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Complex Analysis of the Necessary Geometric Parameters of the Tested Component in the Ring-Core Evaluation Process

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Residual stress measurement in different sorts of mechanical and mechatronic objects has become an important part of the designing process and following maintenance. Therefore, a sufficient experimental method could significantly increase the accuracy and reliability of the evaluation process. Ring-Core method is a well-known semi-destructive method, yet it is still not standardized. This work tries to improve the evaluation process of the Ring-Core method by analyzing the influence of the necessary geometric parameters of the investigated object. Subsequently, residual stress computation accuracy is increased by proposed recommendations.

Keywords: Residual stresses, Ring-Core method, FEM, Incremental method, Differential method, Integral method.

1. Introduction

The Ring-Core method is derived from a hole-drilling method, and both are used to determine uniform and non-uniform residual stress through the thickness of the specimen. The reason for creating the Ring-Core method was to remove some of the shortcomings of the hole-drilling method. In the hole-drilling method, a hole is drilled into the center of the strain gage. In the Ring-Core method, a notch is milled around the rosette. The hole-drilling method is used to evaluate residual stresses, usually to a depth of 2 mm, while the Ring-Core method is used to a depth of 5 mm. This implies that the Ring-Core method is more destructive than a hole-drilling method but is still semi-destructive. On the other hand, the Ring-Core method is less sensitive to errors involved in positioning the cutting tool relative to the strain gage, and stress can be measured more accurately up to the material's yield stress. The Ring-Core method is also more suitable for measuring coarse-grained materials than the hole-drilling method.

Recent progress in hardware and software tools for residual stress determination in materials has led to a rapid development of the Ring-Core method, which could, according to theoretical and experimental analyses, overcome the well-spread hole-drilling method [1]-[5]. There are three commonly used evaluation methods for the Ring-Core measurement: incremental, differential, and integral method [6], [7]. Use of each method depends mainly on the residual stress distribution through the cross-section of the investigated object. Numerical analyses with finite element methods (FEM) are used to determine adequate calculation coefficients for each evaluation method to cover the decrease of the strain gage sensitivity attached to the surface of the component, during depth increase creating the Ring-Core annular notch. The Ring-Core method is usually applied on large objects like castings or large beam constructions. Influence of the geometric parameters of the investigated component on the accuracy and reliability of the Ring-Core measurement and evaluation is an important topic which is not adequately discussed. Therefore, this work focuses on analyses of the influence of the necessary geometric parameters, thickness, width, length and curvature of the investigated component on the accuracy of individual evaluation methods. Using the Ring-Core method, the residual stress is determined only at one point for each milling depth, therefore precise placement of the measurement is required. However, series of the Ring-Core measurements placed next to each other are often used to ensure the reliability of the result. Although individual Ring-Core notch has minimal impact on the residual stress level of the whole component, it is important to calculate with local stress changes when multiple Ring-Core measurements are performed in close mutual distance. Detailed analyses of such problem were performed in subsequent work as well.

2. Residual stress evaluation methods

Finding a suitable model for numerical analyses of the necessary geometric parameters of the investigated component influence is the first and the most crucial step. The model represents the whole investigated object or just the sufficient part of it. Based on the relevant publications

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[8], [9], [10] only one set of universal calculation coefficients, specific for strain gage rosette type, material parameters and notch dimensions, is adequate for residual stress determination by any evaluation method.

The target of this study was not the determination of the coefficients with high accuracy but their relative change with respect to the geometric parameters of the investigated object. Therefore, a simple 3D model of a cube with sufficiently large dimensions to avoid undesirable boundary effects was created with the strain gage placed in the middle of its top face. Use of just a quarter of such model enhanced the simulation speed (Fig.1.). Thus, the dimensions of the used model were: width 50 mm, length 50 mm, and thickness 100 mm [11]. Individual dimensions were changing according to the actual geometric parameter investigation.

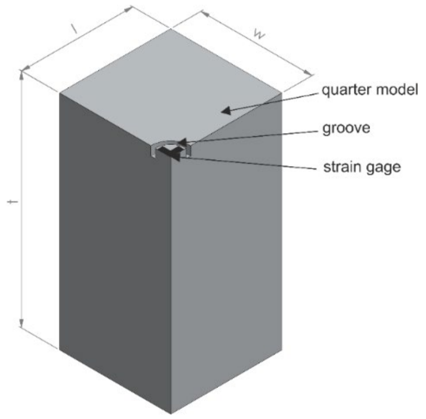

Fig.1. Quarter model.

The created model was loaded by known principal stresses $\sigma_1 = 60$ MPa and $\sigma_2 = 30$ MPa, to simulate inside residual stresses during all analyses in this work (if it is not said otherwise). After successful application of the boundary conditions based on the used model symmetry, the simulation process consisting of a predefined number of steps, during each the depth of annular notch with the inside diameter 14 mm and outside diameter 18 mm increased, up to the final depth of 5 mm, set by sensitivity decrease of the applied strain gage rosette was performed. Relieved principal strain values ε_1 and ε_2 were acquired after each successful step, which with the material properties (Young's modulus E and Poisson number ν) represent input measurand to following analytical computations of the residual stress components.

A. Incremental method

The created Incremental evaluation method is based on the principle that increment of the relieved strain ε, measured at the top of the isolating core after milled depth increment z, is fully caused by stress acting at this increment. Stresses acting at the previous steps or stresses perpendicular to the gage plane are negligible to stresses acting at actual step increment. (Fig.2.).

By marking $d\varepsilon_1$ and $d\varepsilon_2$ numerical derivations of the relieved principal strains and K_1 and K_2 calibration coefficients which consider decrease of the strain gage sensitivity with notch advancing, the principal residual stress components are computed as:

$$\sigma_1 = \frac{E}{K_1^2 - \nu^2 K_2^2} . (K_1 d\varepsilon_1 + \nu K_2 d\varepsilon_2) \tag{1}$$

$$\sigma_2 = \frac{E}{K_1^2 - \nu^2 K_2^2} . (K_1 d\varepsilon_2 + \nu K_2 d\varepsilon_1) \tag{2}$$

According to the assumptions, this method is suitable for determination of the uniformly distributed residual stresses.

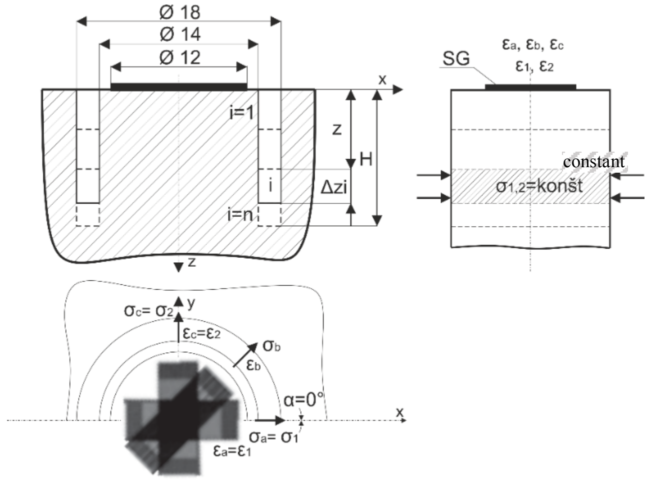

Fig.2. Principle of the incremental method.

The sensitivity of the strain gage located on the surface of the column to the released residual stress decreases with increasing milling depth z, therefore it is necessary to determine the conversion calibration coefficients K_1 and K_2 (Fig.3.). A quarter model was used to determine the most accurate calibration coefficients K_1 and K_2 for a universal, sufficiently large sample.

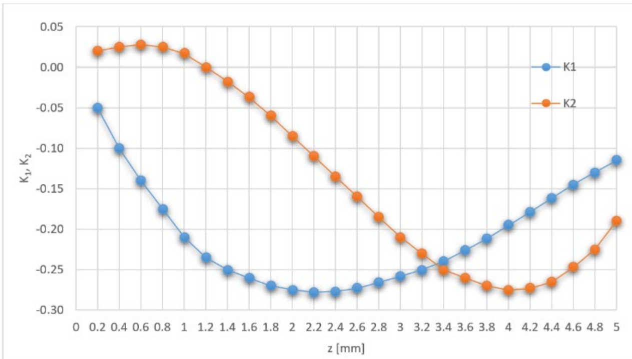

Fig.3. Calibration coefficients K_1 and K_2 of the incremental method.

B. Differential method

Differential method is a specific type of the incremental method. If only two pairs of relieved principal strains are known, acquired at two measuring steps, magnitude of the homogenous residual stress acting between these two steps is successfully computed by this method. By marking $\Delta\varepsilon_1$ and $\Delta\varepsilon_2$ increments of the relieved principal strains between two investigated steps and A or B influential coefficients, the principal residual stress components are computed as:

$$\sigma_1 = A.\Delta\varepsilon_1 + B.\Delta\varepsilon_2 \tag{3}$$

$$\sigma_2 = A.\Delta\varepsilon_2 + B.\Delta\varepsilon_1 \tag{4}$$

Differential method is a quick and reliable tool for first residual stress estimation which is usually followed by another more precise evaluation method. Due to the fundamental similarities with the incremental method, differential method will not be mentioned in following analyses of the influence of the geometric parameters.

C. *Integral method*

Unlike the previous methods, integral evaluation method is based on the principle that each milled depth i is affected by the previous steps j (Fig.4.). Therefore, this method is suitable for determination of the residual stress with non-uniform distribution at the investigated component cross-section. Residual stress computation is derived from the one defined for the hole-drilling method by ASTM E837 [12].

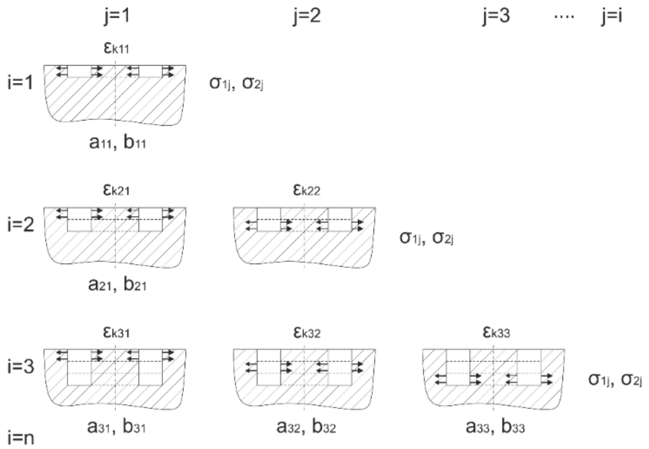

Fig.4. Principle of the integral method.

Final computation of the principal residual stress components is represented by equation (5), where computations of P, Q and T components with computation of influence coefficients A and B are described in mentioned standard and also in [7], therefore they are not listed here.

$$\sigma_{1,2} = P \pm \sqrt{Q^2 + T^2} \tag{5}$$

It is necessary to mention that residual stress computations by the integral method were performed in 8 optimized steps (0.6, 1.05, 1.45, 1.85, 2.3, 2.8, 3.5, 5), proposed by Zuccarello [13].

3. INFLUENCE OF THE THICKNESS

Described simulation model (Fig.1.) was used for the analysis of the influence of the model thickness on individual evaluation methods. Only the thickness of the model was changing with step 1 mm from values 6 to 10 mm and with step 5 mm for models with thickness greater than 10 mm to 100 mm. Other model dimensions remained constant. Milling depth for all simulations was 5 mm, therefore thickness 6 mm was chosen as minimum, with 1 mm of remaining solid material. Furthermore, due to the Ring-Core notch dimensions, calculations in models up to the thickness of 10 mm require more precise analyses as those in thicker models. Adequate calculation coefficients for incremental and integral method were computed from the measured relieved strain values for each specific model. Due to the fundamental similarities between differential and integral methods there are mentioned only coefficients for incremental and integral methods in this paper.

A. *Incremental method*

Parametric functions of calibration coefficients $K_{1,2}(z, t)$, in the dependence on milling depth z and changing model thickness t, were computed for determination of the influence of the component thickness on the incremental evaluation method accuracy. Their graphic interpolations are in Fig.5. Function contour was used for plotting the functions into the plane z, t for better clarity.

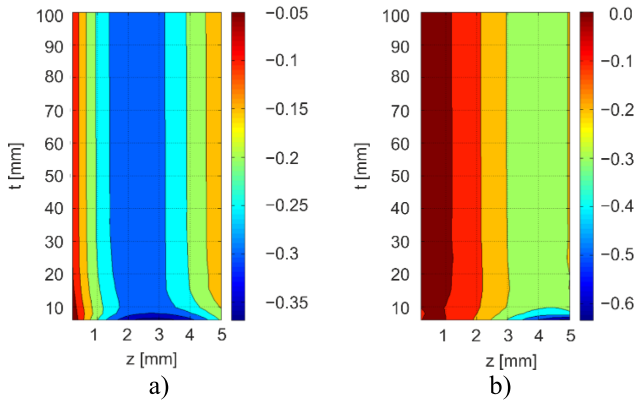

Fig.5. Function contour: a) calibration coefficients K_1 (z, t); b) calibration coefficients K_2 (z, t.).

From the analyses it is obvious that computation of calibration coefficients and subsequent residual stresses is critical for thickness of 6 mm where large systematic errors occur. Thus, three intervals due to the model thickness are proposed. Thin specimens are those with the thickness from 7 to 10 mm, while specimens with the thickness from the range (10-30) [mm] are from the so called middle interval, where adequate calibration coefficients $K_{1,2}$ (z, t) are computed by appropriate polynomial regression. Specimens with the thickness greater than 30 mm are called thick and in this case residual stress computations are performed by using universal calibration coefficients.

B. *Integral method*

Analysis of the influence of the model thickness was performed also for the integral evaluation method, which is usually used for non-uniform residual stress distributions. Integral method guarantees great stability and accuracy of the residual stress computations in thin models with the thickness from 6 to 10 mm only if influence coefficients are calculated specifically for actual model thickness. For example, for a thickness of 10 mm, the coefficients are given in Table 1. and Table 2. Middle interval is unlike the incremental method in the thickness range from 10 to 20 mm. The influence coefficients for a sample of a thickness of 15 mm are given in Table 3. and Table 4. Finally, residual stress computations in specimens with the thickness greater than 20 mm could be successfully performed by using universal influence coefficients.

Table 1. Influence coefficients A_{ij} for a 10 mm thick sample.

	z_i[mm]	A_{ij}							
i=1	0.6	-0.033							
i=2	1.05	-0.052	-0.035						
i=3	1.45	-0.081	-0.046	-0.025					
i=4	1.85	-0.099	-0.060	-0.041	-0.025				
i=5	2.3	-0.116	-0.073	-0.053	-0.040	-0.026			
i=6	2.8	-0.130	-0.083	-0.063	-0.051	-0.043	-0.026		
i=7	3.5	-0.144	-0.093	-0.072	-0.061	-0.055	-0.043	-0.030	
i=8	5.0	-0.156	-0.103	-0.080	-0.069	-0.065	-0.056	-0.053	-0.041
		j=1	j=2	j=3	j=4	j=5	j=6	j=7	j=8

Table 2. Influence coefficients matrix B_{ij} for a 10 mm thick sample.

	z_i[mm]	B_{ij}							
i=1	0.6	-0.056							
i=2	1.05	-0.132	-0.056						
i=3	1.45	-0.171	-0.077	-0.067					
i=4	1.85	-0.197	-0.098	-0.091	-0.056				
i=5	2.3	-0.220	-0.119	-0.109	-0.087	-0.062			
i=6	2.8	-0.241	-0.137	-0.124	-0.105	-0.098	-0.071		
i=7	3.5	-0.264	-0.158	-0.138	-0.121	-0.120	-0.103	-0.092	
i=8	5.0	-0.290	-0.185	-0.155	-0.134	-0.138	-0.128	-0.156	-0.156
		j=1	j=2	j=3	j=4	j=5	j=6	j=7	j=8

Table 3. Influence coefficients A_{ij} for a 15 mm thick sample.

	z_i[mm]	A_{ij}							
i=1	0.6	-0.044							
i=2	1.05	-0.074	-0.036						
i=3	1.45	-0.095	-0.055	-0.031					
i=4	1.85	-0.112	-0.068	-0.047	-0.029				
i=5	2.3	-0.128	-0.080	-0.059	-0.045	-0.030			
i=6	2.8	-0.141	-0.090	-0.068	-0.056	-0.046	-0.029		
i=7	3.5	-0.152	-0.099	-0.076	-0.064	-0.058	-0.047	-0.033	
i=8	5.0	-0.161	-0.106	-0.083	-0.071	-0.066	-0.057	-0.054	-0.039
		j=1	j=2	j=3	j=4	j=5	j=6	j=7	j=8

Table 4. Influence coefficients matrix B_{ij} for a 15 mm thick sample.

	z_i[mm]	B_{ij}							
i=1	0.6	-0.084							
i=2	1.05	-0.126	-0.051						
i=3	1.45	-0.155	-0.078	-0.059					
i=4	1.85	-0.180	-0.099	-0.083	-0.053				
i=5	2.3	-0.203	-0.118	-0.100	-0.083	-0.059			
i=6	2.8	-0.225	-0.137	-0.116	-0.101	-0.093	-0.064		
i=7	3.5	-0.247	-0.156	-0.130	-0.116	-0.115	-0.097	-0.089	
i=8	5.0	-0.274	-0.180	-0.147	-0.130	-0.134	-0.122	-0.153	-0.143
		j=1	j=2	j=3	j=4	j=5	j=6	j=7	j=8

4. INFLUENCE OF THE WIDTH

Similar method as that for thickness analysis was used also for the analysis of the residual stress computation accuracy due to the parametric model width w. Quarter model with dimensions 50x50x100 mm was used where width w was changing from 10 to 50 mm, while other dimensions remained constant. Width of 10 mm is critical, distance between model border and outside notch diameter is only 1 mm. It is necessary to keep in mind that the model of strain gage rosette is placed in the middle of top face, thus the width of the whole model was changing from 20 to 100 mm. Determination of the influence of the model width is equivalent to determination of the influence of distance between midpoint of the strain gage and model border. Simulation model was loaded by known biaxial uniform principal stress where principal stress with greater magnitude was placed in the direction perpendicular to changing model width.

A. Incremental method

Functions of calibration coefficients $K_{1,2}$ (z, w), in the dependence on milling depth z and model width w, are plotted in Fig.6. Influence of the model width was divided into two intervals (w_1 and w_2) by comparison of their projections to plane z, w created by function contour for simulated biaxial loads. Thus, critical width value defining the so called wide specimens was set to 30 mm. Greater principal stress component has significant influence on that parameter and in special occasions, when there is only uniaxial stress in the direction perpendicular to specimen width, critical width could be decreased to 20 mm.

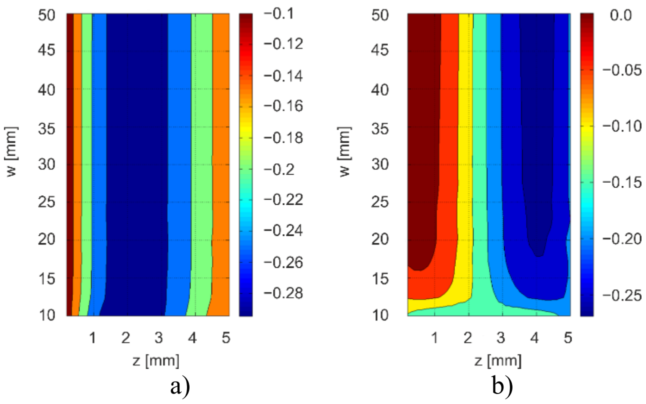

Fig.6. Function contour: a) calibration coefficients K_1 (z, w); b) calibration coefficients K_2 (z, w).

Computation of the residual stress in the so called narrow specimens, up to the width of 30 mm, is performed by using calibration coefficients determined by adequate polynomial interpolation. Computation of the residual stress in wide specimens, where width is greater than 30 mm, is performed by using universal calibration coefficients.

B. Integral method

Analysis of the model width, or of the distance between model edge and strain gage midpoint showed that if the distance is greater than 15 mm, it is possible to use universal influential coefficients for accurate residual stress computation. However, it is necessary to determine adequate influential coefficients for narrower specimens, with respect to magnitude and orientation of the principal residual stress components (Table 5. and Table 6.).

Table 5. Influence coefficients A_{ij} determined for w = 12.5 mm.

	z_i[mm]	A_{ij}							
i=1	0.6	-0.044							
i=2	1.05	-0.072	-0.035						
i=3	1.45	-0.095	-0.055	-0.031					
i=4	1.85	-0.112	-0.068	-0.047	-0.029				
i=5	2.3	-0.128	-0.081	-0.059	-0.045	-0.030			
i=6	2.8	-0.141	-0.091	-0.069	-0.056	-0.047	-0.029		
i=7	3.5	-0.152	-0.099	-0.077	-0.065	-0.058	-0.046	-0.032	
i=8	5.0	-0.162	-0.107	-0.083	-0.072	-0.067	-0.058	-0.05	-0.040
		j=1	j=2	j=3	j=4	j=5	j=6	j=7	j=8

Table 6. Influence coefficients B_{ij} determined for $w = 12.5$ mm.

	z_i[mm]	B_{ij}							
i=1	0.6	-0.065							
i=2	1.05	-0.124	-0.048						
i=3	1.45	-0.154	-0.076	-0.059					
i=4	1.85	-0.179	-0.097	-0.083	-0.052				
i=5	2.3	-0.202	-0.116	-0.100	-0.082	-0.059			
i=6	2.8	-0.224	-0.136	-0.115	-0.101	-0.093	-0.064		
i=7	3.5	-0.247	-0.156	-0.130	-0.116	-0.115	-0.096	-0.089	
i=8	5.0	-0.274	-0.181	-0.147	-0.130	-0.134	-0.122	-0.153	-0.143
		j=1	j=2	j=3	j=4	j=5	j=6	j=7	j=8

5. Influence of the length

The last analyzed dimensional parameter of the flat specimen influencing residual stress computation accuracy is its length l. By length the model dimension in which direction the greater of two principal residual stress components acts is considered. Initial computations by incremental or differential method could help to decide which principal residual stress component is greater. Thus, it is similar to the influence of width. Influence of length could be interpreted as the distance between model edge and the strain gage midpoint, where in that direction acts the principal stress much greater than the stress in perpendicular direction. Again, series of simulations were performed on the quarter model, where its length was changing from 10 to 50 mm, while the other dimensions remained constant.

A. Incremental method

Functions of calibration coefficients $K_{1,2}$ (z, l), in the dependence on the milling depth z and model length l are plotted in Fig.7. Influence of the model length was divided into three intervals (l_1, l_2 and l_3) by comparison of their projections to plane z, l created by function contour for simulated biaxial loads. Thus, first interval for the so called short specimens is determined by the distance between model edge and strain gage midpoint, up to 20 mm. Second, middle interval is defined by the range from 22.5 to 30 mm. Finally, the long specimen is defined by the investigated distance greater than 30 mm and in that case universal coefficients could be successfully used to compute residual stress.

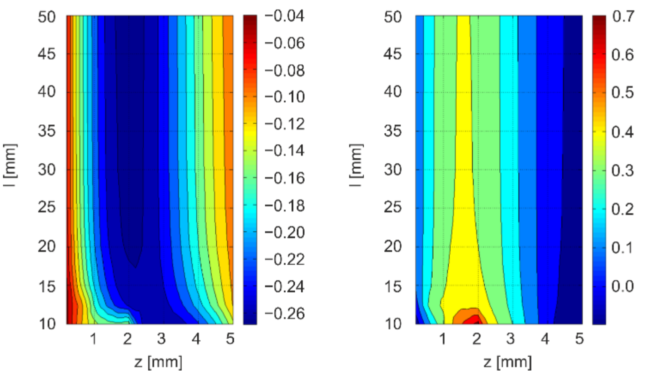

Fig.7. Function contour: a) calibration coefficients K_1 (z, l); b) calibration coefficients K_2 (z, l).

B. Integral method

Analysis of the influence of the model length was performed also for the integral evaluation method, which is usually used for non-uniform residual stress distributions. Integral method guarantees great stability and accuracy of the residual stress computations in long models in which the distance between model edge and the strain gage midpoint is greater than 25 mm. If the investigated distance is shorter than 25 mm, the computation accuracy increases by using adequate influential coefficients, determined for specific model length (Table 7. and Table 8.).

Table 7. Influence coefficients A_{ij} determined for $l = 20$ mm.

	z_i[mm]	A_{ij}							
i=1	0.6	-0.044							
i=2	1.05	-0.073	-0.036						
i=3	1.45	-0.095	-0.055	-0.031					
i=4	1.85	-0.112	-0.068	-0.047	-0.029				
i=5	2.3	-0.128	-0.081	-0.059	-0.045	-0.030			
i=6	2.8	-0.141	-0.091	-0.069	-0.056	-0.047	-0.029		
i=7	3.5	-0.152	-0.099	-0.077	-0.065	-0.058	-0.047	-0.033	
i=8	5.0	-0.162	-0.107	-0.083	-0.072	-0.067	-0.058	-0.052	-0.040
		j=1	j=2	j=3	j=4	j=5	j=6	j=7	j=8

Table 8. Influence coefficients B_{ij} determined for $l = 20$ mm.

	z_i[mm]	B_{ij}							
i=1	0.6	-0.065							
i=2	1.05	-0.124	-0.048						
i=3	1.45	-0.154	-0.076	-0.059					
i=4	1.85	-0.179	-0.097	-0.083	-0.052				
i=5	2.3	-0.202	-0.116	-0.100	-0.082	-0.059			
i=6	2.8	-0.224	-0.136	-0.115	-0.101	-0.093	-0.064		
i=7	3.5	-0.247	-0.156	-0.130	-0.116	-0.115	-0.096	-0.089	
i=8	5.0	-0.274	-0.181	-0.147	-0.130	-0.134	-0.122	-0.153	-0.143
		j=1	j=2	j=3	j=4	j=5	j=6	j=7	j=8

6. Influence of the surface curvature

Next step after successful analyses of the influence of the main geometrical parameters on the accuracy of the residual stress computation is the analysis of the model with curved investigated surface. The limitations for this analysis are set by the used strain gage rosette. For example, producer HBM just says [14] that strain gage rosettes RY51 and XY51 could be attached to weakly curved surfaces only, however, they do not mention the exact radius of the curvature. Simulation analyses were performed on models with curvature radius $R = 250$ mm, 500 mm and 750 mm to achieve the influence of the model curvature on the computation accuracy. These values were chosen in respect to relatively common solid shafts with the diameter of 500 mm and steel pipes with the diameters greater than 1000 mm.

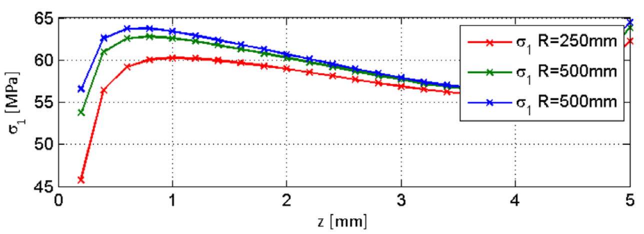

Fig.8. Residual stresses σ_1 evaluated on curved models by incremental method.

Investigated simulation models were loaded by known residual stress with the principal stress components $\sigma_1 = -\sigma_2 = 60$ MPa. Subsequently, the stress components were recalculated from acquired relieved strains after successful Ring-Core milling by each evaluation method.

Fig.8. and Fig.9. show the results obtained by the incremental method, and Fig.10. and Fig.11. show the integral method.

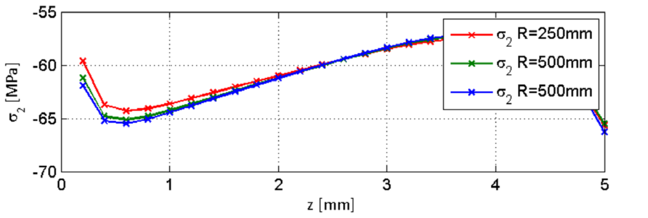

Fig.9. Residual stresses σ_2 evaluated on curved models by incremental method.

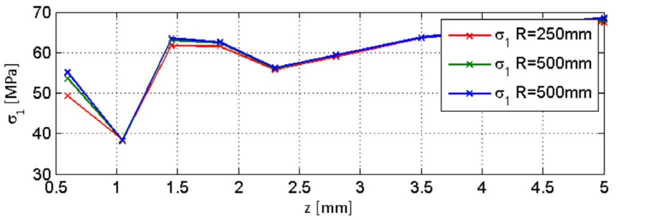

Fig.10. Residual stresses σ_1 evaluated on curved models by integral method.

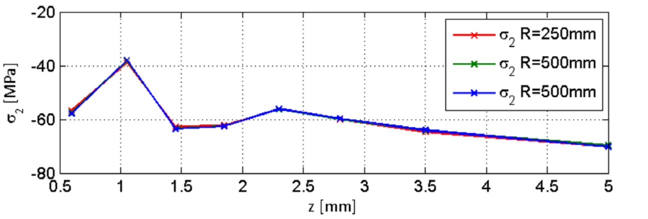

Fig.11. Residual stresses σ_2 evaluated on curved models by integral method.

From the analysis of the plotted residual stresses for incremental and integral method it is obvious that the decrease of the computation accuracy occurs in specimens with curvature radius up to 500 mm. Large deviations specially up to depth of 1 mm of the Ring-Core measurement are present in these strongly curved specimens. Furthermore, these deviations occur mainly in principal residual stress components σ_1, calculated by calibration coefficients K_1 or influential coefficients of type *A*. It is due to the simulated surface curvature in the direction of σ_1. There are deviations up to 20 % in the incremental method and up to 8 % in the integral method. The deviations in milling depths deeper than 1 mm for strongly curved models and the deviations in all milling steps for weakly curved models remain constant for all simulated cases. Therefore, a simple correction function could be used to achieve better accuracy.

7. Influence of the previous measurement

The distance between actual Ring-Core measurement and the previous accomplished measurements is an important influence to consider. The influence of the changing distance between strain gage midpoints was analyzed by a series of simulations with a known load of the model, $\sigma_1 = 60$ MPa and $\sigma_2 = 30$ MPa. The second Ring-Core measurement was always performed in the direction of σ_1. Residual stresses were evaluated using incremental (Fig.12.) and integral methods (Fig.13.). The distances between strain gage midpoints varied in 5 mm increments in the range of 20 to 50 mm. The results show that the influence of the previous measurement on the actual measurement is negligible from the mutual strain gage midpoint distance of 30 mm for both methods.

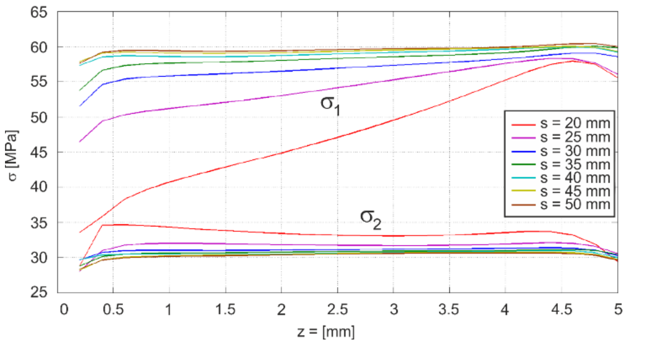

Fig.12. Residual stresses σ_1 and σ_2 computed by incremental method.

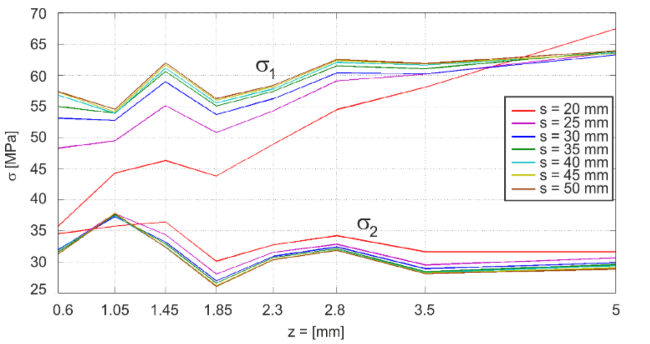

Fig.13. Residual stresses σ_1 and σ_2 computed by integral method.

8. Conclusions

This paper focuses on the determination of residual stresses using the Ring-Core method. Incremental and integral evaluation methods are analyzed. The functional dependence of the determined calibration coefficients on the geometric parameters of the examined object is analyzed, specifically on its thickness *t*, width *w* and length *l*. We can state that universal coefficients in all methods are applicable if the individual dimensions are above 30 mm. If any of the dimensions do not meet the above condition, it is necessary to adjust the coefficients. Subsequently, the effect of the curvature of the examined sample was verified using universal coefficients. Significant deviations were found at a curvature of 250 mm, with an increasing diameter the effect of curvature decreases significantly. The last criterion monitored was the assessment of the impact of the proximity of the previous measurement. It was found that the distance between the midpoints of individual measurements should be above 30 mm. Then the effect of the previous measurement is not significant. In the next phase, experiments were performed to verify the conclusions. However, this section is no longer part of the present paper.

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