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NONDESTRUCTIVE METHOD OF RESIDUAL STRESS DETERMINATION IN WELDED JOINTS BASED ON APPLICATION OF HIGH-DENSITY CURRENT PULSES AND SPECKLE-INTERFEROMETRY

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ABSTRACT

A procedure was developed for nondestructive evaluation of residual stresses in welded joints based on application of high-density current pulses and laser speckle-interferometry. Comparison of the results of residual stress measurement in welded joints, obtained by the developed method and by hole-drilling method, was performed.

KEYWORDS: residual stresses, welded joints, high-density current pulse, speckle-interferometry, electroplastic effect, hole-drilling method

INTRODUCTION

One of the important tasks in manufacturing, designing and operation of welded structures is testing their stressed state, since residual stresses significantly affect the life of structures. To determine residual stresses, such nondestructive methods as X-ray, ultrasonic, magnetic, etc., and mechanical ones based on the principle of stress relaxation are widespread [1–3]. During determination of residual stresses in elements and assemblies of structures for their elastic unloading, different methods are used, such as thermal effect [4], plastic ball indentation [5], hole drilling, etc. The method of drilling small non-through holes (with a diameter of 1.0–3.0 mm and a depth of 0.5–3.0 mm) became the most widespread for elastic unloading of residual stresses. Measurements of deformations and displacements around the zone of elastic unloading (around the drilled hole) are performed using different methods of experimental mechanics, as for example, electric strain gauging, mechanical strain gauges and optical methods, including laser interferometry methods [6–13].

However, despite the widespread use of the hole drilling method, it is still destructive. This imposes a number of restrictions on its application. For example, the method has limited use in the diagnostics of real structures in the process of their operation. In this regard, the determination of residual stresses is often performed on individual mock-ups of elements and assemblies of real structures. Therefore, the development and creation of nondestructive methods for elastic unloading of residual stresses of full-scale structures is a relevant task.

The aim of this study is to create a nondestructive method for residual stress determination, which has high accuracy and reliability inherent in destructive relaxation methods. For this aim, it is proposed to replace the process of drilling holes for stress relaxation, which violates the structural surface integrity, with a nondestructive method of local stress relaxation based on the use of high density current pulses of 10^7–10^{10} A/m^2 (Figure 1) [14–16]. It is believed that upon introduction of a current pulse, a zone with a hemispherical appearance is formed, in which an electroplastic effect arises and stress relaxation around the place of pulse introduction occurs. At the same time, the integrity of the tested area of the material is not violated. Since the size of the area, in which the stress relaxation occurs is unknown in advance and depends on the electrode system parameters, it is necessary to evaluate the effectiveness of residual stress relaxation upon the introduction of a current pulse.

PULSE CURRENT SOURCE

A pulse current source (PCS) was created at the Institute of Electrodynamics of NASU, and two types of shock-pulse and pulse effect electrode systems were developed at the PWI of NASU, which are used to introduce a pulse current into the studied area of the ob-

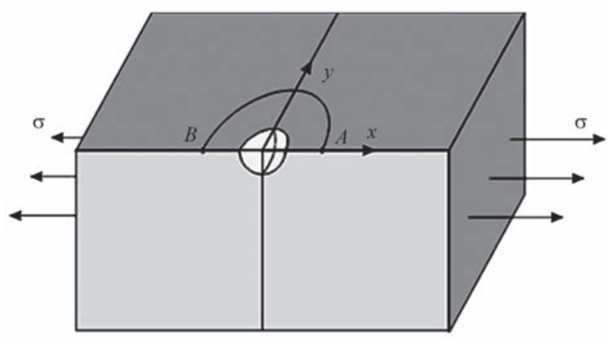

Figure 1. Scheme of residual stress relaxation after introduction of a current pulse

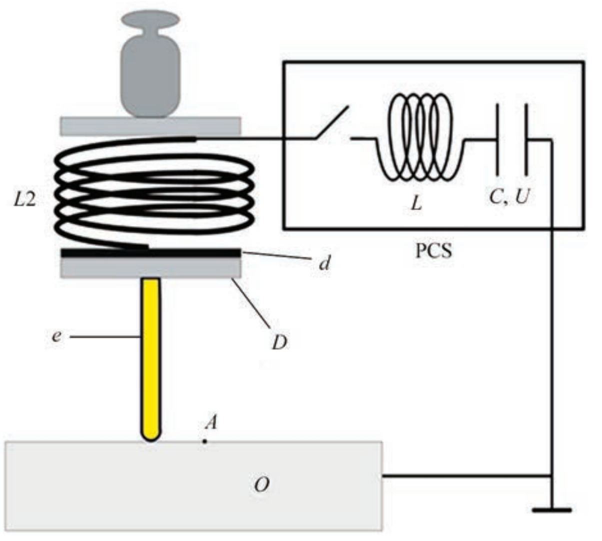

Figure 2. Scheme of the electrode system with a shock-pulse type of action: *L* — inductance coil; *C* — capacitor battery with a charging voltage *U*; *e* — electrode; *D* — disc; *O* — object into which a current pulse is introduced; *d* — dielectric gasket; PCS — pulse current source

ject. The power source has wide capabilities for regulation of the basic electrical parameters of the system, which provide the required shape of current pulses.

The electrode system of a pulse action includes electrode *e*, load *P*, which ensures the necessary contact between the electrode and the point of current introduction and the pulse current source (Figure 2). In the electrode system of pulse action, the inductance *L* of the coil varies in the range of 4700–1900 μH, the capacity *C* of the capacitor battery is 3400–17000 μF, the charging voltage is 50–186 V.

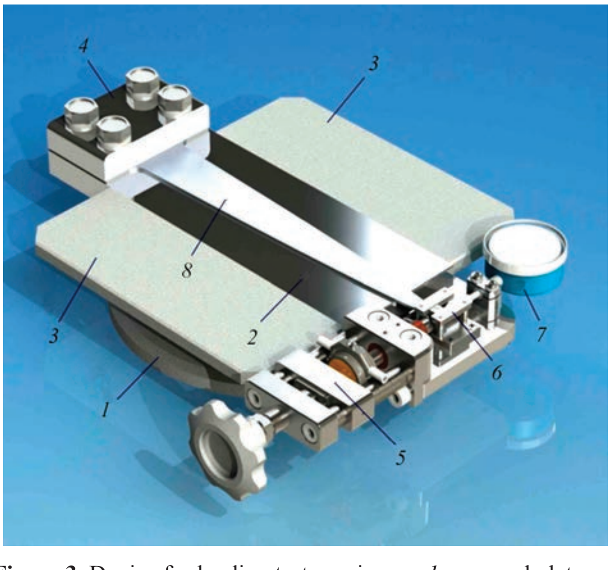

Figure 3. Device for loading test specimens: *1* — round plate, on which a base plate is placed for positioning specimen on the device; *2* — polished plate, on which test specimen is located; *3* — plate for placing speckle-interferometer; *4* — clamping element for fixing test specimen; *5*, *6* — units for loading test specimen; *7* — device for testing beam (test specimen) displacements; *8* — beam of equal bending resistance (test specimen)

The created electrode system provides introduction of a pulsed current into the studied material, the effect of which leads to arising displacements around the point of introduction. The values of displacements depend on the stress state at the point of pulse introduction, as well as on such parameters of the electrode system as charging voltage on the capacitor storage *U*, inductance *L*, etc. In order to determine the effective parameters of the electrode system, it is necessary to assess the degree of stress relaxation upon introduction of a current pulse into the tested area of the studied element.

INFLUENCE OF THE ELECTRODE SYSTEM PARAMETERS ON STRESS RELAXATION

To determine the influence of the electrode system parameters on stress relaxation, a mechanical device for loading test specimens was designed and manufactured (Figures 3, 4). A beam of equal bending resistance is used as a test specimen, as far as stresses in all cross-sections will not exceed the preset ones.

The speckle-interferometry device designed at the PWI [11–13] allows registering displacements of surface points in the range of 0.03–3 μm. Figure 5 presents patterns of interference fringes, that contain information about the displacements u_x obtained after the introduction of a local current pulse into the test specimen under loading (Figure 4). The interference patterns show that with an increase in the values of stresses σ_{xx}, the disturbance area around the point of pulse introduction also grows.

A current pulse was introduced into the area of the specimen being tested at the points n_i with the level of stresses σ_{xx} from –100 to 100 MPa (Figure 4). As a result of the local stress relaxation in the vicinity of the point of pulse introduction, displacements appeared, which were registered by the noncontact method of electron speckle-interferometry.

Figure 6 shows a diagram of dependence of the displacements u_x on the specified stresses σ_{xx}. This diagram shows that the measured displacements u_x at the points *A*, located at a distance of 1.25 mm from the place of the current pulse introduction (Figure 1), depend linearly on the stress state at the place of measurements.

However, the use of data on the displacements only at a point *A* is insufficient for calculating stresses σ_{xx} in real structures, since displacements will also arise at these points due to the action of stresses σ_{xx}.

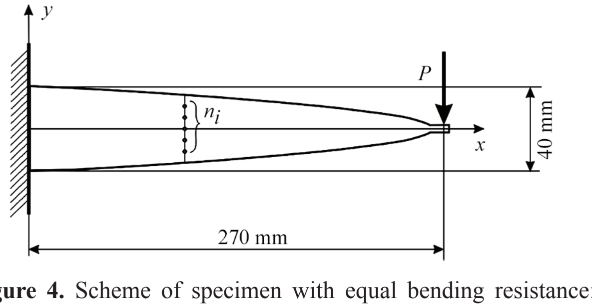

Figure 4. Scheme of specimen with equal bending resistance: n_i — points where a current pulse was introduced

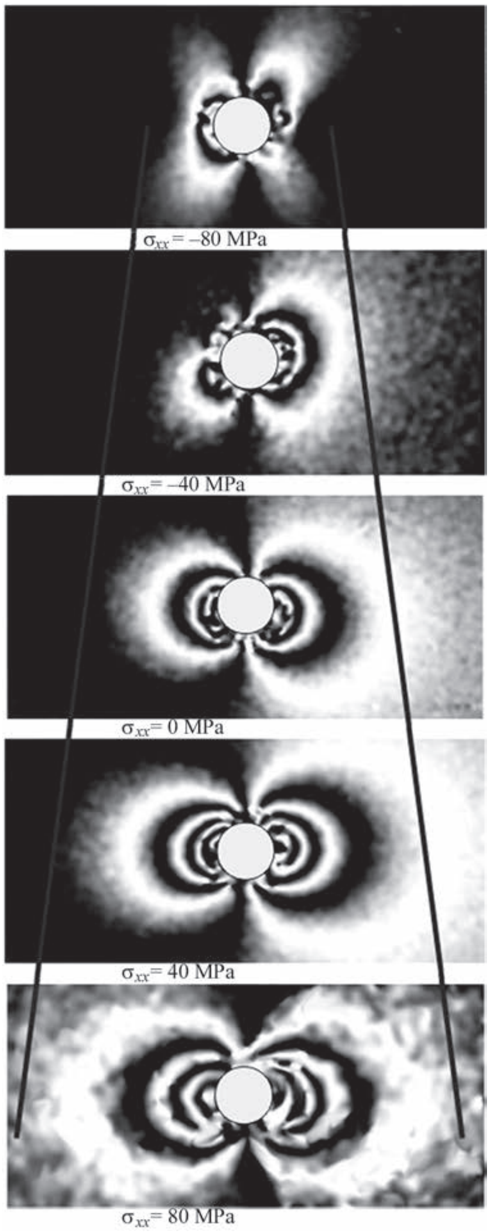

Figure 5. Interference patterns obtained after the introduction of a current pulse in the areas with a residual stress level. Electrode system parameters: $L = 3.26$ μH, $U = 150$ V, $s = 0.5$ mm. The lines indicate an increase in the zone of stress relaxation effect on the displacements with an increase in the stress state

Therefore, it is necessary to introduce a new parameter, that depends linearly on residual stresses and displacements and does not depend on the location of the main coordinate axes and the type of stress state.

NUMERICAL CALCULATIONS

We assume that upon the current pulse introduction, stress relaxation occurs in the region with the axis of *OZ* symmetry, as when drilling a hole. In this case, the dependence of the displacements u_r and u_θ, arising as a result of unloading the stresses σ_{xx}, σ_{yy} and σ_{xy} on the angle θ at some distance from the center of the hole *r* in polar coordinates, is expressed by the following formulas [11–13, 17]:

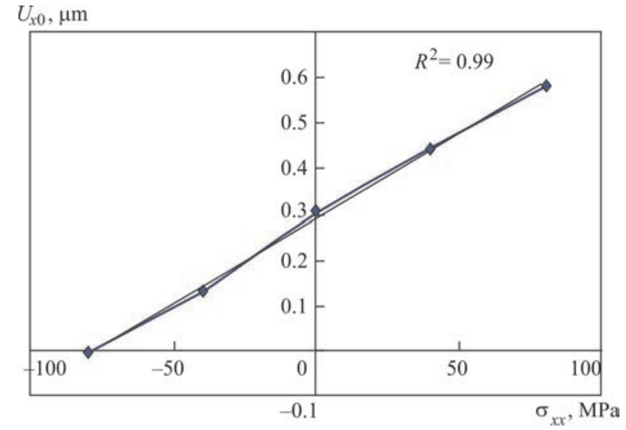

Figure 6. Dependence of displacements u_{x0} measured by the method of electron speckle-interferometry at a distance of 1.25 mm from the point of introduction of a high-density current pulse, on the level of specified stresses σ_{xx} (value of the approximation probability $R^2 = 0.99$)

$$u_r(r,\theta) = A\sigma_{xx} + B\sigma_{xx}\cos 2\theta; \quad (1)$$

$$u_\theta(r,\theta) = C\sigma_{xx}\sin 2\theta, \quad (2)$$

where the coefficients *A*, *B* and *C* depend on the boundary conditions, sizes of stress relaxation area, etc.

Considering that upon the introduction of a current pulse, complete stress relaxation does not occur, and also an initial effect (displacements arise after the introduction of a current pulse in a material without stresses) takes place, we introduce the following notations:

$$\sigma_{xx}^{im} = b_{xx} + k\sigma_{xx}; \quad (3)$$

$$\sigma_{yy}^{im} = b_{yy} + k_{yy}\sigma_{yy}; \quad (4)$$

$$\tau_{xy}^{im} = k_{xy} + \tau_{xy}, \quad (5)$$

where b_{xx}, b_{yy} i k_{xx}, k_{yy}, k_{xy} are the constants that characterize, respectively, the initial effect and the degree of stress relaxation compared to the drilled hole with a diameter and depth of 1 mm.

For a plane stressed state, using the principle of stress superposition and axisymmetric problem, after transforming the equations (1)–(2), we obtain:

$$\begin{aligned} u_r(r,\theta) &= A(\sigma_{xx}^{im} + \sigma_{yy}^{im}) + \\ &+ B\left[(\sigma_{xx}^{im} - \sigma_{yy}^{im})\cos 2\theta + 2\tau_{xy}^{im}\sin 2\theta\right]; \end{aligned} \quad (6)$$

$$u_\theta(r,\theta) = C\left[(\sigma_{xx}^{im} - \sigma_{yy}^{im})\sin 2\theta - 2\tau_{xy}^{im}\cos 2\theta\right]. \quad (7)$$

An important advantage of the electron speckle-interferometry method in registering displacements is the possibility of simultaneous determination of displacements in a large number of points. This makes it possible to obtain data on the displacements u_x at points located around a circle with a radius *r* with the center at the place of the current pulse introduction (Figure 7).

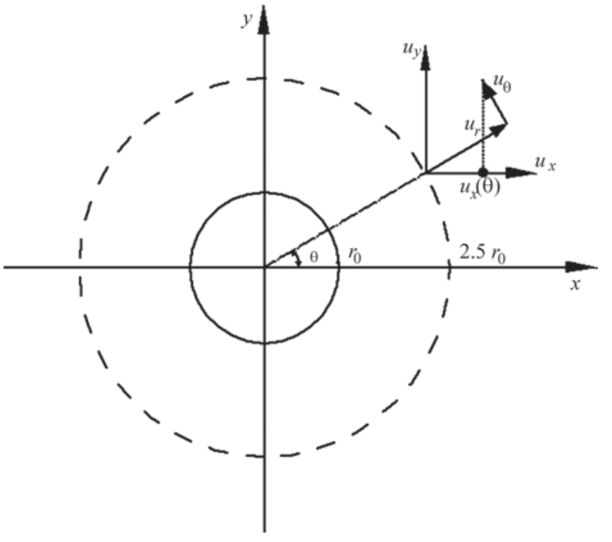

Figure 7. Scheme of displacement measurement in the vicinity of the point (place) of introduction of a high-density current pulse

As a result of preliminary studies, it was established that with the introduction of a current pulse when using different parameters of the electrode system, an electrode imprint with a diameter of 0.4–1.0 mm appears on the object. Therefore, the minimum radius of the circle is selected, in which the ratio "speckle pattern quality – displacement value" is optimal. It is known that when measuring displacements in the vicinity of a drilled hole by the method of electron speckle interferometry, it is optimal to use the distance r, which is equal to 2.5 of the hole radius r_0. Therefore, in the further studies, data on displacements at points located on a circle with a radius of 1.25 mm were used.

To simplify the calculations from the equations (6) and (7), let us separate the multiplier components $F(\theta)$, $G(\theta)$ and $H(\theta)$ before σ_{xx}^{im}, σ_{yy}^{im} and τ_{xy}^{im}, which depend on the angle θ and the coefficients *A*, *B* and *C*, we obtain the following dependence:

$$u_x(r,\theta) = u_r(r,\theta)\cos\theta - u_\theta(r,\theta)\sin\theta; \tag{8}$$

$$u_x(\theta)\big|_{\tau=1.25\text{ mm}} = F(\theta)\sigma_{xx}^{im} + G(\theta)\sigma_{yy}^{im} + H(\theta)\tau_{xy}^{im}. \tag{9}$$

Measuring their displacements u_x at the points of the circle (more than three points) allows calculating the values σ_{xx}^{im}, σ_{yy}^{im} and τ_{xy}^{im} by the method of least squares using a system of equations:

$$\begin{bmatrix} F(\theta_1) & G(\theta_1) & H(\theta_1) \\ F(\theta_2) & G(\theta_2) & H(\theta_2) \\ F(\theta_3) & G(\theta_3) & H(\theta_3) \end{bmatrix} \begin{Bmatrix} \sigma_{xx}^{im} \\ \sigma_{yy}^{im} \\ \tau_{xy}^{im} \end{Bmatrix} = \begin{Bmatrix} u_x(\theta_1) \\ u_x(\theta_2) \\ u_x(\theta_3) \end{Bmatrix}. \tag{10}$$

In order to evaluate the possibility of applying the proposed algorithm and using σ_{xx}^{im}, σ_{yy}^{im} and τ_{xy}^{im} in determination of residual stresses, let us build the diagram of dependence of σ_{xx}^{im} on the specified stress state σ_{xx} on the basis of the data on their displacements u_x presented in Figure 6. As in the case of the data on the displacements u_x (Figure 6), the dependence between σ_{xx}^{im} and σ_{xx} has a linear character (value of the approximation probability $R^2 = 0.99$). This diagram is characterized by the angle of inclination relative to the *OX* axis, as well as by the value at the point with zero stresses. From the diagram, it is possible to determine the values k_{xx} and b_{xx}, which correspond to the set parameters of the electrode system, and calculate the value of residual stresses at the point of the current pulse introduction by the formula (3).

Thus, in order to determine residual stresses in full-scale objects, it is necessary to perform preliminary calibration of the electrode system on the test specimen in order to obtain the dependence of σ_{xx}^{im} on σ_{xx} (3). To do this, stresses σ_{xx} are specified on a beam of equal bending resistance and a current pulse is introduced in the observation area of the speckle-interferometer. Based on the data obtained by the speckle-interferometry method on displacements of the surface points after the introduction of a current pulse into the metal being under the effect of mechanical stresses, the value σ_{xx}^{im} is calculated from the system

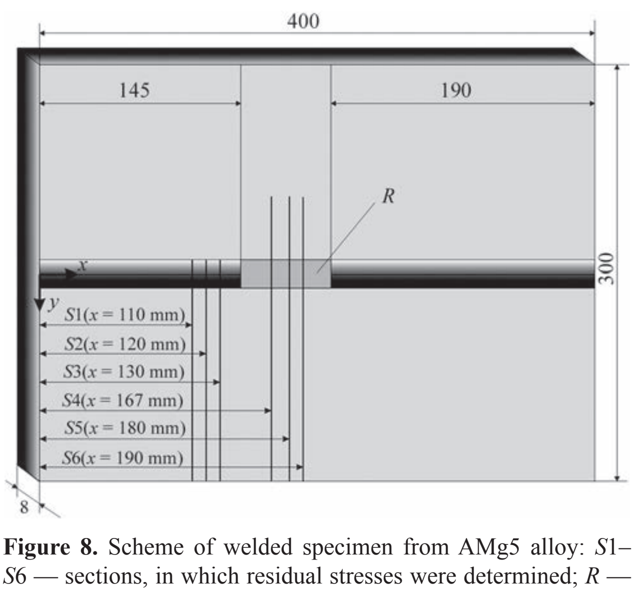

Figure 8. Scheme of welded specimen from AMg5 alloy: *S*1–*S*6 — sections, in which residual stresses were determined; *R* — area, in which the weld reinforcement was removed

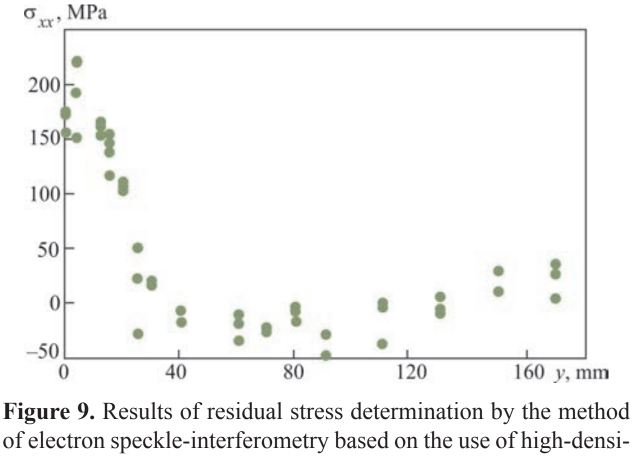

Figure 9. Results of residual stress determination by the method of electron speckle-interferometry based on the use of high-density current pulses for their relaxation

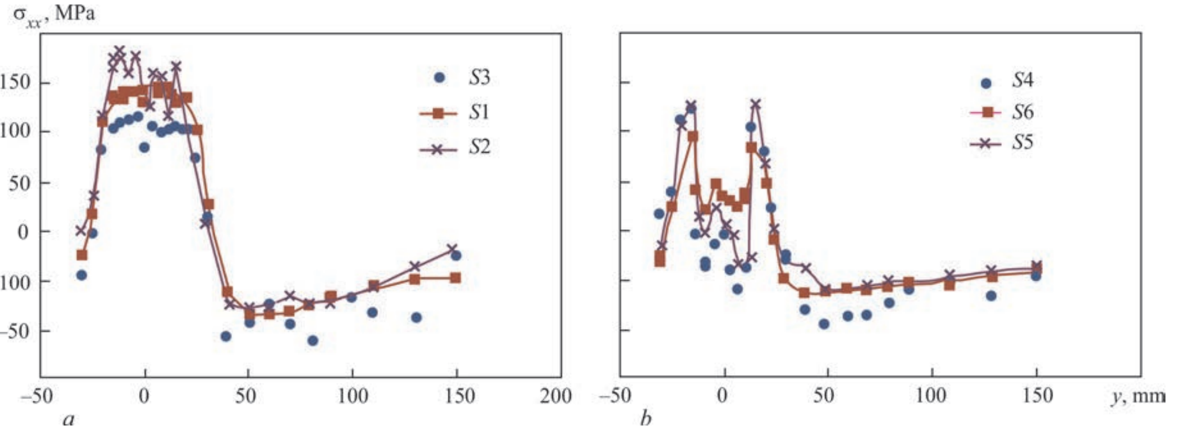

Figure 10. Distribution of stresses σ_{xx} passing through the weld reinforcement in the sections *S*1–*S*3 (*a*) and after its removal in the sections *S*4–*S*6 (*b*)

of linear equations (10). Based on the data of certain values σ^{im}_{xx} at five points, a diagram of dependence of σ^{im}_{xx} on σ_{xx} is constructed, according to which the values k_{xx} and b_{xx} corresponding to the parameters of this electrode system are determined.

Therefore, using the value σ^{im}_{xx} calculated on the basis of the data on the displacements registered by the method of electron speckle-interferometry, and the values k_{xx} and b_{xx} determined from the diagram and by the formula (3), it is possible to determine the stress state at the point of the current pulse introduction.

The use of functions σ^{im}_{xx}, σ^{im}_{yy} and τ^{im}_{xy} is better compared to the data on the displacements u_x at the points *A* and *B* (Figure 1), because in this case the use of information about the displacements u_x at the points along the entire length of the circle reduces the relative error and increases the reliability of determination of residual stresses.

EXPERIMENTAL STUDIES

With the help of the developed technology, the residual stresses in butt-welded joints of AMg5 alloy were determined based on the use of high-density current pulses. The results of stress measurements obtained using current pulses were compared with the data obtained with the use of the equipment of the PWI based on the use of the hole drilling method in combination with speckle-interferometry. The effectiveness and accuracy of residual stress measurement with this device is confirmed by the results of the Round Robin test, which was conducted by the International Institute of Welding [18, 19]. Figure 8 shows a diagram of the welded specimen with the specified cross-sections, along which measurements were made.

Figure 9 shows the results of residual stress determination using high-density current pulses along the section *S*3. In the experiment, data on the displacements were registered after the introduction of current pulses at the points located at the same distance from the center of the weld. The diagram shows that there is a scatter of the obtained experimental data and, therefore, to increase the accuracy of stress determination, it is suggested to use stress values averaged over three points.

Stresses were determined by two methods in the sections passing both through the weld reinforcement (*S*1, *S*2 and *S*3) as well as after its removal (*S*4, *S*5 and *S*6) (Figure 8). The results of residual stress determination obtained based on the use of the pulse method (sections *S*3 and *S*4) were compared with the data obtained by the method of drilling holes with a diameter and depth of 1.0 mm, respectively (sections *S*1 and *S*6) and 0.5 mm (sections *S*2 and *S*5) (Figure 10).

It is important that the results of stress determination in the area of the weld and the near-weld zone using the created nondestructive method are significantly closer to the data obtained by the hole drilling method (drilling holes with a diameter and depth of 0.5 mm), and differ from the data obtained when using holes with a diameter and depth of 1.0 mm (Figure 10.) This indicates that in the welded specimen there is a stress gradient over the thickness of the plates.

The stress curves show the coincidence of the results of residual stress determination obtained by the proposed approach and the hole drilling method, which indicates that the developed nondestructive method for residual stress determination based on the use of high-density current pulses for their relaxation allows obtaining reliable data on the distribution of stresses along the selected section, at the same time not violating the integrity of the studied material. The maximum deviation of the results of stress determination by the nondestructive method compared to the hole drilling method (drilled holes with a diameter of 0.5 mm) does not exceed 20 MPa.

CONCLUSIONS

A new nondestructive method for residual stress determination in welded joints has been developed, which is based on the use of high-density current pulses for local stress relaxation and subsequent registration of displacements by the laser speckle-interferometry method. It is shown that as a result of the introduction of current pulses, a partial relaxation of residual stresses occurs, and the value of measured displacements depends on the level of stresses at the place of pulse introduction. It was experimentally confirmed that the developed method allows determining residual stresses with an error of up to 20 MPa compared to the destructive method of drilling holes.

The proposed approach allows determination of residual stresses directly on real structures during their operation, without violating the material integrity. This opens up wide prospects to use the method for monitoring the stress-strain state of critical welded assemblies and structures in the power, aircraft and space rocket industries, shipbuilding, etc. The use of the proposed approach will increase the reliability and safety of the operation of technical objects due to the timely detection and elimination of dangerous stresses.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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