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CALCULATION-EXPERIMENTAL PROCEDURE FOR DETERMINING WELDING DEFORMATIONS AND STRESSES BASED ON A DIGITAL IMAGE CORRELATION METHOD

Volodymyr Korzhyk
Doctor of Technical Sciences, Head of Department,
Corresponding Member of the National Academy of Sciences of Ukraine
Department of Electrothermal Processing Material*
Vladyslav Khaskin
Corresponding author
Doctor of Technical Sciences, Leading Researcher**
E-mail: khaskin1969@gmail.com
Viktor Savitsky
PhD, Senior Researcher
Department of Optimizing of Advanced Welded Structures*
Illia Klochkov
PhD, Leading Researcher
Department of Strength of Welded Structures*
Viktor Kvasnytskyi
Doctor of Technical Sciences, Professor***
Andrii Perepichay
PhD, Senior Lecturer***
Sviatoslav Peleshenko
Postgraduate Student***
Andriy Grinyuk
PhD, Researcher
The E. O. Paton Research Institute
of Welding Technologies in Zhejiang Province (China)
Shixing Beilu str., 857, Xiaoshan District, Zhejiang, China, 311200
Andrii Aloshyn
Researcher**
Oleksii Shutkevych
Postgraduate Student, Engineer of the First Category
Department of Optimizing of Advanced Welded Structures*
*E. O. Paton Electric Welding Institute
of the National Academy of Sciences of Ukraine
Kazymyra Malevycha str., 11, Kyiv, Ukraine, 03150
**Guangdong Welding Institute (E. O. Paton Chinese-Ukrainian Institute of Welding)
Changxing Road, 363, Tian He, Guangzhou, China, 510650
***Department of Welding Technology
National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute»
Peremohy ave., 37, Kyiv, Ukraine, 03056

The object of this study is determining the stressed-strained state (SSS) of a welded article by applying quantitative non-destructive testing. The relevance of the study is associated with the need to devise a universal methodology for the non-destructive quantification of SSS using the simplest approaches and means of provision. To solve this task, an estimation-experimental procedure has been developed. This procedure is based on comparing digital stereo images of the individual sections (spatial primitives) of an article before and after its welding, followed by computer processing. To validate the developed procedure, the SSS of a cylindrical article made of aluminum alloy 7005, at the end of which two flanges were welded laserly with ring seams, was determined. It was established that after performing four diametrically opposed point tacks, the residual deformations of the ends of the article can reach 0.02–0.05 mm, and after performing continuous ring seams – to decrease to 0.01–0.02 mm. The calculation showed that the residual deformations of the end of the article after welding a ring seam are at the level of 0.02 mm, and the residual stresses in the same zone – in the range of 50–60 MPa. The deviation in the coincidence of residual deformations is in the range of 10–20 %, which is a satisfactory result and can be considered as an error in the results of determining SSS in general. Based on the developed methodology for determining SSS, an experimental industrial complex has been created that allows TIG and PAW to perform welding of objects from steels and alloys with the ability to determine the resulting stressed-strained state of these objects. The procedure devised and the equipment designed can be used for to non-destructively determine SSS of spatial structures made of steels and alloys

Keywords: stressed-strained state, non-destructive testing, digital correlation of images (DIC), laser welding

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1. Introduction

Aluminum alloys are widely used in modern industry, for example, in instrumentation, rocket and aircraft construction. Often these alloys are used to obtain welded structures, including in the form of sealed body articles with welded flanges. As a rule, such structures should have minimal or limited within certain limits residual deformations. It is also important to know the level of residual stresses remaining after welding, often performed in a variety of ways [1, 2]. There is a task of non-destructive testing of the residual stressed-strained state (SSS) to obtain quantitative results. It is relevant to devise a universal methodology for determining SSS using the simplest approaches and means of support.

2. Literature review and problem statement

One of the important tasks arising in the manufacture of welded structures is the need to determine their residual stressed-strained state (SSS). For the experimental measurement of the stressed-strained state, the most common is the use of electrotensometers [3, 4]. However, the use of non-contact optical methods for recording the deformation of the surface of objects under study makes it possible to obtain much more initial data that can be used in calculating the values of internal stresses [5, 6]. Thus, laser speckle interferometry allows one to perform high-precision measurements of movements [7, 8]. The limitation of this method is the need for preliminary drilling of holes on the surface under study, which makes this method acceptable if destructive testing is permissible. In most cases, preference is given to non-destructive testing, which requires the use of other procedures with similar accuracy.

To determine the stressed state, the method of digital image correlation (DIC) is increasingly used [9, 10]. This method has been developed by significantly increasing the quality and reducing the cost of digital cameras, as well as increasing the speed of computer technology. It is based on the calculated processing of the optical flow carrying information about the deformation of solids. Its action is based on the calculation of motion vectors and further calculation of deformation components using the numerical differentiation procedure [11]. The main advantages of DIC method are a sufficiently high accuracy associated with the resolution of the digital cameras used, as well as the absence of impact on the measured structure [10, 11]. The use of this method is becoming one of the most common approaches to the study of the processes of deformation and destruction of structurally inhomogeneous materials. A significant contribution to its development was made by the authors of works [12, 13].

When using the DIC method, comparing images determines the displacement fields taken at different points in the time of the experimen. At the same time, various strategies can be used to determine the displacement of subpixels [13]. Various researchers are developing new identification procedures using measurements of the entire field, which can be both a priori and a posteriori. Thus, work [14] proposes a DIC method using the iterative least squares algorithm (ILS) to measure the displacement field and a pointwise least squares algorithm (PLS) to measure the strain field. From the standpoint of the effectiveness of the application of algorithms of numerical methods, this approach is not the best and loses to the finite-element algorithm.

Hardware and software complexes, the principle of operation of which is based on the correlation of digital images, are commercially distributed [15, 16]. Such commercial systems include the software by Correlated Solutions Inc. (South Carolina, USA) (system VIC 3D), LaVision GmbH (Göttingen, Germany) (StrainMaster system), etc. These complexes, as a rule, are equipped with standard optical systems, the calibration of which is carried out before the experiment depending on the conditions of video (photo) observation. However, the computer code supplied as part of such systems is closed, which does not make it possible to effectively solve a number of applied problems. Therefore, individual research teams are engaged in the development of their own software and algorithmic solutions, as well as the development of hardware for studying the processes of deformation and destruction. One of the promising approaches to determining the deformations and fractures is the calculation of standard parameters based on a DIC method [15, 16].

Compared to interference optical methods used to measure flat deformation, the DIC method has the following advantages:

1) simplicity of experimental installation: the mandatory use of coherent radiation sources and phase-shifting optoelectronic components is not required;

2) minimal surface preparation of the object under study: no preliminary surface preparation is required (if the natural surface of the object has a random distribution of gray intensity). If necessary, it is possible to create artificial speckles, for example, by spraying paint on the surface of the object under study and in other ways;

3) low requirements for lighting conditions: unlike widespread interference methods, DIC does not require a highly coherent laser source. A white light source or natural light can be used for illumination during loading. Thus, the method can be used under both laboratory and industrial conditions;

4) wide range of measurement sensitivity and resolution: since the DIC method processes digital images, it can be directly applied to images obtained by different optical instruments.

Thus, to determine the residual deformations of articles, after welding them, a fairly simple universal method is needed. Such a method should show a quantitative picture of residual deformations and stresses on the surface of the entire article. To do this, it is necessary to devise appropriate procedure and to design equipment for its implementation. It is advisable to base this procedure on measuring the movements of surface points of objects under study by the method of three-dimensional correlation of digital images (Stereo-DIC).

3. The aim and objectives of the study

The aim of this work is to devise a procedure and to design equipment for the quantitative non-destructive determination of residual deformations and stresses in the elements of welded structures of various shapes and configurations. This will make it possible to fairly easily determine the residual deformations of articles after their welding, performed in almost any way.

To achieve the set aim, the following tasks have been solved:

– to devise a technique for determining the deformed state of an article after its welding by processing digital stereo images;

– to devise a procedure for calculating residual deformations and stresses in a welded article according to welding modes;

– to test the developed procedure on the example of laser welding of a cylindrical article from alloy 7005 with sealing seams;

– to develop a hardware system for determining the stressed-strained state of welded articles.

4. The study materials and methods

The object of our research is the stressed-strained state (SSS) of the welded structure or article, which is established at the end of the welding process. The main hypothesis of the research is the possibility of simplifying the problem of non-destructive testing of quantitative SSS indicators by dividing the welded structure into separate spatial primitives in which the movement of objects is determined by the Stereo-DIC method. At the same time, we accept the following as the main assumption. Deformations are determined both empirically (by moving individual sections of the article surface) and by calculated techniques. Residual stresses are determined by a calculation method. Comparison of calculated and measured deformations makes it possible to determine the error of calculations and, if necessary, to enter a correction factor into the calculations.

The following methodology for determining SSS of welded structures (objects) was adopted:

1) fixing an object in the appropriate device and preparing for the welding process;

2) recording a digital image of the welded surface of the object before welding is performed in an undeformed (or initial) state;

3) recording a digital image of the surface of the object after welding is performed in a deformed (or final) state;

4) processing of the obtained images by the Stereo-DIC method using the original software, as well as obtaining the required data on movements (residual deformations);

5) based on data on welding modes, as well as measured movements of surface points, performing predictive calculations and predicting the distribution and values of residual stresses using the original software.

As a study object, an article was used, which is a hollow cylindrical body with a size of ∅40×50 mm, into which lids with a diameter of 38 mm were welded from two ends. The thickness of the walls of the article is about 1.5 mm, the material is the high-strength aluminum alloy 7005 (AlZn4.5Mg1.5Mn). Case lightweight articles of this type are used in instrumentation and aerospace industry. Welding was carried out with non-through ring seams, the depth of the weld was about 0.5 mm. To perform such seams, high-speed laser welding in argon protection was chosen, minimizing residual SSS.

A laboratory bench was designed to register images by stereo-DIC and their subsequent processing (Fig. 1). The bench included digital cameras with a mounting system, a light source for the object under study, as well as the object itself, fixed in the appropriate tooling. Information from high-resolution digital cameras was sent to a computer with the original software, with which it was processed.

At the first stage, a random speckle pattern was applied to the studied surfaces of the object to obtain a high-quality contrast image with an arbitrary distribution of gray intensity over the surface of the object. This speckle pattern will be further distorted along with the surface of the object when it is deformed. The speckle pattern was applied manually using a marker, a special stamp or spray, depending on the size of the study area. Another approach to applying the speckle pattern was also used – spraying fine powder after welding. It should be noted that in some cases, the natural structure of the surface of the object can serve as such a pattern.

Fig. 1. Laboratory bench for measuring movements by a Stereo DIC method: 1 – digital cameras; 2 – lenses; 3 – calibration plate; 4 – the place of installation of the object under study

At the second stage, the optical stereo system was calibrated, the parameters of the lenses were determined, the mutual position of digital cameras that focused on the surface of the studied ends of the object before welding. After that, images that correspond to the initial position of the ends were entered into the computer for their preliminary digital processing.

Further, at one of the ends, four auxiliary points – tacks – were welded. At the third stage, the first examined surface of the object was first photographed after welding the tacks and after welding the ring seam. Then the procedures for welding the tacks and the ring seam were repeated for the second end, after which the second examined surface of the object was photographed. Owing to the laboratory bench, shown in Fig. 1, each time for DIC measurements after welding, the sample was installed in the same position.

In the fourth step, the algorithm shown in Fig. 2 was used to determine displacements by the DIC method. According to this algorithm, the same areas of the initial (initial) and final images are selected, characterizing the state of the surface of the object under study. Correlation parameters of image data are calculated, according to which the mutual displacement of one section of the image (final) from another (initial) is determined. Repeating this procedure for all areas of the surface (or along a certain direction) makes it possible to get two-dimensional fields of movement on the surface of the object that arose between the two exposures for each digital camera.

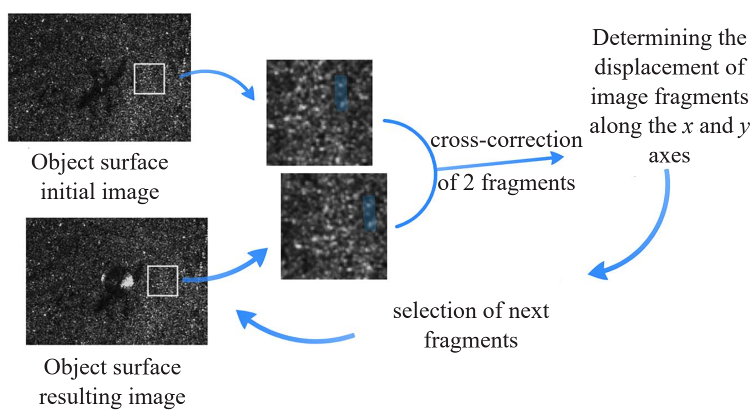


Fig. 2. Algorithm for determining movements by the method of digital image correlation (DIC)

In the fifth step, calculations were performed to predict the distribution and values of residual stresses. For this, the following algorithm based on the calculation methodology was used (Fig. 3):

– selection of the initial physical and mechanical properties of the welded article, based on its material and geometry;

– selection of one of the three welding processes under study (laser, microplasma, or hybrid) and the parameters of its mode;

– calculation of thermal fields during welding and at the end of the process, performed on the basis of mode parameters;

– calculated determination of residual welding deformations;

– comparison of residual welding deformations determined by the calculated method with deformations measured in the fourth stage;

– determining the error and, if necessary, the introduction of a correlation coefficient in further calculations;

– calculated determination of residual stresses on the scale of the entire article.

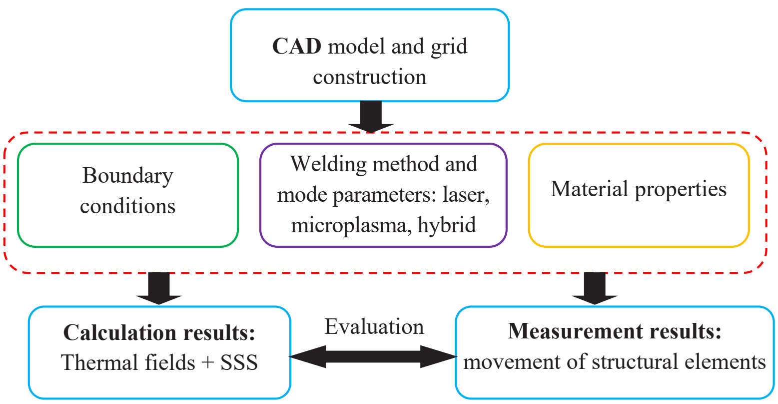


Fig. 3. Algorithm for determining residual stresses

5. Results of studies of residual stresses and deformations in the welded cylindrical article

5. 1. Devising a technique for determining the deformed state of an article after its welding by processing digital stereo images

Using the DIC method, displacements in the entire study area are directly calculated by comparing digital images of the object in the undeformed (or initial) and altered states, respectively. Standard methods for correlating digital images involve determining the displacement of image areas by an amount from one pixel of a digital camera. In this case, the sensitivity of the DIC method is determined by the ratio:

$$\delta u = \frac{\Delta x}{mx} = \frac{\Delta y}{my}, \quad (1)$$

where Δx and Δy are the physical dimensions of the rectangular surface area of the object under study, which is registered with the camera, in the image, mx and my are, respectively, the number of pixels of the sensor (matrix) of the digital camera.

The DIC algorithms used by IC-GN allow one to measure movements with an accuracy of at least 0.01 pixels.

5. 2. Development of a methodology for calculating residual deformations and stresses in a welded article according to welding modes

Any welding process results in residual stresses and deformations that can significantly affect the quality and mechanical strength of the part. Numerical simulation is an additional tool to experimental methods that can be effectively used to optimize welding processes. With this approach, the welded article is described using a finite-element model, the behavior of which is determined by taking into consideration changes in the nodes of the elemental grid covering the article.

To solve the problem of determining the stressed-strained state, the finite-element model is transformed into a system of equilibrium equations by sampling. The task of coherent thermoelastic analysis depends on the «history» of thermal heating of the welded article. The system of equilibrium equations is solved in a series of small increments from the beginning of the welding process to the cooling of the welded joint to the ambient temperature. Each increment includes the calculation of increments of nodal displacements using the Newtonian iteration method. At the end of each iteration, the variables of the deformation and stress states are updated, the residual force is calculated, and the specified tolerance is compared. It is assumed that the equilibrium solution converged if the absolute maximum of all residual forces is less than the user-set tolerance. During the initial iteration of each increment, the stiffness matrix of the material is calculated according to elastic behavior, regardless of whether plastic deformation occurred in the previous increment. The advantage of this method is that the convergence of the solution is achieved in fewer iterations. If plastic deformation occurs during increment, subsequent iterations use a matrix of elastic-plastic stiffness specified by the properties of the material model used.

It is assumed that the model of plasticity with kinematic hardening characterizes the behavior of the metal. Kinematic hardening is the simplest theory that can model the inverse plasticity and the Bauschinger effect [17] that are expected to take place in a welded joint. The basic concept of the kinematic hardening model is that the fluidity surface shifts in the stress space in such a way that tensile strain reduces the yield strength during compression, and vice versa. For $f(\sigma_{ij}-\chi_{ij}) \leq \sigma^y$:

$$\dot{\varepsilon}^p_{ij} = \frac{3}{2}K(\theta) f\left(\sigma_{ij}-\chi_{ij}\right)^{n(\theta)-1}\left(s_{ij}-\chi_{ij}\right), \quad (2)$$

$$\dot{\chi}_{ij} = H(\theta)\dot{\varepsilon}^p_{ij} - C(\theta) f\left(\chi_{ij}\right)^{p(\theta)-1}\chi_{ij} + \frac{1}{\bar{\sigma}}\frac{\partial\bar{\sigma}}{\partial\theta}\chi_{ij}\dot{\theta}, \quad (3)$$

where f represents the Von Mises function $\bar{\sigma} = \sigma(\varepsilon_{eff,\theta}) - \sigma^y(\theta)$, σ is the stress on the tensile curve, σ^y is the yield boundary, ε_{eff} is the strain hardening parameter, θ is the temperature, K is the hardening coefficient, n – the indicator of sensitivity to the deformation rate, s_{ij} – stress deviator tensor, χ_{ij} – internal component tensor, $H(\theta)\dot{\varepsilon}^p_{ij}$ – kinematic hardening duration, $C(\theta)f(\chi_{ij})^{p(\theta)-1}$ – viscous reduction duration [18].

The total deformation $\dot{\varepsilon}$ of the welded article is defined as:

$$\dot{\varepsilon} = \dot{\varepsilon}^e_{ij} + \dot{\varepsilon}^p_{ij} + \dot{\varepsilon}^{th}_{ij}, \quad (4)$$

where $\dot{\varepsilon}^e_{ij}$ is the elastic deformation, $\dot{\varepsilon}^p_{ij}$ – plastic deformation, $\dot{\varepsilon}^{th}_{ij}$ – creep deformation. Creep deformation is neglected on the grounds that high temperatures exist only for a very short period of time during welding.

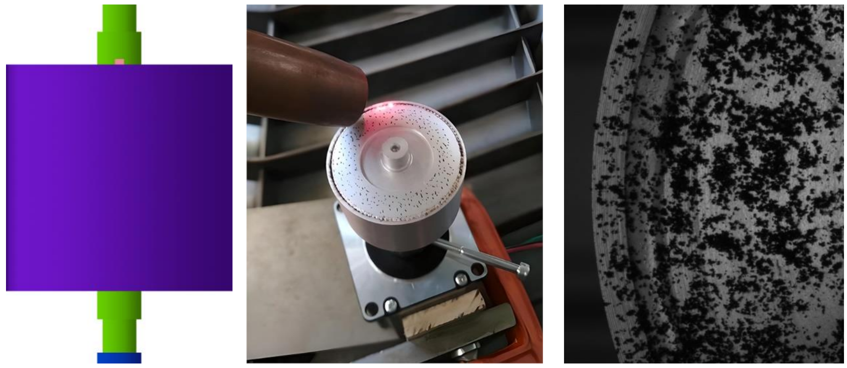
Thus, the proposed calculation methodology is based on dependences (2) to (4) and makes it possible to obtain SSS data on the welded object. The calculated data are compared with the experimental results obtained by photofixation of the state of the object before and after welding at a sensitivity determined by dependence (1).

5. 3. Verification of the developed procedure on the example of laser welding of a cylindrical article from alloy 7005 with sealing seams

We verified the developed hardware and software by conducting an experiment on laser welding of a hollow cylindrical article with a size of ∅40×50 mm from aluminum alloy 7005 (Fig. 4). The welding speed was 4 m/min with a fiber laser radiation power of 400 W. First, the article was assembled by inserting both welded lids into the seats of the case. Then, for one of the lids, four tack points were welded, located diametrically opposite. The radiation power when performing point tacks was 500 W, the action time was 0.2 s. After that, the lid was welded with a sealed ring seam with the docking of the initial and final sections. At the end of welding one side of the cylindrical article, we proceeded to welding the second side, which was performed similarly.

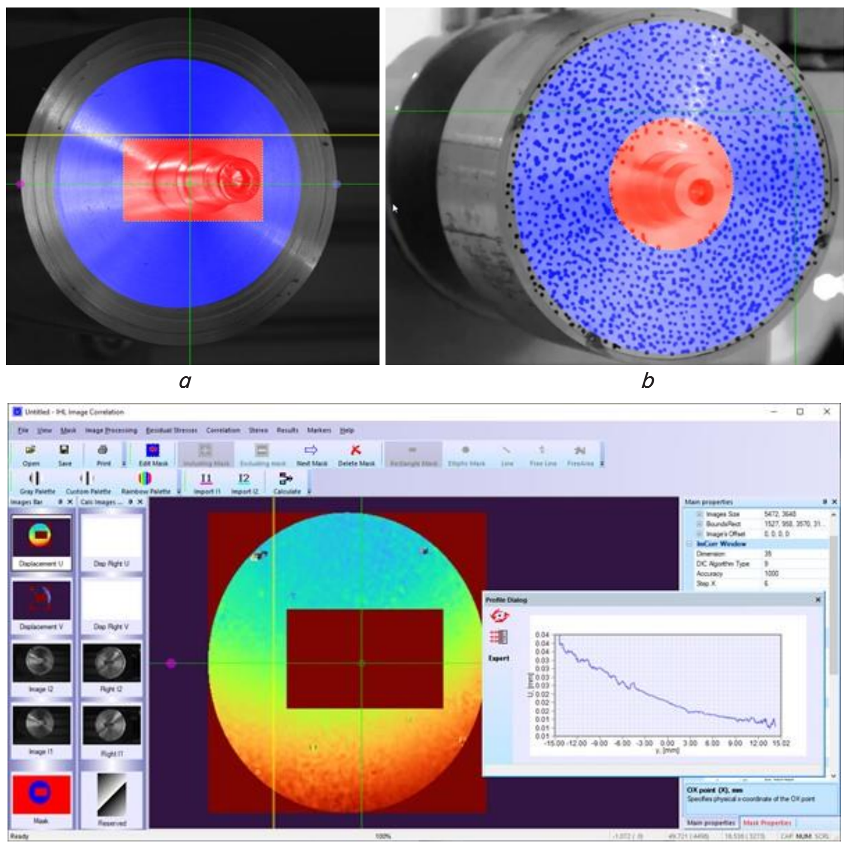
Photographing of the welded sample on each side was performed in 3 steps: before welding, after welding point tacks, and after welding a continuous ring seam. Before photographing, a speckle pattern was applied to the studied surfaces in the form of randomly arranged black dots. After the second and third techniques of photographing the corresponding of the welded sides, programmatic processing of the compared images was performed (Fig. 5). To do this, the original software for determining the deformed state of the article after its welding by the DIC method was used.

Based on the results of software processing of photographic images, general patterns of residual deformations (movements) were obtained with a quantitative indication of the deviation from the basic (initial) position (Fig. 6).



a *b* *c*

Fig. 4. Welding the lid to the cup (material – alloy 7005): *a* – welded part (side view); *b* – a fragment of a welding bench with a welded part; *c* – a fragment of the weld (a contrasting speckle pattern is visible near the seam)



a *b* *c*

Fig. 5. Processing of the obtained digital images: *a* – the area (highlighted in blue) in which movements were measured by the DIC method after welding; *b* – an area with an artificially applied with the help of ink stamps (highlighted in blue) speckle pattern, in which movements were measured and three-dimensional coordinates of surface points were calculated by the Stereo-DIC method; *c* – software interface with the measurement results of the components of the displacement tensor along the vertical section relative to one of the digital cameras

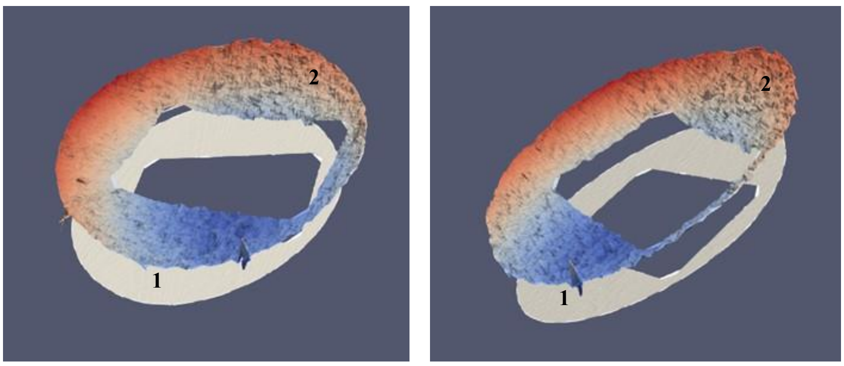
It was found that the greatest residual deformations are observed after welding spot tacks. The magnitude of the deformations, in this case, reached 0.02–0.05 mm, despite the fact that the point tacks were performed diametrically opposite with a radiation power of up to 500 W for 0.2 seconds each. After laser welding of the ring seam, the value of residual deformations decreased slightly – to 0.01–0.02 mm.

Determining the residual stresses was carried out by the calculation method, based on the flow curves of the materials under study and the values of residual deformations. For this, according to the above-described methodology for calculating SSS prediction, based on the parameters of the modes of the corresponding welding methods, the temperature heating fields of the welded article were determined. According to the calculated distribution of temperature fields in the welded article, the values of movements of the elemental grid were determined. That made it possible to calculate the residual stresses in the welded structure (Fig. 7). The calculation showed that the values of the residual deformations of the end of the article after welding the ring seam are at the level of 0.02 mm, and the residual stresses in the same zone are in the range of 50–60 MPa. At the same time, in the seam zone, the stress can reach up to 200 MPa, and in ZTV – from 70 to 150 MPa. At the same time, deformation deviations introduced by pre-made welding points, tacks (about 0.01 mm), almost do not affect the level of residual stresses.

To determine the error of the calculation method, the results of residual deformations obtained experimentally using the DIC method (Fig. 6, *a*) were compared with the results calculated using the SSS calculation prediction method (Fig. 7, *c*).

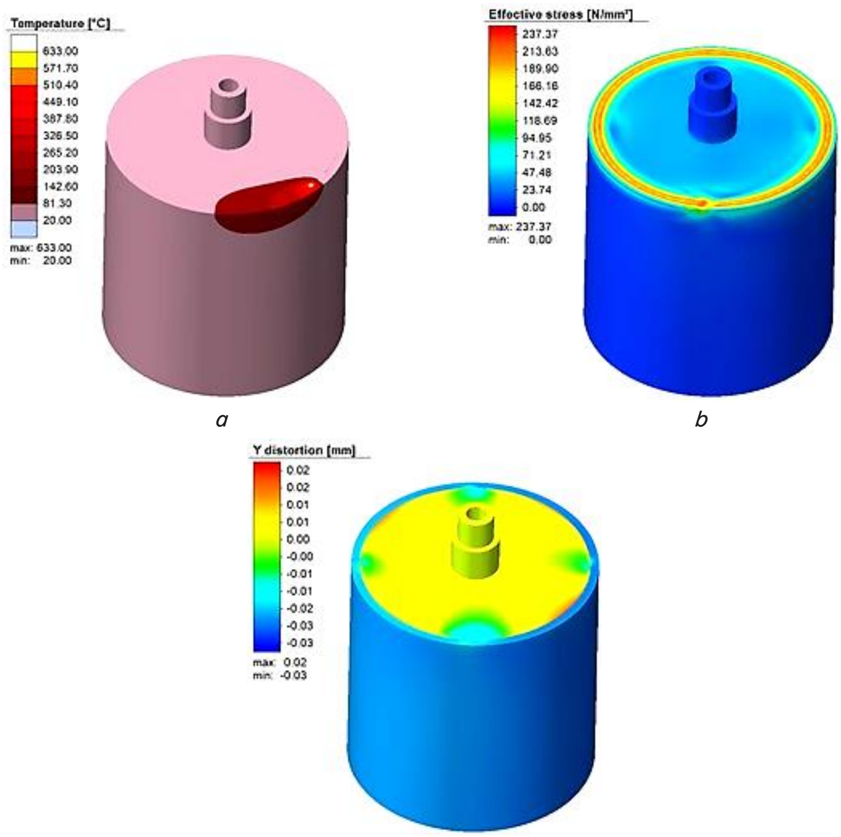
In the example considered, the values of residual deformations coincided (0.02 mm in both cases).

A more detailed study of other samples showed that the deviation in the coincidence of residual deformations (error of calculations) is in the range of 10–20 %, which is a satisfactory result.



a *b*

Fig. 6. Results of determining the deviations of the position of the welded lids of the cylindrical sample from their original position: *a* — the side welded first; *b* — the side welded by the second; 1 — basic arrangement; 2 — position after welding of the ring seam



c

Fig. 7. Calculation results: *a* — temperature fields; *b* — the Misesian residual stress fields; *c* — fields of residual movements (taking into consideration 4 diagonal tacks)

5. 4. Designing a hardware system for determining the stressed-strained state of welded articles

To verify the developed methodology for measuring SSS of welded articles, a pilot industrial complex was designed, including welding and measuring systems (Fig. 8). As a welding system, a 3-D manipulator was used, which provides the possibility of welding with interchangeable heads. This makes it possible to implement two welding techniques: with a non-consumable electrode (TIG) [19] and plasma arc (PAW) [20].

Fig. 8. General view of the set of equipment for welding and determining the residual deformations by the DIC method: 1 — manipulator control panel; 2 — replaceable welding torch; 3 — high-resolution cameras (2 pcs.); 4 — manipulator for performing the welding process; 5 — plasma module; 6 — specialized power supply for TIG and PAW welding; 7 — cooling unit of the welding torch; 8 — equipment rack

The measuring system consists of hardware and software parts of our original design. Hardware includes:

– 3D-manipulator to perform the process of welding and photographing the object;

– remote control of this manipulator;

– a set of two interchangeable welding torches;

– specialized power supply for TIG and PAW welding;

– plasma module, cooling unit of the welding torch;
– two high-resolution digital cameras;
– equipment rack;
– a laptop with original software.

The software includes modules for calculating movements from the images of the initial and final state of the surface of the objects under study and performing predictive calculations of the stressed state of these objects.

The use of a set of equipment is as follows. On the movable carriage of the manipulator (coordinate *Z*), a welding torch is fixed. The torch is chosen depending on the welding process being implemented: a torch for TIG or a plasma torch for PAW. On working table of the manipulator, the sample under study is placed. With the help of two high-resolution cameras, it is photographed. Then, using the control panel, the modes of the selected welding method are set and the welding itself is performed. In the process of TIG welding, only a specialized power supply is involved. In the PAW process, a specialized power supply and a plasma module are involved. Cooling of the welding torch is carried out using a cooling unit. After welding, two high-resolution cameras are used for a second photographic session of the already welded sample. On a computer (with an operating system not lower than Windows 10), two photos are compared using a set of the software modules described above, made before and after welding. At the same time, the magnitudes of the movements of individual points are determined, according to which the residual deformations of the entire sample are calculated. Then, taking into consideration the welding modes, SSS is calculated.

6. Discussion of results of the study of non-destructive determination of the stressed-strained state of a welded article

The experimental and calculated results obtained in the course of our research showed the distribution of temperature fields, as well as fields of deformation and stress after welding. Comparison of the relevant calculated data with the measured displacements suggests that the accuracy of the method is satisfactory. This can be achieved by the applied system of location of digital cameras, as well as the algorithms used to calculate movements from stereo image data. This combination of hardware and software design has proven useful to achieve the goal of our work. The applied specialized equipment for basing the welded article and the fully automated process of photography made it possible to achieve a fairly high accuracy of the results.

In contrast to the modified incremental algorithm proposed in work [11] for determining movements on a series of stereo pairs of images, the algorithm proposed in this work is simpler. By calculating the increments of nodal movements according to the Newtonian iteration method and reducing the number of iterations, the proposed finite-element algorithm provides higher accuracy with lower requirements for the resource of computing equipment.

Determining the sensitivity of the DIC method (1) makes it possible to ensure that this method has sufficient accuracy in measuring the movements and deformations that occur after welding of articles. In the case of obtaining a noisy and heterogeneous deformation pattern, it is necessary to ensure the formation of a chaotic spotted structure on the images of the surfaces of the samples under study. To this end, it is possible to use such methods of surface preparation as its mechanical treatment, application of clearer patttern, spraying finely-dispersed powders, etc. In our example, the state of the surface before welding was sufficient to apply digital image correlation algorithms and calculate 2D displacements relative to each of the digital cameras. To establish the coordinates of the surface points of the welded elements, it was necessary to apply an additional chaotic speckle pattern. Such a pattern was applied using ink stamps, which applied dots to the surface of the article before welding (Fig. 5, *b*), as well as spraying fine powder on an already welded surface (Fig. 4, *c*). A more effective approach was the option of spraying the powder after welding since it provided less effect on the welded material.

When performing calculations using dependence (4), the values of the deformation of the welded article $\dot{\varepsilon}$ were calculated, according to which the residual movements of the surface after welding were determined. The obtained values were compared with the residual movements measured by comparing digital images of the object before and after welding (Fig. 5, *a*, *b*). Based on the results of the comparison of calculated and measured movements, the error of calculations was determined.

Comparison of the residual movements determined by the Stereo-DIC method and the calculated residual movements makes it possible to establish the accuracy of measuring not only the deformations (Fig. 7, *c*) but also to assess the stressed state of the object (Fig. 7, *b*). In addition, in order to improve the accuracy of the results obtained by the numerical method, it is proposed to introduce correction coefficients based on determining the difference in movements by both methods, and then make an adjustment to the calculation method. This technique will contribute to improving the accuracy of the calculated prediction of residual stresses after welding.

The designed hardware system for determining the stressed-strained state of welded articles makes it possible to measure movements from 1 μm or more. Its distinctive features are the simplicity and availability of the equipment used, as well as the possibility of using both special (for example, diode) and ordinary (for example, natural) lighting. To prepare the surface of the object under study, it is necessary to carefully examine it. The purpose of this examination is to choose the best method of applying a speckle pattern before or after welding. This procedure can be carried out using the simplest marking tool such as an ink stamp or a more complex one that makes it possible to spray fine powders.

Our experimental studies and numerical modeling showed a good coincidence of the results, which indicates the correctly selected parameters of the mathematical model used, as well as the measuring system used, to estimate welding stresses and deformations.

Owing to the use of three-dimensional digital image correlation, the developed method is quite simple and universal. It makes it possible to determine the quantitative picture of residual deformations and stresses on the surface of the entire article with acceptable accuracy, which makes it relevant for industrial use. The main limitations of the devised method include the need for special treatment of the measured surface to obtain a chaotic speckle pattern on it. Such processing can be carried out both before and after welding. For it, ink stamping, spraying fine powders, etc. can be used.

Further development of this study is to adapt the devised methodology for the processes of welding with a non-consumable electrode (TIG) and a plasma arc (PAW) using the equipment designed. Also of interest is the study of SSS of other arc welding processes. Experimental studies of changes in the SSS of articles when using traditional arc welding processes will expand the possibilities for further industrial use of the devised procedure and designed equipment.

7. Conclusions

1. A technique for determining the deformed state of a welded article by comparing its digital stereo images before and after welding with subsequent computer processing has been developed. As a light source when photographing the article, natural (workshop) or specialized diode lighting can be used. The technique makes it possible to determine deformations of 1 μm or more with high accuracy using simple and affordable equipment. At the same time, the preparation of the surface of the object under study is minimal and may involve applying a chaotic speckle pattern. Suppose the option of spraying a finely dispersed powder on the surface under study after welding.

2. A combined computational and experimental procedure for determining residual deformations and stresses in a welded article according to welding modes has been devised. The technique is based on the division of the welded structure into primitives, determining the residual deformations of the primitives of the welded article by the method of digital correlation of images that are obtained before and after welding, as well as the calculated determination of residual deformations of the same primitives. Residual stresses in individual primitives and in the article as a whole are determined by the calculation method. Comparison of experimental and calculated results makes it possible to determine the error and, if necessary, to introduce a correction factor to determine the residual stresses.

3. We verified the developed procedure on the example of laser welding of end flanges to a cylindrical article made of alloy 7005 with two ring seams with preliminary execution of spot welding tacks. It was established that after performing four diametrically opposite tacks, the residual deformations of the ends of the article can reach up to 0.02–0.05 mm, and after performing continuous ring seams – decrease to 0.01–0.02 mm. The values of the residual deformations of the end of the article after welding the ring seam are at the level of 0.02 mm, and the residual stresses in the same zone are in the range of 50–60 MPa. At the same time, in the seam zone, stresses can reach up to 200 MPa, and in the ZTV – from 70 to 150 MPa. Deformation deviations introduced by pre-made point tacks (about 0.01 mm) have almost no effect on the level of residual stresses. The error in determining SSS did not exceed 20 %.

4. On the basis of the developed techniques for experimental and calculated determination of SSS, a pilot industrial equipment complex was designed. It allows for TIG and PAW welding of objects from steels and alloys with the ability to determine the resulting stressed-strained state of these objects.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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