



Residual Stresses Measurement in UIC 60 Rail by Ring-Core Method and Sectioning Technique

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ABSTRACT: The measurement of residual stress in rail foot, according to manufacturing standards is mandatory. In this study, the ring-core method and the sectioning technique are used to measure the residual stresses. A calibration technique for the ring-core method has been explained and simulated by the finite element analysis. The calibration coefficient has been determined for certain parameters and various depths of the annular groove. The ring-core method has been simulated for the uniaxial residual stress field and it is observed that the maximum error in the maximum principal residual stress was about 13% which is about 5% of material yield stress. The residual stresses have been measured at the UIC 60 rail foot by the ring-core method and the sectioning technique, and the results are in a good agreement with earlier investigations in this field. Also, it has been indicated that maximum residual stresses on the rail foot are not in the longitudinal direction and in the subsurface of the rail foot, the maximum principal direction coincides with the longitudinal direction. Both methods indicated tensile residual stresses on the rail foot, but the ring-core method predicted 27% higher longitudinal residual stress on the rail foot in comparing with the sectioning technique.

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1- Introduction

Hot rolling, cooling, and straightening are the main steps of rail manufacturing process. After the hot rolling process, the rail temperature is about 900°C and because of the rail cross-section geometric condition, the heat transfer is not uniform in the cooling process [1]. The non-uniform temperature distribution leads to the development of thermal stresses which may be higher than the yield stress of the material at high temperature. Therefore, thermal stresses will bend the rail during the cooling process in the form of circular arcs and hence its straightness will be lost. The bent rails are subsequently straightened in the straightening machine [2]. Straightening process is performed at ambient temperature and in fact, cool work takes place during the straightening process. In the straightening machine, rails pass from several rollers and bending stresses cause plastic deformation on the rails. The non-uniform plastic deformations in the straightening process, develop residual stresses in the rails. The residual stress effect on rail's mechanical properties, flatness, straightness, etc. Fatigue life of the rails is very important for rail's system management. Therefore, they demand a reduction of the residual stresses in the rails. Destructive methods such as hole-drilling [3], slitting method [4-6], and contour method [7, 8], have been used to measure the residual stresses in the different component.

Many efforts have been made for determination of residual stresses in the rails. Basua et al. [9] indicated that residual stresses before straightening process are not significant. This conclusion at first is sensible because in the hot rolling steps, thermally activated deformation mechanisms and in the cooling process, plastic deformation (camber) reduces

the residual stresses. Residual stresses are a consequence of interactions among time, temperature, deformation, and microstructure. In the cooling process change in the phase of the material can produce the high magnitude of residual stresses. Fischer and Schleinzer [10] indicated that knowledge about the residual stresses in the cooling process is necessary for the complete understanding of residual stress development in the rails. Most of the researchers such as the author of the reference [10] believe that roller straightening is the determiner of final residual stress pattern in the rail manufacturing process. Most of the experimental tests have shown a C shape pattern of residual stresses in the rail cross-section. Hodgson [11] used the strain gage for measuring the residual stresses and indicated C shape pattern. Webster et al. [12] used neutron diffraction method and expressed similar results. In addition to experimental tests, some of the other researchers have used numerical calculation to estimate the residual stresses after straightening process. Schleinzer and Fischer [13] by attention to the elastic and plastic behavior of special grades of rail's material and using sub model indicated C shape pattern of residual stresses, but the results of Srimani et al. [14] and Betego et al. [1] were the zigzag shapes.

According to the results of residual stress measurement in the rails, the residual stresses in the rail foot and head are tensile and this condition is not favorable. Rails are subjected to the bending loads from train wheels and tensile stresses from the loads will be added to the tensile residual stresses at the foot of the rail and therefore the critical point in the rail cross section is the foot of the rail. According to these results, the permitted tensile residual stress on the rail foot is limited to 250 MPa [15].

Rolling contact fatigue of the rails is an important problem in railway systems. Ringsberg et al. [16] developed an FE

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model and considered the residual stresses by the non-linear behavior of the material. Turan et al. [17] indicated the effect of residual stresses in the head-hardened rail under a certain condition. Their results indicated compressive residual stress in the rail head from X-ray test. Donzella et al. [18] indicated the effect of braking on the railway wheel. They expressed that plastic deformation due to the braking can reduce the amount of the residual stresses and even change them from compressive residual stresses to the tensile one in the rail wheel, but they didn't state the results of braking on the rail. Several methods are introduced for residual stress measurement to the industry and each one has its limitation. The ring-core method is a semi-destructive method for residual stress measurement. This method was mostly used for measuring the residual stresses in forged materials. Vaklavik et al. [19] measured the residual stresses in a shaft by the mean diameter of 1100 mm by the ring-core method. They have also mentioned that ring-core method is suitable for measuring the under surface residual stresses, where the standard hole-drilling method is less sensitive. Masláková et al. [20] explained the procedure of residual stress measurement by the ring-core method. This reference gives a description of the sample preparation and a detailed description of the application of strain gauge rosette to the surface under measurement. Menda et al. [21] investigate the effect of the cutter geometry in the ring-core method. They indicated that due to the slope at the bottom of the created notch, the relieved strains value was lower than expected. Bouffieux et al. [22] compared the residual stresses on long rolled profiles measured by X-ray diffraction, ring-core, and the sectioning methods. They expressed that in thin wall thickness specimen, the results of residual stress measurement by three methods were close.

Various residual stress measurement methods have been used to evaluate the residual stresses in the rails, but according to the rail manufacturing standard, residual stresses in the rail foot shall be evaluated by sectioning technique. This method is very time consuming and destructive. In this research, the residual stresses in the foot of the rail have been measured by sectioning technique and the ring-core method. According to the knowledge of authors, this is the first time that the ring-core method is experienced for the measurement of residual stresses in the rails. The ring-core method is a semi-destructive method for residual stress measurement. This method is less sensitive to the surface condition in comparison with the other semi-destructive methods and has the ability to measure the subsurface residual stresses. By attention to the rail manufacturing process and final surface condition of the rail foot, the ring-core method may be a suitable method for residual stress measurement of the rail foot. This method can be considered as a fast method for quality control of the rails. In the presented paper, the ring-core method and an FEM model for determination of calibration coefficient are explained.

2- Residual Stress Measurement by Ring-Core Method

2- 1- Theory of ring-core method

Marisa and Peterson [23] described the non-incremental ring-core method. They introduced the relationship between the measured strains and principal residual stresses in the non-incremental ring-core method. By cutting an annular groove in the stressed specimen, the strains will be relaxed in the

core of the ring. It is possible to estimate the residual stresses before cutting the annular groove by using the released strains on the surface of the core. The principal residual stresses and angle between the maximum principal residual stress and first strain gage in strain rosette are calculated by equations (1), (2) and (4) [23]. Fig.1 shows the schematic diagram of the ring-core method and angle between the maximum principal residual stress and the direction of the first strain gage in the strain rosette.

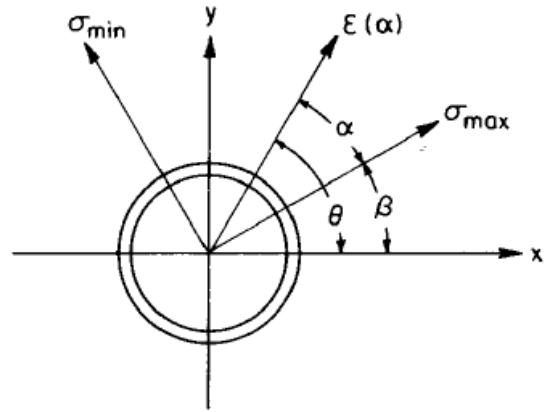


Fig. 1. The angle between the direction of the first strain gage and maximum principal residual stress [23].

$$\sigma_{max} = \frac{\varepsilon_1(A + B\sin(\lambda)) - \varepsilon_2(A - B\cos(\lambda))}{2AB(\sin(\lambda) + \cos(\lambda))} \quad (1)$$

$$\sigma_{min} = \frac{\varepsilon_2(A + B\cos(\lambda)) - \varepsilon_1(A - B\sin(\lambda))}{2AB(\sin(\lambda) + \cos(\lambda))} \quad (2)$$

$$\lambda = \tan^{-1} \frac{\varepsilon_1 - 2\varepsilon_2 + \varepsilon_3}{\varepsilon_1 - \varepsilon_3} \quad (3)$$

$$\beta = \frac{1}{2} \tan^{-1} \frac{2\varepsilon_2 - (\varepsilon_1 + \varepsilon_3)}{\varepsilon_1 - \varepsilon_3} \quad (4)$$

$$A = \frac{k}{2E}(1 - \nu) \quad (5)$$

$$B = \frac{k}{2E}(1 + \nu) \quad (6)$$

In the equations (1) to (6) [23], ε_1 , ε_2 and ε_3 are the measured strain by the strain rosette. σ_{max} and σ_{min} are the maximum and minimum principal residual stresses. The parameter λ is defined by equation (3) and β is the direction of the maximum principal residual stress and first strain gage in the strain rosette. The parameters A and B are two constants which depend on material properties and calibration coefficient K . After determination of the K for certain parameters of the rings such as diameters and depths, A and B could be calculated. In the next step, the residual stresses and their directions could be determined by equations (1), (2) and (4).

2- 2- Calibration

When a ring is cut on the surface of a residually stressed object, there will be a relaxation of the strain inside the ring. This relieved strain can be relevant to the principal residual stresses on the surface by equation (7) [23] (attention to Fig.1).

$$\varepsilon(\alpha) = K(\alpha)\sigma_{max} + K(90^\circ - \alpha)\sigma_{min} \quad (7)$$

In the equation (7), $\varepsilon(\alpha)$ is the measured strain in the surface of the ring by angle α with respect to the maximum principal residual stress. The calibration process is done by using a known residual stress field. If the principal direction is known, then the direction of the strain gage can be aligned in this direction [23]. In this condition, equations (1) and (2) can be written as equations (8) and (9).

$$\varepsilon_{max} = (A + B)\sigma_{max} + (A - B)\sigma_{min} \quad (8)$$

$$\varepsilon_{min} = (A - B)\sigma_{max} + (A + B)\sigma_{min} \quad (9)$$

The relieved strains in this condition also can be written as equations (10) and (11).

$$\varepsilon_{max} = \frac{k}{E}\sigma_{max} - \frac{\nu k}{E}\sigma_{min} \quad (10)$$

$$\varepsilon_{min} = \frac{k}{E}\sigma_{min} - \frac{\nu k}{E}\sigma_{max} \quad (11)$$

In the case of uniaxial residual stress field, the σ_{min} is equal to zero. By inserting $\sigma_{min}=0$ in equation (10), the calibration factor K is determined as equation (12).

$$k = E \frac{\varepsilon_{max}}{\sigma_{max}} \quad (12)$$

Where, ε_{max} is the maximum released strain and σ_{max} is the maximum residual stress on the surface.

Several methods for calibration are proposed by different researchers. Marisa and Peterson [23] proposed to use the pure bending as a known residual stress field. Keil [24] used the uniaxial tension in the calibration process. Civin and Vik [25] used an FE model for determination of calibration coefficient. Except for reference [23], other mentioned references are related to the incremental method. In this paper, the mean value of residual stresses has been considered because the goal is comparing the results of sectioning technique and the ring-core method.

Abaqus finite element analysis products [26] are used to determine the calibration coefficients which is expressed by Eq. (12). The uniaxial tension condition is modeled based on the specimen dimension of $a \times a = 50 \times 50$ mm and thickness $t = 20$ mm. Due to the symmetry, only a quarter of the specimen has been modeled. The stress-strain behavior of the material has been considered as elastic ideally plastic and model parameters have been indicated in Table 1. Annular groove has been modeled in 10 steps and in each step, the groove depth has been increased by 0.5 mm. The model is indicated in Fig. 2.

Table 1. FEM parameters

Parameters	Value
Dimension, mm	50 × 50 × 20
Annular groove, mm	Ø25-Ø20
Elasticity modulus, GPa	200
Yield stress, MPa	250
Uniaxial stress, MPa	100
Element type	C3D20R
Gage length of strain rosette, mm	5

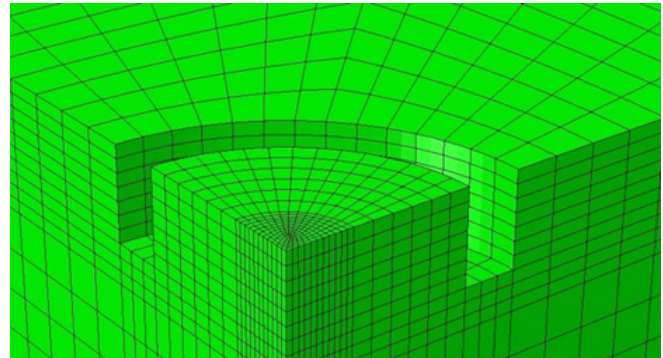


Fig. 2. Calibration model in ABAQUS analysis products

Released strains on the surface of the model based on the depth of the annular groove are presented in Fig. 3. The calibration coefficients have been calculated in different depths by using the information of the Fig. 3 and Eq. (12) and results are indicated in Fig.4. These values of the calibration coefficients are valid for annular groove dimensions as described in Table 1.

The ring core method is simulated for the uniaxial residual stress distribution to find the ability of the formula and accuracy of calibration coefficients. Released strains in the three directions have been extracted and residual stresses have been calculated according to the described procedure in section 2. The maximum calculated, principal residual stresses are indicated in Fig.5 and the direction of maximum principal residual stress with respect to the longitudinal axis of the model is indicated in Fig.6.

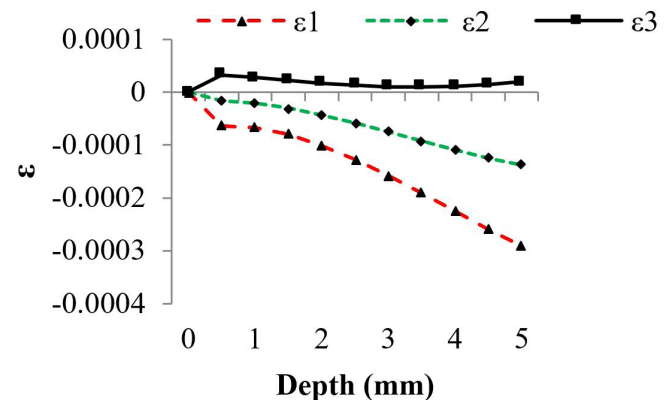


Fig. 3. Measured strains on surface of the model in terms of annular groove depth

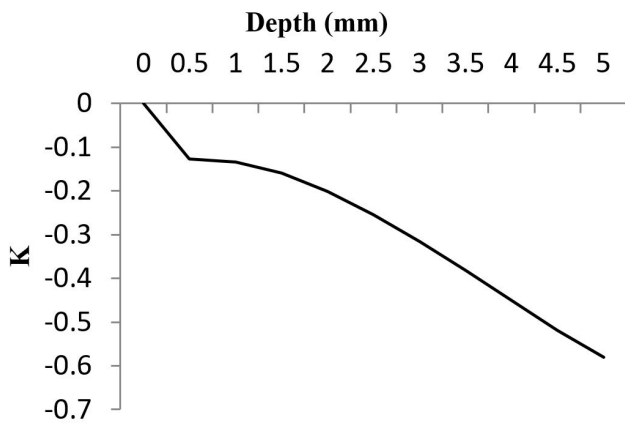


Fig. 4. Calibration factor K in terms of annular groove depth

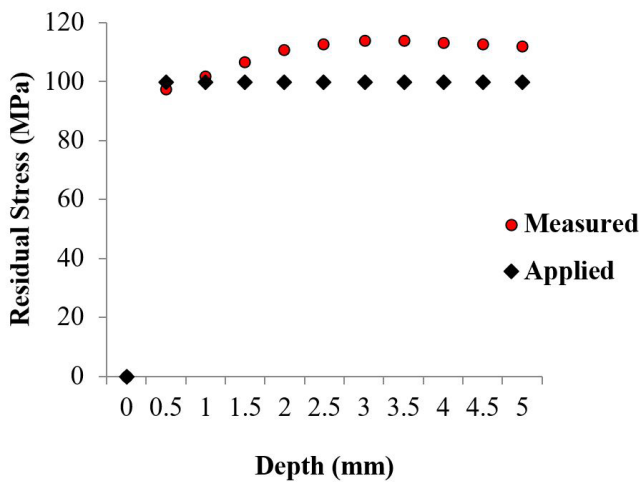


Fig. 5. Measured maximum principal residual stresses and applied residual stress in ring core simulation

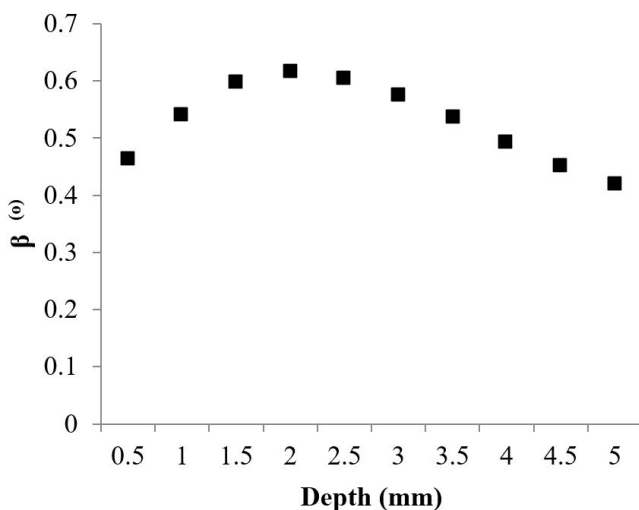


Fig. 6. Direction of maximum residual stress with respect to the longitudinal axis of the model in the simulation of ring-core method

2- 3- Residual stress measurement in UIC 60 rail foot by the ring-core method

To measure residual stresses in UIC 60 rail by the ring-core method, the TML strain rosette has been used. By paying attention to the manufacturer datasheet, the position of the strain gages in the rosette is according to Fig. 7 [27]. Therefore, due to the position of strain gages, correction in the expressed relation by reference [23] is necessary.

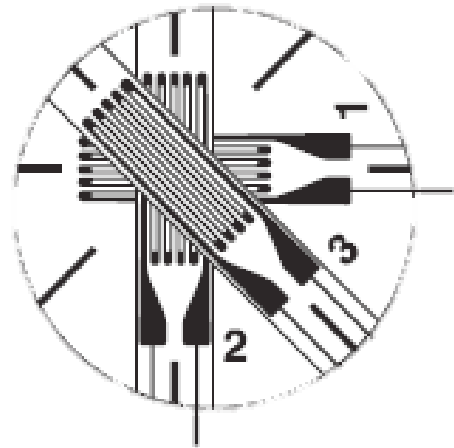


Fig. 7. Patterns of strain gages in TML ring core rosette [27]

The TML FRA-5-11 strain gage rosette has been bonded on the foot surface of the UIC 60 rail and then an annular groove was made around the strain gage and released strains are recorded. The used sample is indicated in Fig.8 and measured strains are indicated in Fig.9.

Principal residual stresses are indicated in Fig. 10. The direction of maximum principal residual stress regarding the longitudinal axis of the rail is indicated in Fig.11 and longitudinal residual stresses are indicated in Fig.12.

3- Residual Stress Measurement in UIC 60 Rail Foot by Sectioning Technique

According to rail manufacturing standard, the [15] measurement of residual stresses in the foot of the rail is mandatory and maximum longitudinal residual stress shall be 250 MPa for all steel grades. The sectioning technique is selected by the standard as the method of residual stress measurement. After bonding the strain gage in the rail foot, two saw cuts cause stress relaxation and strain gage will indicate the resultant strains. Schematic diagram of the



Fig. 8. The used rail for residual stress measurement

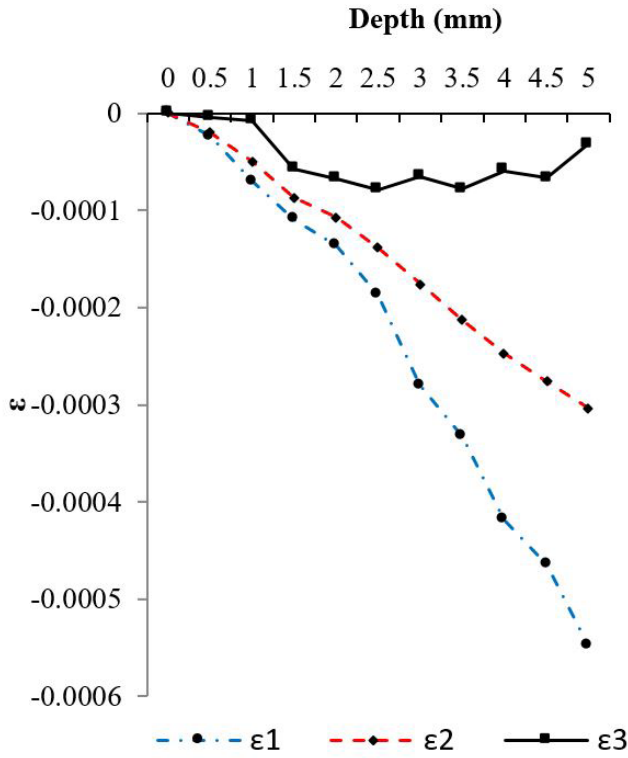


Fig. 9. Measured strains in UIC 60 rail foot by the ring-core method

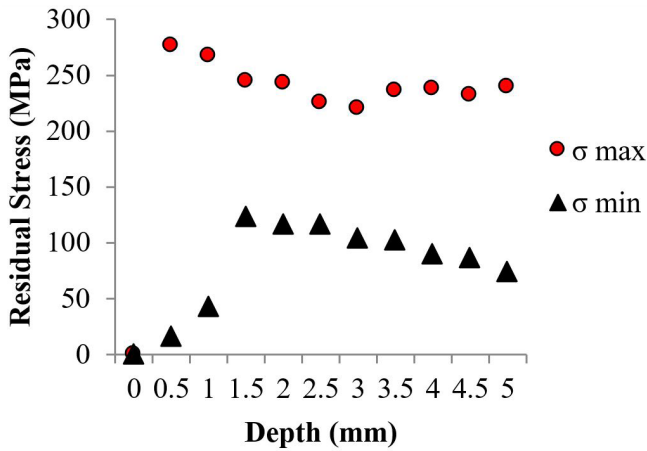


Fig. 10. Minimum and maximum principal residual stresses on the UIC 60 rail foot by the ring-core method

process according to the standard procedure is indicated in Fig. 13. The sign of the measured strains shall be reversed and then it is multiplied by 207 GPa (elasticity modulus of rail material) for residual stress calculation. The results of the test are indicated in Table 2 and the equipment which is used for sectioning test are indicated in Fig. 14.

4- Results and Discussion

In the ring-core method, it is assumed that one of the principal residual stresses is perpendicular to the surface and it is equal to zero, therefore it is possible to determine two in-plane principal residual stresses and related directions. By increasing the depth of the annular groove, the assumption of the plane stress condition is not valid anymore and therefore,

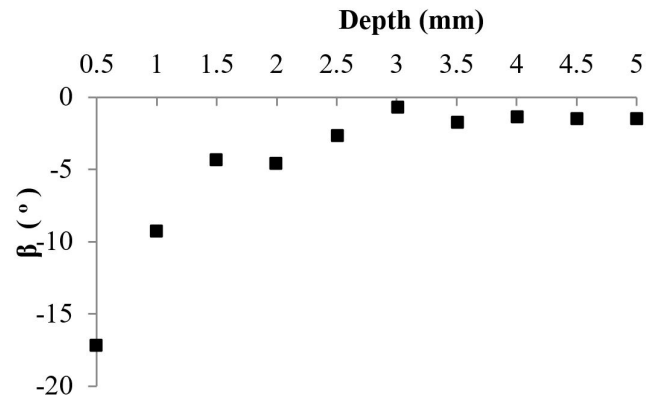


Fig. 11. The direction of maximum principal residual stresses respect to longitudinal axis of the rail.

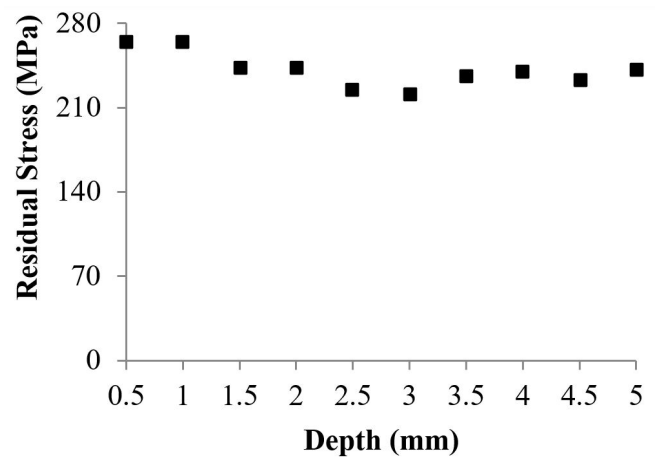


Fig. 12. Longitudinal residual stresses on UIC 60 rail foot by the ring-core method

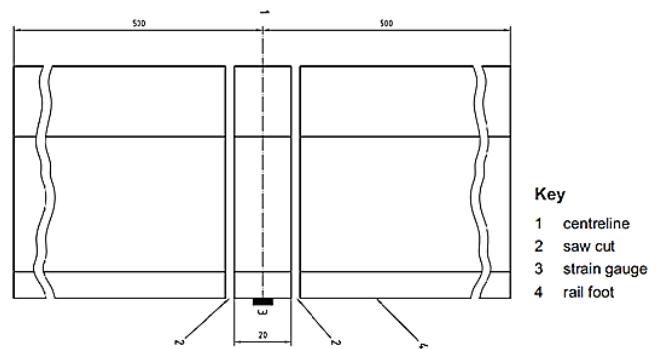


Fig. 13. Schematic of residual stress measurement in the rail foot by sectioning technique [14]

Table 2. Parameters and results of residual stress measurement by sectioning

Parameters	Value
Gage length of strain gage, mm	3
Measured strain, $\mu\epsilon$	-849
Elasticity modulus, GPa	207
Longitudinal residual stress, MPa	175.7



Fig. 14. The used equipment in sectioning test

the percentage of the error will be increased as indicated in Fig.5. An important parameter in the ring-core method is calibration coefficient. This parameter is dependent on groove dimensions, depth of the cut, material properties, geometry of the groove, etc. Results of the ring-core simulation which have been indicated in Fig.5 shows that maximum error is about 13% which is about 5% of material yield stress. The direction of maximum principal residual stress with regard to the longitudinal axis of the model is indicated in Fig.6 and this is clear that maximum error is less than 1°. Therefore, the calibration coefficient and the procedure are acceptable.

Residual stress measurement by the ring-core method indicates that maximum principal residual stress in the rail foot is not in the longitudinal direction, but the maximum principal under surface residual stresses in the rail foot approximately coincides with the longitudinal direction. Sectioning technique is one the oldest method for determination of residual stresses. The output value of this method is the average of residual stresses in the strain gage position. Sectioning method can predict just longitudinal stresses. Longitudinal residual stresses are compared with the two methods in Fig.15. The difference between the two methods is about 65 MPa.

5- Conclusion

Advantages of the ring-core method in comparison with the sectioning technique have been indicated. Residual

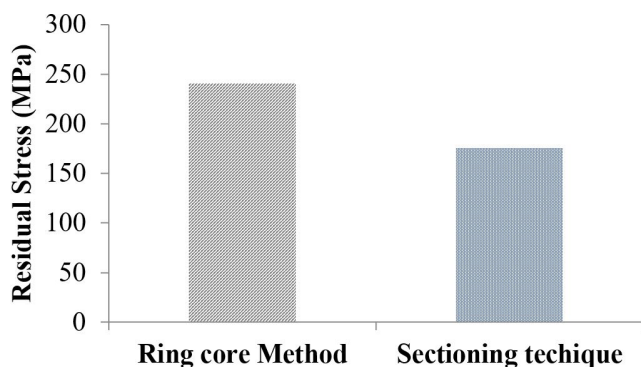


Fig. 15. Compression of longitudinal residual stress in UIC 60 rail by the ring-core method and sectioning technique

stress measurement by the ring core method indicates that maximum principal residual stress in rail foot is not in the longitudinal direction and on the subsurface of the rail's foot maximum principal residual stress coincides with the longitudinal direction. Both ring-core method and sectioning technique predicted tensile residual stresses on the rail foot, but the value of longitudinal residual stresses predicted by the ring-core method in the performed tests was 27% more than sectioning technique.

Sectioning technique is a destructive and time-consuming method while the ring-core is semi-destructive and very faster compared with the sectioning. Calibration coefficients are very important in the ring-core method and have an important effect on the final results. It is indicated that the proposed procedure for the determination of calibration coefficients have a good accuracy. By paying attention to the advantages of the ring-core method over the sectioning, this method may be appropriate for measuring the residual stress in the rail foot and could be considered as a fast method for the quality control.

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