogonal directions. The second UT is used to determine the velocities of subsurface waves in orthogonal directions. Fig. 7 shows the UTs for measurement of residual stresses in surface/subsurface layers of material and scheme of this type of measurement.

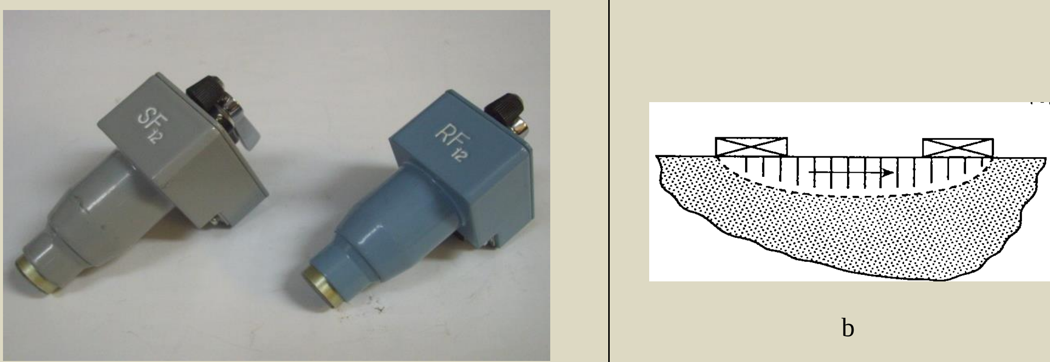

Fig. 7. Ultrasonic transducers for measurement of surface/subsurface residual stresses in parts and structures (a) and the schematic view of ultrasonic surface/subsurface pitch-catch measurement method principle (b)

Surface measurement: colour of UT – blue, measurement base 7mm, depth of penetration 0.4-1.5mm depending on a number of factors. Subsurface measurement: colour of UT – grey, measurement base 7mm, depth of penetration 1-3mm depending on a number of factors.

4. Results of Residual Stress Measurement

4.1.Measurement of Residual Stresses in Welded Samples - Examples

The residual stresses were measured in a specimen measuring 1000x500x36 mm, representing a butt-welded element of a wind tunnel. This and other similar samples were prepared for fatigue testing. The distribution of biaxial residual stresses was investigated in X (along the weld) and Y directions after welding and in the process of cyclic loading of the specimen. Fig. 8 represents the distribution of longitudinal (along the weld) and transverse components of residual stresses along the weld toe. Both components of the residual stress reached their maximum levels in the central part of the specimen: longitudinal at 195 MPa, transverse at 110 MPa.

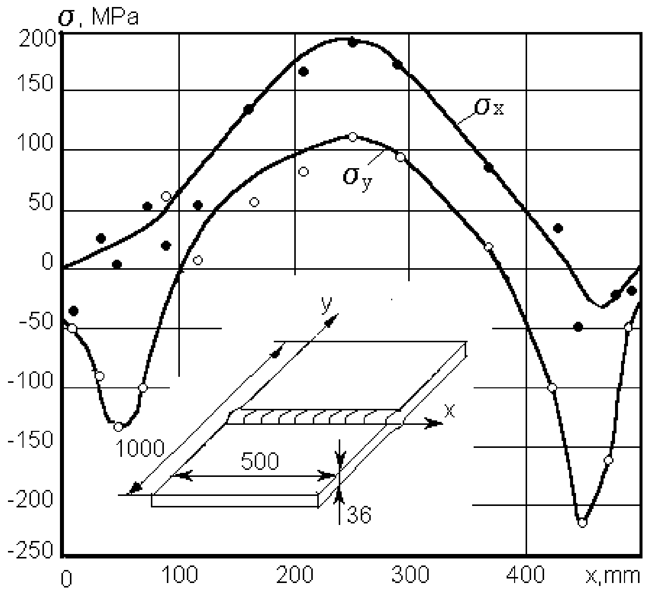

Fig. 8. Distribution of longitudinal (along the weld) and transverse components of residual stresses along the butt weld toe

The ultrasonic method was applied also for residual stress measurement in a specimen measuring 900x140x70 mm and made of low-alloyed steel, representing the butt weld of a structure. The distribution of residual stress components in X_3 (along the weld) and X_2 (perpendicular to the weld) directions as well as through the thickness of the specimen near the weld (X_1 direction) are presented in Fig. 9.

4.2 Measurement of Residual Stresses in Welded Structures

The developed ultrasonic equipment could be used for RS measurement for both laboratory/factory and field conditions. The process and some of the results of ultrasonic measurement of RS in welded elements of a bridge are shown in Figs. 10 and 11. The RS were measured by ultrasonic method in the main wall of the bridge span near the end of one of welded vertical attachments. In the vicinity of the weld the measured levels of harmful tensile RS reached 240 MPa. Such high tensile RS are the result of thermo-plastic deformations during the welding process and are one of the main factors leading to the origination and propagation of the fatigue cracks in welded elements of the bridge.

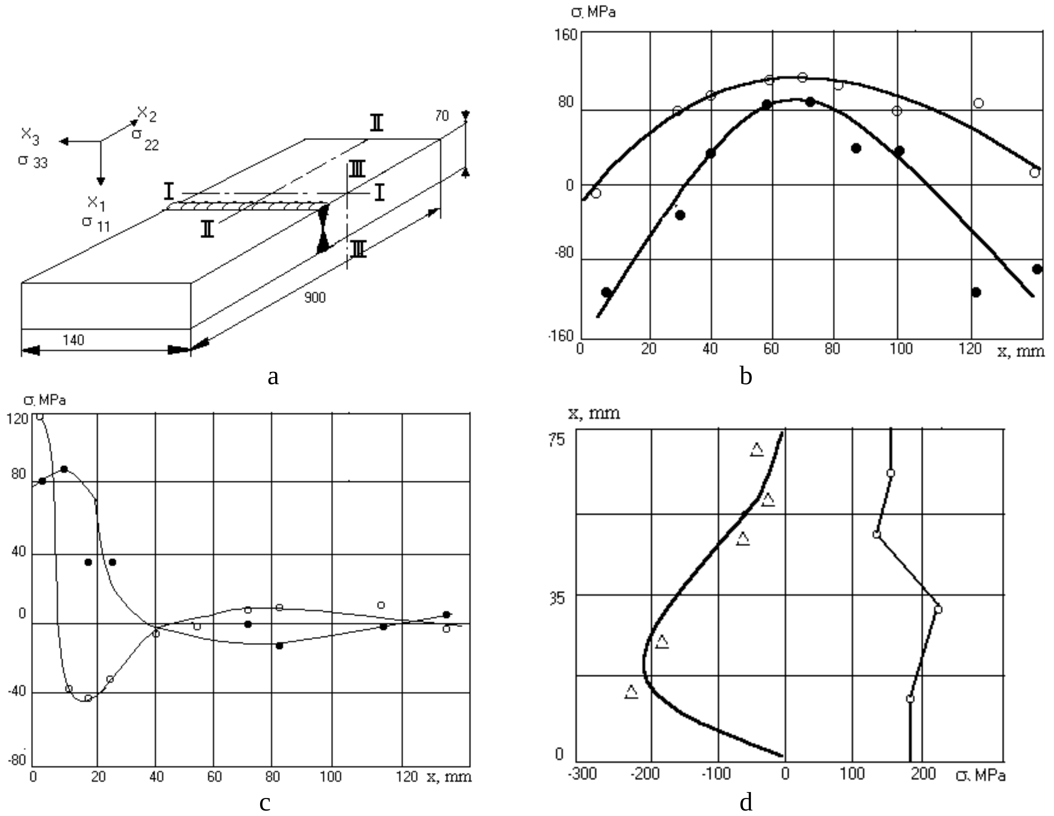

Fig. 9. Welded specimen (a) and distribution of the residual stresses along the butt weld I-I (b), perpendicular to the weld II-II (c) and through the thickness near the weld III-III (d): ● – σ_{22} ; ○ - σ_{33} ; Δ - σ_{11}

Fig.10. Process of measurement of residual stresses in a welded bridge

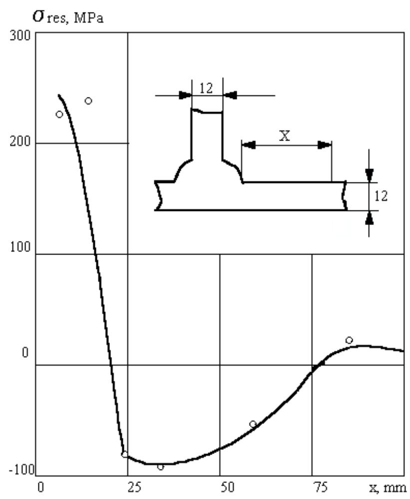

Fig.11. Distribution of longitudinal residual stresses near the fillet weld in a bridge span: x – distance from the weld toe

The residual stresses were measured in the welded elements of the pressure hull of a submarine. Four zones were selected for RS measurement in the welded elements of the hull of submarine. Fig. 12 shows the process of RS measurement in one of the selected zones of the hull of submarine. The data on RS measurement near the butt weld are presented in Fig. 13. Both components of RS are tensile at the distance from the weld toe of 20 mm. The longitudinal component of RS reaches 295 MPa.

Fig. 12. Residual stress measurement in one of the welded elements of the pressure hull of a submarine

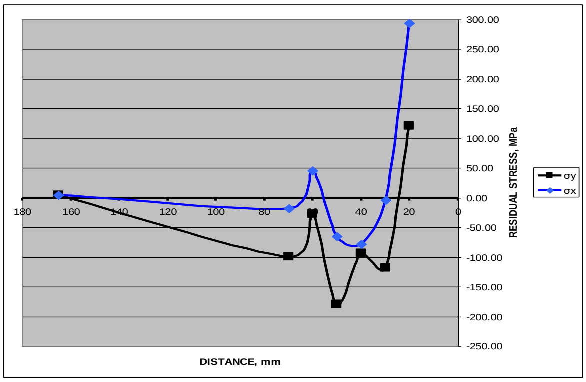

Fig. 13. The distribution of residual stresses near the butt weld of pressure hull: the horizontal axis represents the distance from the weld, σx and σy – components of RS that are parallel and perpendicular to the weld

5. Summary

1. Residual stresses play an important role in operating performance of materials, parts and structural elements. Their effect on the engineering properties of materials such as fatigue and fracture, corrosion resistance and dimensional stability can be considerable. The residual stresses, therefore, should be taken into account during design, manufacturing, maintenance and weld repair of parts and elements.

2. Certain progress has been achieved during the past few years in improvement of traditional techniques and development of new methods for residual stress measurement. The developed advanced ultrasonic method, based on it portable instrument and the supporting software can be used for non-destructive measurement of applied and residual stresses in laboratory samples and real parts and structural elements in many applications for a wide range of materials.

3. The developed ultrasonic technique was successfully applied for residual stress measurement in welded elements and structures in construction industry, shipbuilding, railway and highway bridges, nuclear reactors, aerospace industry, oil and gas engineering and in other areas during manufacturing, in service inspection and repair of welded elements and structures.

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