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Verification Experiment for Evaluation of Uniform Residual Stresses by the Ring-Core Method

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Abstract. Despite the significant advantages of the Ring-Core method over the hole-drilling method, the Ring-Core method is still less common. Recent developments at our department showed the full potential of the method when using the adequate calibration coefficients. In this paper the differential method, a quick and easy method for uniform residual stress evaluation is described and the influence of its relaxation coefficients on the specimen´s dimensions is obtained.

Introduction

Ring-Core method is a semi-destructive method used for residual stress evaluation inside the material. This method improves some weaknesses of the hole-drilling method, but it brings more damage to the tested specimen. Similarly as in hole-drilling method, the principle is about attaching the special strain gage rosette to the specimen’s surface. Instead of drilling a hole through the middle of the rosette, an annular notch is milled around the strain gage. This creates the isolated core, inside which the residual stresses are relaxed. Subsequently the distributions of residual stresses along the milled depth at specific investigated place are determined. Ring-Core method comes just from hole-drilling method, especially from the standard ASTM E837 and can be used for uniform and non-uniform residual stresses. The most significant disadvantages of the Ring-Core method in comparison with the hole-drilling method come from insufficient method development and no existing standardization of measuring and evaluation procedure. For this reason our department gives a special attention to improvement and verification of the Ring-Core method. Goal of our work is also to implement the newest findings from standard ASTM E837-13a [1] to Ring-Core method.

There are two common calculation methods for evaluation of uniform residual stresses [2,8]:

- Incremental method,
- Differential method.

Incremental method is based on the following assumptions:

- the strain (stress) increment is constant at each step of milling procedure,
- state of stress in particular step is not affected by the previous steps,
- stress in vertical direction (perpendicular to the strain gage surface) is negligible according to the strain values in plane of the strain gage rosette.

Principal residual stresses σ_1 and σ_2 are subsequently calculated according the following equations:

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

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

where K_1 and K_2 are the calibration coefficients, μ is the Poisson's number, E is the Young's modulus and dz is the step increment.

Special type of incremental method is the differential method. For evaluating by this method milling the final depth only in two steps is needed. Subsequently there are only two sets of measured strain values. Therefore the size of difference Δz consists of difference of two different milled depths z_i and $2z_i$.

$$\Delta z = 2z_i - z_i = z_i \text{ , pre } z_i = 1,2,3,4 \text{ mm} \quad (3)$$

Residual stresses are calculated according the following equations:

$$\sigma_1 = A.\Delta\varepsilon_1 + B.\Delta\varepsilon_2 \quad (4)$$

$$\sigma_2 = A.\Delta\varepsilon_2 + B.\Delta\varepsilon_1 \quad (5)$$

with:

$$\Delta\varepsilon_1 = (\varepsilon_1)_{2z_i} - (\varepsilon_1)_{z_i} \quad (6)$$

$$\Delta\varepsilon_2 = (\varepsilon_2)_{2z_i} - (\varepsilon_2)_{z_i} \quad (7)$$

A and *B* are calibration coefficients determined for differential method. If $\overline{\varepsilon_1} = \frac{\sigma_1}{E}$ and $\Delta\varepsilon_1^* = \frac{\Delta\varepsilon_1}{\overline{\varepsilon_1}}$, $\Delta\varepsilon_2^* = \frac{\Delta\varepsilon_2}{\mu\overline{\varepsilon_1}}$, then:

$$A = \frac{E.\Delta\varepsilon_1^*}{(\Delta\varepsilon_1^*)^2 - (\mu\Delta\varepsilon_2^*)^2} \quad (8)$$

$$B = -\frac{E.\mu\Delta\varepsilon_2^*}{(\Delta\varepsilon_1^*)^2 - (\mu\Delta\varepsilon_2^*)^2} \quad (9)$$

Determination of the Calibration Coefficients by Finite Element Method

For determining the appropriate relaxation coefficients for differential method, the knowledge from the experimental testing provided at our department, using measuring system MTS 3000 Ring-Core [3,6] and finite element analysis (FEM) [4] were used. Fig. 1 shows the results obtained from the measurement at three places on the same specimen, by using the incremental evaluation method [5]. It is obvious that the most stable waveforms of the resulting residual stresses are in the depth *z* ranging from 2 mm to 4 mm. Therefore the differential method is according the above mentioned theory calculated in depths 2 and 4 mm. The calculation of the universal relaxation coefficients *A* and *B* was provided by FEM, using software SolidWorks 2012. Relaxation coefficients calculated from the simulation data obtained in [3] are in Table 1.

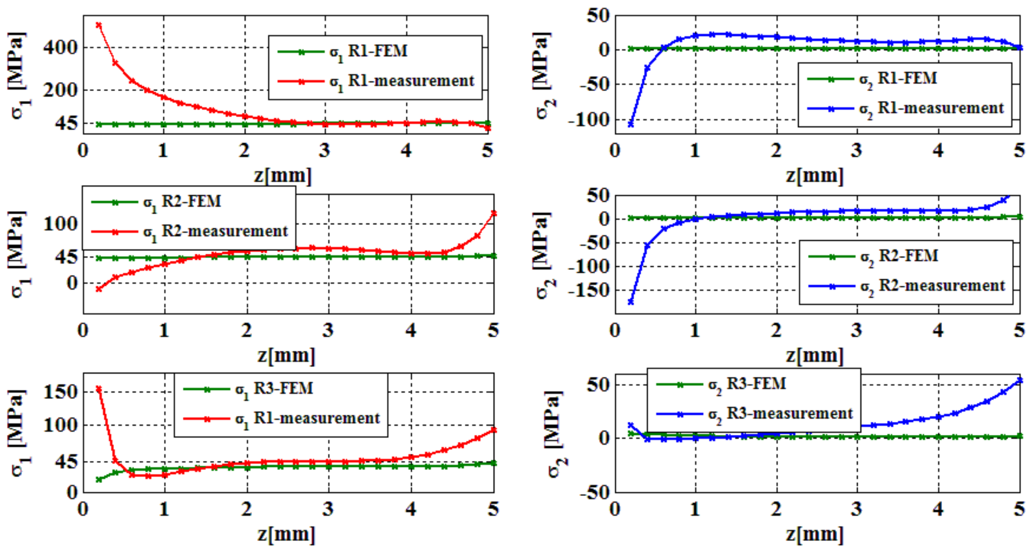

Fig. 1. Comparison of calculated and experimentally acquired residual stresses σ_1 and σ_2 for three strain gage rosettes on the same specimen.

Table 1. Relaxation coefficients.

z_i [mm]	A [MPa]	B [MPa]
2	-4,5034E+05	-1,1271E+05
4		

The calculated relaxation coefficients are universal and can be used for both uniaxial and biaxial state of stress, however only for the specific material, the type of the strain gage rosette and the dimensions of the relieved core. Based on the previous research [3], the coefficients are dependent on the geometric parameters of the tested specimen. For incremental method the minimum specimen's dimensions for using the universal calibration coefficients are: thickness 30mm, width 40mm and length 50mm. The same procedure was carried out for determining the influence of the geometric parameters on the relaxation coefficients of the differential method.

The influence of specimen's thickness. For the analysis of the thickness dependence on relaxation coefficients *A* and *B* same simulated model was used. The only difference was a thickness dimension changing from 10 mm to 100 mm. Re-calculations of residual stresses in dependence on the milled depth "z" were provided according to the equations (4), (5), where the universal relaxation coefficients *A*, *B* defined for the general simulation model were used (Table 1**Chyba! Nenalezen zdroj odkazů.**). The results shows that only the specimens with the thickness less than 10mm provide the error about 4 %.

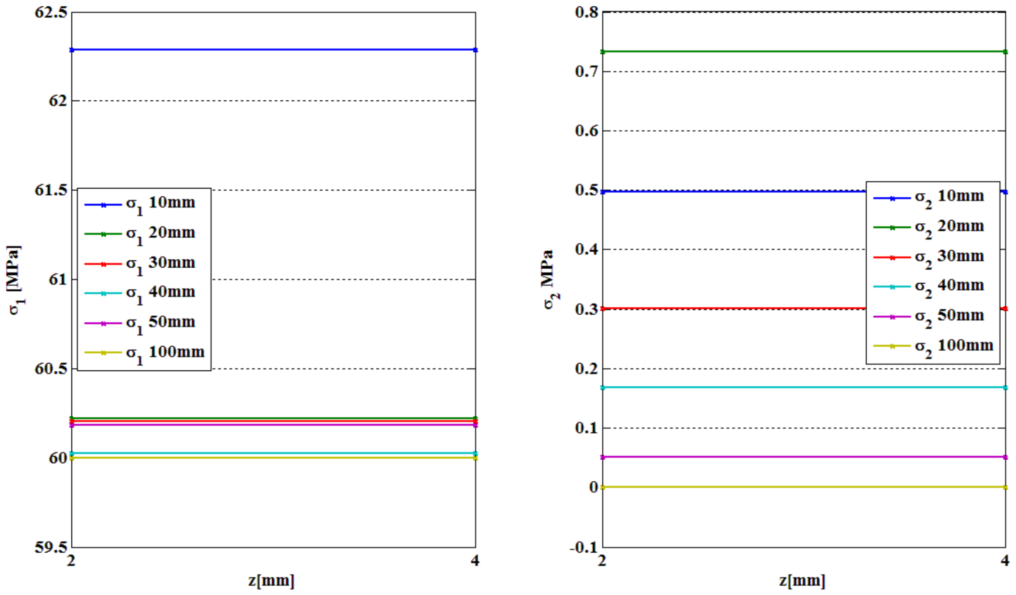

Fig. 2. Calculated residual stresses σ_1 andσ_2 for different thicknesses.

The influence of specimen's width. Same approach used for the determination of the influence of the specimen's width shows the negligible errors.

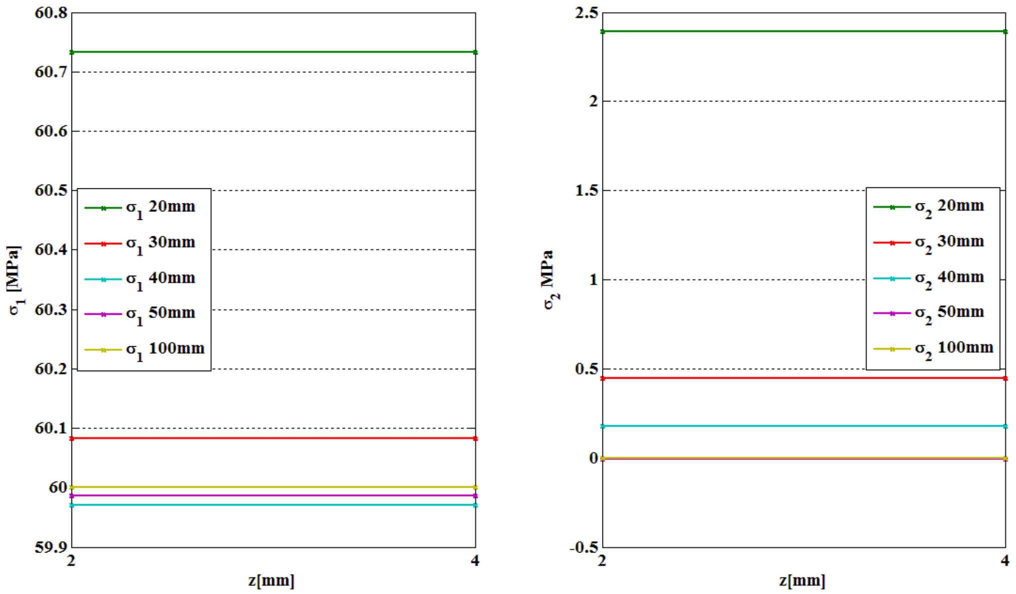

Fig. 3. Calculated residual stresses σ_1 andσ_2 for different widths.

The influence of specimen's length. The errors due to the specimen's length are insignificant with the length greater than 40mm. For the shorter specimens the unique relaxation coefficients have to be determined.

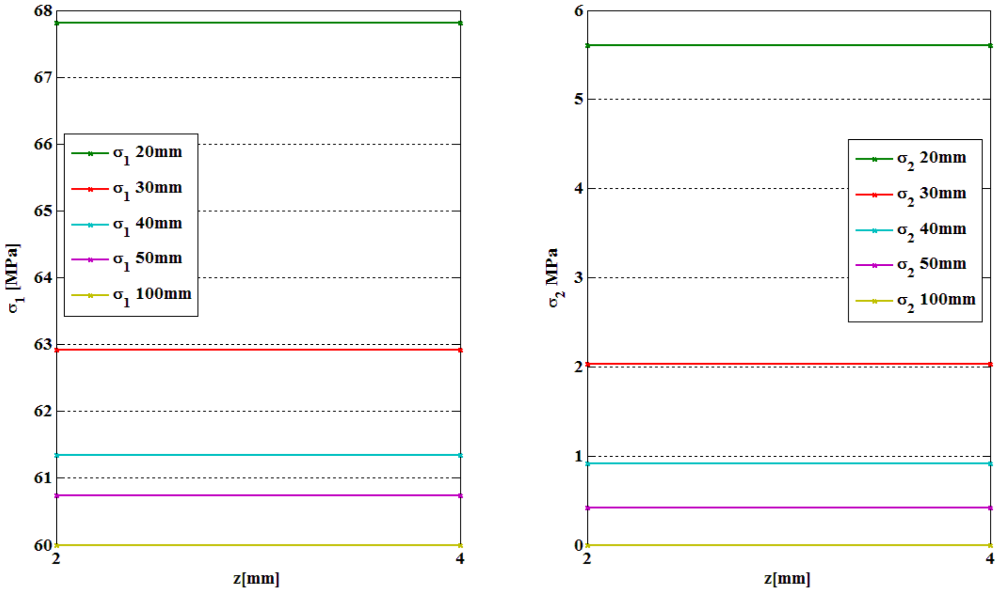

Fig. 4. Calculated residual stresses σ_1 and σ_2 for different lengths.

Experimental Verification of the Relaxation Coefficients

The relaxation coefficients and their dependence on the specimen's dimensions obtained from the simulations need to be verified experimentally [7]. The thin tested specimen was loaded by uniaxial tensile strength σ_1=45 MPa (σ_2=0MPa), as described in [3]. Subsequently three different measurements (R1, R2, R3) were completed. Fig.5 shows the comparison of the recalculated residual stresses at those three places acquired experimentally and numerically.

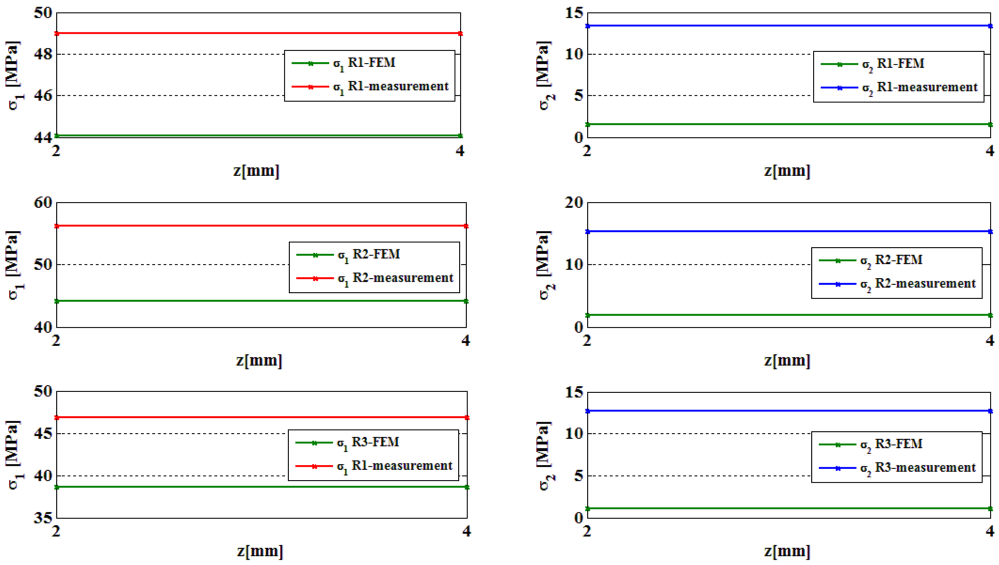

Fig. 5. Comparison of calculated and experimentally acquired residual stresses σ_1 and σ_2 for three strain gage rosettes on the same specimen using the differential method.

The residual stresses recalculation was done according the adequate relaxation coefficients, calculated for the thickness 10 mm by FEM. Despite not completely sufficient loading system the deviations of the experimentally measured residual stresses from the FEM data significantly decreases by using the adequate relaxation coefficients.

Conclusions

Quick and easy evaluation of the residual state of stress conditions could be done by using the differential method, computed in two milled depths. The precision of the evaluation increases by using the adequate relaxation coefficients for each type of the tested component. For specimens thicker than 10mm and longer than 40mm the universal relaxation coefficients could be used, otherwise specific coefficients have to be determined experimentally or numerically. The influence of the specimen's width is negligible for the differential method, which differs from the incremental evaluation method. The precise consideration of each influencing factors on the evaluation process significantly increases the reliability of the results. After the process of development and verification of Ring-Core method it will be possible to measure and evaluate any type of residual stress inside the investigated specimen by using system MTS 3000 Ring-Core.

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