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Determination of principal residual stresses' directions by incremental strain method

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Abstract

The ring-core method is the semi-destructive experimental method used for evaluation of the homogeneous and non-homogeneous residual stresses, acting over depth of drilled core. By using incremental strain method (ISM) for the residual state of stress determination, this article describes procedure how unknown directions and magnitudes of principal residual stresses can be determined. Finite element method (FEM) is used for the numerical simulation of homogenous residual state of stress and for subsequent strain determination. Relieved strains on the top of the model's core are measured by simulated three-element strain gauge, turned by the axis of strain gauge "a" from the direction of the principal stress σ_1 about unknown angle α. Depth dependent magnitudes of relieved strains, their differences and set of known values of calibration coefficients K_1 and K_2 or relaxation coefficients A and B are used together for determination of the angle α and for re-calculation of principal stresses.

Keywords: ring-core method, incremental strain method, residual stress, calibration coefficients, strain gauge

1. Introduction

The ring-core method (RCM) is a semi-destructive experimental method used for the evaluation of homogeneous and non-homogeneous residual stresses, acting over depth of drilled core. Therefore, the specimen is not totally destroyed during measurement and it could be used for further application in many cases.

One of the applicable theories, based on the procedure of evaluating magnitude of the residual stress, is called the incremental strain method (ISM). It is still used quite often, despite its numerous theoretical shortcomings. On the one hand, ISM assumes that the measured deformations $d\varepsilon_a$, $d\varepsilon_b$ and $d\varepsilon_c$ are functions only of the residual stresses acting in the current depth "z" of the drilled hole and they do not depend on the previous increments "dz" including another residual stresses, see Fig. 1. On the other hand, relieved strains do not depend only on the stress acting within the drilled layer, but also on the geometric changes of the ring groove during deepening. Consequently, strain relaxations are still continuing and grooving with drilled depth, even though the next step's increment is stress free. Therefore, the proposed theory purveys only approximate information about the real state of stress and RCM method is not suitable for the types of measurements with a steep gradient of residual state of stress.

By using incremental strain method for the residual state of stress determination and FEM, this article describes procedure how directions of the principal residual stresses can be determined. Finite element method is used for the numerical simulation of homogenous residual state of stress and relieved strains on the top of the model's core are measured by simulated

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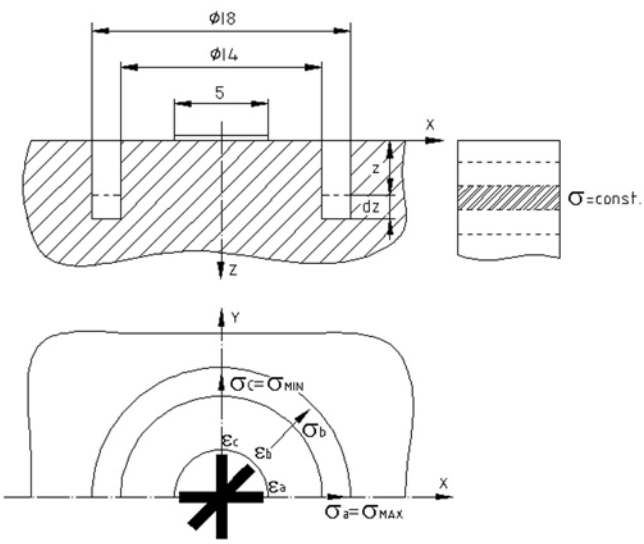

Fig. 1. Principle of ISM with known directions of principal stresses ($\alpha = 0°$)

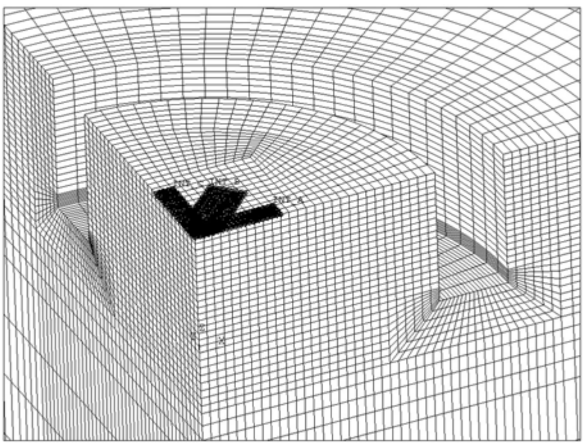

Fig. 2. Strain gauges "a, b, c" placed in principal stress directions

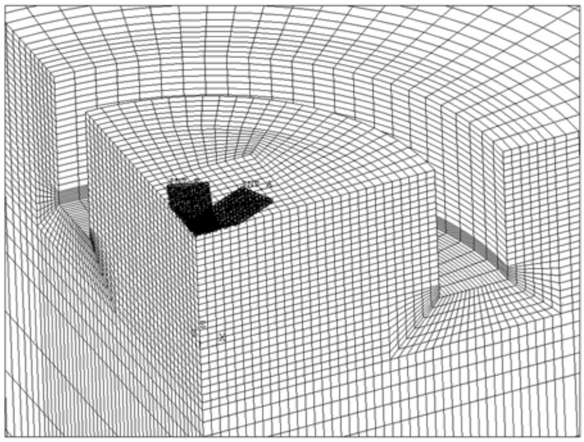

Fig. 3. Strain gauges "a, b, c" placed in general direction

three-element strain gauge rosette, turned by the axis of the strain gauge "a" from the direction of the principal stress σ_1 about unknown angle α (Fig. 3).

2. Problem description

Like the integral method, the incremental strain method requires a set of depth-dependent coefficients, which are necessary for further residual stress determination, carried out by the ring-core method in this case. Values of calibration coefficients K_1 and K_2 have been already determined by the simulation under various types of uniaxial and biaxial state of stress conditions and published in articles [2, 3] and [1, 7]. Their dependence on the depth of drilled hole and on the disposition of the homogenous residual state of stress as well as geometry changes of the annular groove and finite element model's dimensions have been considered too. Another way, how to determine residual state of stress between two specifics depths of drilled groove, is possible by calculation of relaxation coefficients A and B.

This paper deals with results obtained by the FE-measurement of relieved strains ε_a, ε_b and ε_c, by generally placed strain gauge rosette on the top of the core, where their differences and set of known values of calibration coefficients K_1 and K_2 or relaxation coefficients A and B

is used for the proper determination of the principal stresses σ_1 and σ_2. Placing of the three-element strain gauge rosette on the top of the ring-core is shown in case of known direction of principal residual stress (Fig. 2) and in case of general direction (Fig. 3).

3. Basic equations

Like each method, incremental strain method has its own theoretical background to define certain relations between known and unknown parameters. Residual state of stress can be determined either by differentials or differences of relieved strains.

3.1. Using calibration coefficients K_1 and K_2

Equations (2)–(4) describe strain differentials, used to express determination of the principal stress σ_1 and σ_2 by the known set of calibration coefficients K_1, K_2, calculated from principal strains ε_1 and ε_2 on the top surface of the core, where the three-element ring-core rosette is placed ([1–3] and [5]).

Relieved general strains ε_a, ε_b and ε_c are measured every i-th step of drilled depth z_i and size of step's difference Δz is always referred to the previous step's size (z_{i-1}). Magnitude of each step used in FEM simulation (1) is $\Delta z = \text{const.} = 0.2$ mm

$$\Delta z = z_i - z_{i-1} = 0.2\,\text{mm}, \text{ for } i = 1 \div 40. \tag{1}$$

With known magnitude of the calibration coefficient K_1, K_2 (Fig. 4 and 5, Table 1) and relevant derivation of principal strains $d\varepsilon_1/dz$ and $d\varepsilon_2/dz$ in dependence on the specific magnitude of step's increment dz could by principal stresses of *homogenous* residual state of stress obtained by following equations:

$$\sigma_1 = \frac{E}{K_1^2 - \mu^2 K_2^2} \cdot \left(K_1 \frac{d\varepsilon_1}{dz} + \mu K_2 \frac{d\varepsilon_2}{dz} \right), \tag{2}$$

$$\sigma_2 = \frac{E}{K_1^2 - \mu^2 K_2^2} \cdot \left(K_1 \frac{d\varepsilon_2}{dz} + \mu K_2 \frac{d\varepsilon_1}{dz} \right), \tag{3}$$

$$\frac{d\varepsilon_1}{dz} = \varepsilon_1', \quad \frac{d\varepsilon_2}{dz} = \varepsilon_2', \tag{4}$$

where E is Young's modulus, μ is Poisson's ratio and ε_1', ε_2' are numerical derivations of relieved strains.

Attention should be paid to formulations suggested in (2), (3). If the denominator $K_1^2 - \mu^2 K_2^2$ becomes zero for certain values of K_1 and K_2, the stress will become infinite, i.e. for steel material with $0.3 \cong \mu = K_1/K_2$. Further, expressions of (2)–(4) could be modified into equations used for determination of calibration coefficients under uniaxial and biaxial state of stress conditions.

In case of the uniaxial state of stress, ($\sigma_1 \neq 0$, $\sigma_2 = 0$), equations for the calibration coefficients K_1, K_2 are described by:

$$K_1 = \frac{E}{\sigma_1} \cdot \varepsilon_1', \qquad K_2 = -\frac{E}{\mu \sigma_1} \cdot \varepsilon_2'. \tag{5}$$

In case of the biaxial state of stress ($\sigma_1 \neq 0$, $\sigma_2 \neq 0$), equations for calibration coefficients K_1 and K_2 are described by:

$$K_1 = \frac{E}{\sigma_1(1-\kappa^2)} \cdot (\varepsilon_1' - \kappa \cdot \varepsilon_2'), \tag{6}$$

$$K_2 = \frac{E}{\mu\sigma_1(1-\kappa^2)} \cdot (\kappa \cdot \varepsilon_1' - \varepsilon_2'), \tag{7}$$

$$\kappa = \frac{\sigma_2}{\sigma_1}. \tag{8}$$

Formulations suggested by (6) and (7) have a problem with the denominator too. If $\sigma_1 = \sigma_2$ or $\sigma_1 = -\sigma_2$, then $(1 - \kappa^2)$ becomes zero and magnitude of calibration coefficient will become infinite.

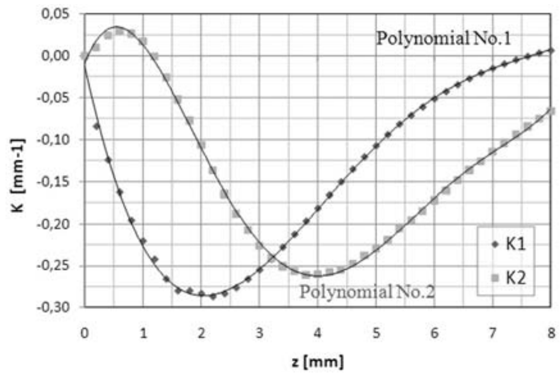

Fig. 4. Calibration coefficients determined under uniaxial residual state of stress simulation

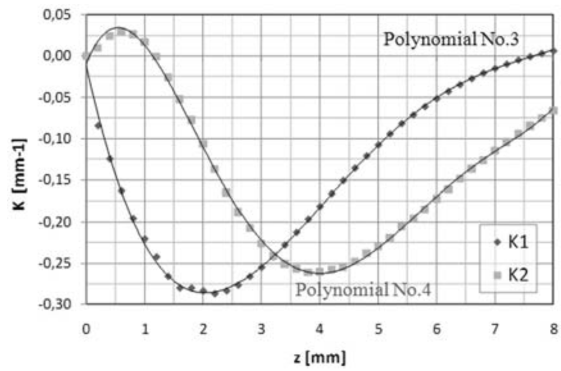

Fig. 5. Calibration coefficients determined under biaxial residual state of stress simulation

Calculated points of calibration coefficients K_1, K_2 in dependence on the drilled depth of the ring-groove are plotted in Figs. 4 and 5. Appropriate polynomial functions of the sixth degree with constants reproduced by (9) are written in Table 1.

Table 1. Coefficients of polynomial functions

Polyno-mial No.:	Coefficients [–]						
	$\mathbf{a}_0$	$\mathbf{a}_1$	$\mathbf{a}_2$	$\mathbf{a}_3$	$\mathbf{a}_4$	$\mathbf{a}_5$	$\mathbf{a}_6$
1	−0,010 670 4	−0,314 649 7	0,111 879 8	−0,011 659 6	−0,000 084 8	0,000 075 7	−0,000 003 0
2	−0,010 055 6	0,173 809 1	−0,205 010 2	0,057 055 6	−0,005 849 3	0,000 150 4	0,000 005 7
3	−0,010 676 9	−0,314 756 6	0,112 016 7	−0,011 715 9	−0,000 074 6	0,000 074 8	−0,000 003 0
4	−0,010 161 6	0,173 977 5	−0,204 814 0	0,056 843 4	−0,005 784 4	0,000 142 2	0,000 006 1

Entire hole was made by 40 increments of step's size $\Delta z = 0.2$ mm. In Figs. 4 and 5 is obvious, that behavior of K_1 and K_2 polynomial functions still remains the same for various magnitudes of simulated uniaxial and biaxial states of stress [3]. Therefore, no change in the numerical evaluation of calibration coefficients K_1 and K_2 is observed, because modification of homogenous state of stress have no influence on calibration coefficients determination. For this reason, only one universal set of calibration coefficients K_1 and K_2 is applicable.

$$K_i = a_0 + a_1 z^1 + a_2 z^2 + a_3 z^3 + a_4 z^4 + a_5 z^5 + a_6 z^6. \tag{9}$$

Polynomial constants in Table 1 prove the fact that the functions of calibration coefficients K_1 and K_2 are the same for various types of simulated homogenous residual states of stress, i.e. only one universal set of calibration coefficients K_1 and K_2 is applicable.

Dependence of the calibration coefficient K_2 on type of the residual state of stress was published by Hwang [4], but this contention was disproved.

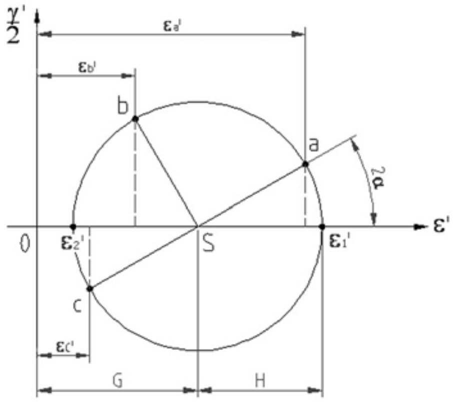

Fig. 6. Modified Mohr's circle for strain

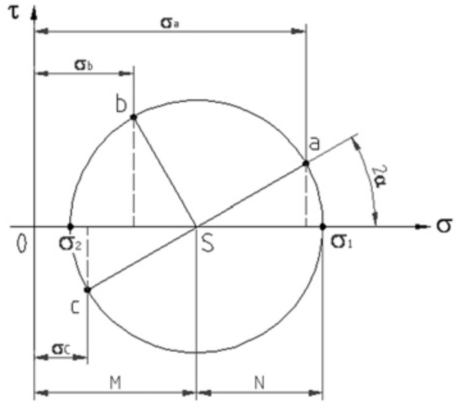

Fig. 7. Mohr's circle for stress

3.2. Determination of principal stresses with unknown principal directions

Relationship between principal strains $\varepsilon'_1, \varepsilon'_2$ and general strains $\varepsilon'_a, \varepsilon'_b, \varepsilon'_c$ measured in unknown angle α between direction of principal stress σ_1 and axis of the strain gauge's measuring grid:

$$\varepsilon'_a = G + H \cdot \cos 2\alpha = \frac{\varepsilon'_1 + \varepsilon'_2}{2} + \frac{\varepsilon'_1 - \varepsilon'_2}{2} \cdot \cos 2\alpha, \tag{10}$$

$$\varepsilon'_b = G + H \cdot \cos(2\alpha + 90^\circ) = \frac{\varepsilon'_1 + \varepsilon'_2}{2} - \frac{\varepsilon'_1 - \varepsilon'_2}{2} \cdot \sin 2\alpha, \tag{11}$$

$$\varepsilon'_c = G + H \cdot \cos(2\alpha + 180^\circ) = \frac{\varepsilon'_1 + \varepsilon'_2}{2} - \frac{\varepsilon'_1 - \varepsilon'_2}{2} \cdot \cos 2\alpha. \tag{12}$$

According to modified Mohr's circle in Fig. 6, relationship between principal strains $\varepsilon'_1, \varepsilon'_2$ and generally measured relieved strains $\varepsilon'_a, \varepsilon'_b, \varepsilon'_c$ is:

$$G = \frac{\varepsilon'_1 + \varepsilon'_2}{2} = \frac{\varepsilon'_a + \varepsilon'_c}{2}, \tag{13}$$

$$H = \frac{\varepsilon'_1 - \varepsilon'_2}{2} = \frac{1}{2}\sqrt{(\varepsilon'_a - \varepsilon'_c)^2 + (\varepsilon'_a + \varepsilon'_c - \varepsilon' b)^2}. \tag{14}$$

Angle between direction of principal residual stress σ_1 and axis of strain gauge's measuring grid "a":

$$\tan 2\alpha = \frac{\varepsilon'_b - G}{G - \varepsilon'_a} = \frac{2\varepsilon'_b - \varepsilon'_a - \varepsilon'_c}{\varepsilon'_c - \varepsilon'_a} \rightarrow \alpha = \arctan\left(\frac{2\varepsilon'_b - \varepsilon'_a - \varepsilon'_c}{\varepsilon'_c - \varepsilon'_a}\right). \tag{15}$$

Table 2. Specified quadrants

Numerator: $2\varepsilon'_b - \varepsilon'_a - \varepsilon'_c$	**Denominator:** $\varepsilon'_c - \varepsilon'_a$	2α [°]
$+$	$+$	$0 \div 90$
$+$	$-$	$90 \div 180$
$-$	$-$	$180 \div 270$
$-$	$+$	$270 \div 360$

Similarly, derivation of strains ε_1', ε_2' and ε_a', ε_b', ε_c' could be used in (10)–(15) instead of ε_1, ε_2 and ε_a, ε_b, ε_c strains in order to evaluate stress σ_a, σ_b and σ_c in direction of strain gauge's axis:

$$\sigma_a = \frac{E}{K_1^2 - \mu^2 K_2^2} \cdot (K_1 \varepsilon_a' + \mu K_2 \varepsilon_c'), \tag{16}$$

$$\sigma_b = \frac{E}{K_1^2 - \mu^2 K_2^2} \cdot [K_1 \varepsilon_b' + \mu K_2 (\varepsilon_a' - \varepsilon_b' + \varepsilon_c')], \tag{17}$$

$$\sigma_c = \frac{E}{K_1^2 - \mu^2 K_2^2} \cdot (K_1 \varepsilon_c' + \mu K_2 \varepsilon_a'). \tag{18}$$

According to Mohr's circle in Fig. 7, principal stress σ_1 and σ_2 could be recalculated by using known magnitudes of non-principal stresses σ_a, σ_b, σ_c measured by generally turned strain gauge rosette:

$$M = \frac{\sigma_a + \sigma_c}{2}, \qquad N = \frac{1}{2}\sqrt{(\sigma_a - \sigma_c)^2 + (\sigma_a + \sigma_c - 2\sigma_b)^2}, \tag{19}$$

$$\sigma_1 = M + N, \qquad \sigma_2 = M - N. \tag{20}$$

3.3. Using relaxation coefficients A and B

Magnitude of principal residual stresses, acting within two drilled depths, can be determined by using relaxation coefficients too. Therefore, relieved strains are measured only at two different depths and step's difference Δz consist of two particular depths z_i and $2z_i$, described by

$$\Delta z = 2z_i - z_i = z_i, \text{ for } z_i = 1, 2, 3, 4 \text{ [mm]}. \tag{21}$$

Assuming that $\frac{d\varepsilon_i}{dz} \approx \frac{\Delta\varepsilon_i}{\Delta z}$, equations of principal strains (2) and (3) can be rewritten:

$$\sigma_1 = \frac{E}{K_1^2 - \mu^2 K_2^2} \cdot \frac{1}{\Delta z} \cdot (K_1 \Delta\varepsilon_1 + \mu K_2 \Delta\varepsilon_2), \tag{22}$$

$$\sigma_2 = \frac{E}{K_1^2 - \mu^2 K_2^2} \cdot \frac{1}{\Delta z} \cdot (K_1 \Delta\varepsilon_2 + \mu K_2 \Delta\varepsilon_1), \tag{23}$$

$$\Delta\varepsilon_1 = (\varepsilon_1)_{2z_i} - (\varepsilon_1)_{z_i}, \qquad \Delta\varepsilon_2 = (\varepsilon_2)_{2z_i} - (\varepsilon_2)_{z_i}. \tag{24}$$

Confrontation of the calibration coefficients K_1, K_2 and relaxation coefficients A, B:

$$A = \frac{E \cdot K_1}{K_1^2 - \mu^2 K_2^2} \cdot \frac{1}{\Delta z}, \qquad B = \frac{E \cdot K_2}{K_1^2 - \mu^2 K_2^2} \cdot \frac{1}{\Delta z}. \tag{25}$$

If $\overline{\varepsilon}_1 = \frac{\sigma_1}{E}$ and $\Delta\varepsilon_1^* = \frac{\Delta\varepsilon_1}{\overline{\varepsilon}_1}$; $\Delta\varepsilon_2^* = \frac{\Delta\varepsilon_2}{\mu \cdot \overline{\varepsilon}_1}$ then relaxation coefficients A, B are determined:

$$A = \frac{E\frac{\Delta\varepsilon_1^*}{\Delta z}}{\frac{1}{(\Delta z)^2}[(\Delta\varepsilon_1^*)^2 - (\mu\Delta\varepsilon_2^*)^2] \cdot \Delta z} = \frac{E \cdot \Delta\varepsilon_1^*}{(\Delta\varepsilon_1^*)^2 - (\mu\Delta\varepsilon_2^*)^2}, \tag{26}$$

$$B = -\frac{E \cdot \mu \cdot \frac{\Delta\varepsilon_2^*}{\Delta z}}{\frac{1}{(\Delta z)^2}[(\Delta\varepsilon_1^*)^2 - (\mu\Delta\varepsilon_2^*)^2] \cdot \Delta z} = -\frac{E \cdot \mu \cdot \Delta\varepsilon_2^*}{(\Delta\varepsilon_1^*)^2 - (\mu\Delta\varepsilon_2^*)^2}. \tag{27}$$

Finally, equations for residual stress determination, which are based on differences of relieved strains and relaxation coefficients A, B are:

$$\sigma_1 = A \cdot \Delta\varepsilon_1 - B \cdot \Delta\varepsilon_2, \qquad \sigma_2 = A \cdot \Delta\varepsilon_2 - B \cdot \Delta\varepsilon_1. \tag{28}$$

4. FEM simulation

A prerequisite for correct and accurate measurement of relieved strains on the top of the core is to use FEM simulation. It is the only reasonable way to obtain desired information or simulate real experiment. The ANSYS analysis system is used for the FE-simulation.

FE-analysis is based on a specimen volume with dimensions of $a \times a = 50 \times 50$ mm and thickness of $t = 50$ mm. Due to symmetry, only a quarter of the model has been modeled with centre of the core on the surface as the origin. The shape of the model is simply represented by a block with planar faces, with a quarter of the annular groove drilled away (Figs. 8 and 9). The annular groove has been made by $n = 40$ increments with the step size of $\Delta z = 0.2$ mm in case of approach described by using calibration coefficients K_1 and K_2. The maximum depth of drilled groove is $z = 8$ mm. Dimension of outer diameter is $D = 2r_i = 18$ mm and groove width is $h = 2$ mm.

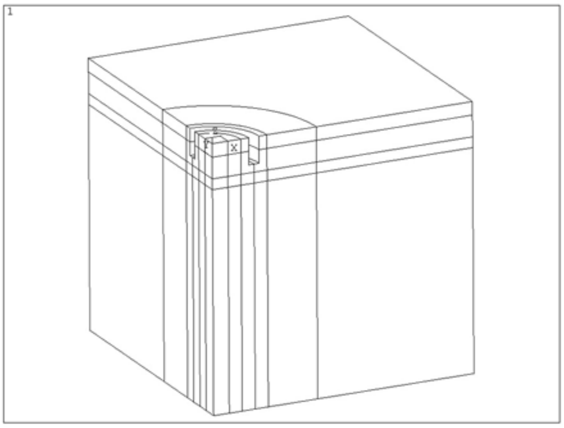

Fig. 8. Quarter of global solid model

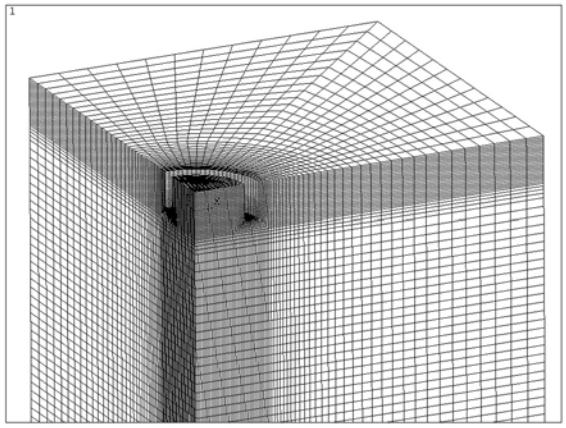

Fig. 9. Finite element model

Linear, elastic and isotropic material model is used with material properties of Young's modulus $E = 210$ GPa and Poisson's ratio $\mu \cong 0.3$. Relaxed strains ε_1, ε_2 and ε_3 have been measured at real positions of strain gauge rosettes' measuring grids by integration across its surface. Type of considered strain gauge rosette is FR-5-11-3LT, with length and width of each measuring grid 5 mm and 1.9 mm, respectively [6].

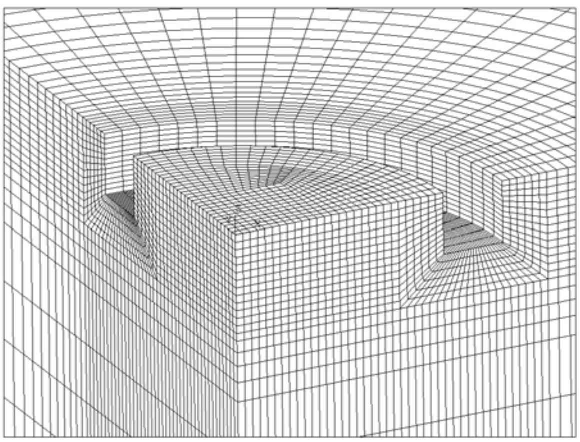

Fig. 10. Depth of drilled groove for $z = 2$ mm

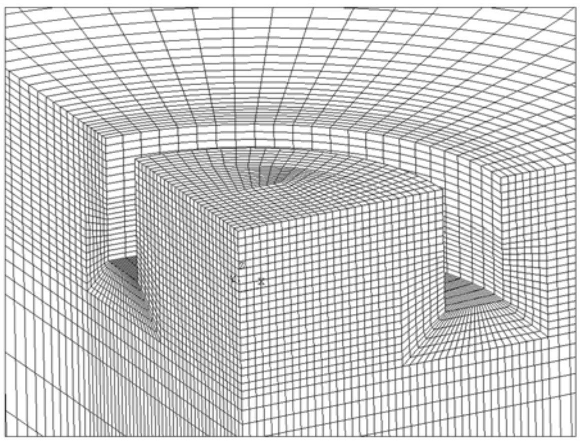

Fig. 11. Depth of drilled groove for $z = 4$ mm

5. Results

5.1. Using calibration coefficients K_1 and K_2

Released strains on the top of the core are obtained by the FE-analysis (Fig. 12). Application of the general-purposed finite element model in order to simulate homogenous uniaxial state of stress with magnitude of principal stress $\sigma_1 = 60$ MPa, $\sigma_2 = 0$ MPa has been used to verify basic equations (10)–(20) and theoretical approach proposed by ISM.

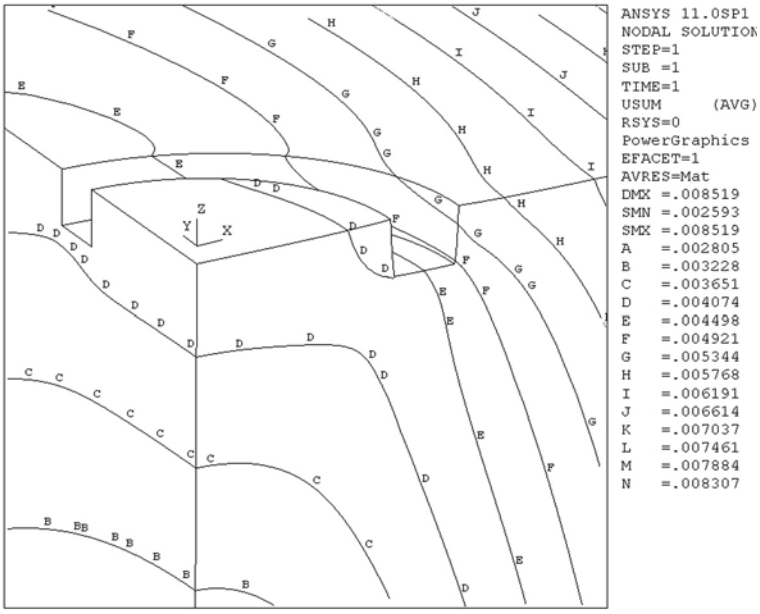

Fig. 12. Plot of total displacement [mm] — uniaxial state of stress, depth of drilled groove $z = 2$ mm

Graphs of relaxed strains calculated by integration across strain gauge's measuring grid [3] are plotted in Fig. 13 and their numerical derivations are plotted in Fig. 14. Axis of strain gauge's measuring gird "a" was for this simulation turned from the direction of principal stress σ_1 about angle $\alpha = 30°$.

Non-principal residual stresses σ_a, σ_b, σ_c acting in axis direction of turned strain gauge rosette's measuring grids "a, b, c", are calculated by (16)–(18) and plotted in Fig. 15 in dependence on the depth of drilled hole. The set of calibration coefficients K_1 and K_2 (Figs. 4 and 5), determined under uniaxial or biaxial state of stress conditions, needs to be used for this reason.

Fig. 16 shows angle α between direction of principal residual stress σ_1 and axis of strain gauge's measuring grid "a" determined in each drilled depth by (15). Table 2 gives an advice how to consider signs of numerator and denominator of (15) in order to determine correct quadrant of strain gauge grid's position.

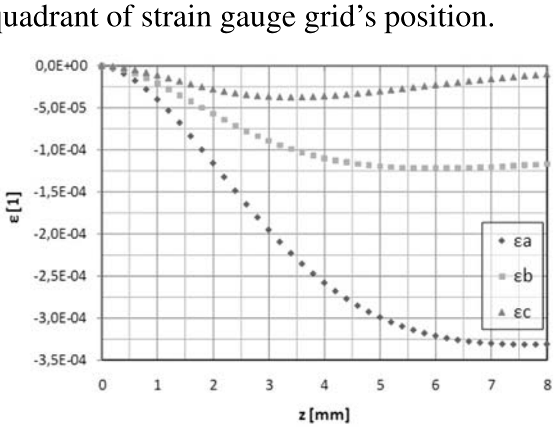

Fig. 13. Measured strains on the top of the core

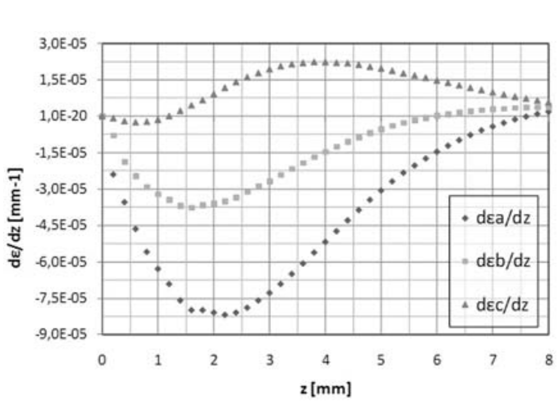

Fig. 14. Derivations of relieved strains

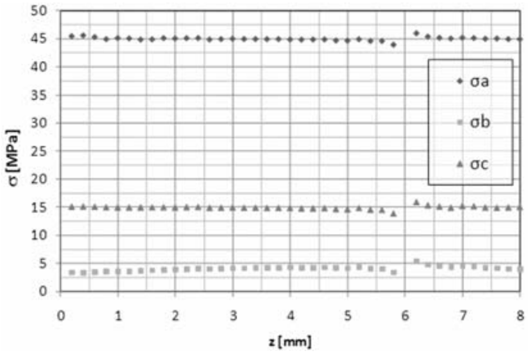

Fig. 15. Measured stress in general direction of strain gauges measuring grid's axis

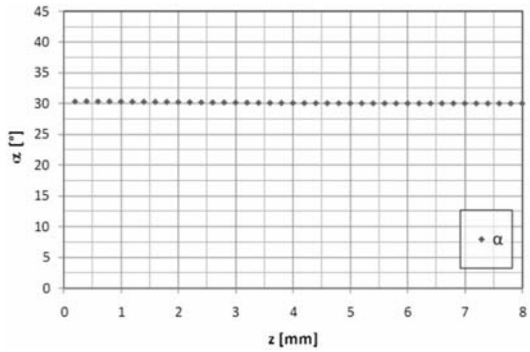

Fig. 16. Determined angle α

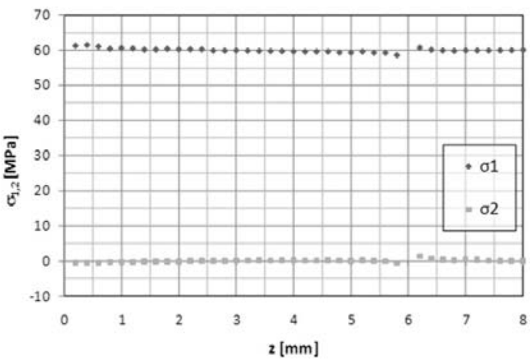

Fig. 17. Re-calculated principal stresses

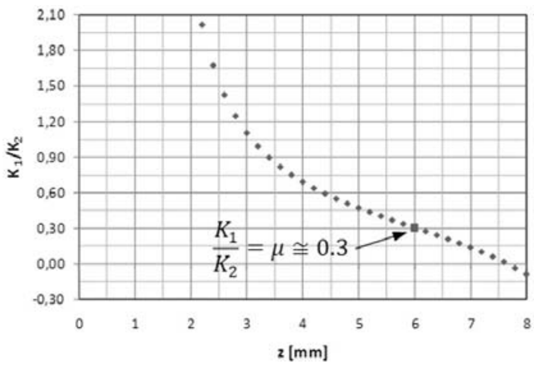

Fig. 18. Ratio of calibration coefficients

Re-calculated magnitudes of principal residual stresses σ_1, σ_2 by (19)–(20) are plotted in Fig. 17 and their magnitudes correctly correspond with simulated homogenous state of stress with principal stresses $\sigma_1 = 60$ MPa, $\sigma_2 = 0$ MPa.

Shortcoming of ISM is obvious in Figs. 15, 17 and 18 where values of results are missing in depth of drilled hole $z = 6$ mm. This problem is caused by denominator $K_1^2 - \mu^2 K_2^2$ in all equations where it appears. Only one case is possible when denominator $K_1^2 - \mu^2 K_2^2$ becomes zero for certain values of K_1 and K_2, and this condition is met in case of Poisson's ration $K_1/K_2 = \mu \cong 0.3$ (steel material) exactly in depth of $z = 6$ mm (Fig. 18). For this reason, magnitude of stress is non-numerable in this depth.

5.2. *Using relaxation coefficients A and B*

Magnitudes of residual stresses, acting between two specific depths z_i and $2z_i$ (Figs. 10 and 11) of drilled groove can be determined by the method using differences $\Delta\varepsilon/\Delta z$ too (21). Values of general strains, used for determination of relaxation coefficients A, B by simulation of homogenous uniaxial stress state ($\sigma_1 = 60$ MPa, $\sigma_2 = 0$ MPa), are measured across strain gauge's measuring grid.

Unknown angle α can be determined for set of strains $\varepsilon_a, \varepsilon_b$ and ε_c in each depth z_i by (15). Principal strains ε_1 and ε_2 can be re-calculated by (10)–(12). After that, calibration coefficients A and B can be determined by (26) and (27), using normalized strains $\Delta\varepsilon_1^*$, $\Delta\varepsilon_2^*$ of differentials $\Delta\varepsilon_1, \Delta\varepsilon_2$ (24). All necessary constants are written in Table 3 for specific variations of drilled depths.

Incontestable advantage of residual stress determination by relaxation functions A and B is independency on determination of depth-dependent calibration coefficients like K_1 and K_2, which are possible to obtain, either by FEM simulation or experimental measurement.

Table 3. Residual stress determination by relaxation constants

z_i [mm]	$\Delta\varepsilon_1$ [1]	$\Delta\varepsilon_2$ [1]	$\Delta\varepsilon_1^*$ [1]	$\Delta\varepsilon_2^*$ [1]	A [MPa]	B [MPa]	σ [MPa]	α [°]
1 **2**	3.671E–06	–7.599E–05	1.285E–02	–8.866E–01	**–3.823E+05**	**–7.914E+05**	60.00	30
2 **4**	3.617E–05	3.753E–04	1.266E–01	4.375E–00	**–1.558E+04**	**1.615E+05**	60.00	30
3 **6**	5.940E–05	–1.248E–04	2.079E–01	–1.456E–00	**–2.958E+05**	**–6.216E+05**	60.00	30
4 **8**	5.791E–05	–7.200E–05	2.027E–01	–8.400E–01	**–1.898E+06**	**–2.360E+06**	60.00	30

6. Conclusions

This paper provided basic information about semi-destructive ring-core method. By using incremental strain method for residual state of stress determination by the finite element method, this article gives additional information about homogenous residual stress measurement. By using slightly turned strain gauge rosettes' measuring grids from the directions of acting principal stresses about general angle α, magnitudes and directions of principal stresses need to be re-calculated.

Theoretical background described by basic differential or difference equations and application of universal set of the depth-dependent calibration coefficients K_1, K_2 or relaxation functions A, B in order to determine principal residual stresses and their orientation, has been presented.

One of the shortcomings of the ISM, such as impossibility of stress measurement in specified depth in dependence on the Poisson's ratio, has been clarified. Another shortcoming of this method is inaccurate non-homogenous stress evaluation and measuring of more than full released strains in depth greater than $z = 5$ mm [2, 3]. Where the steep gradients of residual state of stress are occurred, measurement is not suitable in this case too.

Incremental strain method had been used frequently until the integral method has overcome its shortcomings. By concentrating the research on the observed weaknesses and the ambiguous details the ring-core method can be made an accurate and reliable method for residual stress measurement.

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