53rd CONFERENCE ON EXPERIMENTAL STRESS ANALYSIS
Český Krumlov, Czech Republic, June 1–4, 2015
pp. 454–459

Hole-Drilling Method with Inverse Layers Removing

J. Václavík [1,*], S. Holý [2], J. Jankovec [1], P. Jaroš [3], O. Weinberg [1]

[1] *Výzkumný a zkušební ústav Plzeň s.r.o, Tylova 1581/46, 301 00 Plzeň, Czech Republic*
[2] *CTU in Prague, Institute of Mechanics, Mechanical Faculty, Technická 4, Prague, Czech Republic*
[3] *Private Researcher, Prague, Czech Republic*
[*] *vaclavik@vzuplzen.cz*

Abstract: The method for residual stress measurement using through the hole drilling and investigation of the residual stresses relief with the help of incremental layers removing is presented. Drilling the rosette-hole from the opposite side – the inverse layers removing – have to be used for evaluation of residual stress near the back side of the object wall in cases when this surface is inaccessible for any hole-drilling instrument. The strain gauge rosette is installed on the opposite side of the drilled wall and a new mechanical task of incremental layers removal must be solved. The calibration constants for residual stress evaluation of HBM RY21 type rosette for this case were derived using numerical modelling by FEA and its experimental verification.

Keywords: Hole-Drilling Method; Residual Stresses; Incremental Drilling Method; Thick Specimen.

1 Introduction

Residual stresses are very important characteristics for the structure. Investigation of them is often performed using hole-drilling strain gage method, first proposed by Mathar [1]. The calculation of residual stress distribution around the through-hole can be performed using the analytical solution, obtained by G.Kirsch [2], which however is applicable only for thin specimens. For thick specimens, the possibility of residual stresses determination drilling the blind hole was introduced by Rendler and Vigness [3]. For this calculation some conversion constants have to be derived using FEA. These FEA coefficients for blind-hole analysis were derived first by Schajer [4]. Later, the FEA solution for determination the residual stress profile under the surface using integral method was also proposed by the same author and both methods were implemented to ASTM E837 [5]. At present, both methods are presented in enhanced forms to lower the measurement uncertainty in this standard; for stress uniform with the depth the power-series method and for residual stress, changing with the depth, the regularization method are used. In other works, the correction for drilled hole asymmetry or for elastic – plastic strain have been published. The procedures for common tasks using the hole-drilling method for surface and subsurface stresses were verified for long time.

In some cases the knowledge of residual stress near the back side wall of investigated object is demanded by some customers. These surfaces are often inaccessible for any hole-drilling tool, see the casting of turbine casing in Fig 1 as an example.

However, if this back surface is accessible enough to glue the strain gauge rosette, it can be drilled from front side and the residual stresses can be derived from the relieved strains at this rosette but with inverse sequence of layers removal. This is quite different task in comparison to the standard hole-drilling method, see Fig. 2. We have called this method as *inverse hole-drilling method*. For this method, the depth z represents the thickness of remaining bridge of material under the surface, whilst in standard hole-drilling method z is the direct depth of the hole.

To center the rosette against the drilled hole, the pre-drilling of the hole with smaller diameter is required. The aim of this article is to investigate the sensitivity of this method in comparison with direct hole drilling and the sensitivity drop due to the hole pre-drilling, to examine the feasibility of the procedure and to verify the computational results by experiment.

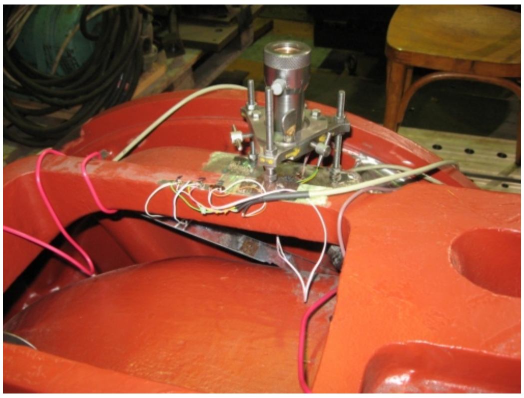

Fig. 1: Example of the turbine case, where the measurement of residual stress on both front and bottom surfaces was performed.

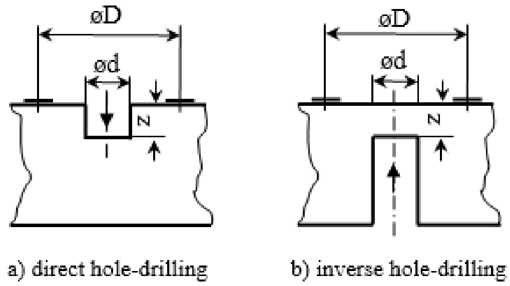

Fig. 2: Comparison of removing layers in direct and inverse hole-drilling methods.

2 Numerical Model of the Method Using FEA

The hole-drilling method involves attaching generally rectangular three-element strain gage rosette to the surface, drilling a hole in the rosette center and measuring the relieved strains ε_1, ε_2, ε_3 at individual counter-clockwise marked strain gauges. The measured strains are related to residual principal stresses through a set of equations using coefficients $\overline{a}$, $\overline{b}$, which are derived using FEA [6] and for three types of rosettes are given in standard [5]. For uniaxial stress uniform through the depth the coefficients are

$$\overline{a} = -\frac{\varepsilon_1 + \varepsilon_3}{(1+\mu)\cdot \varepsilon_{\max}}\,, \qquad \overline{b} = -\frac{\varepsilon_1 - \varepsilon_3}{\varepsilon_{\max}} \tag{1}$$

For our purpose the FEA model for layers removing has been created for geometry of the HBM rosette RY21 on both front and back side of rectangular bar with the uniformly distributed uniaxial stress through the depth. Two cases were solved: i) the hole was directly drilled with diameter 4 mm, ii) the hole was pre-drilled with the diameter 2 mm and then finally drilled with the diameter 4 mm. The thickness of removing layers was 0.5 mm.

- the 2D mesh creation – the areas of hole and strain-gauges are specified
- the 3D mesh creation – extrusion of the 2D mesh, here the lengths of the extrusion correspond to the mentioned hole-depth increments.

In Fig. 3 there are graphically distinguished meshes of different areas - area lying between strain gauges, area of the hole, area of strain gauges, connecting area and area where the element size is growing. Some of these areas are meshed with the automatic meshing procedure (with the specified parameter - basic mesh size) and some of the areas are meshed using parametric meshing procedure. The number of elements on edges of parametrically meshed areas size in the parametric meshing area was calculated along mesh size on boundaries of the automatic meshed area. The used element type is SOLID (8-node solid elements with three translational degrees of freedom per node). The used integration type is the default 8-node hybrid element - displacement and stress-based (mixed) formulation ($2 \times 22 \times 2$ integration points). The iterative PCG-solver was used to solve the linear elastic problem. The average strains computed from the 9 virtual fibers of each strain gauge were the results from these calculations. These values were used for evaluation of calibrating coefficients. For the illustration the resulting equivalent stress field one step before the end of the hole-drilling process is shown also in the Fig. 3.

The relaxation coefficients calculated according Eq. (1) for 2 mm pre-drilled hole, 4 mm final drilling diameter and rosette HBM RY21 based on FEA are given in Tab. 1. Calculation was performed from front rosette strains (dir) and from bottom rosette strains related to the full relieved strain (inv).

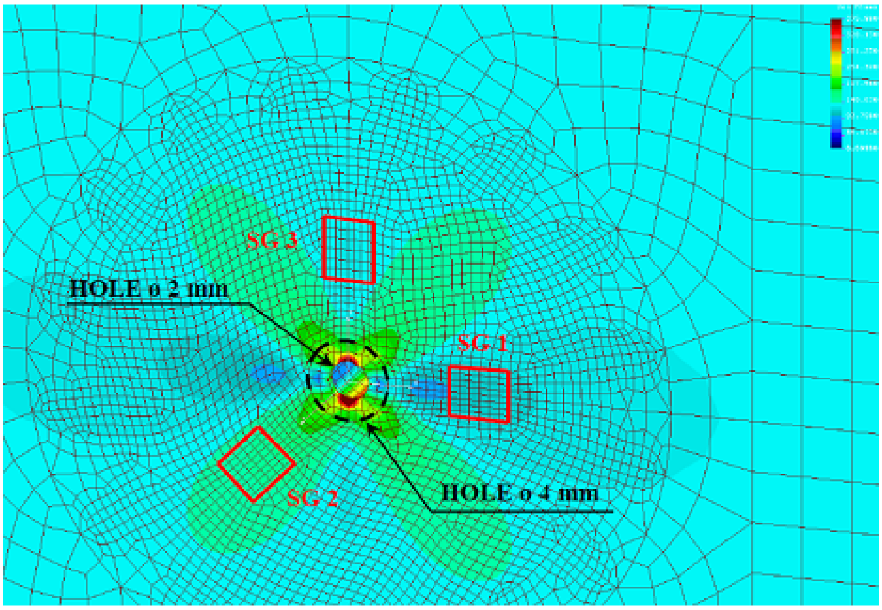

Fig. 3: FEA meshes and HMH stress distribution around the drilled hole including strain gauge rosette position – view from the opposite side, the rest depth before drilling through is here 0.5 mm.

Tab. 1: Evaluated relaxation coefficients for upper and bottom surface residual stresses.

z/D	a - dir	a - inv	b - dir	b - inv
0.038	0.016	0.033	0.030	0.071
0.077	0.035	0.055	0.070	0.125
0.115	0.051	0.070	0.111	0.168
0.154	0.065	0.080	0.147	0.200
0.231	0.080	0.088	0.199	0.237

3 Experimental Verification

3.1 Sample and Loading Machine

The experimental verification was performed on the steel rectangular bar 100 × 80 × 10 mm, material ČSN 11 523 (DIN St 52), yield point Re = 290 MPa, under uniaxial stress (ε_n = 657 μm·m^{-1}). The servo-hydraulic testing machine SCHENCK PC 400M (range 400 kN) under controlled force was used for the test (Fig. 4). The hole drilling was performed at loaded sample.

The strain gauge rosettes HBM RY21 was glued using Vishay AE10 epoxy adhesive.

A precision milling guide, common to Vishay RS 200, the carbide drill ø2 mm and the carbide two-bit end milling cutter ø4 mm driven by a standard hand drilling machine were used for drilling the hole.

3.2 Data Acquisition and Evaluation

Data acquisition was performed using 8-channel measuring amplifier, connected to PC. Evaluation of obtained strains was performed with the help of procedures inside MS Excel.

3.3 Specific Features of Inversion Method

The goal of the inversion method is to obtain the distribution of sub-surface residual stresses on the inaccessible back side of the nearly planar wall of the tested object. The residual stresses on the front side can be measured at the same time.

If this back surface is accessible enough to glue the strain gauge rosette, it can be drilled from front side and the residual stresses can be derived from the relieved strains at this rosette but with inverse sequence of

(a) loading machine used for the test

(b) back side of the sample

Fig. 4: Experimental verification on the testing machine.

layers removal. To center the rosette against the drilled hole, the pre-drilling of the hole with smaller diameter is required.

Firstly the front rosette is glued with standard procedure. Then the hole ø2 mm has to be predrilled through whole the object wall using the milling guide. The second rosette is then glued to the opposite wall. To center this rosette a pin of diameter 2 mm inserted into original rosette centering hole of the same diameter is advantageous. The milling is performed in steps, with higher resolution near both front and bottom surfaces. In comparison with drilling the front side rosette, higher attention has to be paid to the adjustment of the milling device. Small inaccuracies in centering the rosette or bad alignment with the pre-drilled hole create high misalignment of the drilled hole on the back-side rosette.

The evaluation of the actual residual stresses is performed with the help by FEA evaluated constants (1) using power-series method (at present) for measured released strain vectors at each rosette strain gauge ε_1, ε_2 and ε_3. First the combination strains p, q and t (2) and from them the combination stress vectors P, Q and T are calculated (3). Then the in-plane Cartesian stresses σ_x, σ_y and τ_{xy} are given according Eq. (4) and principal stresses σ_{max} and $\sigma_{min}$and the angle β from two-parameter arctan are given according Eq. (5).

$$p = (\varepsilon_3 + \varepsilon_1)/2 \qquad q = (\varepsilon_3 - \varepsilon_1)/2 \qquad t = (\varepsilon_3 + \varepsilon_1 - 2\varepsilon_2)/2 \tag{2}$$

$$P = \frac{\sigma_y + \sigma_x}{2} = -\frac{E \cdot p}{\bar{a} \cdot (1+\nu)}, \quad Q = \frac{\sigma_y - \sigma_x}{2} = -\frac{E \cdot q}{\bar{b}}, \quad T = \tau_{xy} = -\frac{E \cdot t}{\bar{b}} \tag{3}$$

$$\sigma_x = P - Q, \qquad \sigma_y = P + Q, \qquad \tau_{xy} = T \tag{4}$$

$$\sigma_{\max}, \sigma_{\min} = P \pm \sqrt{Q^2 + T^2} \qquad \beta = \frac{1}{2} \arctan\left(\frac{T}{Q}\right) \tag{5}$$

3.4 Realized Experiments

Three tests were performed on separate tested pieces under uniaxial tensile stress in the frame of testing device under testing force of 110 kN. In each sample the hole ø2 mm was pre-drilled. The drilling step was Δz = 0.4 mm to the depth 8.8 mm, after then Δz = 0.2 mm for the diameter ø4 mm.

The last test was performed on the third piece with new set of rosettes, positioned at the sufficient distance from the old ones from the third test. The aim of the last test was to investigate the influence of lower stress level to the profile of released strain.

4 Summary of Retrieved Findings

According performed experiments it has been demonstrated, that the inverse hole-drilling is well applicable method. This fact has been also proven during measurement on turbine case (Fig. 1), which results are not presented here. Nevertheless, there are some shortcomings, which can influence the measurement results.

During each performed test the back-side rosette never has been drilled sufficiently to its centre, e.g. the correction for the hole asymmetry has to be taken in to account. The reason for this was that the milling guide was re-adjusted between pre-drilling and final drilling. It is recommended leave the milling guide in its position when gluing the back rosette.

It was also found, that the shallow circular grove by the depth slightly more than the thickness of the rosette carrier film and the diameter slightly higher than the drilled hole should be performed on the back-side rosette before final drilling. This prevents rosette central part separation after the hole is drilled through.

The most serious finding for all performed tests was that the slope of released strain curves drops expressively starting with the depth of about 0.6 mm under the opposite wall. The first assumption was that it is caused due to high stress concentration leading to plasticization of the rest material bridge. But after lowering the applied stress level, the relieved strain characteristics has not changed. Our hypothesis is that before the drilling the hole through the material plasticizing occurs in the front of drilling milling tool, which causes the relaxation of stresses between the tool and the back surface at the final phase. By reason of this fact, there is not possible at present to evaluate the stress profile at the last layers of the back surface, but only the average stress considering that the stress is homogenous. The best suitable procedure for this is the power series method, described in chapter 3.3.

5 Results of Investigations

The computed relieved strains divided by main principal strain are plotted in Fig. 5 for rosette grid G1 to G3 both for the direct drilled hole 4 mm (0-4) and for 2 mm pre-drilled hole (2-4), z is the hole depth and D rosette diameter. To have direct comparison between the sensitivity of both rosettes, the strains for back-side rosette are plotted here reverse as differences related to full relieved strain. There is clearly seen from these curves that the shape of relieved strains show higher gradient for bottom rosette in comparison with the front one. However the sensitivity drops due to the predrilled hole, which is also demonstrated in Fig. 5. Both facts were also verified by the experiment.

Comparison between calculated (FEA) and experimentally obtained (exp) relieved strains on both upper (dir) and a bottom (inv) rosette is presented in Fig. 6. Only the results from one test are presented here, but there are not fundamental deviations in comparison with other tests. The characters of both computed and measured released strains are similar (for the front rosette is even the same). The experimentally obtained values for the bottom rosette have slightly higher gradient till to 0.6 mm under the surface and then the gradient become very low in comparison with FEA results (see especially the curve ε_1) and expectation.

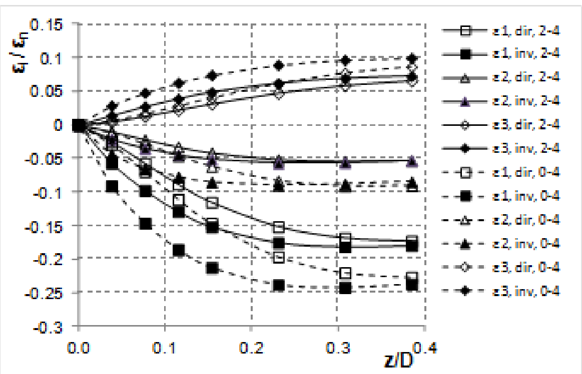

Fig. 5: Relative relieved strains during layers removing on both front and bottom rosettes.

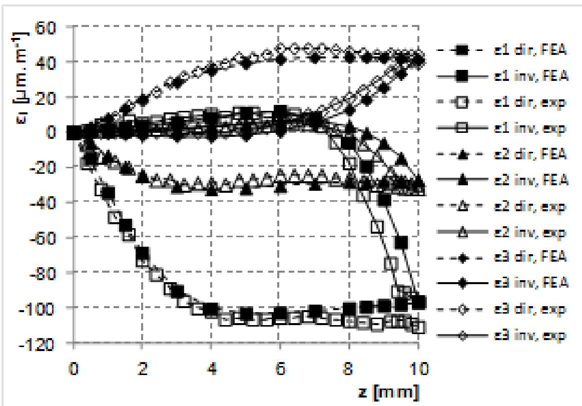

Fig. 6: Comparison of relieved FEA and measured strains on both front and bottom rosettes.

6 Conclusion

It has been both experimentally and theoretically proved, that the *hole-drilling with inverse incremental layers removing* is applicable method for residual stress determination on poor accessible surfaces with noticeable differences in comparison with the direct drilling, which can be summarized as follows:

- the shape of relieved strain characteristics performed higher gradient on hole bottom distance from surface with the rosette,
- necessity of pre-drilling slightly decreases the level of final strain relieve signal, e.g. predrilling of 2 mm through hole reduces the relieve during 4 mm re-drill about 20 %,
- limit of exactly determined residual stress will be probably still lower than in case of direct drilling due to higher stress concentration in area of the hole bottom.

Acknowledgement

The article has originated in the framework of the institutional support for the long-term conceptual development of the research organization.

References

[1] J. Mathar, Determination of Initial Stresses by Measuring the Deformation Around Drilled Holes, Trans., ASME 56, No. 4: 249-254 (1934).

[2] G. Kirsch, Theory of Elasticity and Application in Strength of Materials, Zeitchrift Vevein Deutscher Ingenieure, 42 (29), pp. 797-807, 1898.

[3] N. J. Rendler, I. Vigness, Hole-Drilling Strain-Gauge Method of Measuring Res. Stresses, Exp. Mech. 6, No. 12, (1966).

[4] G .S. Schajer, Measurement of Non-uniform residual stress using the hole-drilling method, Journal of Engineering materials and technology, Vol. 110, No. 4, (1988), Part 1: pp. 338-343, Part II: pp. 344-349.

[5] ASTM E837-13a, Standard Test Method for Determining Residual Stresses by Hole-drilling Strain-gage Method. American Society for Testing and Materials, September 2013.

[6] O. Weinberg et al., Experimental Calibration of Computational Constants for Hole-drilling Method, Proceedings Paper in: 13th conference ICEM 13, Alexandroupolis, Greece, 2007, pp. 477-478.