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Residual Stresses in Railway Axles

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Abstract. The companies producing railway axles are obliged to demonstrate a level of residual stresses in their products based on the specification of standard EN 13261 in which the applicable methods are suggested and the allowable values of residual stresses are specified. An objective of this contribution is to arouse a discussion whether the requirements of the standard can be met by means of the suggested measuring methods - hole-drilling (according to ASTM E837-13 standard) or X-ray diffraction. It especially applies to the ability to determine the residual stress distribution in the depth of 2 mm below the surface. The mentioned issue is demonstrated by means of both measuring methods under various measurement conditions.

Background

The railway axles are exposed to the high operating stress. It especially includes the high-cycle fatigue where the high tension stresses reduce the material fatigue limit. At the same time, unevenly distributed residual stresses may cause the deformation of an axle and increase the stress amplitude originating during the axle rotation. These both values also refer to the quality of heat treatment and the manufacture of the axle. The demonstration of the low level of the residual stress is one part of the existing standards dealing with checking the quality of railway axles EN 13261 [1] and EN 13260 [2].

Both standards require that surface tension residual stresses measured in the depth of 0.1 mm below the axle surface are lower than 100 MPa. The standards also specify three sections where the measurements shall be carried out (Fig. 1). In each section there is requirement for two measurements in the angular separation by 120°. In addition, the standard EN 13261 requires 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 (a difference of the maximal and minimum values) must be within the interval up to 40 MPa (Fig. 1, section A).

All the tests shall be carried out by means of a strain gauge or an X-Ray method. At the present time a new version of the EN 13261 standard is being prepared where in addition to the conventional strain gauge techniques such as the layer removal method and the sectioning method, the hole-drilling method according to ASTM E837-13a [3] standard is recommended.

Measurement Methods

Hole-Drilling Method. A hole is drilled into the centre 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.

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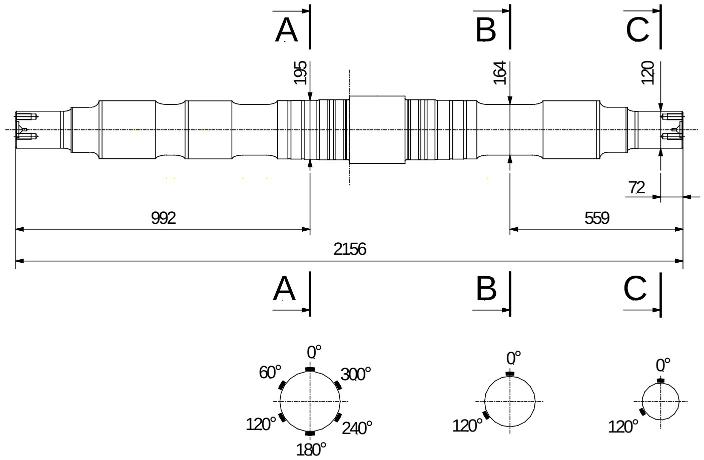


Fig. 1 The points being measured on a railway axle according to the requirement of [1]. The level of the surface residual stresses are demonstrated at three sections (A, B, C). In the centre (A), the evenness of the residual stress is tested at another 6 points by 60° along the perimeter.

(a) (b)

Fig. 2 The equipment used for measuring residual stresses by means of the hole-drilling method RESTAN (a) and for measuring by means of the X-Ray method (b)

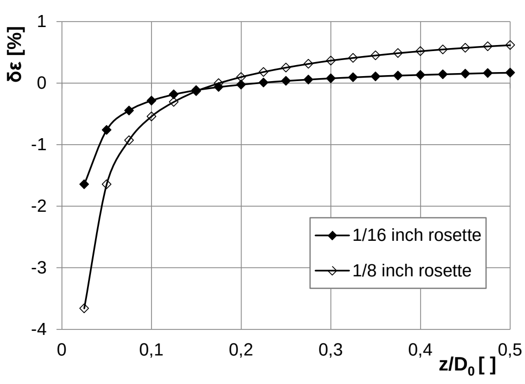
The ASTM E837 standard specifies these constants for the Vishay rosettes of the sizes D 1/32, 1/16 and 1/8 inches. Using the largest rosette it is possible to determine the residual stresses to the depths up to 2 mm. The minimum depth is within the range from 0.025 to 0.1 mm according to a size of the rosette. Thus it would look like the minimum and maximal depths met the requirements of the standard for the tests of the railway axles. However, applying this standard is questionable in several aspects. No other shape of the strain gauge rosette than the one specified in the standard can be used as no calibration constants are specified for it. The hole must be drilled coaxially with the rosette centre with the accuracy of ±0.004D (i.e. 0.016 mm for the largest rosette) which sometimes is difficult to keep. The standard does not state any method for correcting the misalignment. The radial clearance angles on the end face of the cutting tool should not exceed the value of 1°, however, the standard does not give any possibility how to correct the fact that the value would be greater. In the standard the calibration constants are set for a theoretical diameter of the hole being drilled. For the actual diameter of the drilled hole it is recommended to correct them using the quadratic interpolation.

Uncertainty of the Hole-Drilling Method. According to [3] the uncertainty of determination of the uniform stresses by means of the power-series method is ±10%. It is not determined for the integral method. In [4] an extensive analysis of a measuring error is carried out based on the uncertainties of the most of the input parameters. The main source of the uncertainties specified herein is the eccentricity of the hole being drilled (5 %), stress induced by drilling (5.5 %), a diameter of the hole being drilled and the material constants. When using the integral method, the error is the maximal on the surface due to the influence of the high uncertainty of the input parameters (misalignment, presence of large strain gradients, smaller gauge outputs in the first drilling steps, identification of the zero reference surface) and in the last step of the hole drilling when the uncertainty of the input parameters is increased due to the method lowest sensitivity.

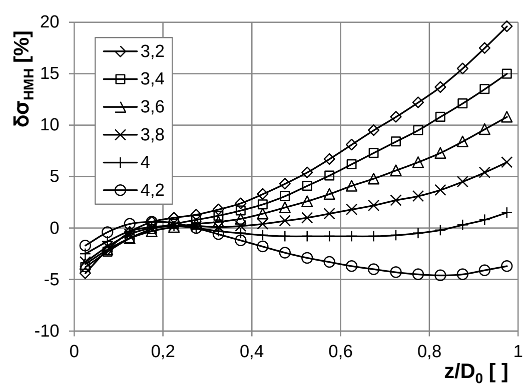
In [5] the effect the hole-bottom fillet radius for the case of using the power-series method is investigated however, the calculated measuring error for the first drilled depth is valid also in case of the evaluation by the integral method. A deviation of the released relative deformation for the radius of 5% of the hole diameter is estimated to be 10%.

The diameter of a railway axle is approx. 200 mm. The derived error when we use the coefficients for flat surface is shown at Fig. 3a for the 1/8 and 1/16 inch rosettes. The released strain and the calculated residual stress are always lower on the curved surface at the surface layer. We derived also the error we would make if we use the correction of the standardized sensitivity coefficients by the quadratic approximation recommended by the standard [3] for the actual diameter of the drilled hole. The resultant error of the released relative deformation is shown at Fig. 3b where the comparison is carried out for the standardized hole diameter of D_0 = 4 mm. The approximation of coefficients is carried out for the other diameters. The error increases with the depth being drilled and with a higher deviation from the standardized diameter. The maximal error is in the maximal depth being drilled.

It is obvious from the considerations performed that the uncertainty of determination of the residual stresses on the axle surface and in the depth of 2 mm below the surface is very high and very hard to identify. We estimate that it can reach even 30% and more of the measured value depending on the stress state of the axle. For roll burnished or surface hardened axles the measuring error is increased due to the tri-axial stress state by additional at least 5% especially in bigger depth being drilled [6].



a)



b)

Fig. 3 The dependence of the released relative deformation on the standardized depth below the surface. Due to the curvature of the surface the maximal error for the axle diameter D = 200 mm is reached on the surface (a). Due to the recalculation of the calibration coefficients to the actual diameter of the hole being drilled for the deviation from the hole diameter 4 mm (b) the error is the maximal in the maximal depth being drilled.

Results

An influence of the drilling steps. An example of the distribution of the measured residual stress on the surface-hardened axle is shown at Fig. 4. Three sets of measurements were carried out with a 1/8 inch rosette (HBM RY61-3.2/120S, an electric motor of 20,000 rpm) with three different steps of drilling Δz = 0.025 mm (96 steps), 0.05 mm (48 steps) and 0.1 mm (24 steps) always to the final depth of 2.4 mm (An evaluation is carried out always for 20 depths).

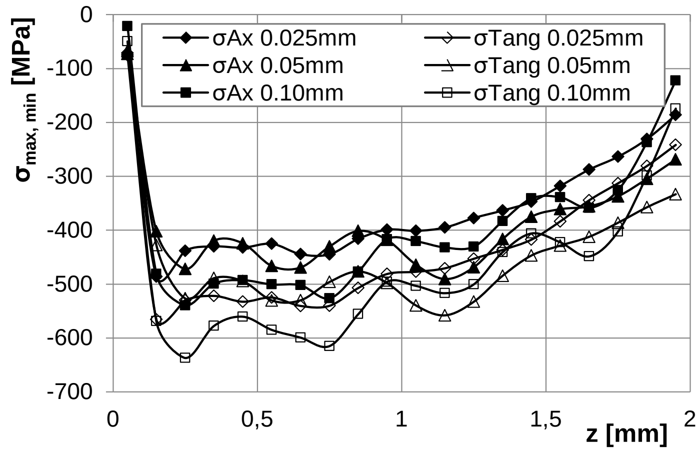


Fig. 4 An influence of the size of drilling steps Δz = 0.025, 0.05 and 0.1 mm on the distribution of the evaluated residual stresses – by making the step finer the curve becomes smoother and correspond more to the reality.

It is obvious that the resultant residual stress depth profile is not so warped for a finer step of the material drilling which rather corresponds to the reality. For the roughest step specified by the standard [3] the profile is the most warped especially at the place of the maximal depth being drilled. This is an undesirable effect, especially in case we evaluate a deviation of the residual stress in the depth of 2 mm at 6 points in one section of the axle. The hole drilling was carried out to the depth of 2.4 mm, not to the depth of 2 mm as required by the standard [3]. If the drilling is carried out only to the depth of 2 mm, then the dispersion of the residual stress value is very high probably for the reason that when the curve is smoothed, there is a lack of the values of bigger depths. Therefore we recommend carrying out the measurements to the depth bigger by approx. 4 steps than for which the evaluation is carried out.

Stress variation around the axle. It was 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 at Fig. 5a where a double standard deviation of the evaluated stresses is given. 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 [1] 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. The stresses drawn at Fig. 5a are not corrected to the elastic-plastic stress state as there is no reliable method for integral method.

A reliable method for the correction of the stresses approximating the yield point is derived for the uniform stress distribution through the depth [4]. This correction is presented at Fig. 5b for one measured point for the roll-burnished axle A1N. The profiles of non-corrected and corrected stresses measured both by a small 1/16 inch rosette (serving for measuring the residual stress on the axle surface), and by a big 1/8 rosette for determining the values in the depth of 2 mm are plotted here. The depth of the roll-burnished layer is approx. 5 mm and a drop of the

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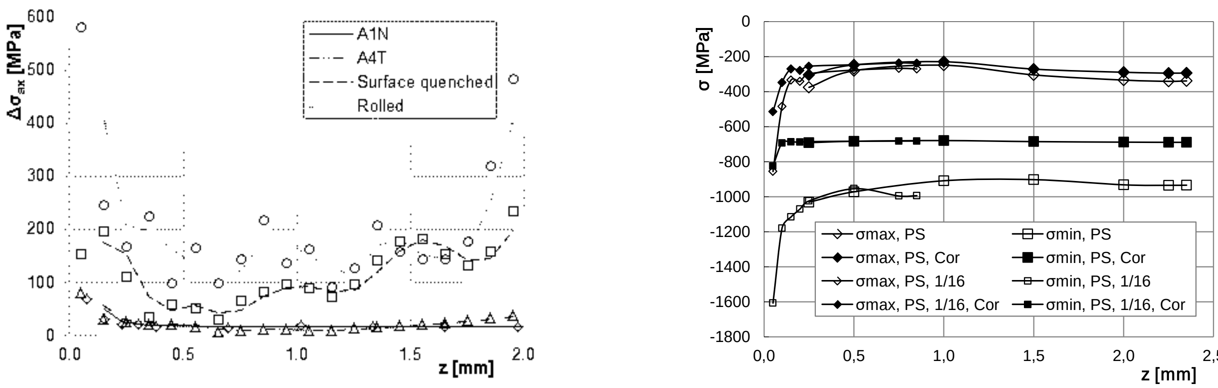
stress to the depth of 2 mm is very low so in our opinion the power-series method can be used for the evaluation although the requirement of the stress uniformity given in the previous versions [3] (e.g. ASTM E837-08) is not met. By the use of the power-series method in drilling to the depth of 4 mm we obtain a rough estimate of the average value of the residual stresses for the mean depth of 2 mm. This value does not show any significant dispersion and it can be used for the demonstration of the requirement of the standard for the uniformity [1].



a) b)

Fig. 5 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 (values non-corrected to the elastic-plastic stress state). An example of such correction of the residual stresses approximating to the yield point (b) represents shifting the distributions of the mean stresses towards the lower values (power-series method).

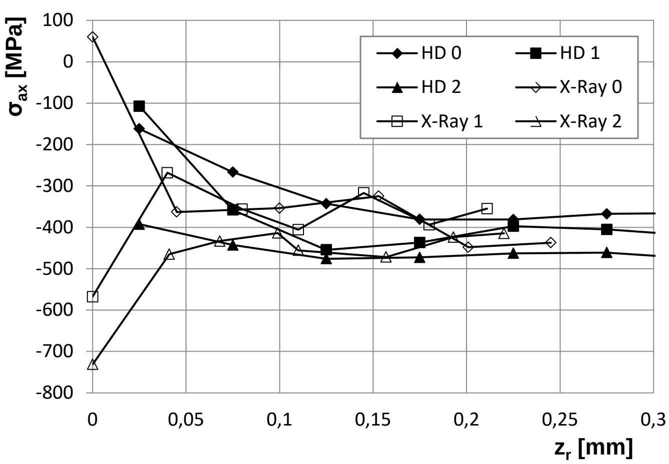


Fig. 6 Comparison of the surface stresses measured by the hole-drilling method (HD) and the X-Ray method on the original (0) and 2 new surfaces (1, 2) after removing 2×1 mm layers.

Another way how to avoid the high uncertainty of the determination the residual stress in the depth of 2 mm is the measurement on the removed layers. The investigation was carried out on the surface-hardened axle A4T on the original not machined surface and after that twice on the new surface where layers of the material of the thickness of 1 mm were removed successively by lathe-turning. The measurement was also carried out by the X-Ray method in several gradually etched depths from these surfaces. At Fig. 6 there is a comparison of the subsurface residual stresses using the 1/16 inch rosette and the X-Ray method. Three measurements on three layers overlapping one another are presented. The residual stress was induced by the lathe-turning in the surface layer but the results are steady for all the layers from the depth of approx. 0.1 mm.

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Summary

The hole-drilling strain-gauge method is an acceptable method to demonstrate the level of the residual stresses in the railway axles required by the standards EN 13 260+A1 and EN 13261 under certain circumstances.

i) The evaluation of the residual stresses for reducing the measurement uncertainty requires carrying out the calculation corrections which are not contained in the standard ASTM E837-13. Therefore the new version of the standard EN 13 260 + A1 being prepared should contain that the measurement of residuals stress shall be carried out in compliance with the methodology of ASTM E837-13 instead of directly using this standard in order to avoid problems with this formulation during the accreditation of the measurement method.
ii) Then, the demonstration of the requirements of the EN 13 260 + A1 standard can be implemented without any problems for the axles made of the standard materials A1N and A4T with the level of the residual stresses up to 100 MPa.
iii) In order to evaluate the residual stresses of the hardened or roll-burnished railway axles in the depth of 2 mm below the surface we recommend using the method of layers removing or the power-series method with the correction to the elastic-plastic stress state as the distribution of state of stress in the subsurface layer is roughly homogeneous. It is problematic to use the integral method for the reason of a high uncertainty comparable with the requirement of the standard for the inspection of the railway axles.
iv) The measurement of the residual stresses in the depth of 0.1 mm by the hole-drilling method is also burdened with a big error. The demonstration of the level lower than the demanded tensile 100 MPa according EN 13 260 + A1 standard usually is without any problems if all the necessary corrections are carried out as the residual stresses in the existing axles are nearly always compressive.

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