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RESIDUAL STRESS MEASUREMENT IN RAILWAY AXLES

MĚŘENÍ ZBYTKOVÝCH NAPĚTÍ V ŽELEZNIČNÍCH NÁPRAVÁCH

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1 INTRODUCTION

The companies producing railway axles are obliged to demonstrate the level of residual stresses in their products based on the specification of standard EN 13261 [1] in which the applicable methods are suggested and the allowable values of residual stresses are specified. The standard requires that surface tension residual stresses measured in the depth of 0.1 mm below the axle surface are lower than 100 MPa (sections A,B,C,D, ***fig. 1***) and in addition that the mutual deviation of the residual stresses measured at 6 points separated by the angle of 60° in the central section of the axle in 2 mm depth (a difference of the maximal and minimum values) have to be within the interval up to 40 MPa.

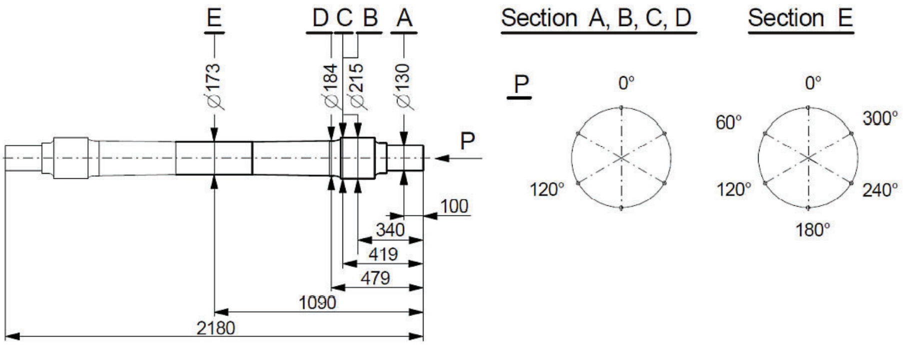

Fig. 1 *According standard EN 13261-2021, at fourteen position the residual stress have to be measured (here the drawing corresponds to real tested railway axle)*

Obr. 1 *Dle standardu EN 13261-2021 je nutno měřit zbytková napětí ve 14 místech (uvedený výkres představuje konkrétní zkoušenou nápravu)*

The hole drilling method is standardly used for this task. However in some cases, especially in the case of hardened or roll-burnished railway axles with 4 mm end-mill diameter this method gives the uncertainties comparable with the demanded stress values

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[2]. With the air turbine and standard hole drilling cutter there is not possible to measure the depths under 1 mm.

Another saw cut method [3] is also recommended in [1], appendix E for residual stress measurement of railway axles.

We propose to use for this task groove grinding method [4]. Here, also single strain gage is used in axle axial direction and the stress relaxation is performed with grinded shallow groove instead of the necessity to saw cut the whole axle. The possibility of calculation of residual stress profile with the depth is another advantage of this method.

2 COMPARISON OF METHODS FOR RESIDUAL STRESS MEASUREMENT

2.1 Hole drilling method

A hole is drilled into the center of the strain gauge rosette in the steps by means of an end mill or a high speed turbine at the revolutions ranging from 20,000 to 400,000 rpm and the residual stress is calculated from the released strains using calibration constants (***Fig. 2a***). The ASTM E837 standard specifies these constants for the Vishay rosettes of the sizes D 1/32, 1/16 and 1/8 inches. Using the largest rosette it is possible to determine the residual stress to the depths up to 2 mm. The minimum depth is within the range from 0.025 to 0.1 mm according to a size of the rosette. However the groove grinding method is nearly three times more sensitive than hole-drilling method as it can be seen from ***fig. 2b***.

The new revision of ASTM E837-20 standard for residual stress measurement using hole-drilling method issued in the year 2020 with successive improving of evaluating procedures dated from first issue from the year 1981 (one step measurement), followed with multiple power series method (2001) and ending with the integral through profile method [2] (2008, 2013).

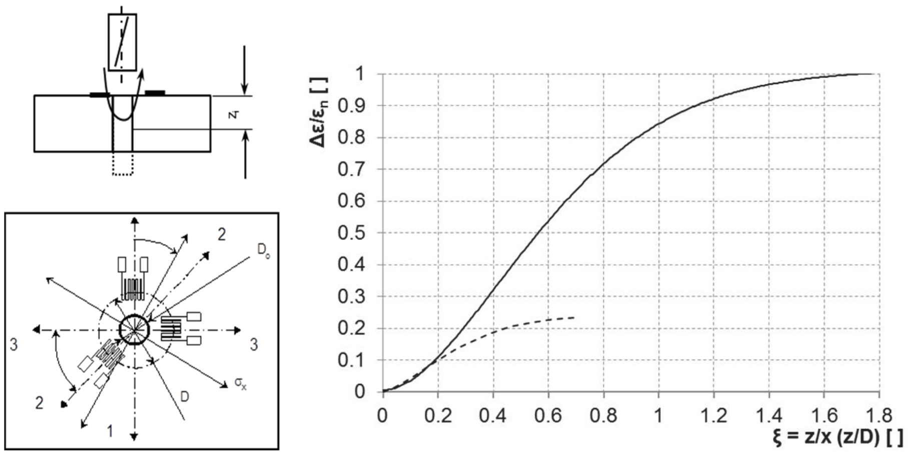

Fig. 2 *Principle of hole-drilling method (a); Comparison of the sensitivity of hole-drilling and groove-grinding methods (b)*

Obr. 2 *Princip metody odvrtání otvoru (a); Porovnání citlivostí metod odvrtání otvoru a vybroušení mezikruží (b)*

Implementation of hole-drilling method

One set of measurement on surface hardened axle (1/8 inch RY61 rosette, electric motor of 20,000 rpm) was evaluated according to both last issues of standard ASTM E837 and also with constants from original integral method; differential Kockelmann's and SINT HDM method were also added for comparison (***fig. 3***). The absolute value of stress evaluated with ASTM E837-20 in comparison with the last issue was at the most of 6% higher.

It was also examined what was the mutual deviation of the evaluated residual stresses in the centre of the axle in the depth of 2 mm. The measurement was carried out with a 1/8 inch rosette again at six points separated by an angle of 60° and the result is shown in ***fig. 4a***.

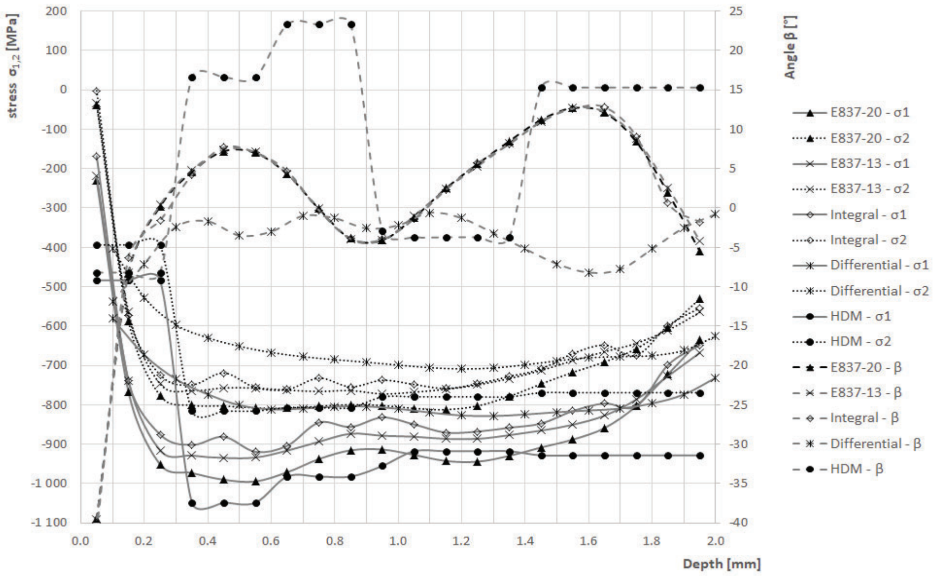

***Fig. 3** Comparison of residual stress evaluation using hole-drilling with various methods using the software SINT Eval 7.20 including both ASTM E837-13 and E837-20 issues*

***Obr. 3** Porovnání vyhodnocení zbytkového napětí, měřeného metodou odvrtání otvoru, různými metodami za použití software SINT Eval 7.20 včetně vydání norem ASTM E837-13 a ASTM E837-20.*

The measurement was carried out for 4 axles made of the material A1N (R_e = 520 MPa), A4T (R_e = 580 MPa), for the surface-hardened axle and for the roll-burnished axle, the material OS (according to GOST 4728). The angular deviation of the residual stress for the axles made from the materials A1N and A4T is low and the requirement of the standard ASTM E837 can be reached. The results for the hardened and roll-burnished axle significantly exceed the permissible deviation of 40 MPa. This fact may be caused not only by a big measuring error which is increased with the measured value of the residual stress but also by the fact that the level of the residual stresses in both axles approximates to the yield point of the material.

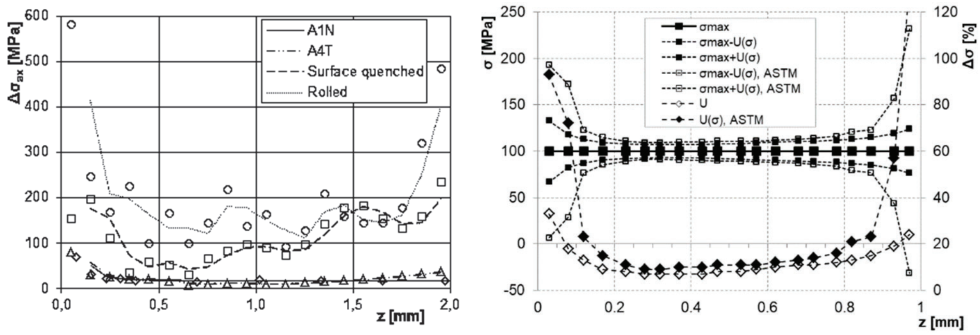

***Fig. 4** The maximal deviation of the axial component of the residual stresses measured in the axle centre for two standard materials of the axles and for the hardened and roll-burnished axles (a); Uncertainty tolerance limits for pre-set and critical ASTM input uncertainties (b)*

***Obr. 4** Maximální odchylka osové složky zbytkového napětí, měřená ve středu nápravy, pro dva standardně používané materiály náprav a pro kalené aválečkované nápravy (a); toleranční limity v software SINT Eval 7.20 pro přednastavené nejistoty měření a pro nejistoty, dovolené ve standardu ASTM*

Using uncertainty computation with the software Sint Eval 7.2 is presented in ***fig. 4b*** for model example for the pure tension. The tolerance limits for 95.4 % coverage probability were evaluated for two cases of input uncertainties. The first case are pre-set "Eval" values labelled as ±U(σ), the second case are uncertainty values specified by ASTM standard as the worst accuracy of measured strains, hole dimensions and the depth (labelled as ±U(σ), ASTM). It is obvious, that the highest uncertainties are at the surface and at the whole depth. The uncertainty at the whole depth increases with the increase uncertainty of the measured input values. For pre-set optimistic parameters the uncertainty is about 33 % at the surface and 23.3 % at the whole depth; for lower input uncertainties the stress uncertainty may reach about 100 %. On the other hand, the uncertainty in the middle depth does not change significantly from depth 0.3 mm to 0.7 mm (uncertainty is here lower than 10 %).

2.2 Saw cut method

Using this method, six strain gauges are attached to the axle in axial direction, separated by the angle 60°. After cutting the plate 25 mm thick with strain gauges in its middle, the residual stresses can be calculated directly from the released strains. The saw cut method is suitable only for cases of homogenous stress field not significantly changed with the depth. The high stress surface peaks cannot be detected with this method. That is, when the stress is presented only in 1 mm surface layer, then less than 20 % of really presented residual stresses are evaluated.

Implementation of saw-cut method

Six strain gauge rosettes HBM RY91-6/120 were glued with the adhesive HBM Z70 at six measured points in one axle section, 50 mm from the axle part end in axial direction angularly of 60°from each other separated, ***fig. 5***. Only two grids from each rosette were used for measurement. The initial reading was made before the cutting. Then the disc of 25 mm thickness was cut from the axle on the saw machine with two cuts just leaving the strain gauge rosettes in the middle of the disc. The second strain gauge reading was made after cutting. Supposing the principal residual stresses are lying in axial end tangential directions the residual stresses were calculated using common relations for bi-axial stress distribution.

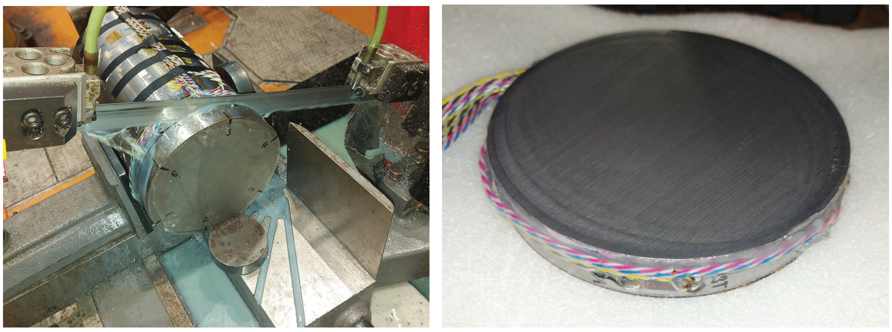

***Fig. 5** Saw-cutting one face disk from the axle (a), cut disc 25 mm width from the axle with installed strain gauges*

***Obr. 5** Řezání strojní pilou jedné strany disku z nápravy (a); vyřezaný disk s tenzometry*

2.3 Grove grinding method

The principle of the method consists in grinding an annular grove at the depth z_i perpendicularly to the surface and calculating the stresses from the relieved strains at the strain gauge glued perpendicularly at a given distance from the groove edge with the help of the calibration constants (***fig. 6***a). The residual stress σ_{xk} at the depth z_j is then estimated using the linear elasticity theory from the relieved strains ε_j, measured at one or more linear strain gauges glued near the edge of the groove (1). The calibration constants a_{jk} indicate the relieved strain in the groove j steps depth due to unit stresses within the groove step *k*. Using the integral method, the residual stresses within each groove depth step can be computed from the measured strains solving the matrix equation (2)

$$\boldsymbol{\varepsilon_i = \frac{1}{E}\sum_{k=1}^{j} a_{jk} \cdot \sigma_{xk}} \tag{1}$$

$$\boldsymbol{\bar{a}\sigma = E\varepsilon} \tag{2}$$

The numerical values of calibration constants were calculated for the given grinding wheel diameter, the strain gauge HBM 0.6LY11 grid dimensions and the given distance of the strain gauge from the groove edge. Also, the influence of the strain gauge misalignment was studied. An FEM analysis was carried out inside the system ANSYS v 19.1. Two cases were modelled: homogenous and non-homogenous stress fields.

The grinding tool has been designed in Research and Testing institute in Pilsen. It works in automatic regime using stepping-motor and microcontroller unit without the necessity to be connected to the computer (***fig. 6b***).

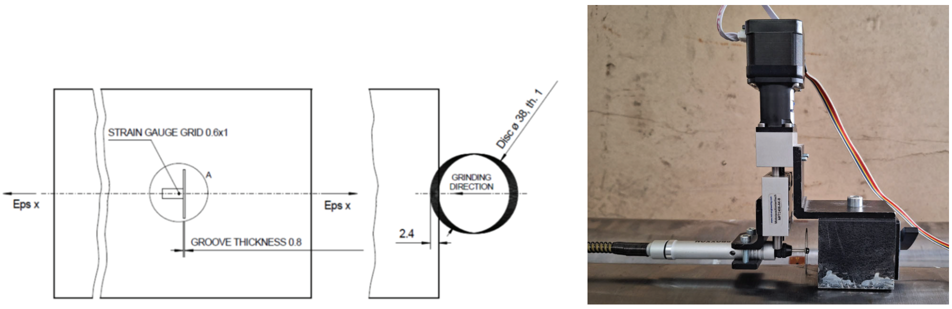

***Fig. 6** Principle of grove-grinding method (a) and the device, used for grinding the grove (b)*

***Obr. 6** Princip metody vybroušení drážky (a) a zařízení pro vybroušení drážky (b)*

Implementation of grove-grinding method

The investigation was made on surface-hardened middle part of railway axle. The diamond cutting wheel ø38 mm was used with 15000 rpm. The relieved strains at 2 mm distance between the cutting wheel edge strain gauge middle point and evaluated axial stresses using integral method are given in ***fig. 7***. The measurement was performed in one axle section at six 60° separated measured points. The dispersion of residual stresses in the 2 mm depth between measured points (***fig. 8***) is lower than 40 MPa, just fulfilling the ASTM E-837 requirements.

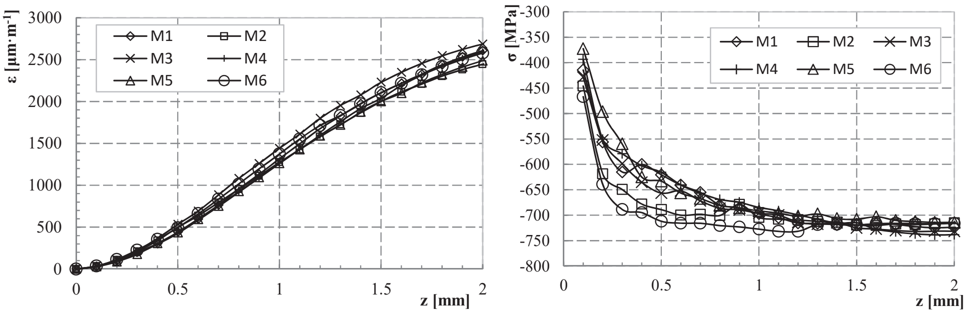

Fig. 7 *Released strain by groove grinding method at six measured points in one axle section, angularly separated of 60°from each other (a); evaluated residual stresses (b)*

Obr. 7 *Poměrné deformace po uvolnění napětí vybroušením drážky v šesti místech v jednom řezu nápravy, rozmístěny vzájemně po 60° (a); vyhodnocená zbytková napětí (b)*

The results of evaluated residual stresses near the surface compared with saw cut method are given in ***fig. 8b***. Dispersion about 20 MPa was measured. Tangential stress component obtained after cutting the disk was low compared with the axial component.

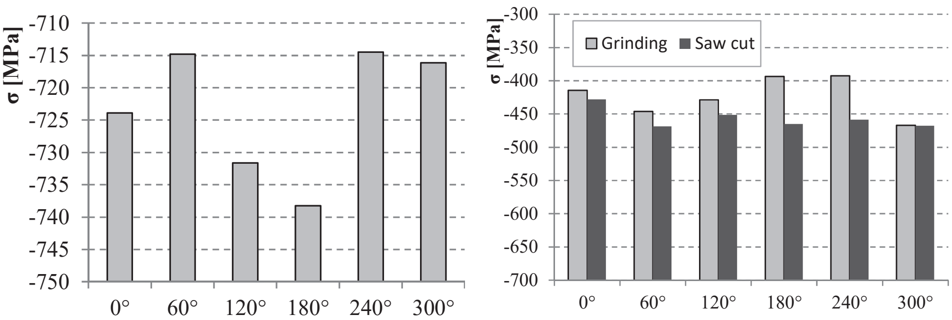

Fig. 8 *Dispersion of residual stresses in the 2 mm depth measured with groove grinding method (a); comparison of residual stress measured with groove grinding and saw cut method at the surface (b)*

Obr. 8 *Odchylka zbytkových napětí v hloubce 2 mm, měřená metodou vybroušení drážky (a); porovnání zbytkových napětí metodou odvrtání otvoru a vybroušením mezikruží na povrchu nápravy*

4 CONCLUSION

It was found that the groove grinding method can be used for residual stress evaluation in railway axles according the standard EN 13261 with sufficient sensitivity even on hardened surfaces, where the hole-drilling method is sometimes difficult to use. The results were experimentally verified with comparison between grove-grinding and saw cut methods. Even if the saw cut method cannot catch the high stress peaks at the surface, both methods give surprisingly comparable results.

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References

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Summary

The semi-destructive methods for investigation of residual stresses in railway axles according EN 13261 standards are discussed and compared: hole-drilling method, saw-cut method and grove-grinding method. The grove-grinding method is recommended for this task, having the highest sensitivity and is easy to use. The tool with stepping motor was designed and implemented for this method.

Abstrakt

Jsou diskutovány a porovnány semi-destruktivní metody pro měření zbytkových napětí v železničních nápravách podle norem EN 13261: metoda odvrtání otvoru, metoda odřezání pilou a metoda vybroušení drážky. Pro měření zbytkových napětí na nápravách článek doporučuje metodu vybroušení drážky, která má nejvyšší citlivost a je snadno použitelná. Pro tuto metodu byl navržen a implementován nástroj s krokovým pohonem.