Conference Paper

Determination of Residual Stresses in the Products with Floating

D. A. Ryabov and A. A. Khlybov

Nizhny Novgorod State Technical University, Nizhny Novgorod, Russia

Abstract

The paper presents the results of the application of the acoustic method for estimating residual stresses in products with surfacing (steel 15H2MFA with austenitic surfacing). The possibility of using this technique on real, particularly responsible constructions is analyzed, without affecting their performance.

Keywords: ultrasonic testing, residual stresses, austenitic surfacing, 15H2MFA.

Corresponding Author:
D. A. Ryabov
ryabovdm1996@gmail.com
A. A. Khlybov
hlybov_52@mail.ru

Received: 21 December 2017
Accepted: 15 April 2018
Published: 6 May 2018

Publishing services provided by Knowledge E

Selection and Peer-review under the responsibility of the MIE-2017 Conference Committee.

1. INTRODUCTION

In the manufacture and operation of complex particularly responsible products, one of the tasks is to evaluate the state of materials. The need for an additive calculation of internal stresses with external loads on the material during the operation period is explained by technical norms that do not allow loading on material exceeding its yield point at operating temperatures. Of particular importance is the estimation of residual stresses (RS) in conditions of brittle fracture. Stretching RS reduce the vibrational strength of welded structures. The localization of RS in zones with stress concentrators or an uneven distribution of mechanical properties may cause destruction.

Therefore, the possibility of timely reliable assessment of RS arising in products as a result of thermal operations, operational factors and other conditions is an actual task.

To solve the problems of evaluating the strength, reliability and optimal design of structures, various methods have been developed that make it possible to evaluate the RS in most practical cases. The methodological features of one or another method of determining RS are related to the geometry of the object under study, the nature of OH distribution, material properties, and other factors [5].

Among these methods, the most applicable are experimental mechanical (hole drilling methods) and physical (acoustic, X-ray, magnetic methods). Each of these methods has its advantages and disadvantages.

The general method of measuring RS by drilling holes was first proposed by Mater, and then modified by Soete [13]. In this method, a small hole is drilled in a plate containing RS, then the stress values and their directions are determined by the deformation measuring device. The disadvantage of this method is the impossibility of carrying out a measurement on the operated product, as well as the need to make a sample, which leads to a violation of the integrity of the constructions.

Magnetic methods of nondestructive testing [2] are comparatively simple and inexpensive, they are quite suitable for express scanning of surfaces of constructions elements for the purpose of control of the near-surface layer. In the framework of magnetic methods, calibration dependencies are applied on the uniaxial stress of coercive force, magnetic permeability, and other characteristics of the magnetic field of the material. The dependencies of the measured parameters on the stresses are empirical.

The X-ray method [11] is based on the measurement of changes in the interplanar distances determined from the displacement of the diffraction line. With its help, it is possible to determine the stress gradients at a depth of 0.1 mm. This method measures surface microdeformations (microstresses), which are not always of interest for coarse-grained materials and large metal structures. Strict requirements are made for the cleanliness of the surface of the material. The displacement of the diffraction profile due to the stress-strain state is a fraction of a degree, such a value should be measured with an error not exceeding hundredths of a degree. Such measurements are possible either in laboratory conditions or using high-precision mechanical systems to move the measuring instrument, which complicates the application of the method in the case of large-sized structures. X-ray radiation is a danger to maintenance personnel and therefore requires special protection.

The acoustic method for measuring the stresses in solids is based on the use of the laws governing the propagation of elastic waves in solids [3, 7]. This method allows you to determine the main stresses not only in models, but also directly in constructions. It has a high enough accuracy, provides quick monitoring, allows you to measure stresses in the surface and in the volume of the material. The equipment is relatively simple and can be mobile.

Using an ultrasonic method for measuring RS, we have: low cost, high evaluation speed and accuracy, and non-destructive advantages over hole drilling methods. Acoustic methods are suitable for measuring stresses in any elastic structural materials.

To protect against corrosion, the technology of building particularly critical products of power engineering (reactor vessels, steam generators, pipelines) provides for the fusion of an austenitic chromium-nickel welding materials onto the inner surface [12].

Surfacing has a complex effect on the metal constructions. High temperatures, uneven heating, structural changes, an infinite variety of external influences, the geometry of welded products and many other factors lead to significant RS.

The application of ultrasonic methods allows the operative measurement of RS in bimetallic constructions.

The purpose of this work is to determine the magnitude of the residual stresses by the acoustic method on real constructions having austenitic surfacing while maintaining the operability of the article.

2. MATERIALS AND METHODS

Samples for the study were bimetallic samples (10 x 10 x 55 mm) made of 15H2MFA steel with austenitic surfacing (Fig. 1).

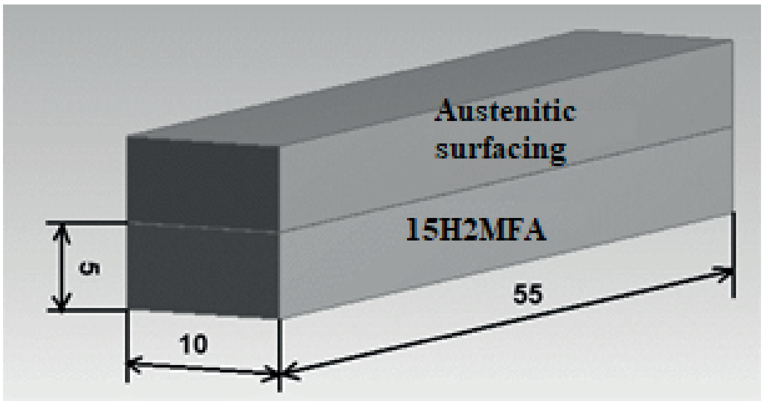

Figure 1: General view of the samples.

The chemical composition of steel 15H2MFA, %: C 0,11-0,21; Si 0.17-0.37; Mn 0.30-0.60; S≤0.020; P≤0.020; Cr 2.0-3.0; Ni≤0.40; Mo 0.60-0.80; V 0.25-0.35; Cu≤0.30. Chemical composition of surfacing Sv-08H19N10G2B, %: C to 0,1; Si 0.9-1.1; Mn 1.3-1.4; S≤0.025; P≤0.020; Cr 17.3-17.6; Ni 10 [12].

In this work, the samples were subjected to heat treatment. Part of samples from steel 15H2MFA and samples with surfacing were subjected to quenching (950 °C, 25 minutes, water), annealing (950 °C, 25 minutes, oven). Samples from surfacing were heat treated at 1050 °C, 25 minutes, cooling in air.

Metallographic studies were carried out using the optical microscope «Keynce VHX-1000».

The current approaches to the control of mechanical stresses in a material by an acoustic method are usually based on general relations of acoustoelasticity [1, 4]. In accordance with the classical papers [1, 3, 6], the basic equations of acoustoelasticity for a plane stress state can be written as follows:

$$V_1 = V_1^0(1 + k_{11}\sigma_1 + k_{12}\sigma_2) \tag{1}$$

$$V_2 = V_2^0(1 + k_{21}\sigma_1 + k_{22}\sigma_2) \tag{2}$$

$$V_3 = V_3^0(1 + k_{31}\sigma_1 + k_{32}\sigma_2) \tag{3}$$

where σ_1 and σ_2 - the principal stress values;

V_1 и V_2 - the propagation velocity of transverse elastic waves propagating perpendicular to the stress plane, the polarization vector, which is oriented along the direction of action of the stresses σ_1 and σ_2;

V_3 - the propagation velocity of longitudinal elastic waves propagating perpendicular to the stress plane;

V_1^0, V_2^0, V_3^0 - the values of the corresponding propagation velocities in the non-stressed material;

k_{11}, k_{12}, k_{21}, k_{22}, k_{31}, k_{32} - coefficients of acoustoelastic coupling.

Transform these expressions into a form convenient for practical use, taking into account the hardware capabilities that realize the measurement of the time parameters of elastic waves.

The calculated relations for the case of a plane stress state with principal stresses σ_1, σ_2 in a plane perpendicular to the direction of propagation of elastic waves, expressions are obtained relating the voltages and delays of pulses of elastic waves of two types: longitudinal and transverse, polarized along the principal stresses:

$$\sigma_1 = k_1\delta d_1 + k_2\delta d_2, \tag{4}$$

$$\sigma_2 = k_3\delta d_1 + k_4\delta d_2, \tag{5}$$

where $\delta d_1 = \frac{d_1 - d_{01}}{d_{01}}$, $d_1 = \frac{t_1}{t_3}$, $d_{01} = \frac{t_{01}}{t_{03}}$, $\delta d_2 = \frac{d_2 - d_{02}}{d_{02}}$, $d_2 = \frac{t_2}{t_3}$, $d_{02} = \frac{t_{02}}{t_{03}}$,

t_1, t_2, t_3 - time of propagation of elastic waves in a stressed state;

t_{01}, t_{02}, t_{03} – respectively, in the relaxed;

k_1,k_2,k_3,k_4 – tensometric [4] or elastic-acoustic [6] coefficients:

$$k_1 = \frac{\alpha_4}{\alpha_1\alpha_4 - \alpha_2\alpha_3},\ k_2 = -\frac{\alpha_2}{\alpha_1\alpha_4 - \alpha_2\alpha_3},\ k_3 = -\frac{\alpha_3}{\alpha_1\alpha_4 - \alpha_2\alpha_3},\ k_4 = \frac{\alpha_1}{\alpha_1\alpha_4 - \alpha_2\alpha_3}, \tag{6}$$

α_1, α_3, α_4 – acoustoelastic coefficients of relative delays;

The relationship between the stresses and delays of surface ultrasonic waves (Rayleigh waves) at a constant base can be described by the following expression:

$$\frac{\Delta\tau_1}{\tau_1(0)} = A_1\sigma_1 + A_2\sigma_2 \tag{7}$$

$$\frac{\Delta\tau_2}{\tau_2(0)} = A_1\sigma_1 + A_2\sigma_2 \tag{8}$$

where σ_1 and σ_2 - the surface stresses along and perpendicular to the axis of the sample;

$\Delta\tau_1$ and $\Delta\tau_2$ - the changes in the delays of the pulses of surface waves propagating respectively along and perpendicular to the axis of the sample;

$\tau_1(0)$ and $\tau_2(0)$ - corresponding pulse delays for the unstressed state;

A_1, A_2 - the coefficients of the acoustoelastic coupling for surface waves, determined experimentally for a particular material.

To excite surface waves, the "wedge method" was used. The wedge method is based on the transformation of longitudinal waves propagating in the wedge material into surface waves propagating in the controlled material. For this purpose, a piezoceramic plate 1 of the CTS-19 was pasted on the inclined face of the prism (Fig. 2).

Piezoplate 1 excites a longitudinal wave in the wedge. The velocity of propagation of longitudinal waves in the piezoceramic of the type used is equal to $4000m \bullet s^{-1}$. The general view of the sensor with a fixed base, which combines the radiating and receiving sensor in one housing, is shown in Figure 2. To expand the sensor bandwidth, an acoustic damper 4 was adhered to the piezoceramic plate, consisting of a mixture of epoxy ED-6 (30%) and cement (70%).

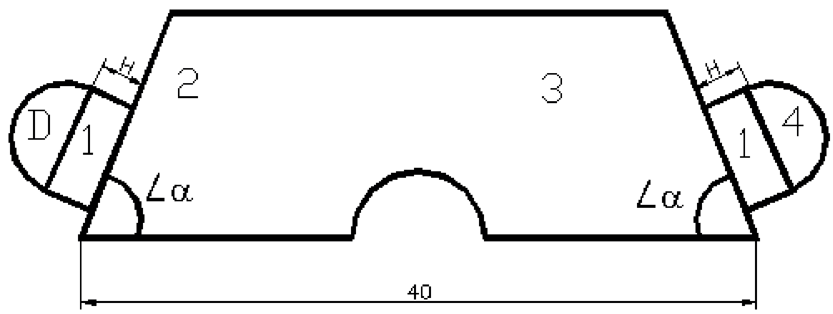

Figure 2: Surface wave combined sensor.

To excite the surface wave, a wedge-shaped sensor with an input angle determined from the condition of maximum excitation of the surface wave (Rayleigh wave) was used:

$$\sin \Theta_R = \frac{V_t}{V_R}, \tag{9}$$

where V_t - velocity of a longitudinal wave in a wedge material, V_R - the velocity of the Rayleigh wave in the sample under study.

Engineering methods of stress control using the most common acoustic echo-pulse method are usually based on measurements of time intervals between repeatedly reflected pulses of elastic waves of different polarization [14]. In this connection, acoustoelastic relations of the type (4, 5) are more preferable.

To carry out calibration and determine the acoustoelastic coefficients [8–10], the samples were cut according to GOST 1497 (Figure 3).

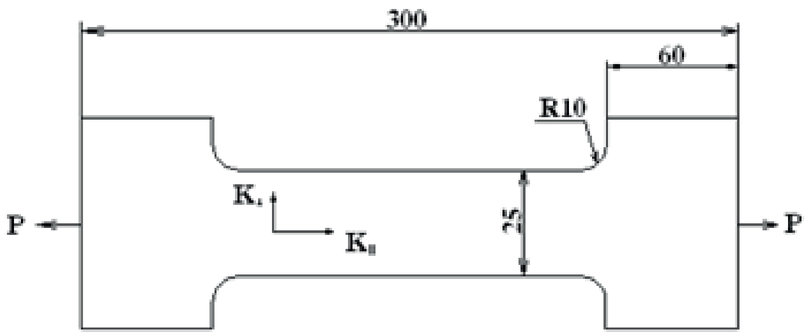

Figure 3: Samples for determining the acoustoelastic coefficients.

Acoustic measurements were carried out using the MCC «ASTRON» (Figure 4). The acoustic complex provides a measurement of the propagation time of elastic pulses with an accuracy of 10^{-9} s. «ASTRON» works both in a combined mode (work with one sensor), and in separately-combined (reception and radiation of elastic waves is carried out through different channels). In this work we used a converter [8, 10] made in one construction, having three active elements: two transversely polarized piezoelectric plates with perpendicular polarization vectors and a longitudinal piezo plate.

Next, calibration results were used for the evaluation of RS using ultrasonic waves. To compare the results obtained, X-ray diffraction analysis was performed on the DRON-2 setup.

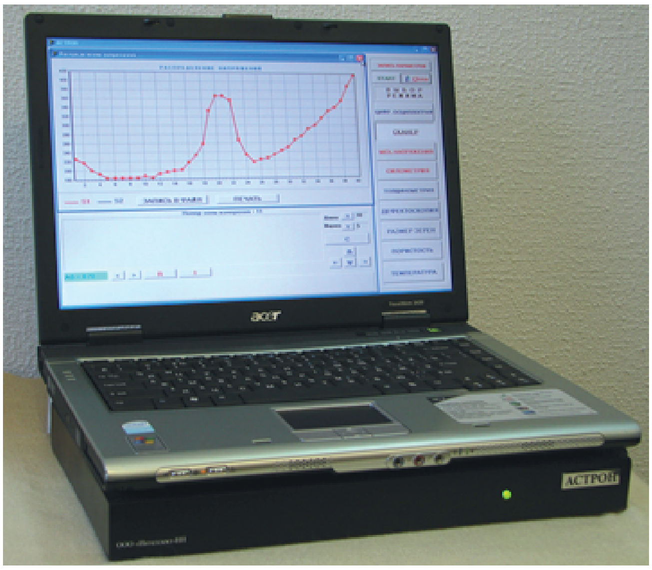

Figure 4: MCC «ASTRON» for performing calibration measurements on a standard sample using acoustic waves.

3. RESULTS AND DISCUSSION

As a result of heat treatment, deformations up to 0.38 mm on the basis of 55 mm after annealing and 0.2 mm after quenching in water were detected in the samples with surfacing. This confirms the presence of significant RS. Steel 15H2MFA was subjected to structural changes. After quenching in water, this steel had a martensitic structure (Fig. 5a), after annealing - ferrite-pearlite (Fig. 5, b). In austenitic cladding structural changes were not observed (Fig. 5, a, b).

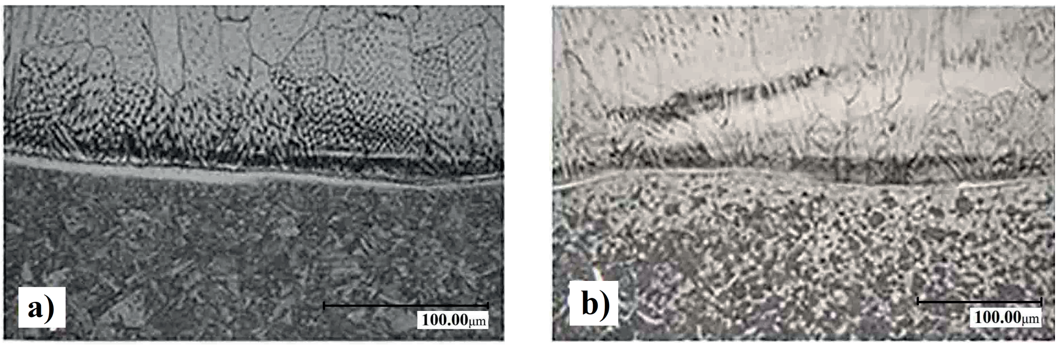

Figure 5: Structures of bimetallic samples after quenching (a) and annealing (b).

Based on the results of tests on flat samples (steel 15H2MFA), the average results of acoustic measurements by bulk waves were obtained (Fig. 6). It was obtained: a change in the delay of shear waves in the elastic region of about 0.4%, and for longitudinal - 0.15%.

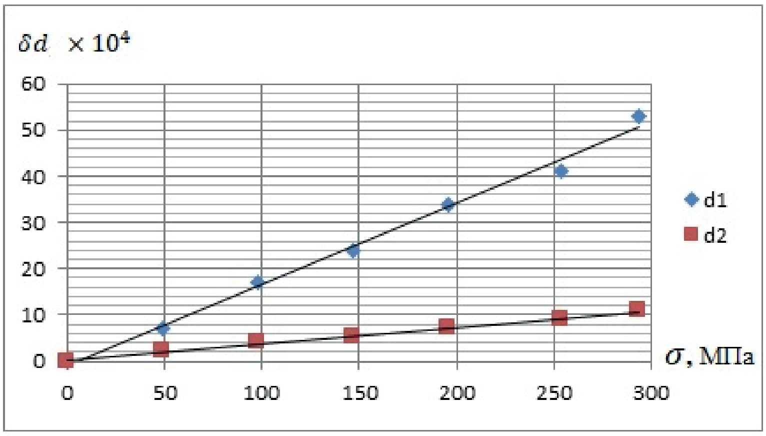

Figure 6: The influence of tensile stresses on $\delta d_1(\sigma)$, $\delta d_2(\sigma)$.

Figure 7 shows the corresponding oscillograms of measurements using shear and surface waves.

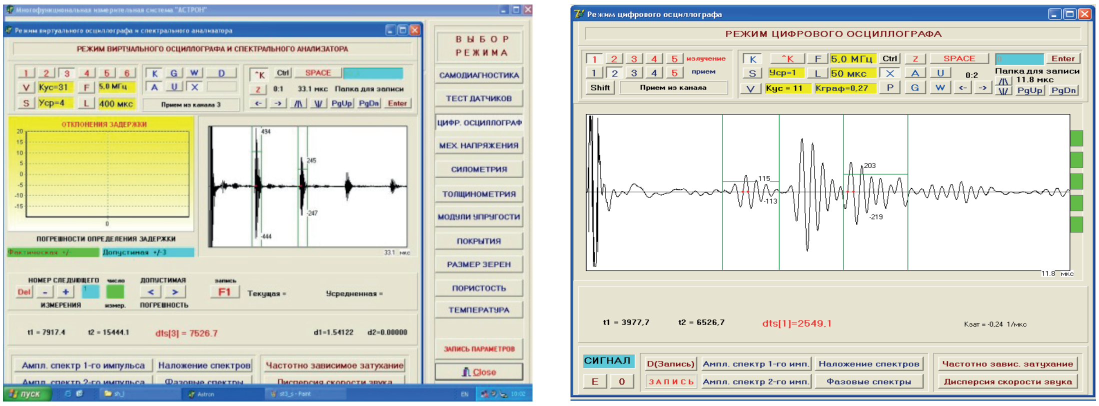

Figure 7: Oscillogram of measurements using shear (left) and surface (right) waves.

For all the dependences obtained, the correlation coefficient turned out to be practically equal to 1, which indicates the existence of a linear dependence of the parameters δd_1,δd_2 on the uniaxial stress.

Regression processing of the obtained data allowed to determine the acoustoelastic coefficients (15H2MFA steel) α_1, α_2, α_3, α_4:

$$\alpha_1 \approx 16,6 \times 10^{-6} \text{MPa}^{-1},$$

$$\alpha_2 \approx 3,6 \times 10^{-6} \text{MPa}^{-1},$$

$$\alpha_3 \approx 2,2 \times 10^{-6} \text{MPa}^{-1},$$

$$\alpha_4 \approx 9,3 \times 10^{-6} \text{MPa}^{-1}.$$

The results of calculations of strain-gauge coefficients according to formulas (6) gave the following values (steel 15H2MFA):

$$k_1 = 0,63 \times 10^5 \text{MPa},$$

$$k_2 = -0,25 \times 10^5 \text{MPa},$$

$$k_3 = -0,15 \times 10^5 \text{MPa},$$

$$k_4 = 1,13 \times 10^5 \text{MPa}.$$

In order to obtain the coefficients for surfacing, tests were carried out on samples of 08H18N10T steel, which was close in composition to the surfacing material.

$$k_1 = 1.04 \times 10^5 \text{MPa},$$

$$k_2 = -0.12 \times 10^5 \text{MPa},$$

$$k_3 = -0,1 \times 10^5 \text{MPa},$$

$$k_4 = 0.3 \times 10^5 \text{MPa}.$$

To obtain the coefficients A1, A2, the surface wave sensor was oriented along and perpendicular to the applied load. The following values for steel 08H18N10T are obtained:

$$A_1 = 9 \times 10^{-6} \text{MPa}^{-1},$$

$$A_2 = 6 \times 10^{-6} \text{MPa}^{-1}.$$

Measurements were made of the time of propagation of surface waves on samples with surfacing after quenching and annealing. The measurements were made on the side of surfacing and on the side of 15H2MFA steel. Shifts and longitudinal waves measured the delay in the thickness of the sample. The measured values of the delays were substituted into equations (7, 8) for calculating the stress state. The results are shown in Figure 8.

For the purpose of comparing the results of acoustic and X-ray methods for determining RS, x-ray diffraction data were obtained (Fig. 9).

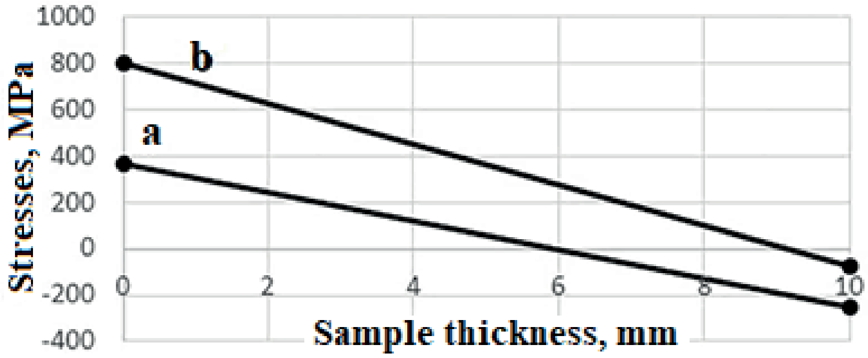

Figure 8: Residual stresses in 15H2MFA steel and surfacing after quenching in water (a) and annealing (b) Note: 0-5 mm - thickness of surfacing, 5-10 mm – steel 15H2MFA.

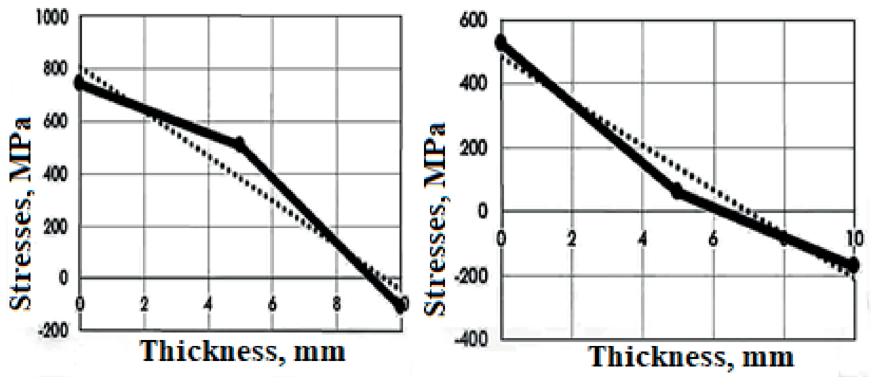

Figure 9: Stress distribution in thickness in the sample with surfacing after annealing (left) and quenching (right) Note: 0-5 mm - thickness of surfacing, 5-10 mm – steel 15H2MFA.

4. CONCLUSIONS

1. The obtained results show the principal possibility of using modern methods of acoustoelasticity in problems of residual stress control in products with surfacing.
2. The possibility of using the MCC «ASTRON» for monitoring residual stresses in products with surfacing is shown.
3. It is experimentally established that there are significant residual stresses in a bimetallic sample made of 15H2MFA steel with austenitic surfacing leading to deformation.
4. Reliability of the determination of residual stresses using the MCC «ASTRON» confirm the results of X-ray diffraction analysis.
5. To quantify residual stresses, it is necessary to carry out tests (calibration) on samples of materials used in the manufacture of structural elements.

References

[1] Bobrenko V.M., Vangeli M.S., Kutsenko A.N. Acoustic tensometry. - Chisinau: Shtiintsa, 1991. - 204 p.

[2] Drozdov V.S. Magnetic methods of nondestructive testing and flaw detection / / Modern scientific research and innovation. 2015. no. 8. Part 1 [Electronic resource]. URL: http://web.snauka.com/issues/2015/08/57254

[3] Klyuev V.V. Unbrakable control. Reference: in 7T. Under the Society. Ed. V.V. Klyuev. 2 nd ed. T. 3: Ultrasonic testing / N. Ermolov, Yu.V. Lange. - Moscow: Mashinostroenie, 2004. – 864 p.

[4] Nondestructive testing and diagnostics: Handbook ed. V.V. Klyuev. 3rd ed., Rev. and additional. - Moscow: Mashinostroenie, 2005. 656 p.

[5] Experimental mechanics / ed. A. Kobayashi, vol.2. M.: the World, 1990.-551c.

[6] Nikitina N.E. Acoustoelasticity. Practical experience. - N. Novgorod: Talam, 2005. -208 p.

[7] Nikitina N.E. Advantages of the method of acoustoelasticity for nondestructive testing of mechanical stresses in machine parts / N.E. Nikitin, S.V. Kazachek // Bulletin of scientific and technological development. - Moscow. - 2010. - No. 4 (32). - pp. 18-28.

[8] Uglov A.L., Erofeev V.I., Smirnov A.N. Acoustic control of equipment during manufacture and operation / otv. Ed. Academician of the Russian Academy of Sciences F.M. Mitenkov. Moscow: Nauka, 2009. - 280 p.

[9] Uglov A.L., Khlybov A.A. On the control of the stressed state of gas pipelines from anisotropic steel by the method of acoustoelasticity, in: Defectoscopy. 2015. S. 51. № 4. pp. 34-41.

[10] Uglov A.L., Andrianov V.M., Batalin O.Yu. Complex ultrasonic sensor. Patent for invention № 2240552, 2004.

[11] Umansky Ya.S., Skakov Yu.A., Ivanov A.N., Rastorguev L.N. Crystallography, radiography and electron microscopy. Moscow: Metallurgy, 2002. 632 p.

[12] Khlybov A.A. Influence of heat treatment on residual stresses in the austenitic and corpus fusion zone // Metallurgy and heat treatment of metals. 2016. Vol. 733. No. 7. pp. 47-51.

[13] Vangi D. "Stress Evaluation by Pulse-echo Ultrasonic Longitudinal Wave", Experimental Mechanics, 2001; 41: 277-281.

[14] State Standart R 56664-2015. Non-destructive testing. Determination of the stress state of the material of engineering products by the methods of acoustoelasticity. - Enter. 2015-10-22. – Moscow, Standardinform Publ., 2016. 15 p. (In Russian)