Therefore, at present the research and development efforts related to application of the spectral analysis for automation and monitoring of the welding process are at their initial stage. The suggested diagnostic features identified in spectrum of the welding arc light allow detection of defects in the welded joints and deviations of parameters of the welding process from the rated values. However, no investigations have been carried out as yet to confirm the high efficiency of the existing solutions required for their commercial application.

1. Kim, E.W., Allemand, C., Eagar, T.W. (1987) Visible light emissions during gas tungsten arc welding and its application to weld image improvement. *Welding Res. Suppl.*, **12**, 369–377.
2. Weglowski, M.S., Mikno, Z., Welcel, M. et al. (2007) Kontrola procesu spawania TIG w oparciu o promieniowanie luku spawalniczego. *Prz. Spaw.*, **12**, 15–19.
3. Li, P.G., Zhang, Y.M. (2000) Analysis of an arc light mechanism and its application in sensing of the GTAW process. *Welding Res. Suppl.*, **9**, 252–260.
4. Weglowski, M.S. (2007) Investigation on the arc light spectrum in GTA welding. *J. Achievements in Materials and Manufact. Eng.*, 20(**1/2**), 519–522.
5. Song, Y., Li, J. (1998) Spectral diagnostics of complex arc plasma. *China Welding*, 7(**1**), 53–59.
6. Kearney, F.M. *Optoelectronic weld evaluation system*. Pat. 4446354 USA. Int. Cl. B 23 K 9/095. Publ. 1984.
7. Garcia-Allende, P.B., Mirapeix, J., Conde, O.M. et al. (2009) Defect detection in arc-welding processes by means of the line-to-continuum method and feature selection. *Sensors*, **9**, 7753–7770.
8. Garcia-Allende, P.B., Mirapeix, J., Conde, O.M. et al. (2008) Arc-welding spectroscopic monitoring based on feature selection and neural networks. *Ibid.*, **8**, 6496–6506.
9. Bebiano, D., Alfaro, S.A. (2009) A weld defects detection system based on a spectrometer. *Ibid.*, **9**, 2851–2861.
10. Mirapeix, J., Fuentes, J., Davila, M. et al. (2009) Use of the plasma spectrum RMS signal for arc welding diagnostics. *Ibid.*, **9**, 5263–5276.
11. Mirapeix, J., Cobo, A., Conde, O. et al. (2006) *Non-invasive spectroscopic system for non-destructive arc welding analysis*. ECNDT.
12. Mirapeix, J., Cobo, A., Gonzalez, D.A. et al. (2007) Plasma spectroscopy analysis technique based on optimization algorithms and spectral synthesis for arc welding quality assurance. *Optics Express*, 15(**4**), 1884–1897.
13. Weglowski, M.S. (2009) Measurement of arc light spectrum in MAG welding method. *Metrology and Measur. Systems*, 16(**1**), 143–159.
14. Yun, S., Zhang, L., Han, G. et al. (2006) Bayesian decision-based pattern recognition on spectrum signal of metal transfer modes. *China Welding*, 15(**1**), 39–42.
15. Dong, Ch., Wu, L., Zhang, H. et al. (1999) Front side keyhole detection in plasma arc welding of stainless steel. *Ibid.*, 8(**2**), 102–110.
16. Heinz, G., Hofmann, F., Schopp, H. et al. (2009) Echtzeitspektralregler fuer Impulsschweissmaschinen. *Schweissen und Schneiden*, **3**, 144–149.

NONDESTRUCTIVE TESTING OF WELDED JOINTS

IN-PROCESS QUALITY CONTROL OF WELDED PANELS OF ALLOY VT20 USING METHOD OF ELECTRON SHEAROGRAPHY

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Application of modern method of nondestructive testing (NDT), i.e. electron shearography, for VT20 alloy titanium panels, manufactured with preliminary elastic tension, is considered. The efficiency of application of NDT of titanium panel without dismantling of fixture for tension is shown, thus allowing the immediate elimination of defects, if required.

Keywords: *arc welding, welded panels, titanium alloy, quality control, in-process control, electron shearography*

The manufacture of welded metal structures, characterized by a low cost, high reliability and strength under different service conditions, is closely connected with the development of effective methods of NDT of their quality. One of the challenging methods of quality control is the electron shearography which is characterized by such advantages as a visualization, no-contact, high sensitivity, feasibility of real time conductance of investigations of objects of intricate geometric shape and large sizes. Comparative simplicity of this method allows it to be applied in the solution of complex problems, connected with analysis of deformations, quality control, etc. Using the electron shearography it is possible to determine deformations without numerical differentiation of data. Moreover, the method is not sensitive to vibrations, i.e. it can be used in different industry branches during in-process control of quality of structures, made of metallic and composite materials [1–5].

At practical application of electron shearography for NDT of quality it is necessary to take into account the following assumptions which resulted from optical scheme of a shearography interferometer:

• sizes of objects being examined or their areas should be much smaller than the distance from source of laser light to the surface of object under examination;

• shear module is located normal to the object surface area being examined;

• direction of illumination of surface of examined object by a laser light is selected as close as possible to the normal of the object surface area being examined.

In this case, the following relationships are used on the shearogram for dark and light interference fringes [6]:

• for dark interference fringes

$$\frac{\partial w}{\partial x} = \frac{(2N + 1)\lambda}{4\delta x}, \quad (1)$$

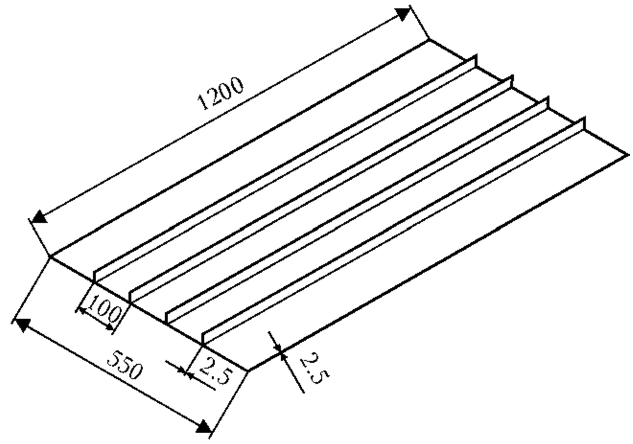

Figure 1. Sketch of welded panel manufactured of titanium alloy VT20

$$\frac{\partial w}{\partial y} = \frac{(2N + 1)\lambda}{4\delta y}; \quad (2)$$

• for light interference fringes

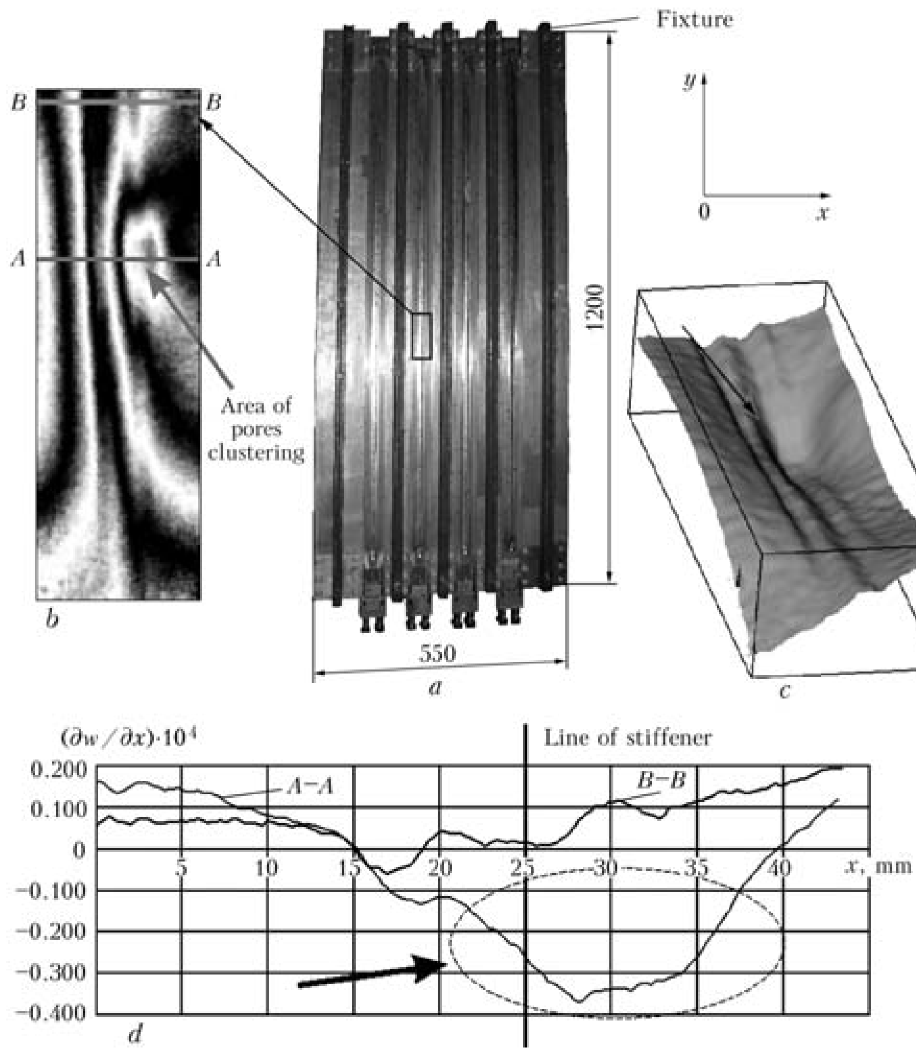

Figure 2. NDT of quality of titanium panel 1 with stiffeners, manufactured under conditions of its preliminary elastic tension: *a* — titanium panel in loaded mechanical fixture after welding; *b* — pattern of interference fringes of area being examined; *c* — 3D pattern of deforming the panel area being examined; *d* — distribution of derivatives $\partial w/\partial x$ along the sections being examined; *A–A* — section with a defect; *B–B* — defect-free section

$$\frac{\partial w}{\partial x} = \frac{N\lambda}{2\delta x}, \qquad (3)$$

$$\frac{\partial w}{\partial y} = \frac{N\lambda}{2\delta y}, \qquad (4)$$

where N is the fringe order; λ is the wave length of laser light source; ∂x, ∂y are the shear dispacements, respectively, in the directions of axes ox, oy; $\partial w / \partial x$, $\partial w / \partial y$ are the derivatives from displacements along normal to the surface of object being examined.

Using equations (1)–(4) it is possible to make a direct estimation of off-plane deformation of object after determination of the fringe order.

Technology of NDT of quality with application of method of electron shearography was used for diagnostics of elements and sub-assemblies of structures manufactured of various structural materials [3].

At present, the welded thin-walled panels with stiffeners, manufactured of titanium alloys, find the wider spreading in aircraft and aerospace industry. Quality control of these panels is rather labor-consuming and causes certain difficulties. In this connection, the development of new methods of investigation of their quality remains urgent.

The method of electron shearography was used for NDT of quality of stringer panels made of high-strength titanium alloy VT20 of 1200 × 550 × 2.5 mm in size (Figure 1). Four longitudinal stiffeners of 25 mm height and 2.5 mm thickness were welded-on to titanium sheet by slot welds. The distance between stiffeners was 100 mm. Welding of titanium panels was performed under the conditions of their preliminary tension. Here, the automatic argon arc welding with immersed arc and automatic argon arc non-consumable electrode welding along the layer of activated

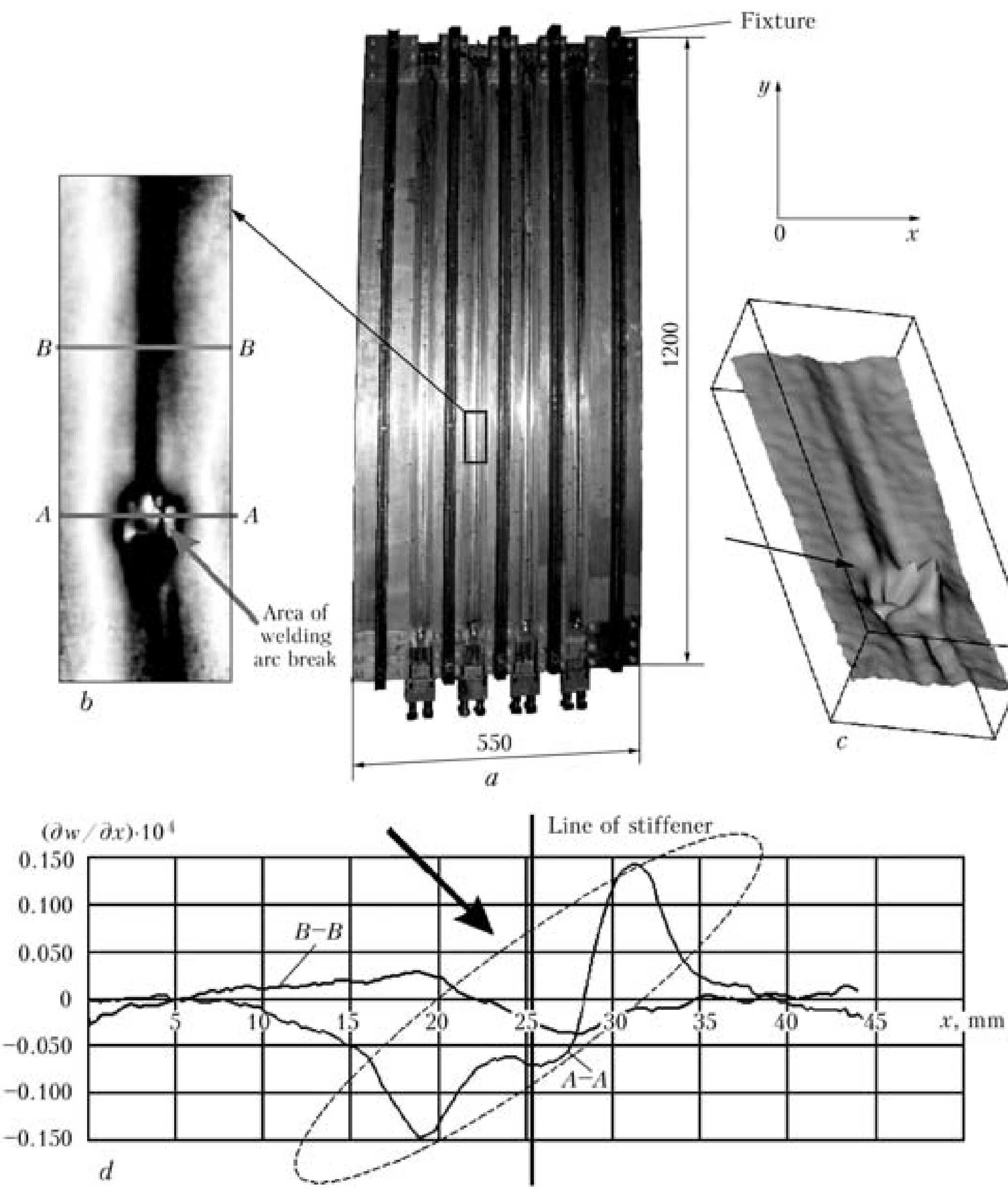

Figure 3. NDT of quality of titanium panel 2 with stiffeners, manufactured under conditions of its preliminary elastic tension: *a*–*d* — the same as in Figure 2

flux were used. After welding the titanium panel remained in fixture in a state of tension.

NDT of quality of panels was performed in the following sequence. The examining area of weld of panel after tension was illuminated by a laser light and reflected light wave, characterizing the initial state of surface being examined, was recorded in the computer memory. Then, the examining area was blown with a hot air at temperature of about 50–70 °C during 25–40 s, thus leading to its deformation. Then the light wave, reflected from the deformed area of surface being examined, was also recorded in the computer memory. Using a special computer program the recorded optical information was processed up to obtaining the shearogram and 3D pattern of deforming the surface being examined.

The result of control of welded panel 1 of alloy VT20, welded by automatic argon arc welding with immersed arc, is presented in Figure 2. The shearogram of examined area of weld (Figure 2, *b*) shows a local change of pattern of interference fringes on the general background of deforming, that proves the presence of internal defects. The plotted 3D pattern of deforming (Figure 2, *c*) and curves of distribution of derivatives $\partial w/\partial x$ along the selected sections *A*–*A* and *B*–*B*, respectively, of defective and defect-free ones (Figure 2, *d*) confirm the presence of defects on the area being examined (shown by arrow).

It should be noted that in examining area of panel a section *A*–*A* is given in Figure 2, *b*, in which the local change of derivative has the highest value (the analysis of several sections was made and section was selected with the highest local value of derivative $\partial w/\partial x$).

The carried out X-ray control of quality of the examined area of weld of titanium panel of VT20 alloy showed the presence of clusters of pores of 0.2–0.4 mm in it.

In examination of welded titanium panel 2 the area of arc break was observed, where the concentration of deformations in the site of welding interruption was observed (Figure 3, *b*). The shearography quality

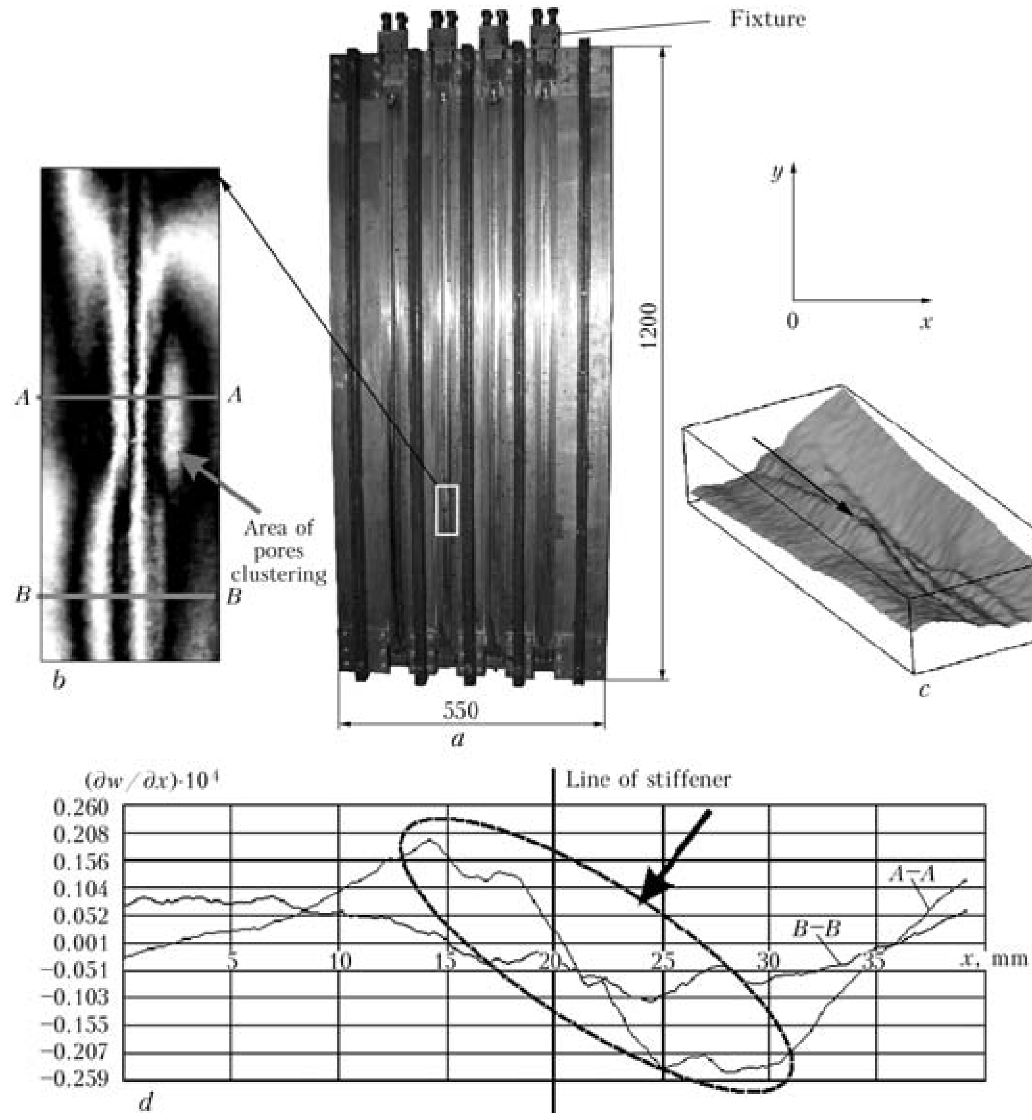

Figure 4. NDT of quality of titanium panel 3 with stiffeners, manufactured under conditions of its preliminary elastic tension: *a*–*d* — the same as in Figure 2

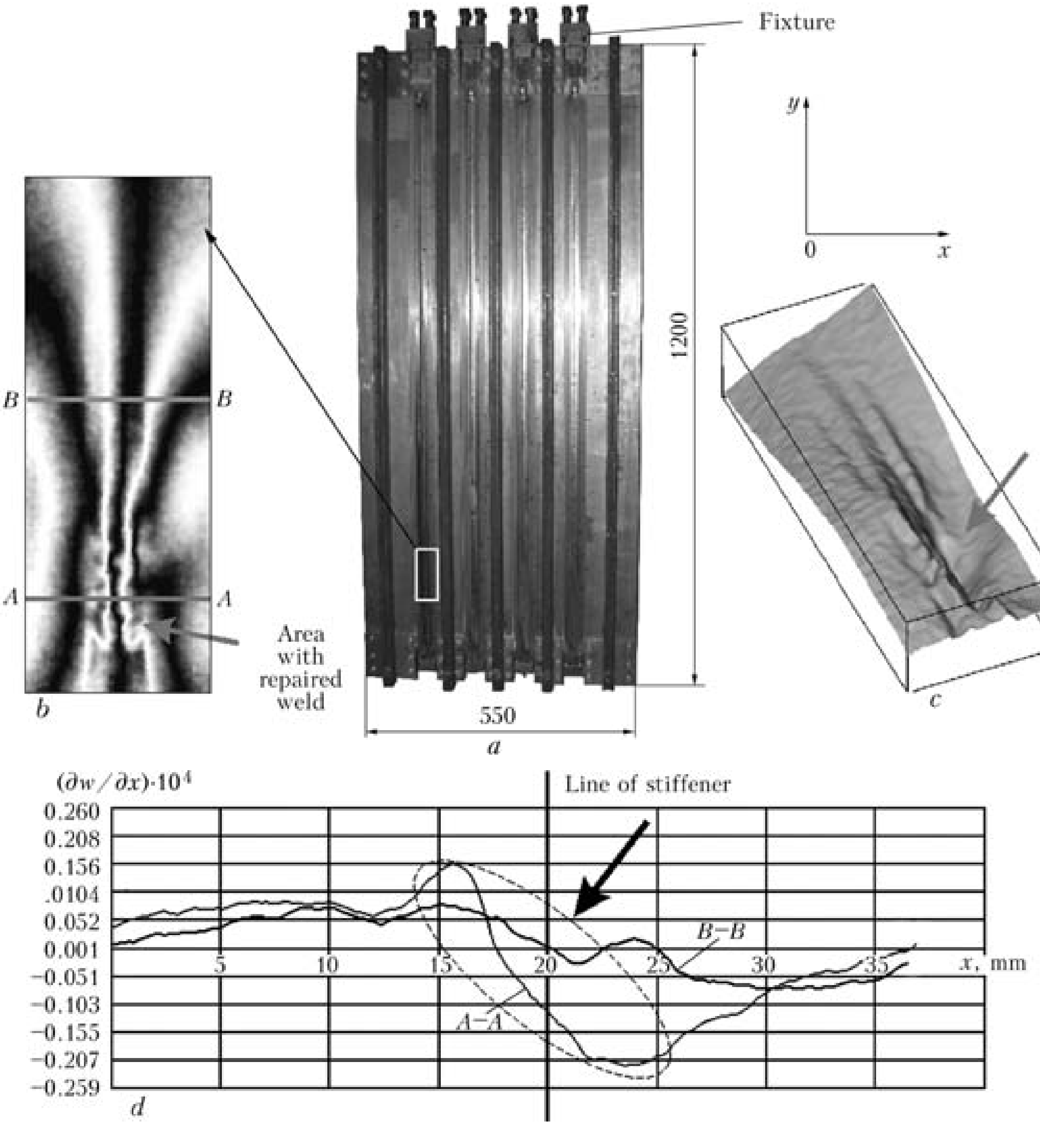

Figure 5. NDT of quality of titanium panel 4 with stiffeners, manufactured under the conditions of its preliminary elastic tension: *a*–*d* — the same as in Figure 2

control was performed using the same parameters of heating as in the previous case.

Results of further processing of interference fringes up to obtaining of 3D pattern of deforming (Figure 3, *c*) and plotting of curves of distribution of derivatives $\partial w/\partial x$ along the sections *A*–*A* and *B*–*B* being examined (defective and defect-free areas of weld, respectively) (Figure 3, *d*) confirmed the presence of a local jump of derivative $\partial w/\partial x$ at the area of arc break during welding panel.

During NDT of quality of panel 3, welded by the automatic argon arc welding with immersed arc, the areas with an abrupt change of derivatives $\partial w/\partial x$ were also revealed. Results of quality control, obtained on one of them, are presented in Figure 4.

The 3D pattern of deforming the examining weld areas and curves of distribution of derivative $\partial w/\partial y$ along section *A*–*A* show a local area of an abrupt its change (shown by arrows) that proves the presence of defects in weld (Figure 4, *c*, *d*).

The X-ray control of examining weld area showed the cluster of pores of 0.2–1.0 mm sizes and inclusions of 0.3 and 0.8 mm sizes in it.

Figure 5, *b*–*d* shows, respectively, pattern of interference fringes, 3D pattern of deforming the examining area of weld of welded titanium panel 4, welded by the automatic argon arc welding with immersed arc, and distribution of derivatives $\partial w/\partial x$ along the sections *A*–*A* and *B*–*B* being examined at the area of weld after its repair using the manual arc welding.

It is seen visually that after the repair of defective weld area an abrupt local change of derivative $\partial w/\partial x$ is observed that characterizes the concentration of deformations in weld area, recovered by repair.

During welding of titanium panel 5 using the automatic argon arc welding with non-consumable electrode along the layer of activated flux, a weld area with a local concentration of deformations, caused by pore clustering, was also observed (Figure 6, *b*, *c*).

Distribution of derivatives $\partial w/\partial x$ along the sections *A*–*A* and *B*–*B* being examined is shown in Fi-

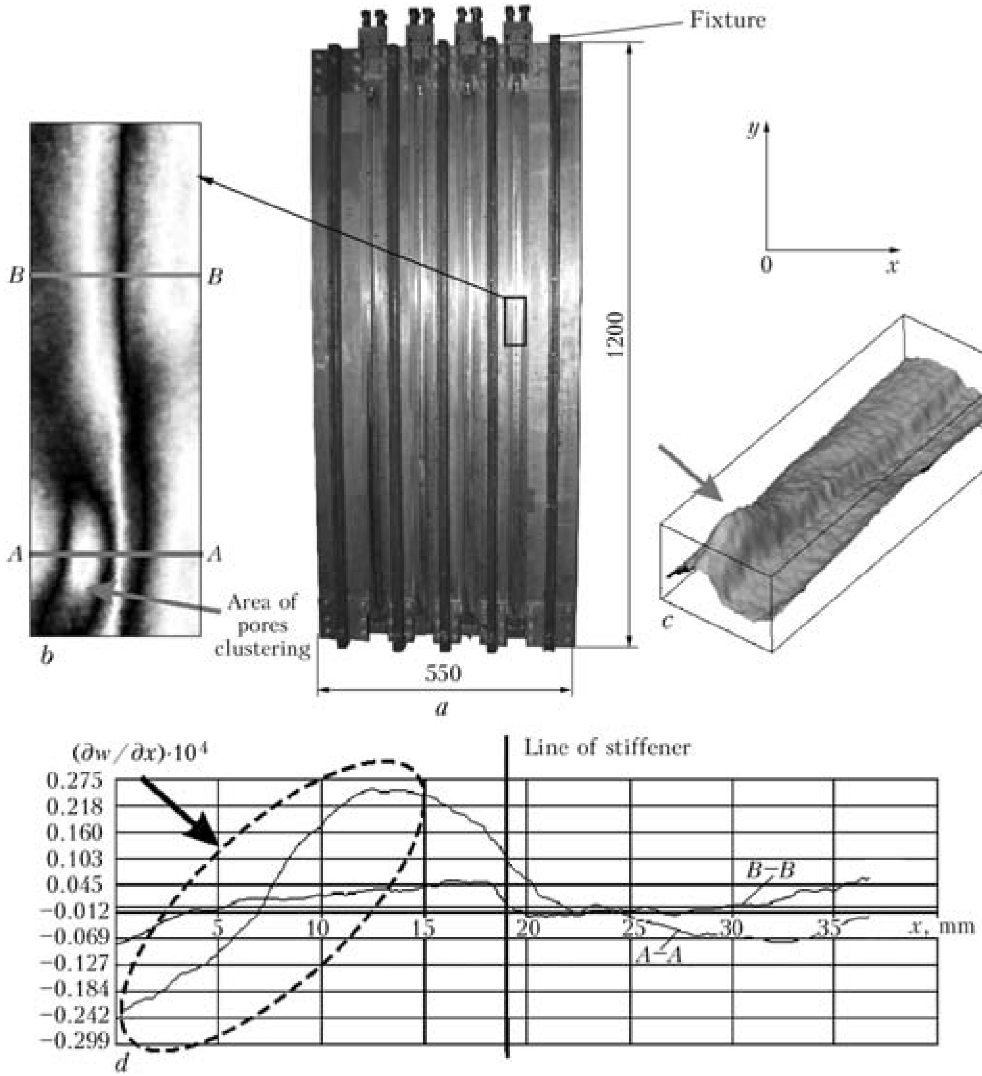

Figure 6. NDT of quality of titanium panel 5 with stiffeners, manufactured under conditions of its preliminary elastic tension: *a*–*d* — the same as in Figure 2; *b* — pattern of interference fringes at the area of pores clustering

gure 6, *d*. An abrupt change of derivative $\partial w/\partial x$ in section *A*–*A* at the weld area being examined characterizes the presence of defects.

Thus, the carried out series of experiments on no-contact NDT of quality of welded titanium panels with stiffeners, manufactured of alloy VT20 and performed under the conditions of their preliminary tension, showed that the method of electron shearography allows in-process examination of quality of welded panels and revealing of defective areas of welds. It is especially important that the method allows revealing the defects without dismantling the fixture for tension of titanium panel and, when necessary, beginning at once their elimination.

During welding of titanium panels it is also necessary to take into account that the break of welding arc in making weld and manual repair welding of weld areas cause the local concentration of deformations, that can lead to the reduction in their service life at the effect of service loads.

1. Rastogi, P.K. (2000) *Trends in optical nondestructive testing and inspection*. Amsterdam; Lausanne: Elsevier.
2. Lobanov, L.M., Pivtorak, V.A., Olejnik, E.M. et al. (2004) Procedure, technique and equipment for nondestructive shearographic testing of materials and elements of structures. *Tekhn. Diagnostika i Nerazrush. Kontrol*, **3**, 1–4.
3. Lobanov, L.M., Pivtorak, V.A., Savitskaya, E.M. et al. (2008) Diagnostics of elements and assemblies of structures using electron shearography method. *Ibid*., **4**, 7–13.
4. Newman, J.W. (2005) Holographic and shearographic NDT. Application in aerospace manufacturing. *Materials Evaluation*, **7**, 746–750.
5. Collrep, J., Krupka, R., Siebert, T. (2007) Industrial applications of shearography for inspection of aircraft components. *NDT World Review*, 36(**6**), 28–31.
6. Hung, Y.Y., Ho, H.P. (2005) Shearography: an optical measurement technique and applications. *Materials Sci. and Eng*., **49**, 61–87.