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Analysis of the causes of defects in structural elements with a combination of hole drilling methods and photoelasticimetry

KOSTKA Ján[1,a], PÁSTOR Miroslav[1,b],ČARÁK Peter[1,c], FRANKOVSKÝ Peter[1,d] and KULA Tomáš[1,e]

[1]Technical University of Kosice; Faculty of Mechanical Engineering; Letná 9, 042 00 Košice, Slovak Republic

[a]jan.kostka@tuke.sk, [b]miroslav.pastor@tuke.sk, [c]peter.carak@tuke.sk, [d]peter.frankovsky@tuke.sk, [e]tomas.kula@tuke.sk

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Abstract. The content of the paper is to acquaint with the problematics of structural failure, description of quantification of residual stresses by the drilling method and design of the methodology of using optical methods for their verification. The solution was based on lot of experience of the workplace (KAMaSI SjF TUKE) in the field of determination of residual stresses by the drilling method and the Ring-Core method, as well as the use of optical methods (photoelasticimetry and DIC) for full-field analysis of investigated objects. Although the optical methods have been used for stress and strain analysis for decades, with the continuous development of new and more accurate measuring instruments and devices, the possibilities of creating new application methodologies are opening up. To advisement the possibility of using the Optical PhotoStress method for quantifying residual stresses, has been designed an accurate positioning device to analyze the released deformations around the drilled hole in multiple steps as defined by ASTM E837-13a for drilling methods.

Introduction

Determination of causes and the prediction of the failure of the bearing members of structures is still a highly topical issue related to the assessment of the lifetime of structures, machines, equipment, etc. It should be pointed out that many failures of parts of structures, systems or machines are not only due to the stress induced by the load, but are also due to the occurrence of residual stresses. These also occur in unloaded structures or machine parts. They can be caused not only by the operating load, but also by the production technology (casting, rolling, pressing, etc.) as well as by welding. Determining the occurrence of residual stresses, their size and direction is problematic without carrying out experimental measurements. The risk of their occurrence is mainly related to the fact that they are superimposed on operating stresses, which can significantly affect the life of machines and equipment. For this reason, it is necessary to know and quantify these stresses to predict the occurrence of disorders. Currently, the drilling method is most commonly used to determine residual stresses in the material. This is a semi-destructive experimental method of quantifying residual stresses in a selected point. The authors use the SINT MTS 3000 drilling equipment or the RS 200 drilling machine to solve specific practical tasks. At the (Fig. 1) is an illustration of the determination of residual stresses in the deburring drum (Fig. 1a) in order to advisement their impact on cracking (Fig. 1b) [4-6].

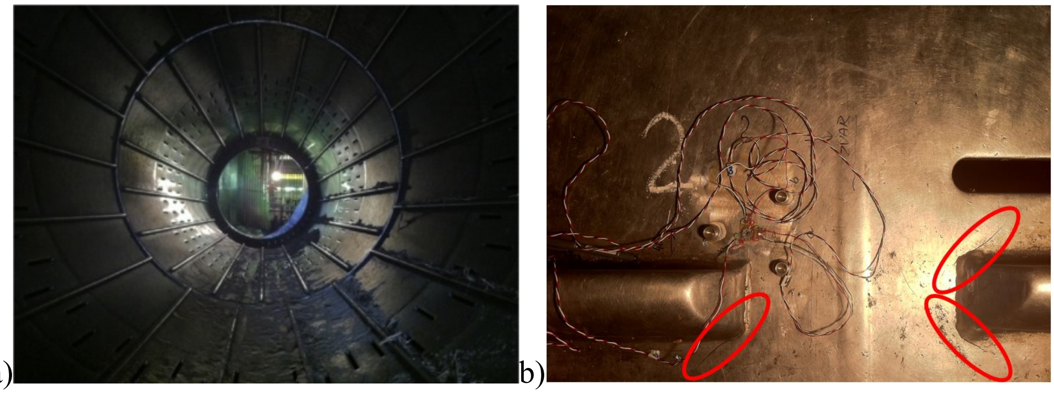


Fig. 1 Deburring drum: a) inside view, b) drilling location near identified cracks

Hole drilling method

The hole drilling method is the most common universal technique for measuring residual stresses in materials. They have standardized procedures, good reliability and accuracy. The principle of drilling methods is base on the chang of tension or deformation generated by drilling holes into materials or samples whitch include residual stresses. By knowing the size of the holes, directions and the size of the relaxed deformations and material properties, we can determine the residual stresses through the experimental analysis. We can rightly consider this method as a semi-destructive method, since the drilled hole can be negligible and can be repaired by welding or inserting a bolt or pin. It is often possible that this correction will alter the stress distribution and therefore blind holes are used instead of through holes [4].

Among the benefits of hole drilling method include:

1. application of the method is possible not only in laboratory conditions but also in practice,
2. usability for a wide range of materials - metal and non-metallic,
3. a fast and easy to apply process,
4. suitability to measure residual stresses even after surface treatment of component,
5. repeated measurements of residual stresses during various phases of component life,
6. nominal accuracy: steel - 30 MPa, aluminum - 10 MPa, titanium - 15 MPa [14].

The drawbacks of the drilling method include:

1. the resulting hole needs to be repair or welded again,
2. the maximum measuring depth is 2 mm,
3. measurement is not possible on very curved surfaces for attachment of the device - application on complicated components is limited,
4. strain gauges used for drilling are susceptible to noise and requires good surface preparation at the drilling site,
5. a strong deformation response rate from the material is required,
6. inaccuracies due to stress release after gradual drilling in depth [14].

At the Fig. 2a is a diagram of a uniformly distributed tension along the drilling depth. At the Fig. 2b, the structural view of the tension is unevenly distributed along the drilling depth. The individual drilling step profile corresponds to a "staircase" increment during progressive hole formation and residual stress measurement [1].

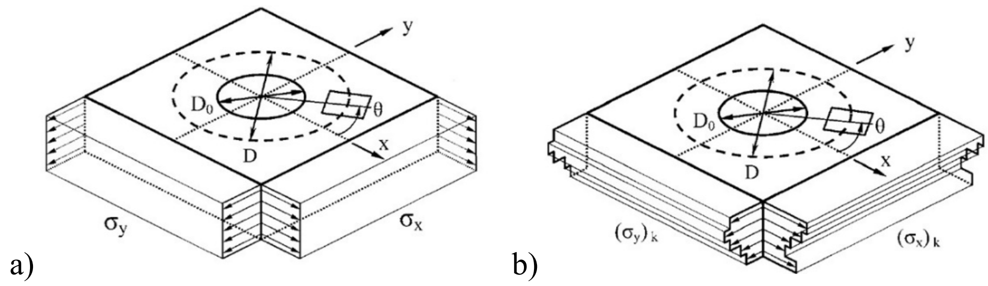


Fig. 2 Uniformly (a) and unevenly (b) distributed stress

Blind hole analysis

In many cases, through the drilling process, through-holes cannot be realized due to the dimensions and different shapes of the components and therefore is used the shallow "blind" hole drilling method. But then there is the problem of local tension, for which there is no exact solution to date in the mathematical theory of flexibility. The previous equation can be applied only to the calculation if the appropriate coefficients $\bar{A}$ and $\bar{B}$ are used for the blind hole. These coefficients are obtained empirically (by experimental calibration or numerical modeling using FEM) because they cannot be obtained from theoretical considerations [4]. It is necessary to introduce another independent variable, namely the dimensionless hole depth Z/D. The generalized form of functions for coefficients can be expressed by:

$$\bar{A} = f_A(E, \mu, r, Z/D) \quad , \tag{1}$$

$$\bar{B} = f_B(E, \mu, r, Z/D) \quad . \tag{2}$$

In some casis of residual stress and the selected hole diameter, the released deformations grow when the hole depth increases. The specified process continues to a hole depth that is equal to its diameter or slightly larger. For the purpose of obtaining maximum deformation signals, the hole is drilled to a depth that corresponds to a ratio of at least $Z/D = 0{,}4$ [4,15].

It is also important to know the behavior of the local thin plate region when analyzing the blind hole. In ASTM E 837-13a, it is recommended to create holes in small depth increments [8]. This is done in order to obtain data to advisement whether the residual stress is uniform over the depth. If the residual stress varies, the calculated stress is always less than the actual maximum. At the Fig. 3 is a diagram for investigating relaxed deformations at any point in planar stress.

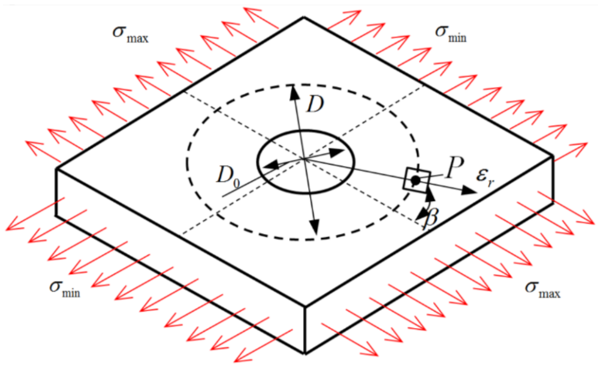


Fig. 3 Investigating loose deformations at any point at plane stress

Released surface radial deformations correspond to lightened main stresses as shown below:

$$\varepsilon_r = (\bar{A} + \bar{B}\cos 2\beta)\sigma_{max} + (\bar{A} - \bar{B}\cos 2\beta)\sigma_{min} \quad , \qquad (3)$$

where:

- ε_r represents the released deformation in the radial direction by a strain gauge centered at point P,
- $\bar{A}, \bar{B}$ are calibration constants,
- β is the angle measured against in the clockwise from the direction strain gauge to the σ_{max} direction,
- σ_{max} is the maximum main normal stress at the hole location before drilling,
- σ_{min} is the minimal main normal stress at the hole location before drilling,
- D is the mean diameter of the strain gauge,
- D_0 is the diameter of the drilled hole.

The following relationships are used to quantify the constants $\bar{A}$ and $\bar{B}$ for a material with given elastic properties:

$$\bar{A} = \frac{-\bar{a}(1+\mu)}{2E} \quad , \qquad (4)$$

$$\bar{B} = \frac{-\bar{b}}{2E} \quad , \qquad (5)$$

where:

- E is Young's modulus of elasticity,
- μ is Poisson's ratio,
- $\bar{a}, \bar{b}$ they are dimensionless and almost material-independent constants determine by the standard ASTM E837-13a.

Dimensionless and almost material-independent constants $\bar{a}$ and $\bar{b}$ vary with hole depth. $\bar{a}$ is independent of material, and $\bar{b}$ is dependent only to a small extent on Poisson's ratio. For blind holes in the Poisson's ratio in range from 0.28 to 0.33, the constants $\bar{a}$ and $\bar{b}$ change less than 1% [4].

Reflexive Photoelasticimetry

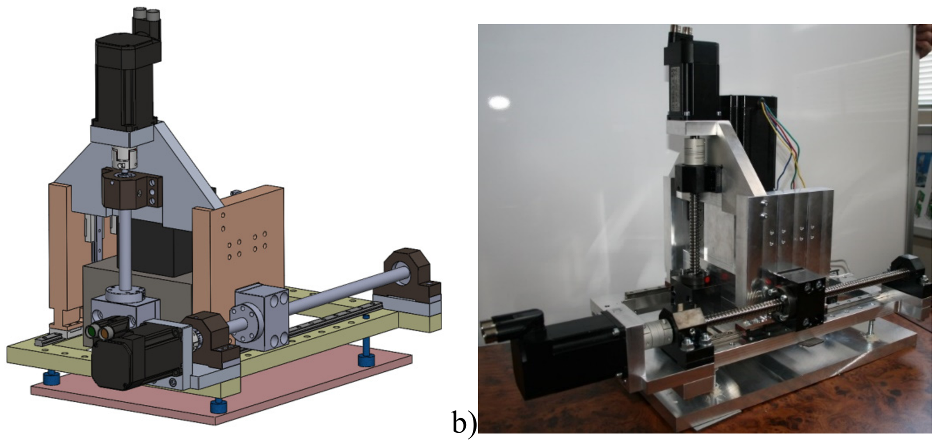
Utilization of reflexive photoelasticimetry (PhotoStress methods) is not only bound to the models of the objects under investigation, but also to the actual machine parts and assemblies. When the actual components have a high modulus of elasticity are produced their models with a lower modulus of elasticity, thereby achieving greater deformation at the same load. Neither the actual research object nor the model is made of optically sensitive material, but a thin film of optically sensitive material from the liquid components is applied thereto. Polariscop is use to investigate deformations and stresses on the surface of the test objects. After illumination with polarized light and subsequent loading can be observed through the analyzer isochromatic or isoclinic bands [13].

Design and verification of residual stress determination method using optical methods of mechanics

Despite the advances made in numerical methods, it is still not possible to unambiguously analyze the residual stresses using numerical methods. Therefore, even nowadays experimental methods in the area of detection and measurement of residual stresses have their irreplaceable place. It is necessary to know the individual stages of the experiment when stressing machine components or assemblies with drilling and optical methods and then determining stress and deformation sizes. The aim of this experimental part was to propose a methodology for determining residual stresses using optical methods, namely the PhotoStress method together with hole drilling method [11,12].

American norm ASTM E837-13a is currently the only generally accepted standard that deals with investigating residual stresses by experimental mechanics. However, there are a number of limitations in this standard. For direct drilling into the component and subsequent examination of the deformation values by optical methods, it was necessary to design and manufacture the device (Fig. 4 a,b), which would connect the two mentioned methods of detecting stresses and deformations in structural members. The idea was to design a device with an adjustable drilling head and an optical device for detecting deformation fields - the LF/Z-2 polariscope. The principle was to accurately drill into a defined depth of the component with a special cutting tool. Subsequently, by means of a stepper motor, is released by the horizontal displacement of the drilling head outside the opening the space for measuring the residual stresses by the LF/Z-2 polarisop with a compensator [8,15].

At the Fig. 4a is a view on one of the designs of a 3D model of a positionable drilling device, and at the Fig. 4b is the resulting real constructed device. The motors are used for horizontal and vertical movement of the drilling head and for rotating the drill or milling cutter.



a) b)

Fig. 4 Proposal of the drilling device (a) and really configurable positioning drilling device (b)

The precise positioning drilling device was largely constructed from aluminum alloy due to its satisfactory strength and total weight of the device. Subsequently was tested the accuracy of the drilling device for horizontal and vertical movement of the drilling head and drilling through the unloaded samples with already applied photoelastic coating. Also tested was a hydraulic load device located in the newly built Prototyping and Innovation Center of the Faculty of Mechanical Engineering TUKE, which is capable of generating loads of up to 100 kN in two direction. The annealed samples were drilled under load and through the polarizing device and the photoelastic coating were examined the formed entities [16].

In the following section of experimental testing and investigatinf of stress fields, was designed an aluminum sample of dimensions and shape as shown in Fig. 5. The shape of the samples, resp. its 65 mm edges, were adapted for further testing by other methods for detecting stresses and deformation fields in the component.

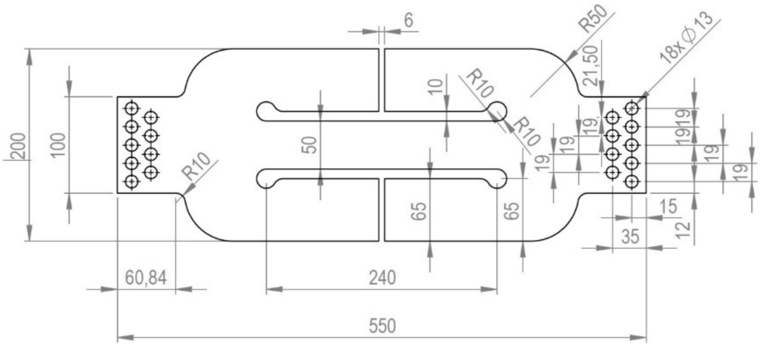


Fig. 5 Shape and dimensions of samples used for drilling detection and optical method PhotoStress

The sample was annealed to eliminate residual stresses. A photoelastic coating PS-1D was consist of a two-component adhesive (resin + hardener) was applied to the sample from aluminum as indicated by the manufacturer [15,16].

Furthermore, the simulated stresses were determined on a uniaxially loaded aluminum sample. It consisted in the gradual drilling of the blind hole and the subsequent observation of the emerging photoelastic entities in its vicinity. A strain gauge cross was applied to the test sample to check the stability of the induced load (Fig. 6). Each grid was connected to the quarter bridge. Time warp was recorded and evaluated by Catman Easy.


Fig. 6 Aluminium sample with applied strain gauge cross

At the Fig. 7 is a view on a drilling process on an aluminum sample loaded with a hydraulic loading apparatus and stress measuring by optical apparatus LF/Z-2 .


Fig. 7 Drilling with positioning device and measuring of stresses with the optical device LF/Z-2

The mill cutter speed with diameter 3.2 mm (or 18 mm) was 120 rpm. The released relative deformations around the blind hole were analyzed in twenty steps with an increment of 0.1 mm. During the whole measurement, the tensile force was 7.5 kN. By moving the drilling head in the horizontal direction to a position allowing the use of the polarisop, directions and differences of the main proportional deformations were observed. After each step were created images of isoclinic and isochromatic lines (Fig. 8).

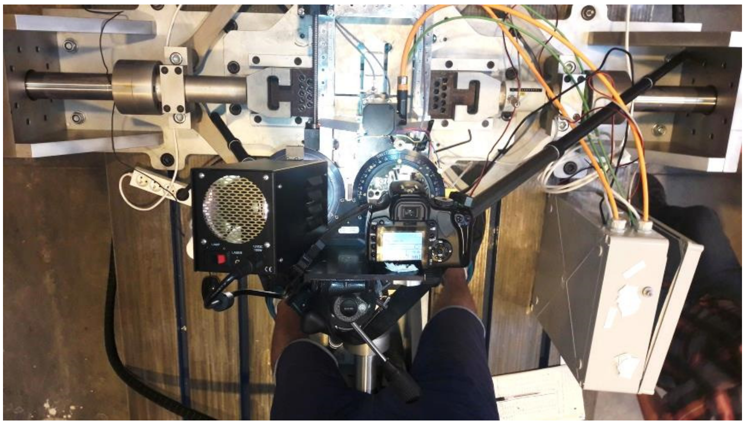


Fig. 8 Process of registration of isoclinic and isochromatic lines with a polarisope LF/Z-2

The entire measurement phase without the application of strain gauge and photoelastic coating took approximately 2 hours. At the Fig. 9 is a more detailed time record of the vertical displacement of the drilling head into the annealed sample registered by the displacement sensor.

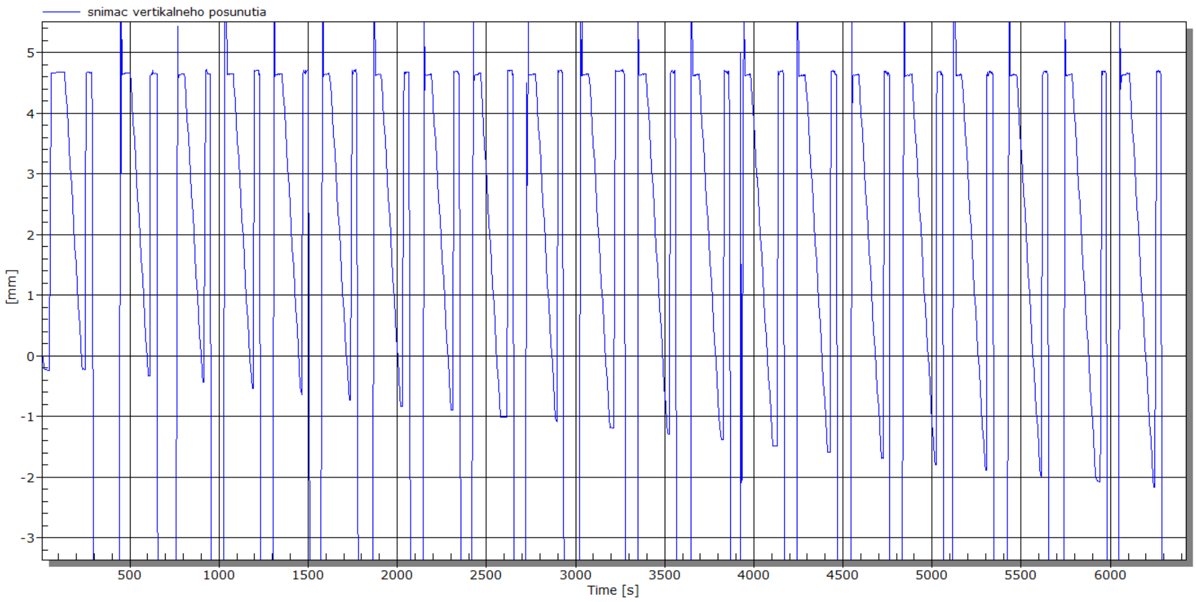


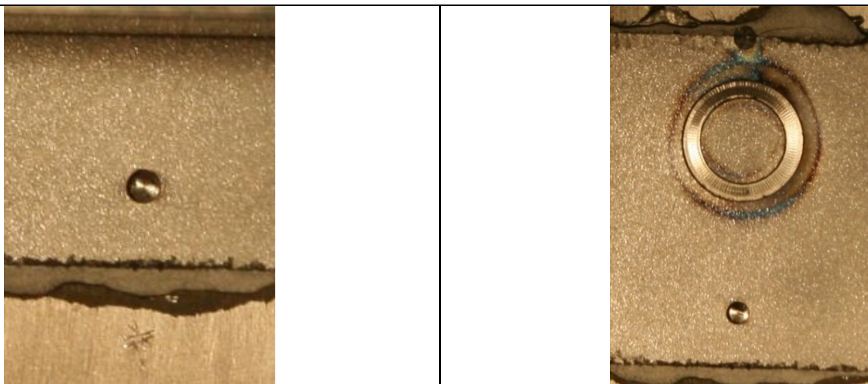
Fig. 9 Time recording from vertical movement of hole drilling

In the next section, isochromatic lines for a given depth of 0.5 mm (Fig. 10), 1.0 mm (Fig. 11), 1.5 mm (Fig. 12) and 2 mm (Fig. 13) are given for comparison of the released strain ratios. Blind hole drilling was not realized for larger depths (in teres of ASTM E 837-13a). From Fig. 10 - Fig. 13 it stands to reson that more pronounced bands (isochromatic lines) are more visible when drilling an annular groove, which corresponds to the results of numerical modeling. Despite this, it can be stated that these are relatively low stresses levels, their quantification is more demanding and the measurement inaccuracy is also higher in this case. On the other hand, low levels of simulated "residual" stresses do not pose a risk to the safe operation of machinery and equipment. Higher sensitivity of the simulated stress measurement is possible by using an optically sensitive coating with a greater thickness, which however limits the use of cutting tools (milling cutter or hollow cutter).

Within the proposed methodology of quantification of residual stresses using the PhotoStress method, it was due to the comparison of achieved results with the method of drilling, resp. Ring-Core method considered using identical cutting tools 3.2 mm diameter cutter used with RS-200 and hollow cutter used with SINT-MTS 3000 Ring-Core. The limiting factor is the shape of the cutting tools for drilling the blind hole, respectively. an annular groove, since the thickness of the adhesive and the coating used had to be added to the depth itself. Therefore was used the thinnest coating of PS-1D with a thickness of 0.5 mm.

a) b)

Fig. 10 Isochromatic lines for 0.5 mm depth a) blind hole, b) annular groove

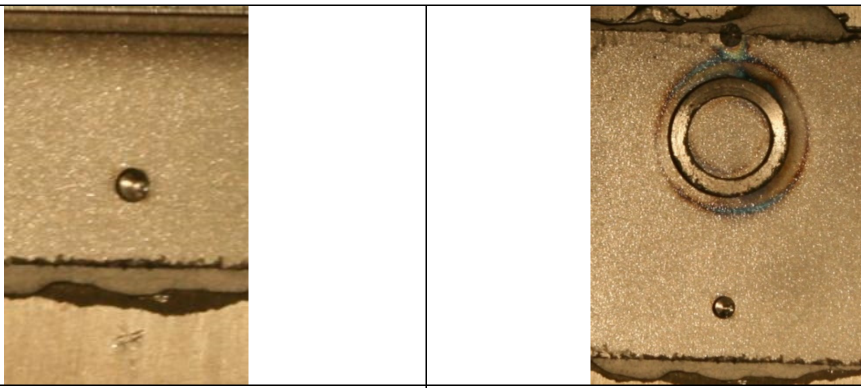


a) b)

Fig. 11 Isochromatic lines for 1.0 mm depth a) blind hole, b) annular groove

a) b)

Fig. 12 Isochromatic lines for 1.5 mm depth a) blind hole, b) annular groove



a) b)

Fig. 13 Isochromatic lines for 2.0 mm depth a) blind hole, b) annular groove

The time recording of the relative deformations in the test sample during the experimental measurements is shown in Fig. 14. It is clear from the figure that there were no significant variations during the measurement, the correct operation has been confirmed of the simulated load-causing hydraulic load device. The hydraulic loading device can be considered as one of the key elements of the measurement chain, since if the stress in the sample analyzed is changed in the experiment, the obtained results could not be considered as relevant.

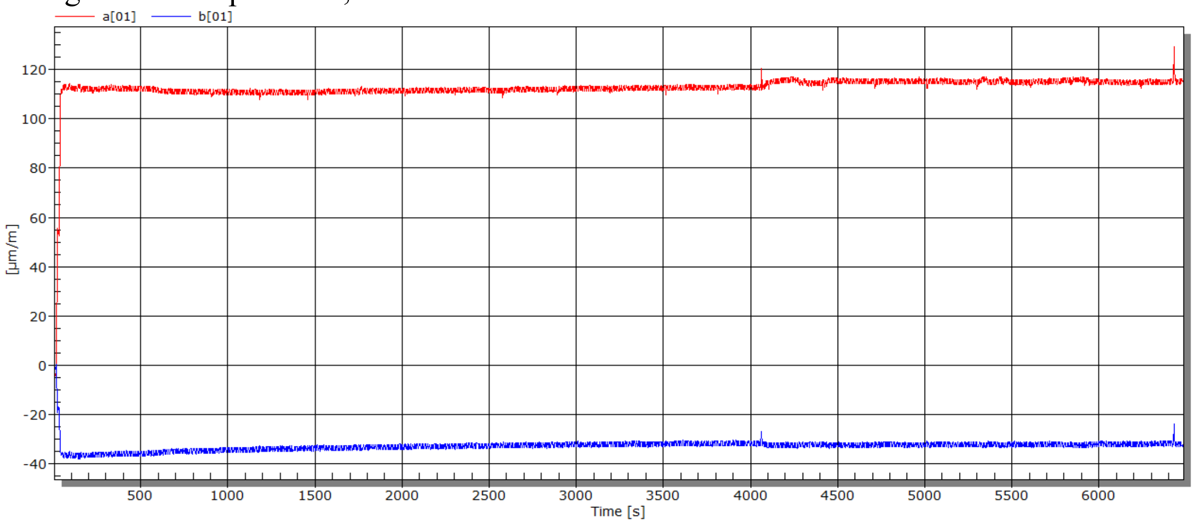


Fig. 14 Time recording of relative deformations on loaded test sample

Conclusions

In the submitted paper, the methodology of quantification of residual stresses was proposed and verified. On the basis of the results obtained, it can be stated that an accurate positioning device has been designed to evaluate the released relative deformations during the progressive drilling of the blind hole, respectively an annular groove using the PhotoStress optical method. These devices were used in experimental measurements on unloaded samples as well as annealed samples loaded with simulated loads. On the basis of the analysis of isochromatic bands around a 3.2 mm diameter blind hole and around a groove with an outer diameter of 18 mm and an internal diameter of 14 mm registered with a reflection polarisop, it can be concluded that the more visible deformations are around the annular groove. For experimental measurement, the PS-1D coating was chosen to achieve the lower adhesive and coating thickness. The disadvantage of said coating is less sensitivity to the deformation released. It is true that the thicker the coating, the more accurate the measurement. This fact will be dealt with in the next period, as the cutting tools used by RS-200 or SINT-MTS 3000 Ring-Core devices were used in the present work.

The advantage of applying the optical method for quantifying residual stresses is, among other things, the possibility of full-field deformation analysis in the investigated area on a real structure or device. Despite the good consensus of the results obtained by experimental measurement and numerical computation, which is part of the work [16], the results achieved cannot be considered final.

There is wide scope for:

- research into the possibility of using the proposed methodology for inhomogeneous, anisotropic, composite materials,
- optimizing the design of the pointing device not only to reduce its weight but also to position it in the third axis, allowing the device to be used for the drilling method, respectively Ring-Core,
- use of the proposed equipment not only for the PhotoStress method, but also in combination with the DIC (Digital Image Corelation) method, with which we also have extensive experience in the area of deformation and stress analysis in the vicinity of concentrators at the KAMASI workplace,
- automating the drilling and strip reading process by compensator, not only significantly reducing the length of the experimental measurement, but also eliminating the adverse effect of the human factor e.g. when positioning the device, etc,
- testing new cutting tools.

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