Determination of Residual Stresses in Structural Elements Using Electron Speckle Interferometry Method

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Abstract Electron speckle-interferometry can be used in combination with hole drilling for an accurate determination of residual stresses (ESPI-HD method). Technology and compact equipment for efficient measurement of residual stresses based on ESPI-HD method have been described.

The computation method for calculation the values of stress tensor components based on surface displacements data has been suggested. Use of the ESPI-HD method allows increasing the accuracy of residual stress determination. High sensitivity of the instrumentation allows conducting investigations of the stressed state on a small base (0.5 mm) without loss of the experiment accuracy.

A special new approach to the conventional method of speckle-interferometry in order to investigate stress gradients over the surface of the test object has been added. The efficiency of application of the offered procedure for evaluation of the gradient of stresses is shown for investigation of residual stresses in welded structures.

Keywords residual stresses, electron speckle-inteferometry, hole-drilling method, welding

1. Introduction

In the production of the welded structures the high-strength steels and cast alloys find the more wide application. However, the serviceability and reliability of these materials depend greatly on the effect of residual stresses, the high level and the local gradient of which can lead to the initiation of cracks, reduction in corrosion resistance, etc. Therefore, the development of the reliable and informative methods of investigation of a stressed state in structures is important.

One of the most widely used methods for determination of residual stresses is the hole-drilling strain-gage method, in which a through-thickness or blind hole is made in the inspected point of the surface, and the strains, caused by unloading of the material volume during the residual stresses release, are measured in the vicinity of the hole. The values of these strains are subsequently used to calculate the main directions and appropriate values of the residual stresses.

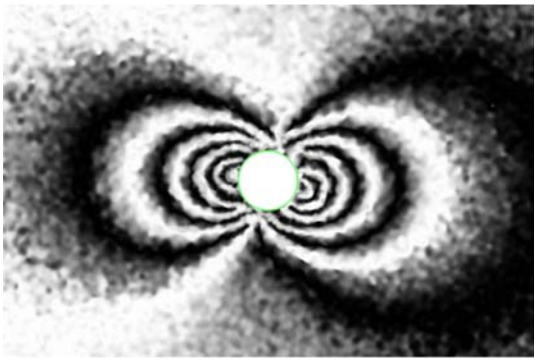
The contactless methods, based on the laser interferometry for measuring the surface displacements, can overcome the difficulties, related to the bonding of the strain gauge arrays in the vicinity of the holes, and can also provide more information about the residual stress state of the object [1-3].

2. Determination of residual stresses by means of the ESPI-HD method

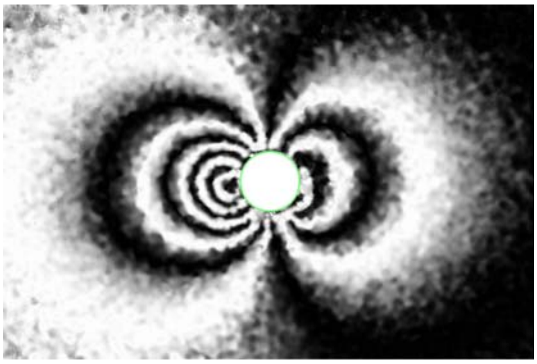
The electron speckle-interferometry (ESPI) in the combination with the hole-drilling can be used for fast and accurate determination of residual stresses [4, 5]. The speckle-interferometry method for determination of residual stresses is based on the application of the optical scheme of the interferometer in which the investigated section of the object is illuminated under the same angle symmetrically from two directions, so that it is possible to determine the in-plane components of the displacement vector, which characterize the deformation of the object.

The displacements, caused by relaxation of residual stresses in the bulk material due to drilling of the blind holes, are measured using the ESPI method. The measurements are made in the following sequence [4]: the device is placed on the surface of the object. The reflected speckle-pattern, characterizing the initial condition before hole-drilling in the controlled section, is stored in the computer memory using a CCD-camera.

After unloading of the stresses due to drilling of a blind hole with the diameter and depth of approximately 0.4-1.0 mm, the reflected second speckle-pattern is also stored in the computer. After the computer processing of these two speckle-patterns, the monitor shows the interference fringes in the vicinity of the hole that contains the information about the displacements (Fig. 1).



a)



b)

Figure 1. Typical fringe patterns in the vicinity of a drilled blind hole in a stressed material: a) symmetrical fringe pattern. The gradient of residual stresses over the surface on the base of the measurements is absent; b) non-symmetrical fringe pattern. The gradient of residual stresses over the surface is present

Based on the computer processing of the fringe patterns, the displacements in the irradiated area can be evaluated, as well as the residual stresses can be calculated.

The developed procedure provides the measurement with the help of the speckle-interferometry of a displacement component u_x at a constant distance from the hole center (for instance, $r = 2{,}5r_0$). In this case the dependence of the measured displacements u_x, resulting from relaxation of stresses σ_{xx}, σ_{yy} and τ_{xy} is expressed by the formula [3]:

$$u_x(\theta)=F(\theta)\,\sigma_{xx} + G(\theta)\,\sigma_{yy} + H(\theta)\,\tau_{xy} \tag{1}$$

where F(θ), G(θ) and H(θ) are the functions, which depend on the mechanical properties of the material, the distance from the hole center and its diameter, angle θ determines the coordinates ($x = 2{,}5r_0\cos(\theta)$; $y = 2{,}5r_0\sin(\theta)$) of the point, where the displacement is measured.

Determination of residual stresses, using the offered procedure, is realized in the following stages:

- points at distance of $2.5r_0$ from the center of the drilled hole of the radius r_0 at the different angles θ relative to the axis of illumination are selected;
- displacements $u_x(\theta)$ at the chosen points are measured, using a speckle-interferometer;
- components σ_{xx}, σ_{yy} and τ_{xy} are calculated from Eq. 1, using the least squares method;
- values of principal stresses σ_1, σ_2 and principal angle are determined.

A small device, positioned directly on the surface of the investigated object (Fig. 2) has been designed for determination of residual stresses in the elements and sections of the structures. Software 'Fringe Editor' for automatic image processing has been developed (Fig. 3).

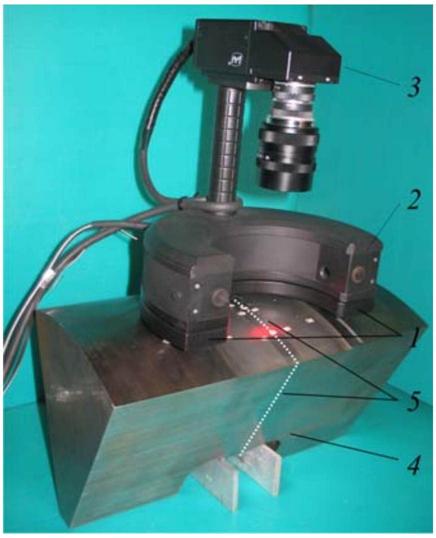


Figure 2. General view of the optical device, including: 1 – basement; 2 – removable module of speckle-interferometer; 3 – CCD-camera; 4 – sample of a welded joint; 5 – a weld seam

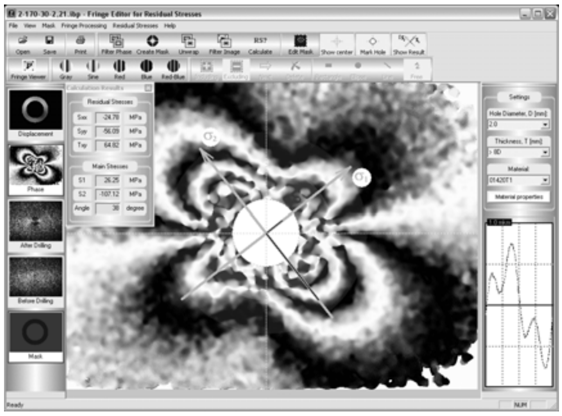


Figure 3. General view of the software user interface

The unit for determination of residual stresses, using the ESPI-HD method, includes a system of illumination and observation, which makes it possible to measure the displacements in the plane of the object examined. The unit consists of two parts: a basement 1 and a removable module 2, in which the optical system of the interferometer is assembled (Fig. 2). The basement is mounted on the sample examined and remains fixed while the measurements are being carried out for the point selected.

The solution of the well-known problem about the bending of a console beam with a fixed end by a force applied to a free end was used to evaluate the accuracy of the displacement measurements, using the developed small-sized speckle-interferometer and automated computer processing of speckle-patterns. The experiments have shown that the deviation of the values of stresses, which were determined by the ESPI-HD method, from the analytically estimated values, does not exceed 6 % of yield strength of the material tested [5].

3. Stress gradient over a surface

Determination of residual stresses on the basis of the hole-drilling methods assumes that stresses in the directions *x* and *y* are not changed. However, there is a non-homogeneous stressed state in the weld and HAZ, i.e. a gradient of residual stresses is present in those areas. (Fig. 4, 5). In this connection, it is suggested to use the drilling of the small-diameter holes at these areas to increase the accuracy of stress determination. It should be noted here, that the decrease of the holes' diameter leads to the reduction of the displacement measuring sensitivity and to the complication of the the process of drilling the holes in the high-strength metals and alloys.

It is known that the application of electron speckle-interferometry for determination of residual stresses makes it possible to gather more information about the residual stress state of the object compared with the data from the resistance strain gauges, that is achieved by calculating a significantly larger amount of values of the displacements caused by the hole-drilling.

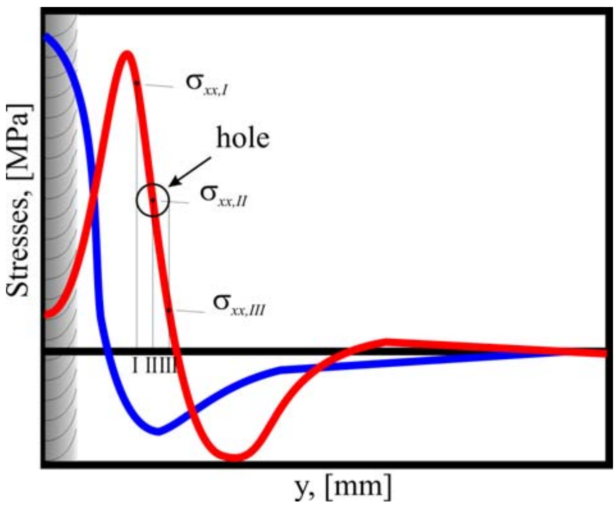


Figure 4. Typical distributions of longitudinal residual stresses versus distance from the weld center line

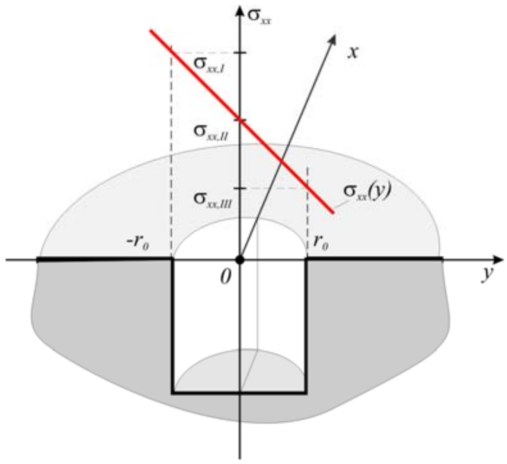


Figure 5. Local distribution of residual stresses across the hole

The ESPI-HD method for determination of residual stresses has been improved with a new approach for investigation of the stress gradient over the surface of the objects being examined. The principle of the approach will be briefly described below.

The area around the hole is divided into sectors. The displacements and their values, which are used for computing the stresses, are measured in those sectors (Fig. 6). The displacements data in the first and fourth circumference quadrants are used to determine the residual stresses for sector C_1, in the second and third quadrants – for sector C_2, the whole data about the displacement values along the circumference are used for determination of residual stresses corresponding to sector C_0 (Fig. 6).

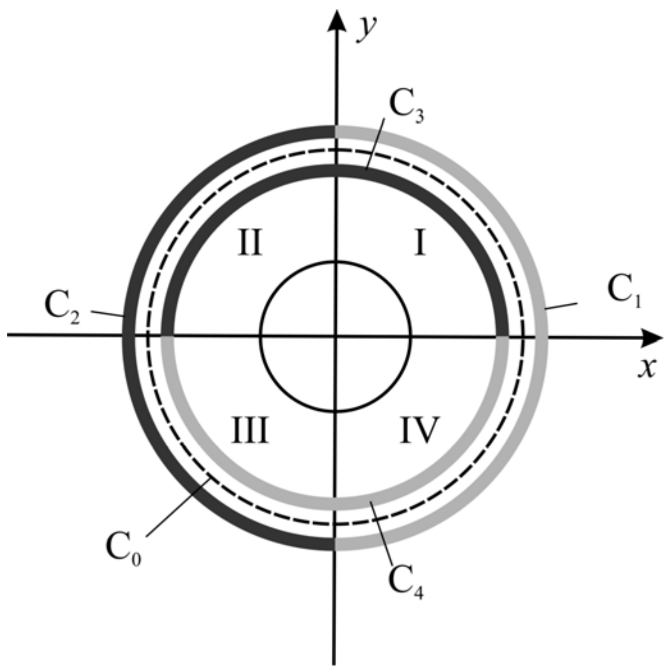


Figure 6: Scheme of an area division into sectors for investigation of the stresses' gradient in the hole zone

In order to assess the stress gradient it is necessary to determine stresses, using the data about displacements in the points both along the entire circumference around the drilled hole (Fig. 5) and in the points, located in the separated sectors around the drilled hole (compare Fig. 5). The computations, made with FEM, have shown that stresses, calculated from the data about displacements in all the points of the circumference (C_0), will have averaged values ($\sigma_{xx,avr}$) as compared with stresses from the measurements in the separated sectors (C_1 and C_2). The higher the stress gradient in the hole zone is, the larger the difference between the results of the stresses' calculation from displacements data in sectors C_1 and C_2. This gives the possibility to determine the direction of the stress gradient around the hole contour that allows to find the extreme values of residual stresses at a high accuracy.

To evaluate the gradient of stresses we have to plot the stress diagram. The data of the displacements, measured in the points along the circumference *2* (Fig. 7), located at a certain distance ($2.5r_0$) from the drilled hole center *1* (radius r_0), are used for determination of averaged residual stresses. If the stresses $\sigma_{xx},$ calculated from the data from the different sections, are not equal, then the gradient of stresses over the object surface is present. In that case there is a dependence of stresses, being calculated on angle α (angle between radius-vector *b* and axis *OX*, Fig. 7). To assess the gradient of stresses in the hole vicinity, the diagram of the changes of stresses along the circumference is plotted on the base of the displacements data in the points of the sector 3 from angle α (the points of the sector 3 have polar coordinates within the range from $\alpha - \pi/2$ up to $\alpha + \pi/2$).

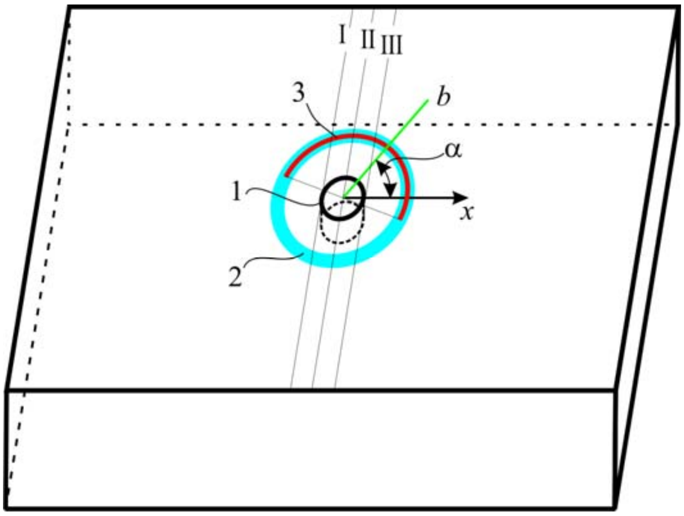


Figure 7. Scheme of the location of the points, in which the stresses are determined from the displacements data, where: 1 – hole; 2 – circumference, along which the displacements have been measured, used for calculation of stresses; 3 – circumference sector, in which the displacements are measured, used for determination of the stressed state when analyzing the stress gradient over the surface

An example of the calculated stress diagram is shown in Fig. 8. A conclusion about the presence of the residual stresses gradient can be drawn based on deviation of a curve of stresses from the circle with the radius, which is equal to the averaged value of stresses.

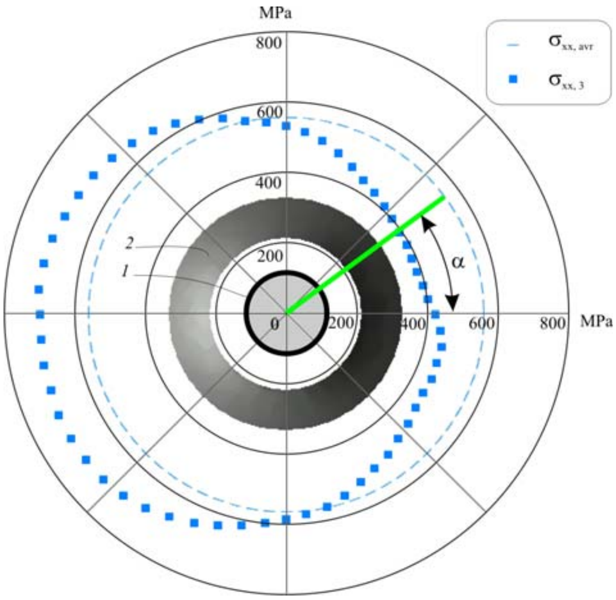


Figure 8. Graphical presentation of stresses σ_{xx} (square dots), with the use of the data about the displacements in the sector 3 (Fig. 7), illustrating deviations from the averaged values $\sigma_{xx,\mathrm{avr}}$ and indicating the gradient of residual stresses over the surface. 1 – hole; 2 – measured displacements are presented in the form of a grayscale values

4. Application

The procedure of determination of residual stresses and the equipment, designed for this purpose, have been used for study of the stressed state in 1020 mm diameter welded gas and oil pipelines (Fig. 9). The ESPI-HD method has made it possible to determine residual stresses in the different areas of the welds. This technique does not require strong surface preparation. Drilling of holes with diameters and depths from 0.5 up to 1.0 mm provided high accuracy and relatively small damage.

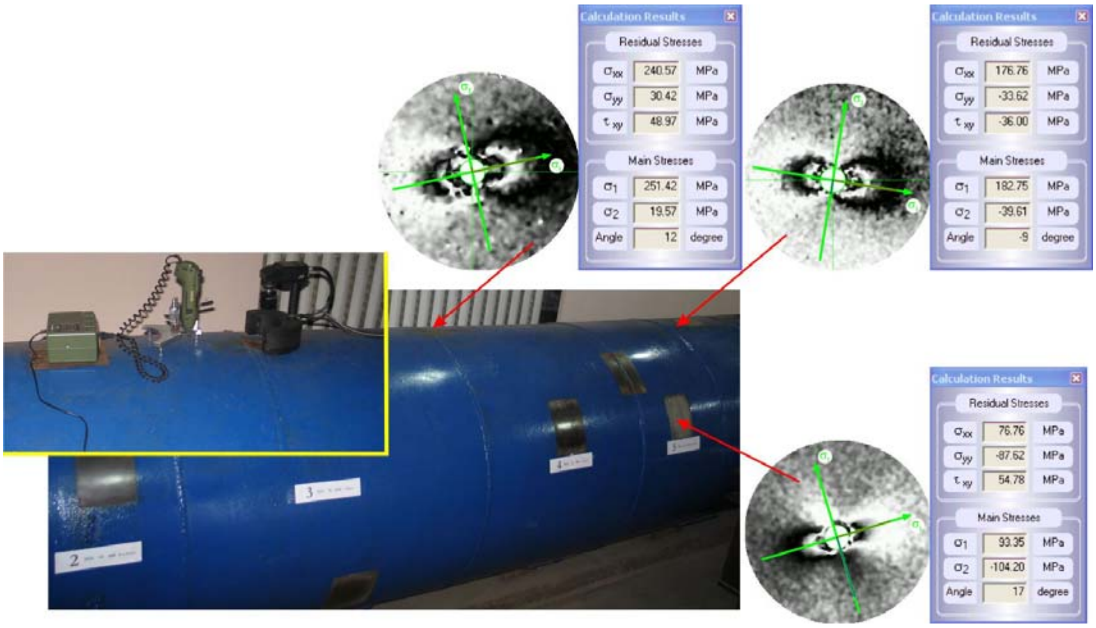


Figure 9. Determination of residual stresses in welded joints of gas and oil pipelines.

Another important advantage of the ESPI-HD method in comparison with the strain-gage hole-drilling method is that it does not require the removal of the weld reinforcement, which can lead to a redistribution of residual stresses.

Residual stresses have been determined in the Cr-Mo-V turbine element (Fig. 2). Typical distribution of circumferential residual stresses in the surface welded turbine rotor is presented at Fig. 10a, where compressive residual stresses are obtained due to phase transformation. However, the use of the proposed methodology for evaluating the stress gradient over the surface revealed two sharp peaks in HAZ, which have resulted from the martensitic transformations in the narrow zones of the width up to 2 mm (Fig. 10b). Thus, the use of the proposed techniques for the stress gradient analyses enabled to clarify the data about distribution of residual stresses and to identify a number of the important features.

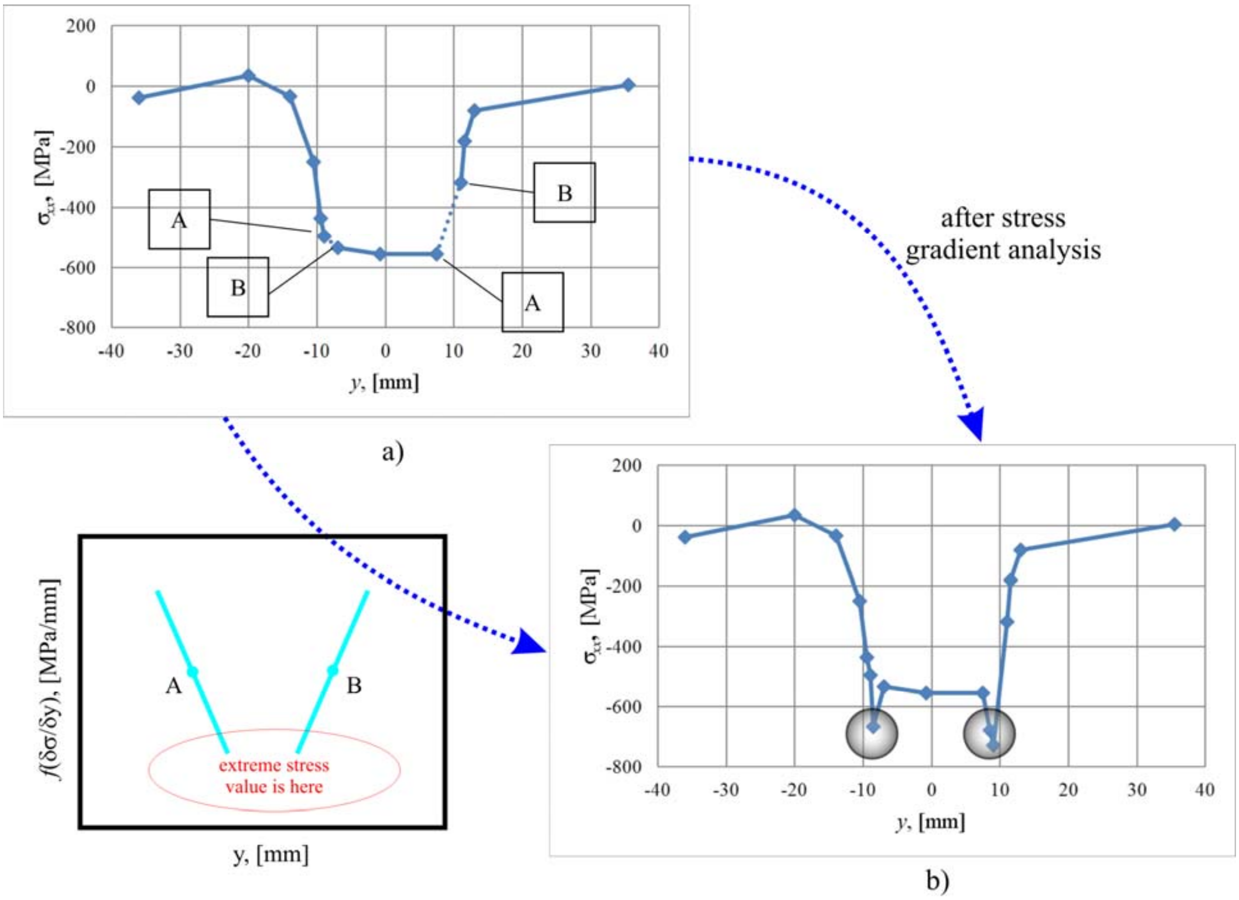


Figure 10. Distribution of circumferential residual stresses in the surface welded rotor obtained by: a) – conventional method of determination of residual stresses; b) – ESPI-HD – method with the technology of evaluating the stress gradient over the surface

5. Summary

Thus, the use of the ESPI-HD method makes it possible to increase the accuracy of residual stress determination and also gives an additional opportunity of the stress gradient assessment on the basis of the drilled out hole. The high sensitivity of the device enables to conduct the investigations of the stressed state on a small base (from 0.5 mm) without any loss of the experiment accuracy. The developed procedure of residual stress determination, compactness of the equipment and efficiency of the computer processing of the optical information open the new possibilities for examining the structures under the laboratory and industrial conditions.

The efficiency of the application of the offered procedure for evaluation of the stress gradient over the surface in order to investigate residual stresses in the welded structures has been shown.

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