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AN AUTOMATIC SYSTEM FOR MEASURING RESIDUAL STRESSES BY THE RING-CORE METHOD

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Abstract

This paper presents an automatic system for the measurement of residual stresses by the ring-core method. Compared with all other methods for residual stress measurements, the ring-core method has some distinctive features: it enables the profile of residual stresses in material up to a depth of approx. 5 mm. to be determined. It consists of a mechanical section that physically produces the core, an electronic device that controls the machining and the feed motion of the machining tool and a control software for acquisition of data from a strain gage rosette with three overlapping measuring grids (HBM K-RY51-5/350). The machining tool is a hollow milling cutter: the strain gage rosette and the machining axis are centered using a USB Webcam and special centering software.
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Sommario

Il presente lavoro ha lo scopo di presentare un sistema automatico per la misura delle tensioni residue con il metodo della cava anulare. Rispetto a tutti gli altri metodi di misura delle tensioni residue, il metodo della cava anulare presenta alcune caratteristiche peculiari: il metodo infatti permette la ricostruzione del profilo delle tensioni residue presenti nel materiale sino ad una profondità di circa 5 mm. Il sistema automatico di misura è costituito da una parte meccanica che realizza fisicamente la cava, una parte elettronica che controlla la foratura e gli avanzamenti ed un software di controllo per l'acquisizione dei dati provenienti da una rosetta estensimetrica a tre griglie sovrapposte (HBM K-RY51-5/350). L'utensile di foratura è costituito da una speciale fresa cava: il centraggio tra la rosetta e l'asse di foratura è realizzato sfruttando una Webcam USB ed uno speciale software di centraggio.
(*Pubblicazione in lingua Inglese al sito web: http://www.mts3000.com*)

Key terms: residual stresses; ring-core method; residual stress ring-core method.

1. INTRODUCTION

The ring-core method is a partially-destructive test method for measuring the residual stresses present in a mechanical component and consists in machining an annular groove around a special strain gage rosette.
It can be used for determining uniform and non-uniform residual stresses and is often used in industry to determine residual stresses on large-size forgings or castings. In such cases, residual stresses are measured during the production cycle and not at the final stage of production. Since these are usually single components or small lots, the measurement points are at locations that will in any case be machined in order not to damage the surface of the component. In these specific applications, the ring-core method enables the residual stresses in the component to be determined without considering the effects of operations performed on the surface of the part.

2. COMPARISON BETWEEN THE RING-CORE METHOD AND THE HOLE-DRILLING STRAIN GAGE METHOD

The ring-core method is a strain gage method for measurement of macroscopic residual stresses.
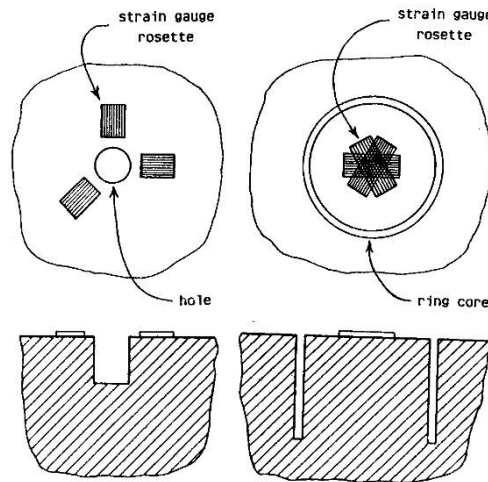

Figure 1: Differences between the hole-drilling strain gage method and the ring-core method

The ring-core method is undoubtedly less common than the hole-drilling method. In addition to being more "destructive", the fact that actual performance of the test is more complex has limited evolution of the method. It has considerable similarities to the hole-drilling method, in fact, the two methods are complementary as they are based on the same mathematical equations for calculating residual stresses from measured strains, although the methods clearly have totally different calibration constants and curves.

One of the major advantages of the ring-core method is its greater sensitivity (with the same measured residual stresses, relaxed strains are 3 to 4 times greater), which enables the influence of error in the acquisition stage of testing to be reduced.

The influence of core-rosette eccentricity error is also less than with the hole-drilling method as the eccentricity errors tend to compensate each other. Lastly, the ring-core method allows the stress profile to be reconstructed to greater depths, even exceeding 4mm.

The drawbacks are the fact that the ring-core method of testing takes longer, applying the strain gage rosette is more elaborate, and it produces greater surface damage causing it to be considered "more destructive" than the hole-drilling rosette method.

The automatic system, described here, facilitates the measurement procedure and allows more accurate results to be obtained than with manual systems.

3. DESCRIPTION OF THE SYSTEM – MEASURING CHAIN

Figure 2 shows the measuring chain for residual stress testing by the ring-core method. The system, which is fully automatic, consists of a mechanical unit for machining the annular groove, an electronic control unit to control the cutter feed and actual machining, a digital strain gage amplifier (in the diagram, for example, HBM Spider 8-30 or Quantum X), and finally a personal computer. The system uses the RSM program for system control and acquisition of strains measured by the strain gage rosette and Eyeshot for centering the system in relation to the strain gage rosette. Finally, a calculation program is used to process the acquired strains and determine the residual stresses.
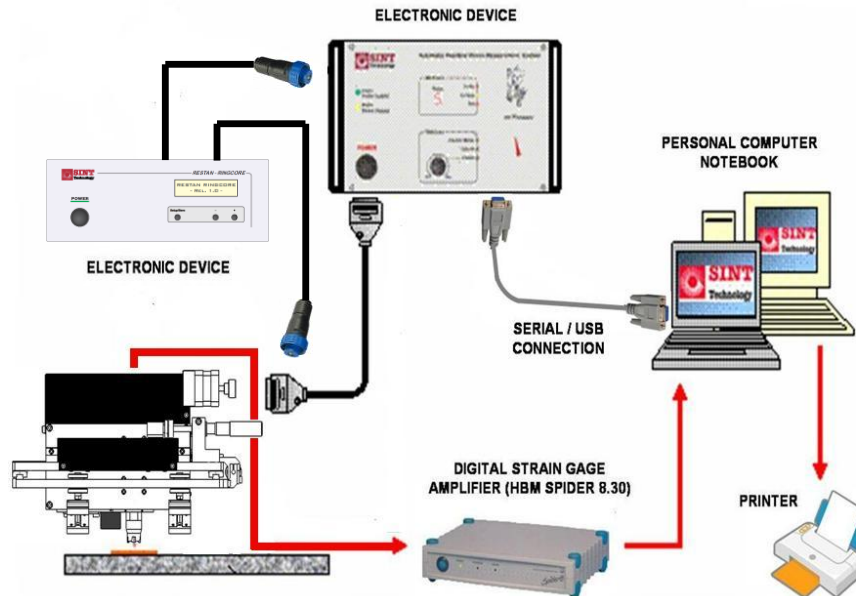
Figure 2: The MTS3000 - RingCore measuring chain for residual stress measurement
by the ring-core method.

3.1. Mechanical unit

A photograph of the mechanical section of the instrument is shown below.
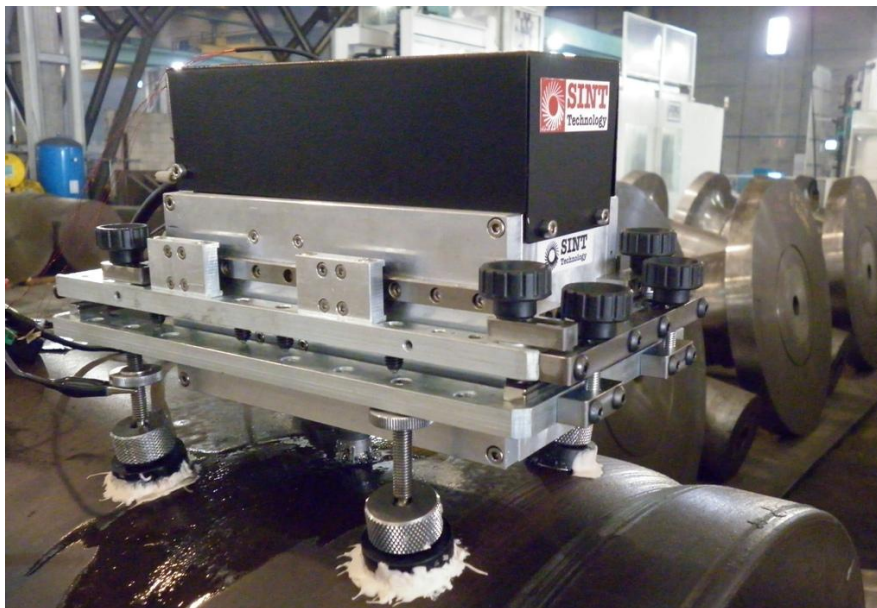

Figure 3: The mechanical unit of the MTS3000 - RingCore automatic system
for measuring residual stresses by the ring-core method

The mechanical system enables the machining axis to be centered with the strain gage rosette, operation of the electric motor in d.c. for machining the annular groove around the strain gage rosette and control of the vertical feed motion for the machining with drive by a stepping motor.

The mechanical system is formed of a double structure: a central body housing the two motors (the stepping motor to move the cutting tool and the d.c. gear motor for the machining) and the centering webcam, and an external frame, integral with the central body, for effecting the manual translations used for centering and positioning the mechanical part of the instrument.

The overall dimensions of the system are small (310 mm long, 160 mm wide, 230 mm high max.).

The cutting tool is a special cup mill (Figure 5) with an outer diameter of 18 mm and an inner diameter of 14 mm. The tool rotates at approx. 350 rpm.

Feed motion in the direction of the depth (direction Z) is automatic and is at a speed that depends on the material to be machined. The travel in this direction is approx. 20 mm.

Translation in directions X and Y is manual and allows a traverse of approx. 20 mm, in order to be able to center the system in relation to the strain gage rosette.

By suitably adjusting the magnetic feet, the instrument can be used to carry out tests on flat, concave and convex surfaces. It can also be used for testing inside bores of a minimum diameter of approx. 230 mm; this feature makes it suitable for use also inside large forged disks used for producing turbine and compressor disks.
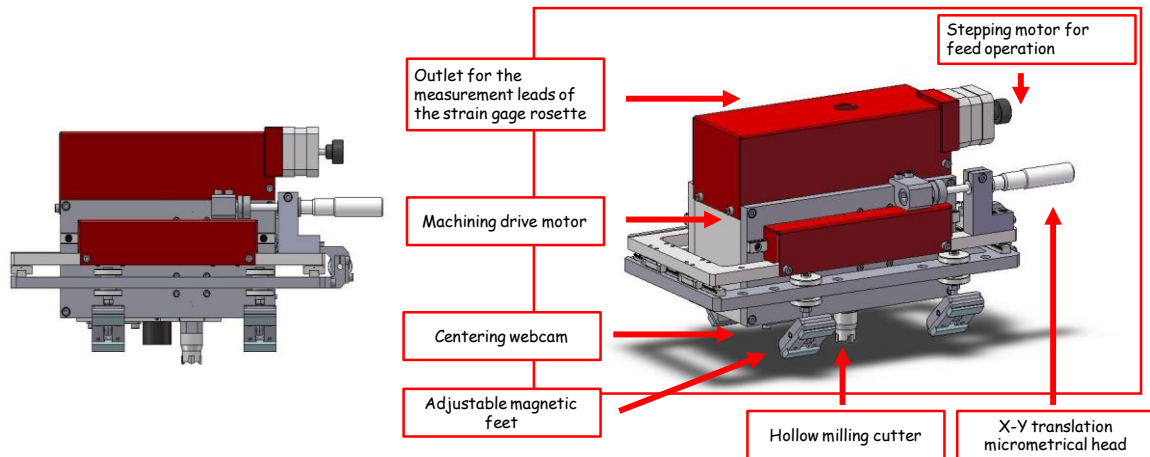

Figure 4: Side view of the instrument. The optical axis of the webcam is parallel to the drilling axis

The mill and strain gage are aligned with a special webcam fitted on the instrument: the optical axis and drilling axis are not aligned and it is therefore necessary to effect a translation before beginning testing. The drilling spindle of the instrument is hollow and this allows the leads from the strain gage rosette to reach the digital strain gage amplifier avoiding disconnections during measurement.

On the back of the instrument there are the connections to the electronic part (feed lead, power lead) and to the personal computer (webcam video signal output lead).

3.2. Electronic unit

The MTS3000 - RingCore system for the measurement of residual stresses by the ring-core method uses the same feed control unit used in the system for measuring residual stresses by the hole-drilling method (MTS3000 - Restan) produced by SINT Technology.

Along with that control unit, the instrument uses an additional control unit to operate the motor used for the machining.

3.3. Centering software (Eyeshot)

The Eyeshot centering software enables the optical axis of the instrument to be aligned with the center of the strain gage rosette applied on the workpiece being tested.

Once the webcam is connected to a USB port on the computer, the software automatically manages all the images from the webcam mounted on the mechanical section of the instrument.

In particular, the software allows a guide plate to be applied on the screen that the user can adjust, thus enabling the milling cutter to be aligned with the strain gage rosette.
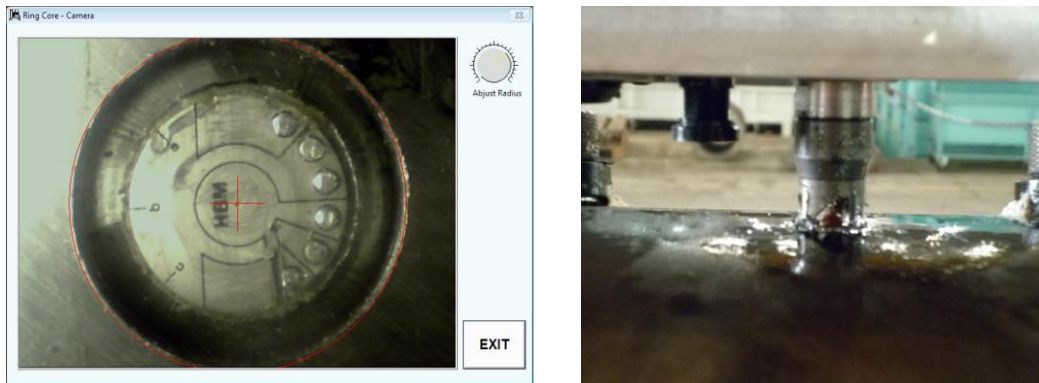
Figure 5: On the left, Eyeshot software for aligning the milling cutter and strain gage rosette. On the right, a detail of the milling cutter and centering Webcam

3.4. Control and acquisition software

The instrument for measurement of residual stresses by the ring-core method is automatically controlled by a specific software which allows the testing to be run (zero depth detection by electrical contact, control of machining and cutter feed), management of acquisition (selection of the strain gage amplifier and rosette) and automatic acquisition of the strain values for each drilling step.
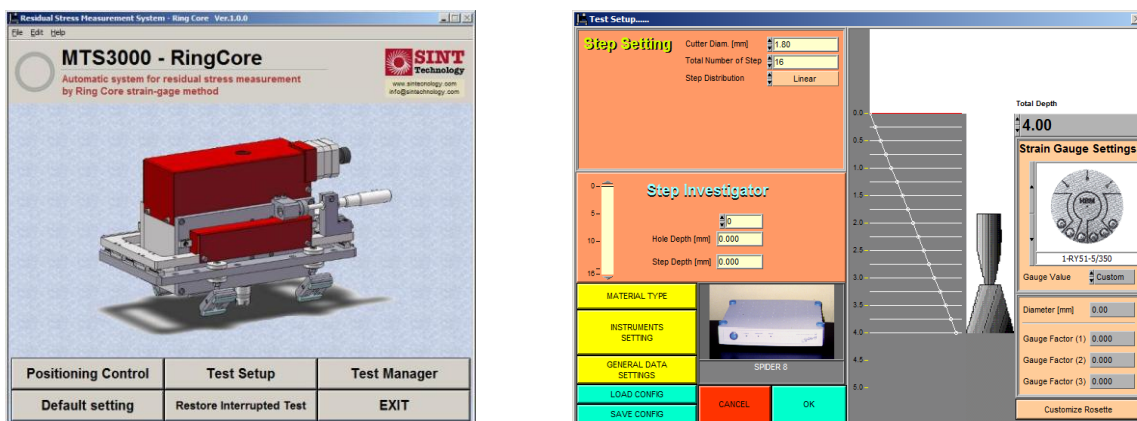

Figure 6: RSM software for automatic control of testing and acquisition of strains

3.5. Post-processing software

The post-processing software makes it possible to manage the acquired data (interpolation of the strains) and to automatically calculate the stresses according to the established calculation methods (integral equation method, incremental strain method, differential method, etc.).

4. STRAIN GAGE INSTALLATION

The HBM K-RY51-5/350 strain gage, used for the testing, is shown is Figure 7. As already indicated in the previous section, material is removed around the strain gage rosette using a particular hollow mill with a suitable geometry (inner diameter, outer diameter, cutting angles).
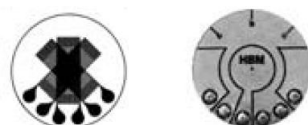

Figure 7: Strain gage rosette with overlapping measuring grids (HBM K-RY51-5/350)

Lubricating the milling cutter during machining with cutting fluid for metals is advisable for improving the efficiency of the cutting process. Since the presence of oil could cause problems in acquisition of the strain gage rosette, it is essential to protect the rosette. This protection is achieved using a nitrile rubber based protective coating (HBM NG-150) which ensures electrical protection of the rosette even in the presence of oil.

The leads from the measuring grids of the rosette are protected with a heat-shrink tubing. Before the leads reach the strain gage amplifier, they have to run the whole length of the hollow drilling spindle without any abrasion or breaks that could affect the measurement.
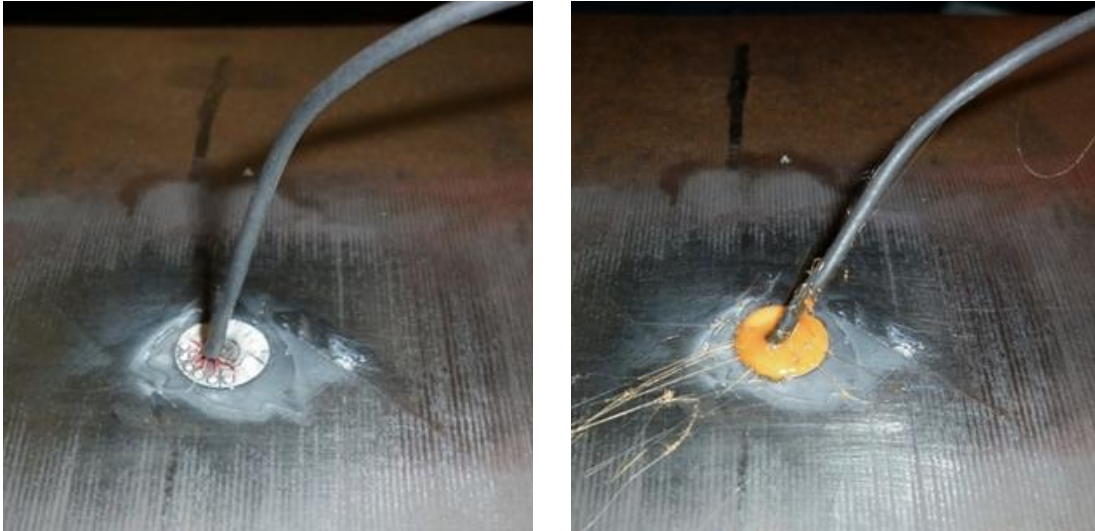

Figure 8: Protection of the strain gage rosette with overlapping grids (on the left protection of the lead, on the right protection of the grid with HBM NG150 nitrile rubber)

The individual measuring grids of the strain gage rosette, with a resistance of 350 Ω, are connected by three-wire quarter-bridge connections (to compensate any variations in temperature on the measuring cables) to the digital amplifier (HBM Spider 8.30).

5. TEST PROCEDURE

The test procedure used by SINT Technology for measurement of residual stresses by the ring-core method, using the MTS3000 – RingCore system, is as follows:

- Apply a strain gage rosette with three overlapping grids in the test area (prepare surface, bond and solder leads).
- Protect the strain gage leads with heat-shrink tubing.
- Protect the rosette with HBM NG150 nitrile rubber based protective coating.
- Place the mechanical section of the instrument on the area to be measured, lay the cables from the strain gage rosette through the hollow drilling spindle and secure the instrument with the magnetic clamps (or with HBM X60 adhesive).
- Center the crown milling cutter and strain gage rosette using the Webcam installed on the instrument and the centering software (Eyeshot).
- Zero depth is automatically detected by the electrical contact technique.
- An annular groove is machined around the strain gage rosette in depth increments of 0.25 mm, and at each step the strain values measured by the three grids are automatically acquired.
- The previous step is repeated to reach a minimum depth of 4 mm.
- The acquired strains are processed by the method considered most appropriate, using the EVAL – RingCore post-processing software.

6. CALCULATION OF RESIDUAL STRESSES BY THE RING-CORE METHOD

Calculation of residual stresses by the ring-core method presents strong analogies to the calculation of residual stresses by the hole-drilling method. In the case of the ring-core method, the calculation methods most widely-covered in literature are the integral equation method [3] and the incremental strain method [1,2]. Another method, used in industry, is the differential one, for determining stresses in a set interval [1,4].

SINT Technology is committed to extending applicability of the calculation methodologies present in standard ASTM E837-08 to the ring-core method. This would make it possible to introduce a determination of residual stresses for uniform and non-uniform stress fields. Tikhonov regularization would reduce the effect of errors in the measured strains on the calculated strresses, also with this method.

6.1. Incremental strain method

The incremental strain method [1,4] for calculation of residual stresses by the ring-core method was developed in Germany by H. Wolf and W. Böhm [1] in the seventies.

The method is based on measurement of the variation in strain during drilling and presents analogies to the Schwarz - Kochelmann method [7] applied for calculating residual stresses by the hole-drilling method.

For the various in-plane measurement directions i, the incremental equation takes the following form:

$$\frac{d\varepsilon_i}{dz} = \frac{1}{E} \cdot K_i(z) \cdot \sigma_z \tag{1}$$

where $K_i(z)$ is the relaxation function in direction i.

From equation (1) it is possible to produce the following equations, which allow the stresses in the directions of the three measuring grids (a,b,c) to be calculated:

$$\sigma_a = \frac{E}{K_1^2 - v^2 K_2^2}\left[K_1 \frac{d\varepsilon_a}{dz} + vK_2 \frac{d\varepsilon_c}{dz} \right] \tag{2}$$

$$\sigma_a = \frac{E}{K_1^2 - v^2 K_2^2}\left[K_1 \frac{d\varepsilon_b}{dz} + vK_2 \left(\frac{d\varepsilon_a}{dz} - \frac{d\varepsilon_b}{dz} + \frac{d\varepsilon_c}{dz} \right) \right] \tag{3}$$

$$\sigma_c = \frac{E}{K_1^2 - v^2 K_2^2}\left[K_1 \frac{d\varepsilon_c}{dz} + vK_2 \frac{d\varepsilon_a}{dz} \right] \tag{4}$$

By combining the stresses in the three directions the principal stresses $\sigma_{1,2}$ and principal angle β are determined.
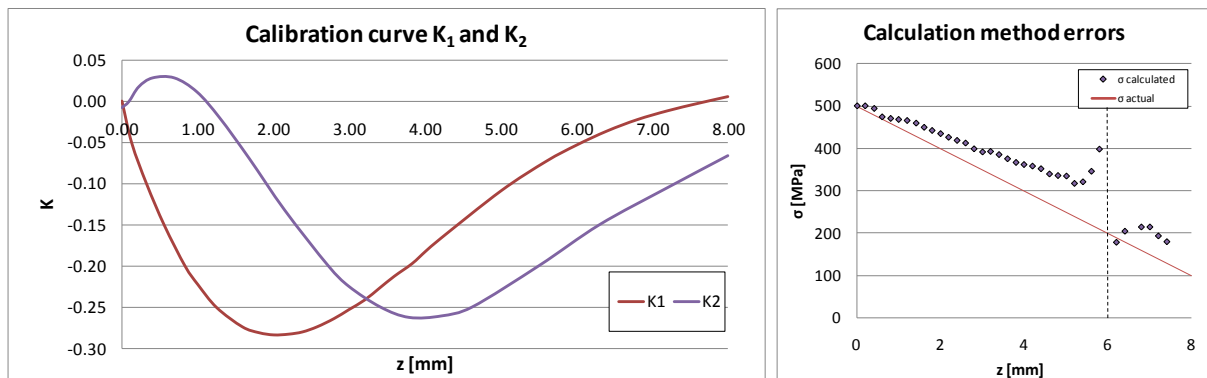

Figure 9: On the left, calibration curves of the incremental strain method.
On the right, incremental method errors in a non-uniform stress field [4]

The functions $K_1(z)$ and $K_2(z)$ that are in equations (2), (3) and (4) are determined experimentally with a stress test on a test piece applying a known monoaxial stress.
The values of functions K_1 and K_2 as a function of the groove depth z are indicated in figure 9.
The equations (2), (3) and (4) are indeterminate at a critical point of depth z which is equivalent to the depth z of approx. 5.9 mm., for which the difference between the values of K_1 and vK_2 to the denominator of the equations is null. Figure 9, on the right, shows how the incremental strain method is strictly applicable only for stress fields that are uniform in depth; when applied to non-uniform stress fields the incremental method overestimates the actual stress.

6.2. Differential method

The differential method [1,4] has been developed for quick evaluations of residual stresses calculated from the strains measured by the strain gage rosette installed on the workpiece. The method is applied for quality control on large forgings, for example.
It is a particular alternative of the incremental strain method and has been developed for the HBM type K-RY51-5/350 strain gage rosettes with three overlapping grids (and when the principal directions are known , also for K-XY51-5/350 rosettes with two measuring grids).
Having called z the total depth of the annular groove, the principal stresses are calculated, in the interval [z/2; z], with the following equations:

$$\sigma_1 = A \cdot \Delta\varepsilon_1 + B \cdot \Delta\varepsilon_2 \qquad\qquad \sigma_2 = A \cdot \Delta\varepsilon_2 + B \cdot \Delta\varepsilon_1 \qquad\qquad (5)$$

$$\Delta\varepsilon_1 = \varepsilon_{1;z} - \varepsilon_{1;z/2} \qquad\qquad \Delta\varepsilon_2 = \varepsilon_{2;z} - \varepsilon_{2;z/2} \qquad\qquad (6)$$

The constants A and B used in the calculation are determined performing an experiment with a known monoaxial stress condition applied in the direction normal to the annular groove.
A preliminary evaluation, between 2 and 4 mm, of the residual stresses on steel (E = 210GPa, v = 0.30) is obtained using the following calibration constant values: **A** = -0.4444 MPa, **B** = -0.1074 MPa.

6.3. Integral equation method

The integral equation method for calculation of residual stresses by the ring-core method was proposed by Ajovalasit, Petrucci and Zuccarello [3] in 1996.
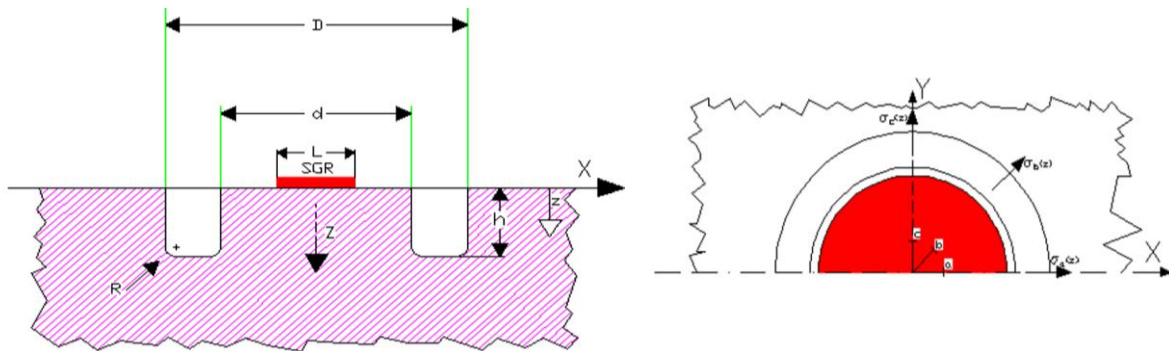

Figure 10: Integral method for calculating residual stresses by the ring-core method

The integral method for calculating residual stresses is based on the following equation, which describes the variation of stress for every step of depth z:

$$\varepsilon_x(H) = \frac{1}{E} \int_0^H F(H,z) \cdot \sigma_x(z) \cdot dz \qquad\qquad (7)$$

In the case of a two-dimensional stress field, the equation can be re-written as:

$$\varepsilon_x(H) = \frac{1}{E} \int_0^H \left\{ A(H,z) \cdot [\sigma_1(z) + \sigma_2(z)] + B(H,z) \cdot [\sigma_1(z) - \sigma_2(z)] \cdot \cos[2 \cdot \alpha_k(z)] \cdot dz \right\} \tag{8}$$

Considering n finite depth increments, the equation can be re-written, for any direction k, in the following form:

$$\varepsilon_{kni} = \frac{1}{E} \sum_{i=1}^n a_{ni} \cdot (\sigma_{1i} - \sigma_{2i}) + \frac{1}{E} \sum_{i=1}^n b_{ni} \cdot (\sigma_{1i} - \sigma_{2i}) \cdot \cos(2\alpha_{ki}) \tag{9}$$

where $k = a, b, c$

The above equation has the same form as the equation that applies for the integral method used for measuring non-uniform residual stresses by the hole-drilling method and therefore the theory for calculation of residual stresses from the strain values is the same.
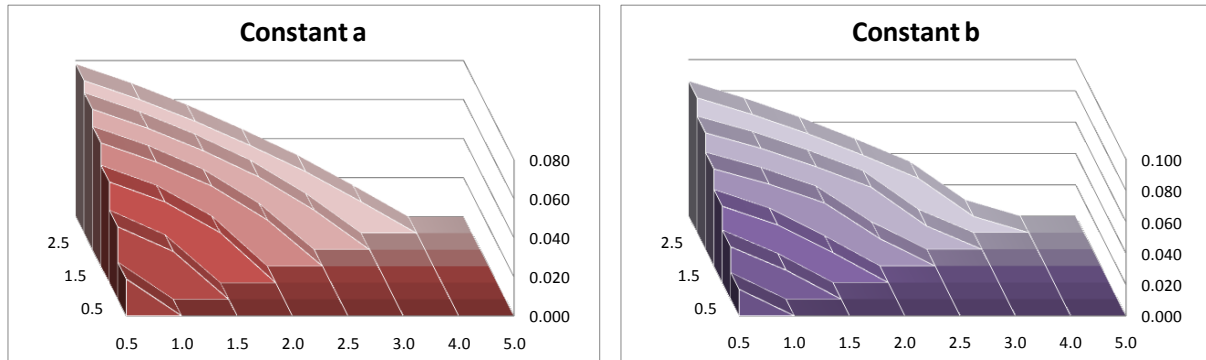

Figure 11: Constants a and b of the integral method for calculation of residual stresses by the ring-core method

6.4. General strategy of calculation. Uniform and non-uniform stress fields

Considering the analogies with the hole-drilling method, some of the test conditions prescribed in the ASTM E837-08 method, which applies to the hole-drilling method, can be transferred to the ring-core method.
In particular, it is possible to establish the following testing strategy:
- Acquisition of strains for every drilling increment.
- Uniform stress field test.
- If stresses are uniform, the differential method is applied [1,4].
- If stresses are not uniform, the integral equation method is applied [3], using also the Tikhonov regularization criterion.

First of all, it is necessary to select the strain gage rosette, to establish the technique for machining the annular groove and the number of acquisition points required for reconstruction of the stress profile. It is proposed that a special hollow mill with an inner diameter of 14 mm and an outer diameter of 18 mm be used. It is advisable to use HBM K-RY51-5/350 rosettes, with 5 mm long measuring grids, as they are widely available on the market. As far as concerns the strategy for acquisition of the strain values, it is proposed that an annular groove be machined in several drilling increments (it is advised that the groove be machined in increments of 0.25 mm up to a depth of at least 4 mm).
Relating to the residual stress calculation, a preliminary stress uniformity test is proposed to verify that the residual stresses are uniform within the groove depth, similar to the procedure prescribed by standard ASTM E837-08. This calculation is still useful even if the residual stresses prove to be non-uniform as it allows a preliminary evaluation of the residual stresses present in the material, for

example, for a quick quality control data analysis. The calculation corresponding to the total relaxation of the stresses is not applicable as the depth of the groove is less than the minimum depth (1.2 times the outer diameter of the groove) corresponding to the total relaxation.[8]

For computation of non-uniform stresses, the same method laid down by the standard, including Tikhonov regularization of the calculated stresses, can be used.

The calibration matrices **A** and **B** can be calculated using finite element methods and have the same format as those provided in standard ASTM E 837-08.

The calculation increments could have a constant size of 0.25 mm.

7. ACHIEVED RESULTS

Figure 13 shows the workpiece on which residual stress measurements were made by the ring-core method using the MTS3000 - RingCore system
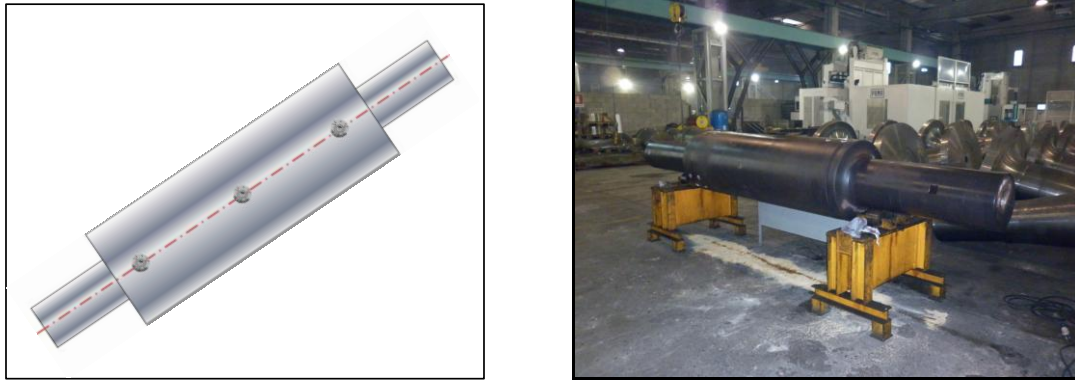

Figure 13: Steel forgings used for testing

The measurements were made on a forged shaft made of steel after stress relieving heat treatment. Three measurements were taken approx. 600 mm apart and on different generatrices (0°, 120° and 240°).

Figure 14 shows as an example, the strains acquired by the instrument and the stresses calculated by two of the methods described in section 6 (the integral equation method and the incremental strain method).
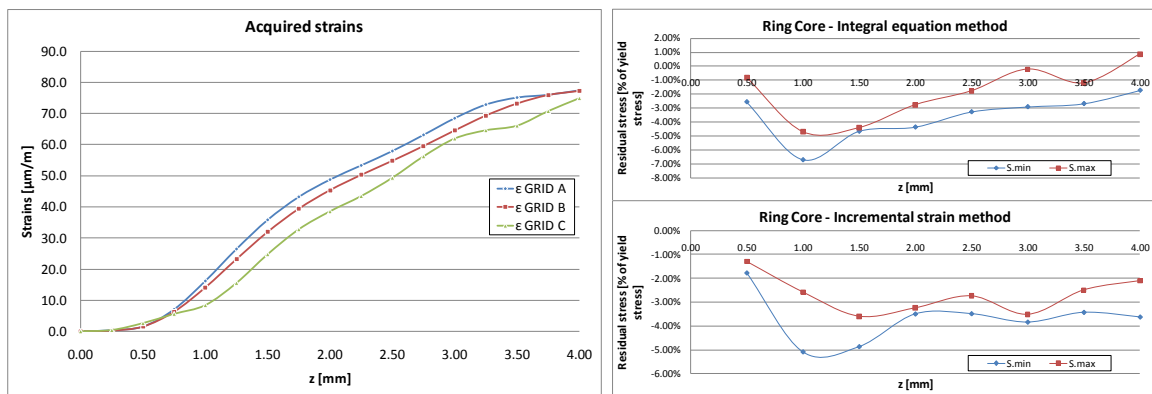

Figure 14: On the left, acquired strains. On the right, residual stresses calculated by the ring-core method.

In both cases, the stresses are within a range from -7% to 1% of the yield stress of the material.

The values obtained at the three measurement points, using the differential method described under 6.2. are shown in Figure 15. As can be seen, the values are repeatable and in addition to showing that the residual stresses are low, this demonstrates that the measurement system does not introduce significant stresses caused by machining the groove.

Residual stress [% of yield stress]		
Point	σ_{AXIAL}	$\sigma_{TANGENTIAL}$
	[MPa]	[MPa]
RC - 0°	-15.8	-15.5
RC - 120°	-13.0	-12.9
RC - 240°	-16.5	-17.9

Figure 15: On the left, the results obtained with the differential method at the various measurement points on the forging. On the right, a typical annular groove made by the instrument.

8. CONCLUSIONS

- The ring-core method is the optimum method when residual stresses need to be anaylzed at a depth (approx. 4 mm) considerably greater than the depth that can be analyzed by the hole-drilling method (1-2 mm).
- An automatic system has been developed for measuring residual stresses by the ring-core method. The procedures for protecting the strain gage installation and for machining the annular groove in a series of depth steps have been established.
- Finally, some typical results obtained on steel forgings with the MTS3000 – RingCore measurement system, using the various calculation methods, have been shown. The results are repeatable and the machining system does not introduce significant residual stresses.

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