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# USING OF ABRASIVE WATER JET FOR MEASUREMENT OF RESIDUAL STRESS IN RAILWAY WHEELS

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Preliminary notes

The paper provides a general introduction to methods of measurement of residual stresses on railway wheels. Determination of residual stress distribution is necessary for the prediction of wheel service life and possible catastrophic failure. Therefore experimental section is devoted to residual stress measurement using strain gauges according to standard EN 13262 + A1. During measurement, several segments of tested wheel were cut by abrasive water jet to detect changes of residual stresses on specified places. It was found that abrasive water jet technology can cut wheel segments faster, more accurately and with negligible mechanical and thermal load compared to mechanical cutting by band saw. Therefore the use of abrasive water jet is recommended for the measurement of residual stresses in railway wheels.

***Keywords:*** *abrasive water jet, railway wheel, residual stress*

## Uporaba abrazivnog vodenog mlaza za mjerenje zaostalih naprezanja u željezničkim kotačima

Prethodno priopćenje

U članku se daje opći uvod u metode mjerenja zaostalih naprezanja na željezničkim kotačima. Određivanje raspodjele zaostalih naprezanja potrebno je za predviđanje vijeka trajanja kotača i mogućih katastrofalnih kvarova. Stoga je eksperimentalni dio posvećen mjerenju zaostalih naprezanja uporabom mjerača deformacija prema normi EN 13262 + A1. Tijekom mjerenja, nekoliko segmenata testiranog kotača je prerezano abrazivnim vodenim mlazom radi otkrivanja promjena zaostalih naprezanja na određenim mjestima. Utvrđeno je, da tehnologija abrazivnog vodenog mlaza može brže rezati segmente kotača, točnije i s neznatnim mehaničkim i toplinskim opterećenjem u odnosu na mehaničko rezanje trakastom pilom. Stoga se uporaba abrazivnog vodenog mlaza preporuča za mjerenje zaostalih naprezanja u željezničkim kotačima.

***Ključne riječi:*** *abrazivni vodeni mlaz, zaostala naprezanja, željeznički kotač*

## 1 Introduction

Knowledge of residual stresses is very important. Residual stress is defined as the tension that is present in a material without the action of external loads. All mechanical processes can cause deformation that may lead to residual stresses. For example, non-uniform heating or cooling causes thermal strains, plastic deformation induces incompatible deformation, and mismatched thermal expansion coefficients produce discontinuity in deformation under temperature change. Thus, the state of a residual stress depends on both the prior processes it has undergone, and the material properties that relate the current mechanical process to deformation [1, 2].

Macroscopic residual stresses are most important for technical practice. Their existence is reflected in practice by a number of important effects. Interventions to the stress balance are reflected on dimensional and shape changes that affect the usability of components or further technology processing. Residual stresses have a large influence on the lifetime, reliability and corrosion resistance.

Residual stresses can be useful but also harmful. Useful stresses are for example the compressive stresses induced by some forms of surface treatment of cyclically loaded parts that leads to prolongation of service life. The consequence of the negative effect of residual stress (usually tensile) is creation of cracks, stress corrosion and reduction of fatigue strength, fracture resistance, etc.

## 2 Problem definition

Knowledge of residual stress distribution is necessary for the prediction of railway wheel service life and its possible catastrophic failure. Residual stresses are caused primarily by the wheel manufacturing. Later, thermal cycles combined with contact stresses affect residual stresses during standard operation of the wheel. A good understanding of stress distribution and its variation over time can help in developing a better wheel design that would minimize the danger of catastrophic failure of a wheel. The knowledge can also help in improving the techniques used for routine inspection of wheels and the detection of potentially dangerous stress distribution. Certainly, it helps to the safety of railway transportation [3÷8].

The presented work deals with the analysis of residual stresses occurring in railway wheels, caused by the technology of their production. Destructive cutting method was used to determine the size of the residual stresses. It is possible to determine the course of circumferential residual stresses below the tread of the railway wheel using this method. The method is based on the release of residual stresses of examined components by cutting. The released residual stresses are measured using strain gauge sensors, which are in contact with the deformed surface. Measured deformations are recalculated to components of stress using Hooke's law.

## 3 Residual stress analysis – state of the art

A number of methods for residual stress measurement was developed in the past. Many aspects can be applied for their classification. Most often used methods classified according to degree of destruction of the examined components are as follows: destructive methods (complete destruction of the measured sample), semi-destructive methods (partial destruction of components that do not affect its function) and non-destructive methods.

The use of destructive methods involves gradual removal of layers of the material sample or its cutting on several parts. This leads to an imbalance of residual stress, which causes deformation of the sample. Relaxed deformations are most often measured using strain gauges which are glued to the measured sample prior to destructive testing. It is able to re-determine the residual stress from the measured deformations. Material removal can be done not only mechanically but also for example chemically (etching) or electrochemically.

Mechanical material removal can cause a formation of additional residual stress and thus reduce accuracy of measurement. Using of abrasive water jet cutting can eliminate this negative effect.

## 4 Abrasive water jet disintegration of materials

Effects of high-speed abrasive water jets (jets with abrasive particles addition) during disintegration of materials are well known to technical public. The principle of disintegration is based on high-energy transmission to an extremely small area. The material destruction is caused afterwards by complicated physical processes during jet impact - erosion, shearing, failure under rapidly changing localized stress fields, or micromachining effects, depending upon the specific properties of the material being disintegrated (see for example [9, 10]). No thermal interference of the material to-be-cut and the universality are great benefits of the abrasive water jets. With a single water jet based system, several machining operations can be performed on a wide range of materials and geometries. An abrasive water jet can cut, drill, turn, mill etc. difficult-to-machine materials such as composites, structural ceramics, high-strength alloys, glass, rocks, etc.

A number of decades of research and development in this area imply that this jet type has unique capabilities also as a tool for cutting of railway segments during residual stress measurement. The advantage of the use of abrasive water jet cutting in the measurement of residual stresses in railway wheels over conventional methods is that there is no production of heat affected zone and minimal reactive forces act on the material. Therefore no additional residual stresses are generated in the wheel [11÷13].

## 5 Experimental procedure

Although it is evident that the actual state of stress in a manufactured railway wheel is generally triaxial, measurements were performed according to standard EN 13262 + A1 exploiting biaxial strain gauges. Strain gauges HBM 1-XY91-10/120 were used during the measurement. Strain gauges were glued to the surface of the railway wheels using glue HBM Z 70. Strain gauges were treated with a protective layer of polyurethane lacquer HBMPU140 and insulated by aluminum foil with kneading compound HBM ABM 75 due to the use of the water jet cutting technology. Necessary data about connection of individual strain gauges to measuring card and other partial information needed for calculation of the released residual stress were recorded before measurements.

A railway wheel was cut by three cutting operations. Segment S1 of the railway wheel was created in the cutting operation No. 1, see Fig. 1. Five strain gauges were placed on segment S1, labelled as T1, T2I, T2E, T3E and T3I.

Strain gauge T4 was glued to segment S1 before the cutting operation No. 2. Only strain gauges T1 and T4 were active in this operation. The cut according to Fig. 2 was performed in cutting operation No. 2. Segments S11 and S12 were created by this cutting operation.

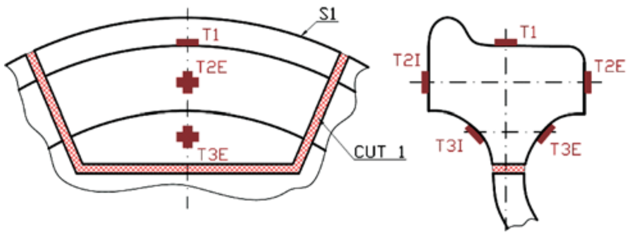



**Figure 1** Location of strain gauges on railway wheel - Operation No. 1.

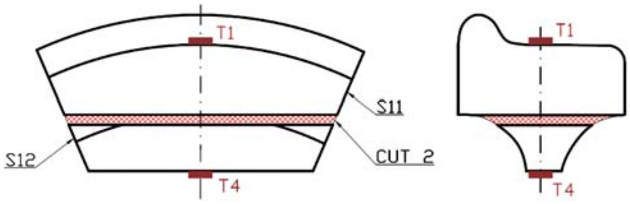



**Figure 2** Location of strain gauge sensors

Strain gauge T5 was glued to segment S11 before the cutting operation No. 3. Strain gauges T1 and T5 were active in this operation. Cut according to Fig. 3 was carried out in this operation.

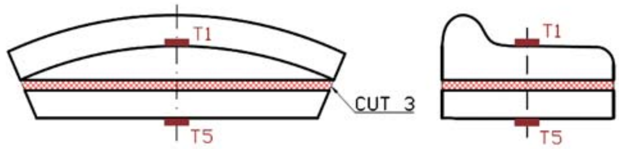



**Figure 3** Location of strain gauge sensors

The railway wheel was cut at the Institute of Geonics of the AS CR, v. v. i. Technological parameters used for cutting were as follows: water pressure $p$ = 380 MPa, water nozzle diameter $d_v$ = 0,3 mm, focusing tube diameter $d_a$ = 1 mm, focusing tube length $l_a$ = 76 mm, cutting speed $v_p$ = 4 to 40 mm/min, abrasive mass flow rate $m_a$ = 400 g/min, type of abrasive material - Australian garnet (80 MESH abrasive size).

**Figure 4** Cutting of railway wheel by abrasive water jet

## 6 Experimental results and discussion

Tab. 1 shows measured values of deformations from the individual strain gauges for cutting operations No. 1, No. 2 and No. 3. The largest value of deformation was measured in the circumferential direction for strain gauge T1 (554 μm/m).

Generalized Hooke's law for biaxial stress gives formulas for calculating the components of stress in

**Table 1** Resulting values of measured deformations for individual cutting operations

| | | Deformation $\varepsilon$ /μm/m | | |
|---|---|---|---|---|
| | | Operation No. 1 | Operation No. 2 | Operation No. 3 |
| $\varepsilon_{T1}$ | circ. | 554 | 66 | 13 |
| | axial | 90 | –26 | –94 |
| $\varepsilon_{T2I}$ | circ. | –302 | – | – |
| | radial | 94 | – | – |
| $\varepsilon_{T2E}$ | circ. | 92 | – | – |
| | radial | 155 | – | – |
| $\varepsilon_{T3I}$ | circ. | –4 | – | – |
| | radial | 192 | – | – |
| $\varepsilon_{T3E}$ | circ. | –118 | – | – |
| | radial | 195 | – | – |
| $\varepsilon_{T4}$ | circ. | – | –101 | – |
| | axial | – | –184 | – |
| $\varepsilon_{T5}$ | circ. | – | – | –37 |
| | axial | – | – | –38 |

measured directions, see equation (1) and (2). Values of the modulus of elasticity $E$ = 210 GPa and Poisson's ratio $\nu$ = 0,28 were used in the calculation.

$$\sigma_{\text{circ}} = -\frac{E}{1-\nu^2}\cdot(\varepsilon_{\text{circ}} + \nu\cdot\varepsilon_{\text{axial/radial}}), \quad (1)$$

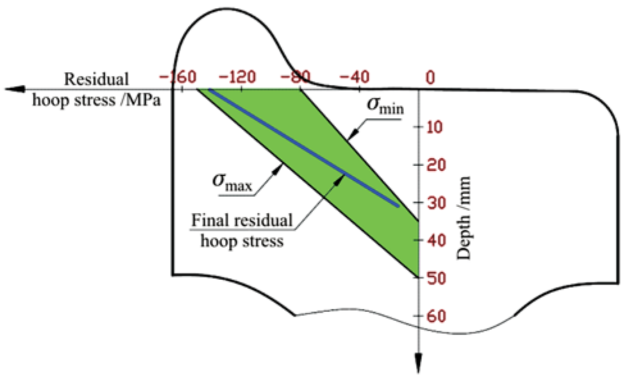
$$\sigma_{\text{axial/radial}} = -\frac{E}{1-\nu^2}\cdot(\varepsilon_{\text{axial/radial}} + \nu\cdot\varepsilon_{\text{circ}}). \quad (2)$$

Tab. 2 shows the calculated values of residual hoop stresses for individual strain gauges for cutting operations No. 1, No. 2 and No. 3 according to equations (1) and (2).

Final distribution of residual hoop stresses below the tread of the railway wheel was calculated from the knowledge of released residual stresses and geometric dimensions of railway wheel. Fig. 5 shows the final distribution of residual hoop stress with respect to limit values given by EN 13262+A1 standard (area between lines $\sigma_{min}$ and $\sigma_{max}$). The tested railway wheel meets requirements given by the standard, as can be seen in Fig. 5.

**Table 2** Calculated values of residual hoop stresses

| | Residual hoop stress /MPa | | |
|---|---|---|---|
| | Operation No. 1 | Operation No. 2 | Operation No. 3 |
| $\sigma_{T1}$ | –131,98 | –13,38 | 3,04 |
| $\sigma_{T2I}$ | 62,82 | – | – |
| $\sigma_{T2E}$ | –30,85 | – | – |
| $\sigma_{T3I}$ | –11,34 | – | – |
| $\sigma_{T3E}$ | 14,45 | – | – |
| $\sigma_{T4}$ | – | 34,75 | – |
| $\sigma_{T5}$ | – | – | 10,86 |




**Firure 5** Final distribution of residual hoop stress below the tread of the railway wheel with respect to standard limits

The advantage of abrasive water jet cutting technology over standard mechanical cutting of wheel segments (most often by band saw) is negligible thermal effect on cut material (temperature at the place of cutting does not exceed 70 °C) and negligible force influence of cutting tool on the test sample (units to tens of N). Another significant advantage is the precision of cutting (CNC cutting table), narrow kerf (1 mm) and substantial speedup of the cutting process. However, using of abrasive water jet cutting method requires adequate covering of strain gauges and good insulation of measuring wires.

## 7
## Conclusions and recommendations

The presented method of cutting using abrasive water jet was successfully applied to assess the extent of residual stress in the railway wheel according to standard EN 13262+A1. This method helped to improve the accuracy of measurement of residual stresses, as compared to other methods. This is due to the fact that the abrasive water jet cutting does not induce thermal stresses, which negatively affect measured values of residual stress. Another advantage of cutting by abrasive water jet compared to conventional methods is that minimal reactive forces act on the workpiece material. The disadvantage of this method is the necessity to perfectly insulate strain gauges to prevent penetration of water and moisture, which would affect measured values.

The method of residual stress measurement using abrasive water jet can be applied to other structural components that are dynamically loaded and for which is very important the knowledge of distribution of residual stresses in terms of their durability, reliability and thus safety.

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## 8
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