Experimental Verification of the Geometric Parameters in the Ring-Core Measurement

P. Šarga [1,*], F. Menda [2], F. Trebuňa [3]

[1] *Technical University in Košice, Faculty of Mechanical Engineering, Department of Applied Mechanics and Mechatronics, Letná 9, 042 00 Košice, Slovakia*
[*] *patrik.sarga@tuke.sk*

Abstract: Unlike the principally similar hole-drilling method residual stress evaluation by the Ring-Core method is still unstandardized. The aim of this work is to contribute to the improvement and automatization of the measuring process and to consider necessary geometric parameters of the testing object which influence result accuracy. The assumptions of the chosen influencing parameters obtained numerically were used for the design of a tested specimen and subsequently experimentally verified in case of the simulated uniform residual stress field.

Keywords: Ring-Core; Residual Stress; Strain Gage Rosette; FEM.

1 Introduction

The Ring-Core method is a semi-destructive method for residual stress determination inside materials. This method overcomes some of the disadvantages of the commonly used hole-drilling method, but at the same time it creates a bigger damage to the specimen [1]. Similarly as in the hole-drilling method, the principle is based on the attachment of a special strain gage rosette on the surface of the tested object. Subsequently the annular notch is being created around the applied rosette. This creates the isolated core, inside which the stress state changes. It is measurable by means of relieved strains. The process of notch creation is divided into small steps, which ultimately enables the evaluation of the residual stress components in the dependence on the material thickness. No standard for the Ring-Core measurement forces to use the principles of the hole-drilling method described by the standard ASTM E837-13a [2]. The residual stress measurability by the Ring-Core method is guaranteed up to the material yielding stress, moreover in comparison to the hole-drilling method this method is less sensitive to the eccentricity errors of the milling cutter against the middle of the strain gage rosette [3], and is suitable for residual stress determination even in coarse-grained materials. Nowadays there are three commonly used methods for residual stress evaluation by the Ring-Core method: incremental, differential and integral method [4]. Each evaluation method requires the determination of the specific conversion coefficients in the dependence on the created notch dimensions, used strain gage rosette and material parameters of the examined object [5, 6]. This work deals with the uniformly distributed residual stress components through the material thickness z. According the incremental method, the most suitable evaluation method for this case, the principal residual stress components σ_1 and σ_2 are derived from the relieved strains ε_1 and ε_2 by the following:

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

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

where μ is the Poisson's ratio, E is the Young's modulus and K_1, K_2 are calibration coefficients.

Like the residual stress evaluation by the hole-drilling method is slightly different for the thin and thick specimen [2], the validity of conversion coefficients in the Ring-Core method depends on the geometric parameters of the specimen. The aim of this work is to experimentally verify the published results [6], setting out the dependence of the calibration coefficients of the incremental evaluation method on the thickness, width and length of the tested component, and to determine the influence of the created annular notch on the following operational functionality of the component as well.

2 Measuring String

Our department uses automated system MTS3000 Ring-Core from SINT Technology [3] for experimental residual stress measurement by the Ring-Core method. The measuring string of the system (Fig. 1) consists of the mechanical unit housing the electric motor, the hollow mill for the annular notch creation, the step motor for vertical mill positioning and the optical system; the electronic control unit, digital strain gage amplifier (e.g. HBM Spider 8.30 or Quantum X) and personal computer with the measuring and evaluation software EVAL. The mill adjustment against the applied rosette is provided by the integrated webcam. Manual adjustment in × and y axis within 20 mm × 20 mm range is used for planar centering. The outer diameter of the mill is 18 mm, the inner being 14 mm, which enables the cables to cross through the hollow shaft and the entire mechanical unit. Milling speed is 350 RPM, maximum milling depth is 5 mm. Total dimensions of the mechanical unit are: 340 mm length, 154 mm width, 200 mm height and weight 10 kg. The height adjustable magnetic feet ensure attachment of the machine on the tested component.

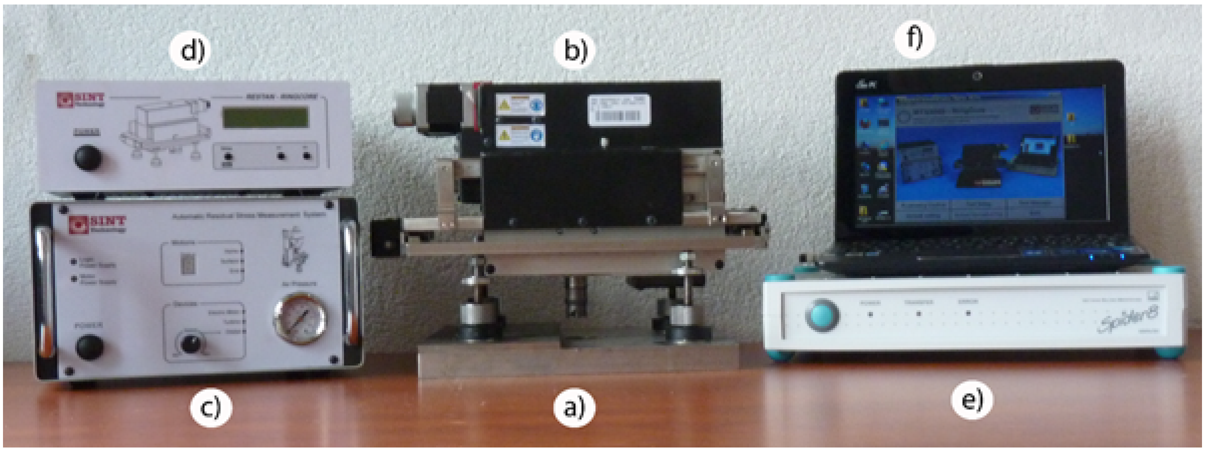


Fig. 1: Measuring system MTS 3000 Ring-Core: a) specimen, b) mechanical unit, c) electronic unit, d) controlling unit, e) amplifier, f) computer.

3 Design of the Specimen

On the knowledge from the numerical calculations [6] it is possible to define the space around the applied strain gage rosette, which is influenced by the stress changes occurring during the notch creation. We call this space "the outlining space of the strain gage rosette in the Ring-Core method". From the above mentioned publication the following is obvious: if the strain gage rosette has its specific outlining space with the minimum dimensions 20 mm × 40 mm × 50 mm (thickness × width × length) as seen on quarter model in Fig. 2, then it is possible to use the universal calibration coefficients in the evaluation process. Universal calibration coefficients K1 and K2 were determined based on the simulation of a model with the dimensions 100 × 100 × 100 mm. If e.g. weld, other shape or dimensional changes of the specimen's cross-section are situated in the specific outlining space of the rosette, then the precision of the residual stress evaluation increases by using the calibration coefficients obtained from the model of individual (smaller) outlining space. The tested specimen was designed in order to verify these assumptions in case of uniformly distributed residual stress components through the material thickness.

The design was based on the knowledge of the outlining space of the strain gage rosette, as well as on the parameters of the measuring system MTS 3000 Ring-Core and loading machine TIRA-test 2300 used for the creation of the known uniaxial uniform tensile stress. Mechanical gripping jaws, size of the working space and the loading force were essential. Created flat specimen passes smoothly from the narrow ends limited by the jaws to the parts for supporting the mechanical unit of MTS3000 during the measurement and finally to the narrowed working area (Fig. 3). In an effort to verify the influence of the thickness parameter on the calibration coefficients the thickness of the specimen was set to 20 mm. Nominal force 60 kN was chosen with respect to maximum tensile load of the loading machine equals to 100 kN. It was possible then to set the thickness of the working area to 50 mm, which according the numerical computations does not affect the magnitudes of the

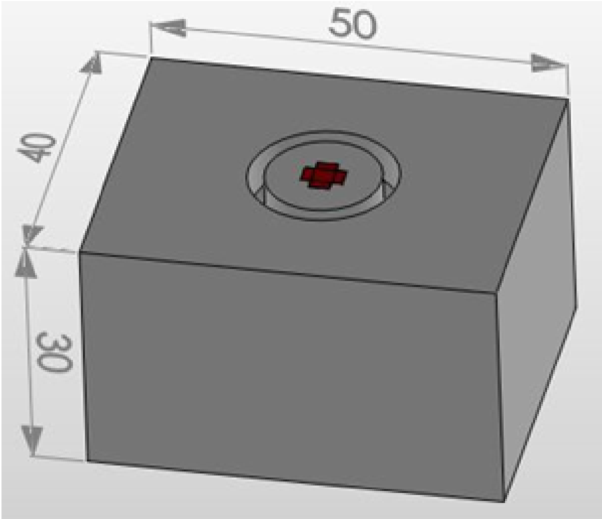


Fig. 2: The quarter model of the outlining space of the strain gage rosette.

relieved strains in the longitudinal direction (x axis). Thus the nominal loading stress was 60 MPa. Sufficient length of the working area has enabled measurements at three different places (R1, R2 and R3).

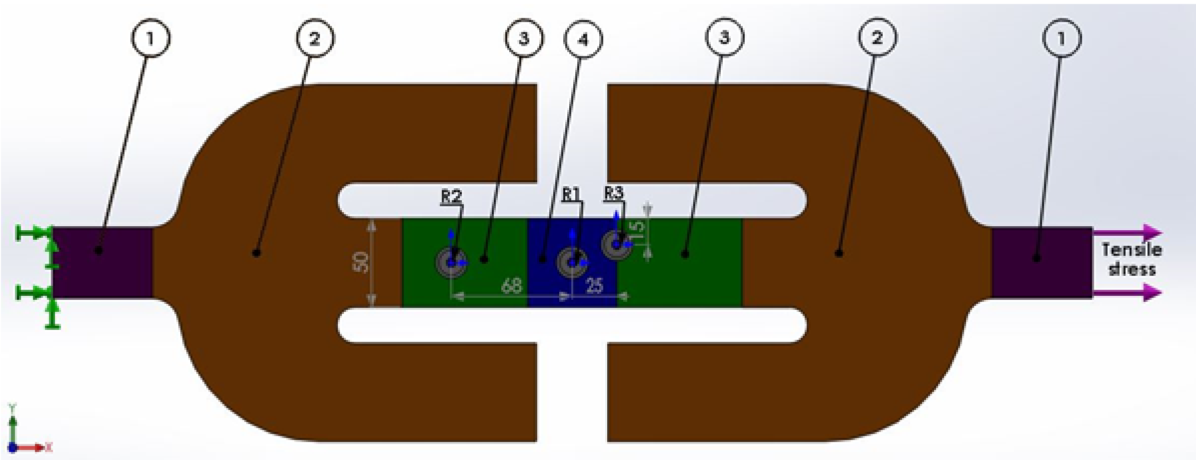


Fig. 3: Tested specimen with the areas: 1-fixing, 2-for placement of the milling device, 3- working, 4-outlining space of the first measurement.

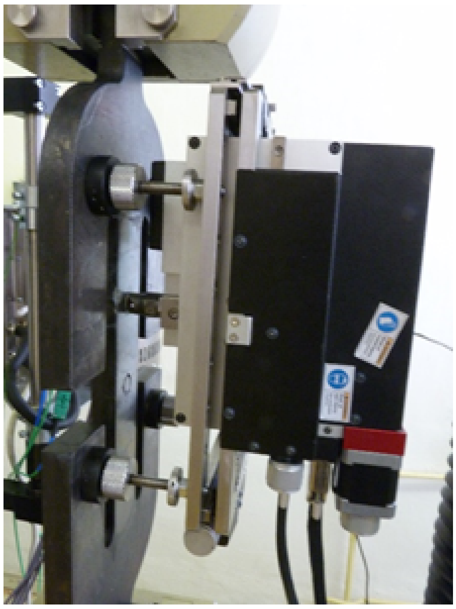
4 Experimental Testing

The need of experimentally simulated uniaxial uniform load inside the specimen requires no residual stress inside the material in unloaded conditions. This is achieved by its annealing. Appropriate parameters of annealing were determined by precise analysis of the material composition by spectrometer Belec Compact Port. The following parameters of annealing process were set for identified material S355J2G3: annealing temperature 600 °C, with 4 hours maintaining and cooling slowly in the furnace. The material hardness before and after annealing was also controlled, because the lower material hardness is more suitable for fixing the specimen in the loading machine and for the easier notch creation. Decrease of the material hardness is the by-product of the annealing process. The material hardness was determined by Vickers using the machine HPO 250. Before the annealing it was 176HV30 and after the annealing the value decreases to 170HV30. The following experimental measurements were carried out on the vertically positioned specimen which verified the measuring system functionality in this untypical position as well.

4.1 First Measurement (R1)

The residual stress evaluation in the middle of the working area of the specimen was carried out in the first stage of the experimental verification. The aim was to verify the nominal load, the functionality of the measuring system in the vertical position and also the assumption of the increasing accuracy of the calculated residual stresses by using the calibration coefficients derived from finite element analysis (FEM) for the thickness 20 mm instead of using the universal calibration functions (derived for thickness 100 mm). The strain gage rosette RY51S-24/350 from HBM was attached to the surface of the specimen. The application procedure was performed according to known recommendations [1, 3]. To check the magnitude and uniformity of the load, the strain gage 6/LY11/120 from HBM, placed on the opposite side of the specimen was used together with RY51S-24/350 in the loading stage. After fixing and loading the specimen with nominal stress (σ_1 = 60 MPa) it was discovered by the strain gages that the loading is not completely uniform, therefore the whole process was repeated until the conditions were sufficient. Non-uniform load distribution was probably caused by a bit inappropriate mechanical gripping jaws. However, their usage was conditioned by the final specimen design which could not be transferred for another jaw type. Subsequently, the adequate measuring string was created (Fig. 4) [7]. The procedure of notch milling by the MTS3000 Ring-Core was divided into 20 linearly distributed steps, up to the final depth 4 mm.

(a) measuring string for the experiment



(b) detail of the measurement

Fig. 4: Measuring string for the experiment with detail of the measurement.

The evaluation process by the incremental method was carried out according to the manufacturer recommendation to the depth 4 mm, with the step size 0.2 mm [3]. Firstly, by using FEM the results accuracy was compared in case of the thickness influence. The comparison of numerically obtained results is in Fig. 5, where the principal residual stress σ_1 was calculated by universal calibration coefficients and also by the coefficients derived for the thickness 20 mm. Relieved residual strains were approximated by the fourth order polynomial before the calculations according Eq. 1 and 2. Coefficients derived specially for the thickness 20 mm significantly decrease the deviations in the first steps and subsequently smooth and stabilize the waveforms of the evaluated residual stresses through the material thickness.

Similar comparison of the different evaluation approaches was used in our experimental case (Fig. 6). First steps of the measurement have shown significantly overestimated values of the residual stresses which may be caused by the mill influence in the first steps and by the changes of the surface structure after annealing process. In the next evaluated steps, the waveforms are smoother and close to the nominal stress 60 MPa. The thickness of 20 mm may be considered as a minimal size for the universal calibration coefficients application.

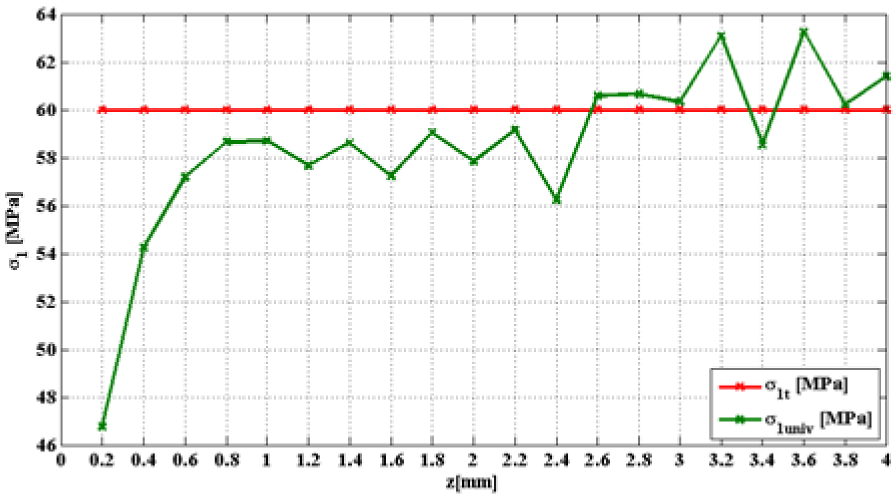


Fig. 5: Measuring Comparison of the evaluated principal residual stresses by using universal (σ_{1univ}) and thickness considering (σ_{1t}) calibration coefficients, by using finite element analysis.

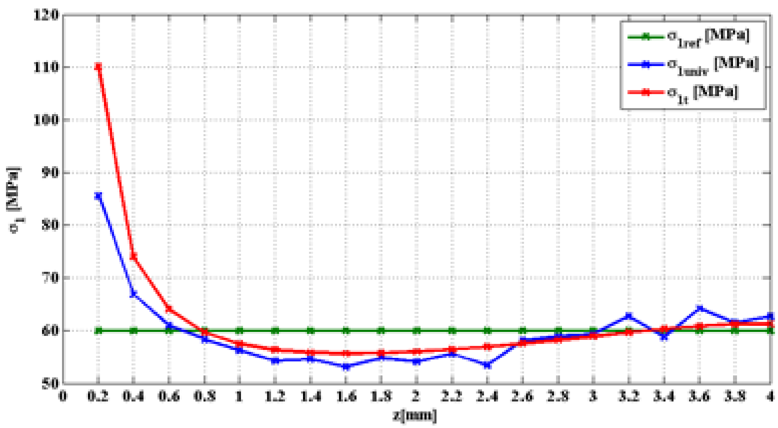


Fig. 6: Comparison of the evaluated principal residual stresses by using universal (σ_{1univ}) and thickness considering (σ_{1t}) calibration coefficients, in experimental testing with nominal load (σ_{1N}).

4.2 Second Measurement (R2)

Based on the assumptions of the strain gage rosette outlining space (see Chapter 3) was the second measurement carried out also on the longitudinal $\times$ axis, but 59 mm from the first measurement (Fig. 3). By using the thickness considering calibration coefficients the decent smoothness of the waveform of the valuated principal residual stress σ_1 through the material thickness is obvious from Fig. 7. The assumption of the independence of the second measurement results placed in the specific distance from the first measurement was verified as well.

4.3 Third Measurement (R3)

The measurement number three was carried out 16 mm in longitudinal distance from the first measurement and 15 mm from the edge of the specimen (Fig. 3). Thus the aim was to measure in the area close to the previous measurement and also close to the sharp edge of the specimen's surface. The comparison of the waveforms of the evaluated residual stresses calculated by specific calibration coefficients in respect to nominal uniaxial stress 60 MPa is shown in Fig. 8. Evaluation by means of the calibration coefficients considering the specimen's thickness 20 mm again proved only slight increasing of the accuracy, therefore the influence of other geometric parameters was considered. From the comparison it is obvious that it is not necessary to calculate with the combination of influences of thickness and width of the specimen all together with the longitudinal distance from the measurement number 1 (σ_{1twl}). The combination of only the thickness and width

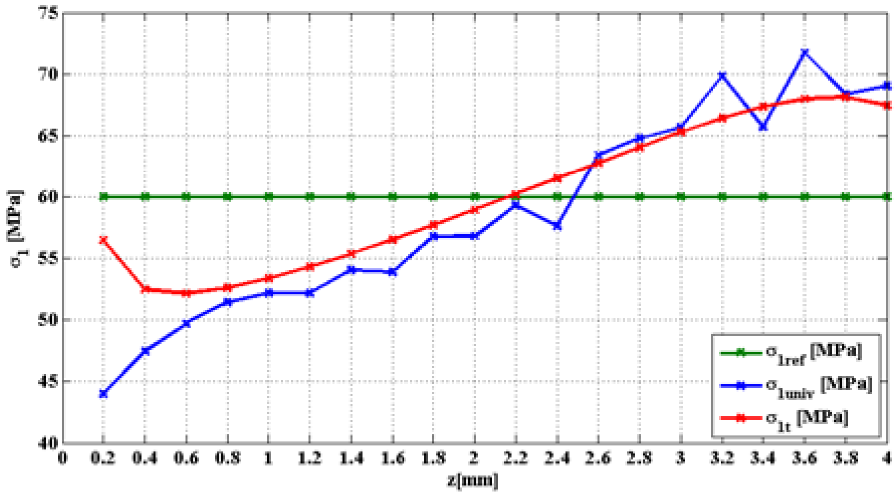


Fig. 7: Comparison of the evaluated principal residual stresses by using universal (σ_{1univ}) and thickness considering (σ_{1t}) calibration coefficients, in second measurement with nominal load (σ_{1N}).

of the specimen (σ_{1tw}) seems to be more accurate than the combination of thickness and length (σ_{1tl}). From the mentioned it is obvious that the specimen's thickness has the most significant influence on the evaluation process accuracy. Considering the proximity of the specimen's edge refines the results. The area close to the previous measurement is affected minimally which guarantees the unchanged functionality of the component after the measurement.

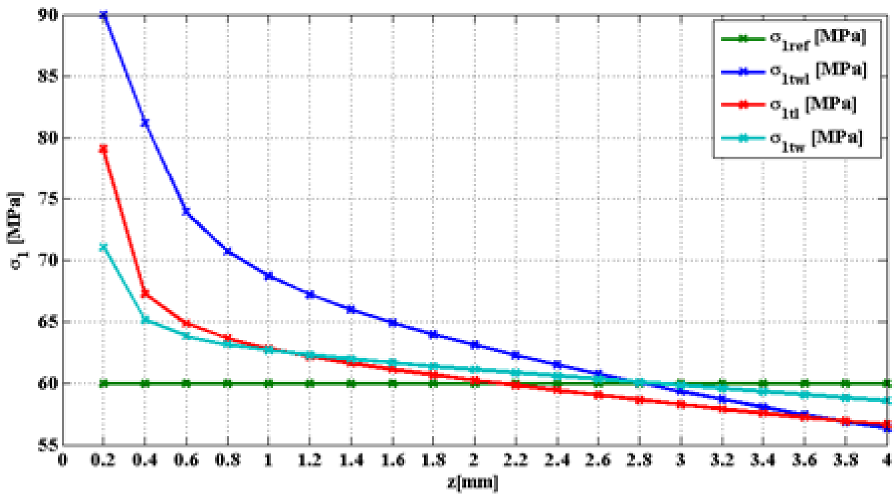


Fig. 8: Comparison of the evaluated principal residual stresses by using different calibration coefficients, in third measurement with nominal load (σ_{1N}).

5 Conclusion

Experimental verification of the accuracy of the residual stress evaluation in the Ring-Core method on the specially designed specimen confirms the assumptions obtained from the finite element analysis. Significant increase of the accuracy in calculations by incremental evaluation method in case of the specimen thickness 10 mm achieved by using the adequate calibration coefficients is proved in previous work [6]. This work experimentally confirms the limit for specimen's thickness 20 mm for the usage of specific thickness considering calibration coefficients. Residual stresses in specimens thicker than 20 mm may be evaluated by universal calibration coefficients without the accuracy loss. Verification experiment confirms the assumption of so called outlining space of the strain gage rosette in the Ring-Core method. The accuracy of the evaluation process is increased by considering sharp edges located close to the applied strain gage. The annular notch is not a significant source of usability restrictions after the component testing. In case of several measurements close to each other, the accuracy will not change. Experimental testing proved the possibilities of MTS 3000 Ring-Core measuring string on vertically placed object. The measurement is possible even in this untypical position but it requires greater precision in the preparation of the measuring string and mainly during the mill centering against the middle of the strain gage rosette. Results also confirm that evaluation process of the residual stresses is in shallow depths (up to 0.5 mm) significantly affected by various parasitic phenomena, therefore the deeper measurement is always recommended. The continuing research is focused on the analysis of the evaluation techniques in case of different types of non-uniform stress fields.

Acknowledgement

The authors would like to thank to Slovak Grant Agency – project VEGA 1/0937/12 "Development of unconventional experimental methods for mechanic and mechatronic systems".

References

[1] F. Trebuňa, F. Šimčák, Handbook on experimental mechanics (In Slovak "Príručka experimentálnej mechaniky"), first ed., Košice SjF TU, 2007, 1526 p., ISBN 970-80-8073-816-7.

[2] ASTM International Designation E837-13a: Standard Test Method for Determining Residual Stresses by the Hole-Drilling Strain-Gauge Method, United States, 2013, 16 p, doi: 10.1520/E0837.

[3] E. Valentini, A. Benincasa, L. Bertelli, An automatic system for measuring residual stresses by Ring-core method, Italian Stress Analysis Association, 40th National convention, University of Palermo, 2011.

[4] F. Menda et al., SolidWorks API for Ring-Core Simulations, In: SAMI 2014: IEEE 12th International Symposium on Applied Machine Intelligence and Informatics: proceedings: January 23-25, 2014, Herľany, Slovakia, doi: 10.1109/SAMI.2014.6822397.

[5] B. Zuccarello, Optimization of Depth Increment Distribution in the Ring-Core Method, Journal of Strain Analysis for Engineering Design, July 1996, Vol. 31, no. 4, p. 251-258, doi: 10.1243/03093247V314251.

[6] F. Menda, F. Trebuňa, P. Šarga, Determination of the Necessary Geometric Parameters of the Specimen in Ring-Core method, In: Applied Mechanics and Materials, Vol. 486, p. 90-95, 2014, doi: 10.4028/www.scientific.net/AMM.486.90.

[7] P. Šarga, F. Menda, Analysis of Measuring Chain for Evaluating Residual Stresses by Ring-Core Method, In: American Journal of Mechanical Engineering, Vol. 1, no. 7 (2013), p. 313-317, doi: 10.12691/ajme-1-7-32.