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NON-DESTRUCTIVE EVALUATION OF RESIDUAL STRESSES IN WELDED JOINTS ON THE BASE OF A COMBINATION OF ULTRASONIC TESTING AND SPECKLE-INTERFEROMETRY

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ABSTRACT

It was found that a combination of the advantages of ultrasonic testing and electronic speckle-interferometry in the case of elimination of their disadvantages is the base for development of the method of non-destructive evaluation of residual welding stresses in full-scale structures. A procedure of non-destructive evaluation of the distribution of residual tensile welding stresses in the weld zone of a butt welded joint was developed. It is based on a simultaneous application of ultrasonic testing and electronic speckle-interferometry and fulfillment of the condition of "area equality" of the epures of balanced compressive and tensile residual stresses. The procedure was proposed for the application on specimens of single-pass welded joints of thin-sheet constructions from metallic materials with a stable structure. The subject of the study is tensile residual welding stresses in a MIG-welded specimen of a butt joint of structurally stable 1561 aluminium alloy. Residual welding stress σ_x component longitudinal relative to the weld was evaluated in the plate central area. It was found that the discrepancy of the values of residual welding stresses near the center of the welded joint of 1561 aluminium alloy is equal to approximately $0.1\sigma_{0.2}$ for this material, which corresponds to the claimed accuracy of the methods. Based on the research results, a range of procedures was proposed for the non-destructive evaluation of the residual welding stresses in full-scale welded structures, based on a combination of ultrasonic testing and electronic speckle-interferometry.

KEYWORDS: residual welding stresses, ultrasonic testing (UT), electronic speckle-interferometry (ESPI), butt joint specimen, MIG welding, compressive and tensile testing, longitudinal component of stresses, aluminium alloy, procedure of non-destructive evaluation of stresses

INTRODUCTION. RELEVANCE AND AIM OF THE WORK

Residual welding stresses (RWS), arising after welding in structural elements, are one of the factors that determine the strength, reliability and service life of products. For engineering practice, the development and improvement of experimental methods for stress determination, which are divided into two groups — destructive and non-destructive, are traditionally relevant [1].

Destructive methods are based on the measurement of deformations occurring when a welded structure element is completely or partially destroyed. They are quite common in scientific research. However, the use of destructive methods is not always appropriate for high-cost full-scale products and structures being in operation. Therefore, in engineering practice, non-destructive methods for RWS evaluation are used, during implementation of which, an examined structure remains undamaged. This is the main advantage of non-destructive methods over destructive ones.

Among non-destructive methods, the most famous are X-ray, magnetic and ultrasonic (UT-method) [2]. The latter is currently used both in the industry of Ukraine and abroad to measure residual stresses averaged over the thickness of the material [3–5]. However, for the correct evaluation of RWS, the UT-method has certain limitations related to the peculiarities of welded joint formation. Thus, the zone of tension (active) of RWS in the weld and in the area around it is formed by the field of plastic compression deformations, the values of which are characterized by a rather high gradient. A reliable evaluation of components of the plane stress state when applying the UT method, based on the propagation of elastic waves in metallic materials, is possible only in the field of elastic stresses [1]. In the zone of tensile RWS, formed as a result of plastic deformation of the weld metal and near-weld zone during shrinkage of the deposited metal,

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Table 1. Characteristics of RWS evaluation methods

Number	Method of RWS determination/Availability of standard	Thickness of metal with RWS δ, mm	Base of measur. B, mm	Accuracy of the method	Advantages of the method	Drawbacks of the method
1	ESPI-method/DSTU 8852:2019	≥2	1.0	$\pm 0.1\sigma_{0.2}$ in all areas of RWS	1. It is possibile to register RWS on the surface of metal and membrane. 2. It is possibile to register RWS on the base of $B_{\text{ESPI}} = 1$ mm.	1. Local surface damage while drilling. 2. Difficulties in drilling solid materials.
2	UT method/none	≥3	10.0	$\pm 0.1\sigma_{0.2}$ in the zones of joints, where the values of elastic-acoustic coefficients were experimentally determined	1. There is no need to destroy metal during RWS registering. 2. It is possibile to apply the method on full-scale structures.	1. It is impossible to obtain RWS on the metal surface. 2. Averaging of RWS on the base of measuring $B_{\text{UT}} = 10$ mm. 3. It is necessary to determine elastico-acoustic coefficients of various zones of welded joint.

the values of elastic-acoustic coefficients differ from their values in the elastically-strained metal [6]. This reduces the reliability of RWS evaluation in the plastically-strained zone of the metal without establishing their values for this zone [7].

For engineering practice, it is relevant to obtain reliable values of tensile RWS, which (in contrast to compressive RWS) have a negative effect on the service life of welded structures. In addition, the values of RWS when using the UT-method are averaged on the measuring base B_{UT} of the UT-waves transducer, which is 10 mm. The half-width of tensile RWS distribution in the weld zone, which have a high gradient, is comparable to the value of B_{UT}. Therefore, the use of the UT-method does not allow setting the peak values of RWS in the center of the weld and close to it. However, the determination of RWS by the UT-method in the reactive compression zone, which is characterized by an insignificant stress gradient, the absence of plastic deformations and shrinkage of the weld metal, is implemented with satisfactory accuracy (Table 1).

In modern studies, to determine RWS, the method of electronic speckle interferometry (ESPI-method) is used, which is based on the elastic unloading of RWS as a result of drilling holes with a diameter d_{h} and a depth h_{h} of 1 mm on the surfaces of examined areas of a welded joint, and can be considered as conditionally non-destructive [8]. Tensile RWS when measured by the ESPI method are averaged on the base $B_{\text{ESPI}} = d_{\text{h}}$. This implements a localized determination of RWS, i.e. minimizes their averaging due to a small measurement base, which results in a high reliability of evaluating the peak stress values in the center of the weld (in contrast to the UT-method).

The characteristics, advantages and disadvantages of both methods of RWS evaluation are summarized in Table 1, from the data of which it can be seen that the combination of advantages of both methods while excluding their disadvantages will allow improving the reliability of non-destructive determination of RWS in full-scale welded structures.

THE AIM OF

the work is the development of RWS evaluation procedure, which is based on the combination of advantages of UT- and ESPI-methods.

PROCEDURE, OBJECT AND SUBJECT OF RESEARCH

As an object, the processes of RWS determination in a butt joint specimen were studied using the UT- and ESPI- methods.

RWS were studied in welded joints of aluminium alloy with a stable structure, during welding of which no microstructural phase transformations occur in the melting zone and HAZ, which are associated with the volume effects and can lead to a change in residual stresses from tensile to compressive.

Consideration of the residual stress state of the welded joint when comparing membrane and surface stresses is correct for small thicknesses and in a single-pass welding. Therefore, the subject of the research was RWS in a plate of a structurally stable 1561 aluminium alloy with the dimensions of 320×205×5 mm with a longitudinal butt weld (Figure 1, *a*), produced

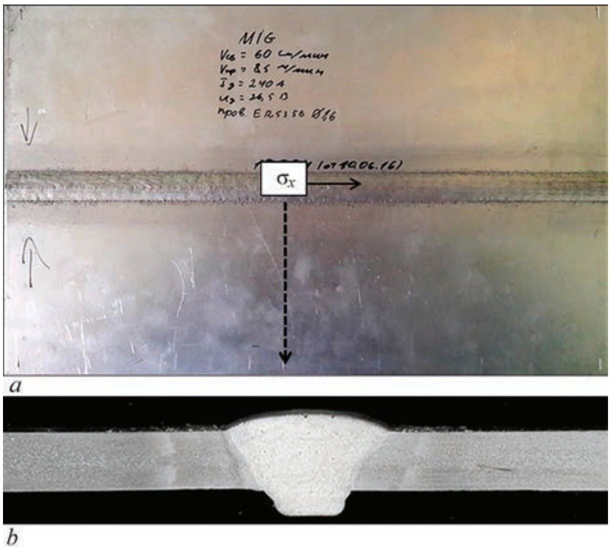

Figure 1. Specimen of butt joint of 1561 alloy: *a* — outer appearance of butt joint specimen, where a solid arrow shows the direction of σ_x action, a dotted line — the direction of stress registration by the UT and ESPI methods; *b* — macrosection of welded joint

by a single-pass MIG welding. The appearance of the macrosection of the welded joint is shown in Figure 1, *b*. MIG welding mode, residual longitudinal f_1–f_3 and transverse Δ_1, Δ_2 deflections of the plate after welding are presented in Table 2.

It can be seen that the values f_1–f_3 and Δ_1, Δ_2 are insignificant and do not exceed 1.5 mm, which excludes considerable differences between the values of membrane RWS and on the plate surfaces.

Diagnostics of the longitudinal (along the weld) σ_x component of RWS in the central part of the plate was carried out using the ESPI- and UT-methods [8, 9]. The choice of σ_x component (Figure 1) for evaluating RWS is predetermined by its larger values in the tension area (compared to the transverse component σ_y). The consequence of this is a more significant influence of σ_x (compared to σ_y) on the characteristics of the loads of the joints in operating conditions.

When registering the values of σ_x stresses using the UT-method, the UT-waves transducer was moved along the surface of the plate on the side of the weld root along its central cross-section in the directions indicated by the dotted arrows in Figure 1, *a*.

When applying the ESPI-method, the stress values σ_x on the surface of the specimen were registered on both sides of the plate in the weld center and at a distance of 7 mm from it in the directions indicated by the dotted arrow (Figure 1, *a*). The values of membrane σ_x were obtained by averaging the values of stresses over the thickness on the surface of the specimen on the corresponding areas of the outer and back surfaces of the plate.

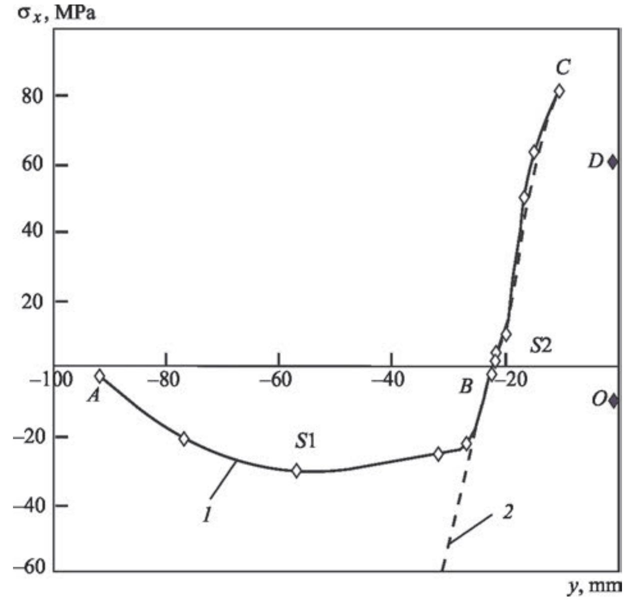

Figure 2. σ_x stresses in the central cross-section of welded joint specimen of 1561 alloy (Figure 1), obtained by the UT-method (curve *1*) and the ESPI-method (point *D*), where 2 is a straight line, showing the gradient of growing tensile RWS, *S*1 is the area of the compression epure, *S*2 is the area of the tension epure

RESULTS OF EXPERIMENTS AND THEIR DISCUSSION

Figure 2 shows σ_x stress distributions (curve *1*) in the central cross-section of the welded joint specimen (Figure 1), produced by the UT-method. The straight line *2* shows the gradient of growing tensile RWS in the active zone.

Taking into account the fact that the application of the UT-method excludes the determination of stresses in the center of the weld, the value of σ_x in this area was performed by the ESPI-method (point *D* in Figure 2). Epures of tensile and compressive RWS should have equal areas, i.e. be "balanced". Thus, the area *S*1 of the curvilinear surface between the 0–*Y* axis and the curve *AB* (compression zone) should be equal to the area *S*2 of the quadrilateral *BCDO* (tension zone) (Figure 2). However, in this quadrilateral, the position of the point *C* remains undefined on the straight line *2*, since the UT-method does not allow measuring tensile σ_x stresses in the area close to the weld metal.

Table 2. MIG welding modes and deflections of butt joint specimen from 1561 alloy

Welding speed V_w, mm/s	Welding current I_w, A	Welding voltage U, V	Grade/diameter of filler d_f, mm	$f_1^*/f_2/f_3$, mm	Δ_1/Δ_2, mm	$\sigma_{0.2}$, MPa (for BM)
10	240	26.5	ER5356/1.6	1.0/1.5/1.2	1.5/1.5	180
Note. $^*f_1$ and f_3 are the deflections of longitudinal edges of the plate; f_2 is the longitudinal deflection of the plate along the weld; Δ_1 and Δ_2 are the deflections of transverse edges of the plate, respectively, at the beginning and end of the weld; BM is the base metal.						

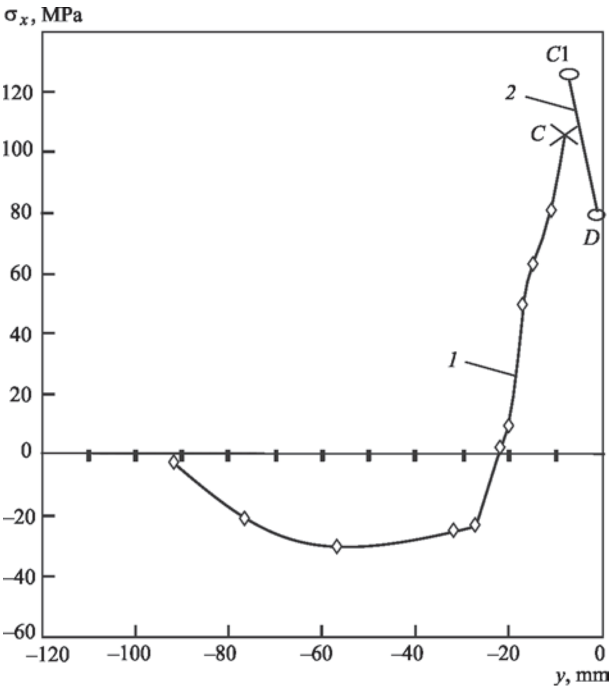

Figure 3. Residual σ_x stresses in the central cross-section of welded joint specimen of 1561 alloy (Figure 1), obtained by the UT-method (curve *1*) and the ESPI-method (curve *2*)

In the quadrilateral *BCDO*, the length of the side *BO* (the size of the width of the tensile stress zone) and the length of the side *DO* near the right angle, which in the selected scale of the ordinate axis corresponds to the value of the tensile σ_x stresses in the center of the weld produced by the ESPI method, are unchanged. Thus, the condition of equality of the areas *S*1 = *S*2 is set by the position of the point *C* on the straight line *2* (Figure 2). The coordinate of this point *C* on the ordinate axis (if the condition *S*1 = *S*2 is fulfilled) determines the value of σ_x stresses in the area near the weld, and the center of the weld on the abscissa 0–*Y* axis. Thus, the fulfillment of the condition *S*1 = *S*2 determines the position of the point *C* on the straight line *2* (Figure 2).

The distribution of σ_x stresses in the central cross-section of the plate (UT-method), which was extended to the point *C*, is shown in Figure 3 (curve *1*). The coordinates of the point *C* were determined under the condition that the corresponding areas of the tension and compression epures are equal. With the use of the ESPI method, the values of membrane σ_x in the center of the weld (point *D*) and near it (point *C*1) were obtained, which are shown by the straight line *2*. It should be noted that obtaining reliable values of σ_x in the region *C*1–*D* by the UT-method is impossible.

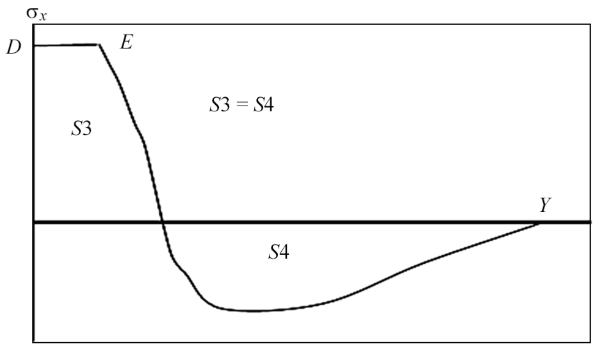

Figure 4. Epure of membrane RWS obtained using the procedure according to variant 1, where *S*3 and *S*4 are the areas of the tension and compression epures, respectively, points *D* and *E* are the values of RWS in the weld center and in the fusion zone

When comparing the values of σ_x at the points *C* and *C*1 (Figure 3), obtained by the UT- and ESPI-methods, respectively, it can be seen that their difference does not exceed 18 MPa, i.e., it is close to $0.1\sigma_{0.2}$ for 1561 alloy (Table 2), which corresponds to the claimed accuracy (Table 1).

Based on the abovementioned results, the procedure of diagnosing RWS in thin-sheet full-scale structures with single-pass welds, which is based on the combined application of UT- and ESPI-methods, is promising. However, it should be noted that the proposed procedure has certain limitations. Thus, with significant thicknesses and multipass welding, there is always a non-uniform distribution of residual stresses over the thickness, even with a change of sign, and the determination of the averaged stresses over the thickness is not of interest. Eliminating these limitations is the direction of further research, including using methods based on other physical principles.

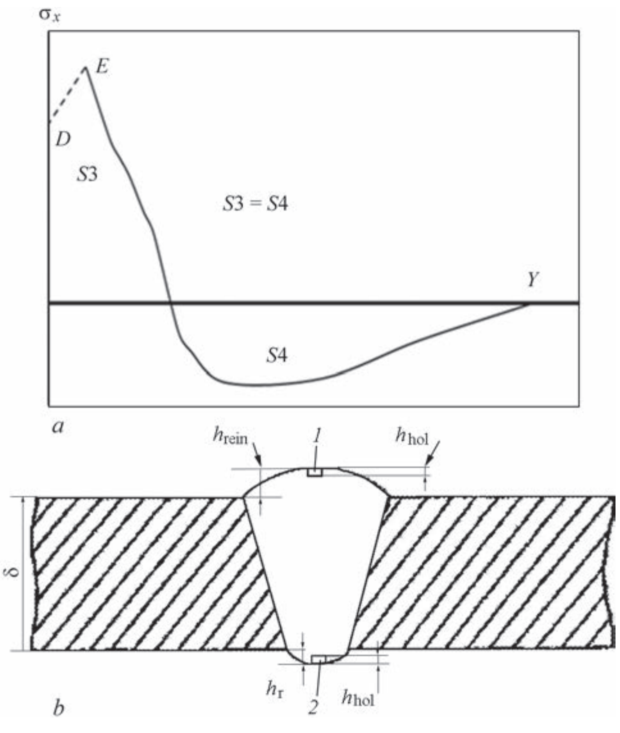

Figure 5. Procedure of RWS evaluation according to variant 2: *a* — epure of membrane RWS, where areas *S*3, *S*4, points *D* and *E* are similar to Figure 4; *b* — location of holes *1* and *2* for stress evaluation by the ESPI-method, respectively, on the outer and back surfaces of the weld

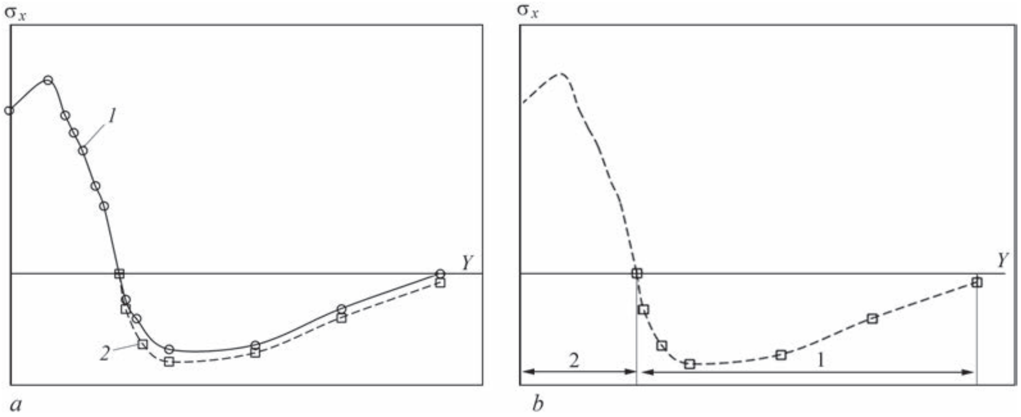

Figure 6. Procedure of RWS evaluation according to variant 3: *a* — curve *1* — epure of membrane RWS obtained by the ESPI-method on the witness specimen; curve *2* — epure of membrane RWS, obtained by the UT-method in the reactive compression zone of the witness specimen; *b* — 1 — area of the epure of membrane compression RWS, obtained by the UT-method on the structure; *2* — area of the epure of membrane tensile RWS, constructed by the method of analogies

It is possible to use the procedure in three variants.

VARIANT 1

(Figure 4) is the express-evaluation of RWS by the UT-method, which allows a quick non-destructive determination of the general level of tensile stresses in the active zone on a full-scale structure. When applying the procedure, the condition of equal stresses in the center of the weld (point *D*) and near it (point *E*) is accepted. At the same time, the geometric shape of the tension epure is taken in the form of a trapezoid (Figure 4). This excludes the determination of the features of RWS formation in the central part of the joint, which is a disadvantage of this procedure despite its advantages such as speed and ease of implementation.

1. Stages of RWS evaluation according to variant 1:

1.1. Distribution of RWS in the reactive zone (compression) is determined by the UT-method.

1.2. The area of the compression epure *S*4 is calculated (Figure 4).

1.3. Under the condition *S*3 = *S*4, the height of the trapezoid with the area *S*3 of the tensile stresses epure (Figure 4) is calculated, which on the ordinate axis determines the value of RWS at the points *D* (weld center) and *E* (fusion zone).

VARIANT 2

is the evaluation of RWS (Figure 5) by a combination of ESPI- and UT-methods, which allows obtaining the values of tensile RWS in the active zone on a full-scale structure with minimal mechanical impact on the surface of the weld metal.

The minimization of the impact is achieved due to the application of the ESPI-method for determination of RWS (in Figure 5, *a*, point *D*) exclusively on the areas of root reinforcement in the weld center (on the condition of free access to them). At the same time, the heights of the reinforcement h_{rein} and the root h_{r} of the weld should be greater than h_{h}, as is shown in Figure 5, *b*. After the determination of RWS values on both surfaces of the weld, the holes for stress registeration can be (if necessary) removed by mechanical methods of metal layers from the mentioned surfaces, provided that the thickness δ of the working cross-section of the base metal is preserved.

2. Stages of RWS evaluation according to variant 2:

2.1. The value of membrane RWS in the weld center is determined by the ESPI-method (in Figure 5, *a*, point *D*).

2.2. The UT-method determines the distribution of RWS in the reactive (compression) zone.

2.3. The area of compressive stresses *S*4 is calculated (Figure 5, *a*).

2.4. Under the condition *S*3 = *S*4, where *S*3 is the area of the tensile stress epure, the coordinates of the point *E* and the relative value of RWS (Figure 5, *a*) are calculated similarly to the method corresponding to Figure 2.

VARIANT 3

is the non-destructive evaluation of RWS (Figure 6) in full-scale structures by combining the ESPI and UT methods with the simultaneous use of a witness specimen from a similar material. Basing on the method of analogies, the procedure allows obtaining values of membrane tensile RWS in the specimen, which are equal to the stresses in a full-scale structure. The error between the distributions of compression RWS in the specimen and the structure should not exceed the claimed accuracy of the methods (Table 1). This is achieved by the equivalence of such components of the criterion of similarity of the specimen and structure as their geometric characteristics and welding modes.

3. Stages of RWS evaluation according to variant 3 (Figure 6):

3.1. The ESPI-method is used to determine the distribution of membrane RWS in the witness specimen (Figure 6, *a*, curve *1*).

3.2. The UT-method is used to determine the distribution of RWS in the reactive zone (compression) in the witness specimen (in Figure 6, *a*, curve *2*).

3.3. The UT-method is used to determine the distribution of RWS in the reactive zone (compression) in a full-scale structure (in Figure 6, *b*, area *1*).

3.4. The characteristics of the compressive stress epures of the specimen and structure are compared according to the curve *2* (Figure 6, *a*) and the curve in the area *1* (Figure 6, *b*) and their identity within the accepted measurement error is established.

3.5. Taking into account the results of the item 3.4 (identity of the compressive stress epures of the specimen and structure), the distribution of tensile RWS in the structure is constructed by the method of analogies (in Figure 6, *b*, area *2*).

Analyzing the abovementioned results, it should be noted that a combined application of the UT- and ESPI-methods allows minimizing their disadvantages (Table 1) while combining their advantages. This creates prerequisites for the development of a number of procedures for the non-destructive determination of stress states in full-scale welded structures.

CONCLUSIONS

1. It was established that the combination of the advantages of the UT- and ESPI-methods while eliminating their drawbacks is the basis for developing a method for non-destructive determination of RWS in full-scale structures.

2. It was established that the difference in the values of tensile RWS in the butt joint weld zone of 1561 aluminium alloy, obtained by the UT- and ESPI-methods, is close to the index $0.1\sigma_{0.2}$ for this material, which corresponds to the claimed accuracy of the methods.

3. A procedure for the non-destructive determination of peak values and distribution of tensile RWS in the butt joint weld zone was developed, which is based on the combined application of the UT- and ESPI-methods and compliance with the condition of “equal areas” of the epures of balanced tensile and compressive residual stresses.

4. Based on the results of the research, three types of procedures for the non-destructive determination of RWS in full-scale welded structures were proposed based on the combination of UT- and ESPI-methods.

REFERENCES

1. Guz, A.N. (1986) *Elastic waves in bodies with initial stresses*. Vol. 2. Regularities of propagation. Kyiv, Naukova Dumka [in Russian].
2. Kasatkin, B.S. et al. (1981) *Experimental methods of stresses and strains examination*. Kyiv, Nukova Dumka [in Russian].
3. Lutsenko, T.M. (2022) New systems and technologies of non-destructive testing for industry of Ukraine under current conditions. In: *Abstr. of Papers of Sci. Conf. on Welding and Technical Diagnostics for Economic Revival of Ukraine*. IAW, 66 [in Ukrainian].
4. Kudryavtsev, Y., Kleiman, J., Gushcha, O. (2000) Ultrasonic measurement of residual stresses in welded railway bridge. In: *Proc. of Conf.* on *Structural Materials Technology (Atlantic City, NJ, February 28–March 3, 2000)*, 213–218.
5. Kudryavtsev, Y., Kleiman, J., Polezhaeva, H. (2011) Ultrasonic measurement of residual stresses in welded elements of ship structure. *Applied Mechanics and Materials*, **70**, 273–278. DOI: https://doi.org/10.4028/www.scientific.net/AMM.70.273
6. Javadi, Y., Akhlaghi M., Najafabadi M. (2013) Using finite element and ultrasonic method to evaluate welding longitudinal residual stress through the thickness in austenitic stainless steel plates. *J. Mater. Des.*, **45**, 628–642. DOI: https://doi.org/10.1016/j.matdes.2012.09.038
7. Guz, A.N., Makhort, F.G., Gushcha, O.J. (1977) *Introduction into acoustoelasticity*. Kyiv, Naukova Dumka [in Russian].
8. Lobanov, L.M., Pivtorak, V.A., Savitsky, V.V., Tkachuk, G.I. (2006) Procedure for determination of residual stresses in welded joints and structural elements using electron speckle-interferometry. *The Paton Welding J.,* **1**, 24–29.
9. Gushcha, O.J. (1995), Makhort, F.G. (1995) Application of acoustic method for determination of residual stresses in welded structures. *Tekh. Diagnost. ta Nerazrush. Kontrol,* **4**, 8–15 [in Russian].

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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