Non-Destructive Evaluation Of The Stress State In The Rim Of The Railway Wheels

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Abstract
Residual stress can significantly influence and particularly reduce engineering properties and fatigue life of materials such as railway components. The paper presents results of stress state investigation of rail wheels new and in service by using different NDT methods. The combined use of ultrasonic, electro-magnetic Barkhausen noise and magnetic acoustic emission provide better reliability than any of separately used methods. The study will give possibility to check the state of the materials in situ, but not only in factory condition. The aim of the work is to find dependence between stress state and eventually microstructure parameters and non-destructive parameters (velocity of ultrasonic waves, Barkhausen noise and magnetic acoustic emission intensities).

Keywords: non-destructive evaluation, stress state, railway wheels, ultrasonic and magnetonoise methods

1. Introduction
The production of railway wheel includes a heat treatment to obtain a fine grained ferrite-pearlite microstructure, compressive stresses close to the rolling surface and the tensile stresses - inside the wheel [1-4]. This heat treatment creates conditions for suppressing the appearance and development of cracks. Nevertheless during service the wheel is loaded with cyclic forces that cause fatigue and possibly fatigue cracks. For this reason the control of the residual stress level is included in the regulations as a requirement in the maintenance repair (in-service) [7-8]. The wheels are usually subjected to preventive control by non-destructive testing methods after approximately 224,000 km mileage [2].

General non-destructive method for residual stress determination is the ultrasonic method based on the acousto-elasticity effect [9-15]. The technique is founded on the measurements of the difference between times-of-flights of ultrasonic shear waves polarized along the radial and the circumferential direction. Different ultrasonic set-ups for stress state evaluation in the rims of wheels are in use in the railway repair industry [9,10,11,15]. The apparatuses are specialized and usually are stationary systems that work in factory conditions. The aim of this study is to compare the results of several NDT methods for residual stress evaluation of railroad wheel. The combined use of ultrasonic, electro-magnetic Barkhausen noise and magnetic acoustic emission enables the evaluation of stress and microstructure states of all volume and in the surface layers in wheels and can be used as a current control with portable and convenient device.

2. Experimental methodology. Material characterization

2.1.Materials
Railroad monoblock wheels were used as the test specimens. The type of wheels is R7 407 [5,15]. The carbon content of the steel is 0.55%, yield stress is of 550 N/mm², a tensile strength 820-940 N/mm² [5].

2.2. Experimental procedure
The experiments were carried out in Vagonoremonten Zavod (VRZ) Septemvri, Bulgaria. The procedure of the experiment includes the measuring of the residual stresses in the wheel rims by standard apparatus UER-T-Germany[15], registration the Barkhausen noise intensity and magneto acoustic emission by device “MULTITEST MC10”-Bulgaria. Additionally the velocities of surface ultrasonic waves are measured by computerized ultrasonic instrument US-box “Lecoeur”.

After data processing the results are compared with obtained by standard method ones. The experiment includes following stages:

- Evaluation of the residual stress level by UER-T in the rims of the wheels;
- Measurement of the magnetic-noise voltage (Um) on the faces of the rim and rolling surface of the wheels new production and after service;
- Measurement of the magnetic-acoustic voltage (Ua) on the faces of the rim and rolling surface of the wheels new production and after service;
- Measurement of the velocities of the ultrasonic surface wave by ultrasonic US-box;

The measurements are carried out at 8 positions of the wheels, as shown in the scheme of Figure 1.

2.1 Ultrasonic measurement

The automated computerized equipment UER II-T was used to evaluate the residual stress by standard method with EMAT transducers (Figure 2). The experimental set-up for investigation by ultrasonic surface waves is presented in details in [18]. The computerized ultrasonic instrument [24] allows measuring the time of ultrasonic impulse with accuracy up to 1 ns and 10 bits resolution at sampling rate of 160 MHz. Surface Rayleigh ultrasonic waves are excited by an angular transducer with variable angle at 3 MHz. The propagation depth of the surface wave is of the order 1,7 of wavelength or about 2 mm. The signal is emitted by the transducer E, received by the transducer R and recorded as shown in Figure 3. The receiving transducer registers the signals in two positions R1 and R2 at the distance ΔL.

2.2 Barkhausen measurements

The magnetic Barkhausen emission technique is a non-destructive testing method for evaluation of microstructures and stresses in ferromagnetic steels. The advantages of this method are faster measurements, portability of equipments, and capability to measure components in complex geometries.

Mechanical stresses influence on the distribution and the domain walls' motion through the magnetoelastic interaction [18-22]. Several studies [19, 12, 21] show the effect of stresses on Barkhausen noises parameters and its application in industry. The stress levels can be determined during the test system calibration operations [18, 22].

Magnetonoise and magnetic acoustic emission measurements is conducted by the device “MULTITEST MC10” (Figure 4) with magnetic-noise transducer and acoustic piezotransducer[1,2], placed on the outside of the rim wheels in positions 1, 2 and on the working surface of the wheel - positions 3, 4 (Figure 5). The frequency of magnetizing current is 80Hz. The current automatically increases from 1 to 500 mA. The penetration of the magnetic field depends on the size and shape of the excitation magnets. The orientation of the poles does not significantly affect the results.

The non-destructive parameters (magnetic-noise voltage Um and magnetic-acoustic voltage Ua) are measured, saved in device memory and can be graphically presented.
Software for data acquisition, treatment and assessment is developed in a Math Lab environment.

3. Results and discussion

3.1. Calibration curves

Figures 6a and 6b present the dependences of the magnetic noise voltage (Um) on the excitation current (I) obtained from new railway wheels (a) and railway wheels in maintenance repair (b). The values are averaged from measurement of 10 wheels.

Fig.6a Magnetic noise voltage Um(I) wheels (new production)  
Fig.6b Magnetic noise voltage Um(I) –wheels (in-service) 1,2 correspond to rims, 3-4 – rolling surface
The results show high intensity magnetic noise in new wheels with grained microstructure and suitable heat treatment of the rims that results a good level compression stresses. The results in Fig.6b present the reduction of the magnetic noise of about 50% for wheels being in service. Positions 1,2 indicate the results from the rims and positions 3,4 correspond to the rolling surfaces.

3.2. Distribution of magnetic noise in wheels

The distribution of the magnetic noise parameters on the circumference of the two wheels of wheel body are shown in Figure 7. The curves 1 represent the data for wheel rims, the curves 2 - the rolling surface. The reduction of the values on the rolling surface is due to the surface hardening.

![Fig.7 Distribution of magnetic noise in wheel body (a-wheel A, b-wheel B)](image)

The problem is to find the correlation between internal stresses in the wheels and the level of the magnetic noise. A way to do it is to carry out the suitable experiments in order to establish a calibration curve as shown in [22]. It is the next task of our research team.

In the current study we seek the correlation between the mechanical stresses measured by standard ultrasonic apparatus *UER II-T* and magnetic noise.

![Fig.8.Distribution of internal stresses measured by UERII T and magnetic noise parameters on the wheel circumference](image)
Figure 8 presents comparative measurements by two non-destructive testing methods. It can be supposed that the magnetic noise parameters in the surface layers of the rim wheels correspond to the level of mechanical compression stress. It requires additional research.

### 3.3. Magnetic acoustic emission

Magnetic acoustic emission (MAE) measurements are carried out by the device MC010. This method is based on acoustic effect of Barkhausen. MAE signals are registered by acoustic emission transducer “Vallen System”. Figure 9a shows low intensity of MAE parameter (Ua) in the rim of new wheels. The position of magnetizing device is close to the position of the acoustic emission receiver. This can be explained with microstructure and stress state conditions. The investigation of the wheels in maintenance shows that the apparatus can not achieve the required intensity of the magnetic field. It is found that the MAE can be induced using an excitation electromagnet with greater power. For this purpose the magnetizing device with greater power is carried out and applied. Some results from the rim of the wheels after service are presented in Fig.9 b. Curve 1 indicates very low magnetic acoustic emission. Curve 2 shows the results after amplification of magnetizing device. The experiments presented in this study are initials and have to be continued.

![Fig.9a MAE in new wheels](image1)  ![Fig.9b MAE in wheels in service](image2)

### 3.4. Ultrasonic measurements by the ultrasonic surface wave

The velocities of surface waves are measured along and across in the wheel rims in the new wheels and wheels after maintenance as shown in Figure 3. The velocity $C_R$ is estimated in the following way

$$C_R = \frac{2(L_2 - L_1)}{\tau_2 - \tau_1} = \frac{2\Delta L}{\Delta \tau}$$

Where $\Delta L$ is the distance between the positions R1 and R2 of the receiver, $\tau_1$ and $\tau_2$ are the arrival times of the wave obtained at the distance $L_1$, $L_2$ (Figure 3).

The relative change of the surface wave velocity measured along and across the rims is about of 1% for the new wheels. Figure 10 presents ultrasonic signals obtained across (a) and along (b) the rims at positions R1 and R2.

The results from the wheels in service show the relative change of about 0.2% between the same directions compared to the new wheels.

The changes of arrival time of ultrasonic wave can not be estimated by classical ultrasonic flaw detector. However the using of the computerized ultrasonic instrument allows measuring the time of ultrasonic impulse with high accuracy.
Fig. 10. Ultrasonic signals across (a) and along (b) the rim of the wheels.

The registered signals from surface ultrasonic waves are processed as described in [25]. The complex frequency spectrum of signals is found after performing Fourier transformation [25]. Figure 11a,b show the dependence of the phases of the spectra at two positions R1 and R2 and different directions on the wheel rim.

Fig. 11. Phase spectra of ultrasonic signals a) across the rim, b) along the rim

Fig. 12 Phases $\Phi$ of cross spectra obtained along and across the wheel rim

The present study shows that there are changes in the phase and shape of the signals propagating in the stressed media. To assess the difference between signals we use a cross-spectrum analysis [25] applied to signals at the same distance and shifted with respect to the time of arrival. The phases $\Phi$ of the cross-spectra are presented in Figure 12 and determine the phase differences between the initial signals and signals passing some distances in different directions. It can be noted that the slope of the curve $\Phi$ along the wheel rim is greater and can be a factor for estimation the stress state in materials.
The results illustrate that the phase spectrum of the signals are very sensitive parameter and could be recommended for stress state evaluation in the rims of railway wheels.

**Conclusion**

The special feature in the work is the comparative non-destructive measurements of the stress state in railway wheels and can be used for current control after service. The results show good sensitivity of the applied non-destructive techniques and parameters. The variations of non-destructive parameters are quite discernable and useful for stress, microstructure and anisotropy estimations.

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