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ULTRASONIC EVALUATION OF STRESS STATES OF RIMS OF RAILROAD WHEELS. PART 2 – EXPERIENCES AND FUTURE ADAPTATIONS

An ultrasonic technique was developed and different systems are in use to evaluate the stress state of the rim of solid railroad wheels. The measure results received with the UER system versions developed by IZFP as well as the Russian version УКОН-01 was shown and described in the paper. Because the stress state of new wheels is smaller in value than the stress in braked wheels, the influence of a slightly developed texture in new wheels cannot be neglected as it can in case of used wheels. This part of the paper informs on the experimental evaluation of the acousto-elastic constant. A new approach is discussed to take the texture of new wheels into account. Using that approach the established systems can also been applied on new wheels with texture. Furthermore, it is suggested to discuss a new criterion to evaluate the measured stress state of braked wheels with regard to the risk of crack growth and wheel break.

railway wheels, rim, residual stress, ultrasonic stress analysis, texture.

Introduction

In order to contribute to the safety of the cargo train traffic the stress state of all block braked wheels have to be tested routinely. An ultrasonic technique was developed and different systems are in use to evaluate the stress state of the rim. The standard DIN EN 13262 describes the technique and the measuring procedure. The first part of the paper describes the physical basics and shows the significant change of the circumferential stress in rims after the application of different braking loads. The UER system versions developed by IZFP as well as the Russian version УКОН-01 are shown and described.

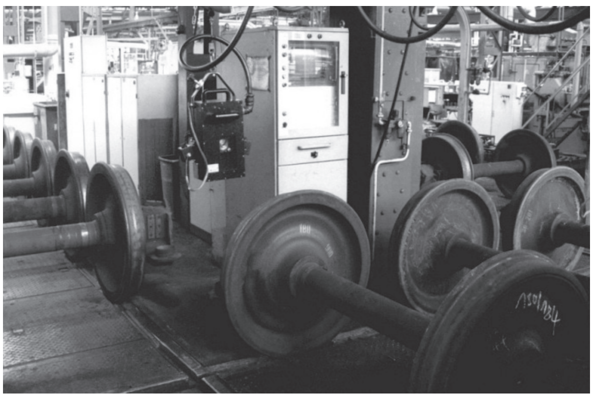
1 Application and Experiences

Part 1 of the paper [1] describes shortly the fundamentals of the ultrasonic technique as well as the UER system to evaluate the stress state of the rim of block-braked railroad wheels. The prototype set-up developed by IZFP was tested and validated by DB AG. For the validation, DB AG compared the results of the UER-prototype system with the results of x-ray diffraction and of the destructive stress analysis. The results were found in good agreement. The validation was made by DB AG; the results are not property of IZFP. Similar investigations have been performed in Russia by the Research Institute of Bridges and Nondestructive Testing (НИИ мостов) in cooperation with Railway Research Institute (ВНИИЖТ) using both, a UER system and the Russian version УКОН-01. The УКОН-01 system, developed in 2008 by the Research Institute of Bridges and Nondestructive Testing, Petersburg State Transport University and the company "Introtest", uses the same physical fundamentals as the UER system.

Since December 1992 UER systems are in daily use in workshops of railroad authorities as well as of wheel set manufacturers. Figure 1 shows applications in a workshop and in a station. During the test period of the first UER systems DB AG as well as the Swiss Railroad Authorities made a lot of results available for statistics. Among others it was found that the stress-depth-profiles taken at the two wheels of the same wheel set can be quite different due to different braking conditions.

The figures 2 and figure 3 show some of the results of the application of the set-ups. The stress-depth-profile of the wheel in the as delivered state is as expected: a compressive stress state is found with its maximum value in the depth right underneath the tread (figure 2, *a*). After a few month of use, the influence of the braking sequences causes a shift towards tensile stresses in the area underneath the tread. In the deeper part of the rim, the stress state is not yet changed (figure 2, *b*). After another period of use, the state of stress changed significantly towards tensile values with a maximum in the area close to the tread (figure 2, *c*).

Figure 3 displays a result, found on a wheel which was severely braked. The very high stress values in the area deeper than about 15 mm underneath the tread indicate a very strong influence of temperature. The temperature was caused by the application of a high braking pressure of the brake shoe on the wheel. The temperature in the part closer to the tread was higher than in the deeper parts of the rim. The high temperature reduced the value of the Young´s modulus; the material of the part of the rim close to the tread became softer. This effect and the axle load caused a plastic deformation of the upper part of the rim, which again reduced the residual stress state in the surface near area until a depth



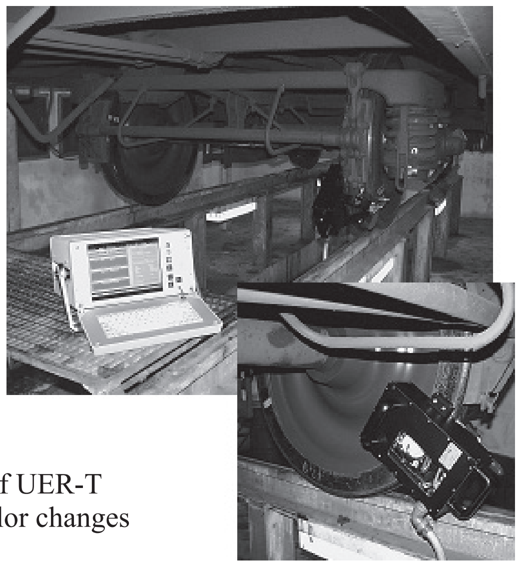


Fig. 1. Application of UER in a workshop and of UER-T in a station in order to inspect a wheel showing color changes because of high temperature influence

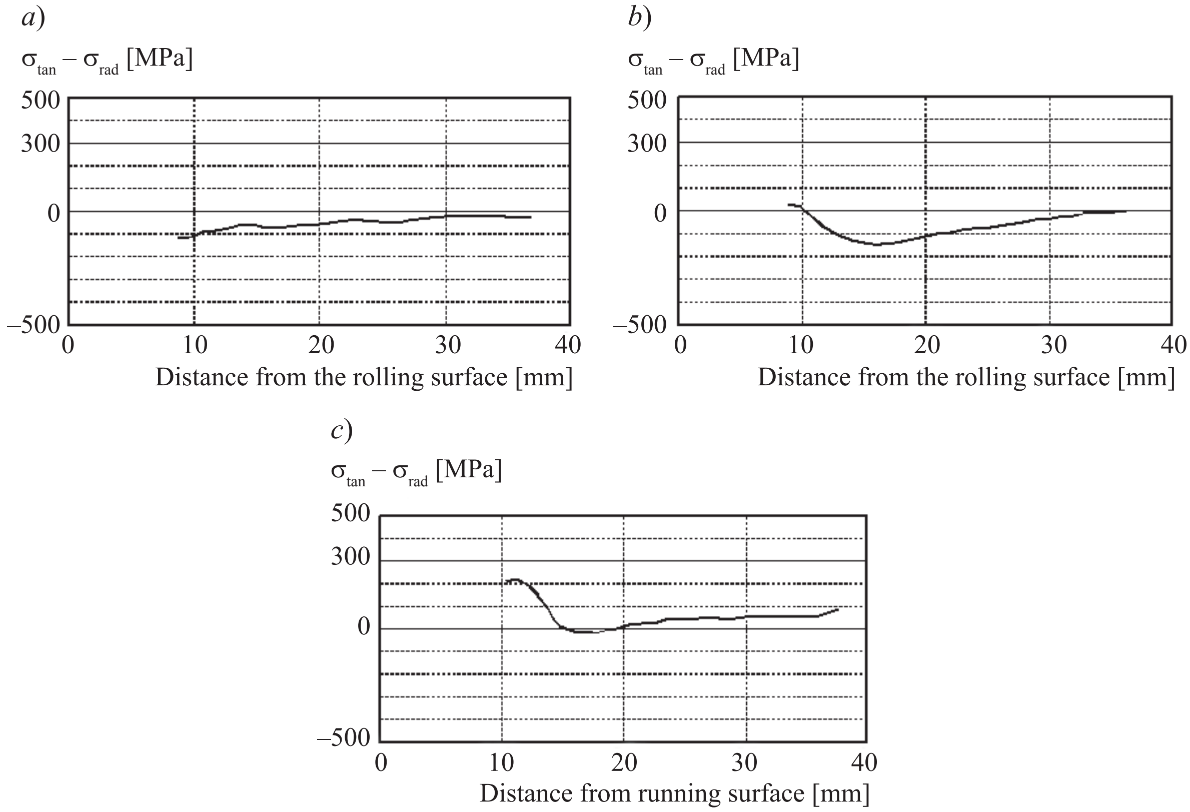


Fig. 2. Stress-depth-profile of a new wheel (*a*), of the wheel after a few month of use (*b*), and of the wheel after some more month of use (*c*)

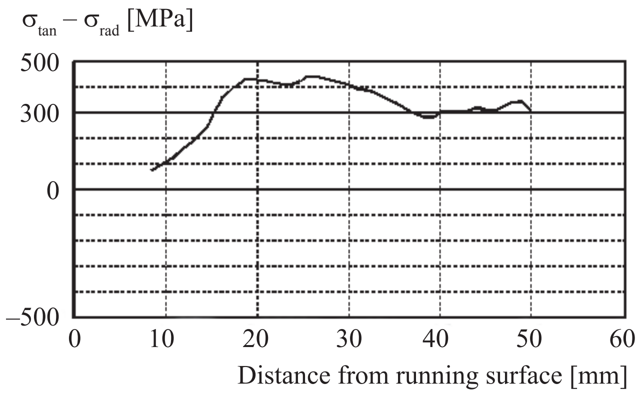


Fig. 3. Stress-depth-profile of a severely braked wheel

of about 15 mm. The plastic deformation of the rim was clearly to be seen.

2 Evaluation of K-value

As explained in [1], the stress component $\sigma_{circumferential}$ along the circumference of the wheel can be calculated using the measured times-of-flight of a shear wave being polarized along the circumferential and the radial direction of the wheel, respectively.

$$\sigma_{circumferential} = K\,(t_{circumferential} - t_{radial})\,/t_{radial}. \quad (1)$$

K is the proportionality factor. It is obvious, that the error associated with the K-value is directly influencing the error of the final result.

K is a material dependent acousto-elastic quantity which can be easily evaluated in a tensile test experiment.

The UER systems use a linear polarized shear wave; the mass particles vibrate linearly in a plane perpendicular to the propagation direction. In case of a longitudinal wave the particles vibrate along the direction of wave propagation. The propagation velocity is influenced by the elastic strain or stress state of the part of sample propagated by the wave. The effect is different in size and sign, depending on the propagation and vibration direction of the ultrasonic wave with respect to the principal stress directions. In the simple case of a tensile test sample, there are principally five possibilities of propagation and vibration as shown in figure 4: a longitudinal wave propagating along the applied stress (5), a longitudinal wave propagating along the direction perpendicular to the applied stress (2), a shear wave propagating along the stress, polarized perpendicular to it (4), a shear wave propagating perpendicular to the stress, polarized perpendicular to it (1), and a shear wave propagating perpendicular to the stress, polarized parallel to it (3). The situation as shown in figure 4 can be taken to describe the situation of the stress state of the wheel.

As it has been experienced in all cases of application up to now, the stress state of the rim of a forged and annealed wheel can be regarded as a one dimensional stress state with the dominant stress component along the circumferential direction of the wheel. The stress component along the radial direction is small in value and is not significantly changing under the influence of braking. Hence, the stress direction shown in figure 4 represents the circumferential stress direction in case of the wheel and the shear waves 1 and 3, shown in the figure 4, represent the two shear waves as used for stress analysis on wheels. The wave 3 in the figure 4 corresponds to the shear wave propagating the rim width, polarized along the circumference and the shear wave 1 in the figure 4 corresponds to the shear wave polarized along the radial direction of the wheel.

The change of the ultrasonic velocities with the tensile strain or stress is schematically shown in figure 5. In case of compressive stress the velocities change with the same slopes, respectively. With increasing tensile strain or stress the velocity of the shear wave 3, polarized along the circumferential direction in case of the wheel, decreases. With increasing tensile stress the velocity of the shear wave 1, that is the wave polarized along the radial direction in case of the wheel, increases slightly.

In order to evaluate the K-value tensile tests are applied using a representative sample cut from the rim of a wheel. As function of applied stress, the relative change of the time-of-flight of the shear waves 1 and 3 are measured. As mentioned earlier [1], the change of the times-of-flight of the two shear waves is a function of the difference of the stresses ($\sigma_{circumferential} - \sigma_{radial}$) along the two principal directions.

In case of the tensile test sample, the stress σ indicated in figure 4 corresponds to $\sigma_{circumferential}$ in the case of wheel and σ_{radial} in case of wheel is regarded as small and neglected. Hence, it follows from equation (1):

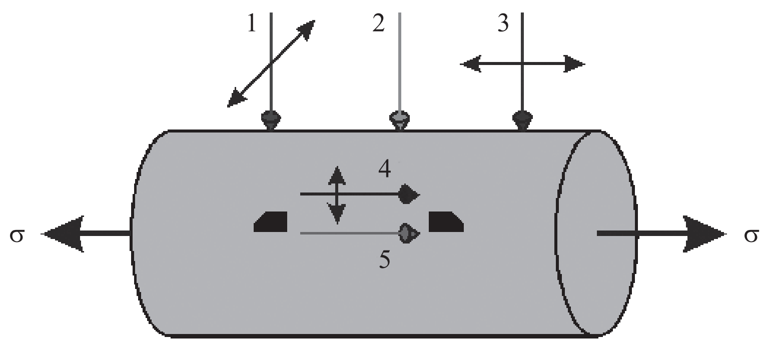


Fig. 4. Propagation (cone arrow) and vibration directions (flat arrow) of ultrasonic waves propagating a tensile test sample

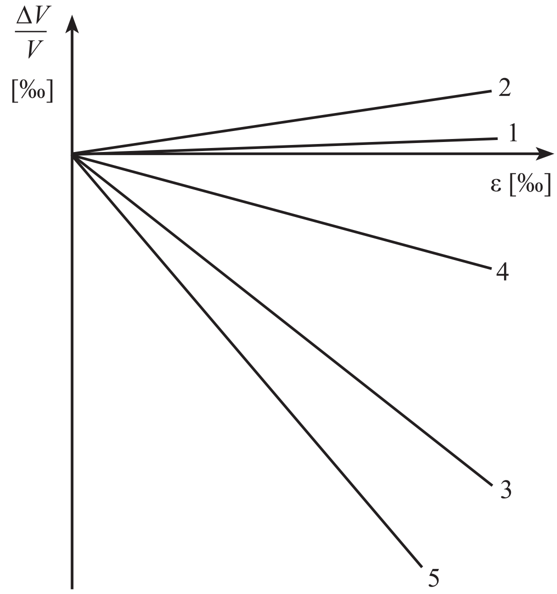


Fig. 5. Schematic of the relative change of ultrasonic velocities as function of elastic tensile strain

$$K = \sigma_{circumferential} / ((t_{circumferential} - t_{radial}) / t_{radial}) \quad (2)$$

Or in terms of the notation as shown in the figures 4 and 5:

$$K = \sigma / ((t_3 - t_1) / t_1). \quad (3)$$

In order to get *K*-values representing the acousto-elastic material properties at its best, it is recommended to use two or even more samples cut from different positions of the rim for the experimental evaluation of the *K*-values.

A representative experimental result will be discussed. For the application of tensile stress the sample has to be gripped by the sample holders of the tensile test machine. In many cases, the length of the material samples, cut from the rim along the circumferential direction is too short. There is not enough length in order to grip the sample and to apply tensile stress. In those cases the tensile test machine is used in the compression mode. As function of the applied compressive stress the times-of-flight of the two shear waves are measured at each step of applied stress. The relative change of the times-of-flight $(t_{stressed} - t_0) / t_0$ of each of the two shear waves is calculated for each step of applied stress and displayed in figure 6. As to be seen in the figures 6, the absolute values for the relative changes of the times-of-flight $(t_3 - t_1) / t_1 = (t_{parallel} - t_{perpendicular}) / t_{perpendicular}$ are 1,430 ‰ at 230MPa for sample 1 and 1,495 ‰ at 235 MPa for sample 2. That means:

the *K*-value for sample 1 is 230 MPa/ 1,430 ‰ = 161 MPa/‰;

the *K*-value for sample 2 is 235 MPa/ 1,495 ‰ = 157 MPa/‰.

The ultrasonic times-of-flight are measured at one measuring position only. It has been found in previous experiments that the relative change of time-of-flight as function of applied stress can scatter in a range of up to 10 % if the measurements are performed at different positions on the same sample. Hence the *K*-value has an uncertainty of up to about 10 % because of local inhomogeneity of the material under test.

As said, the *K*-value is dependent on the kind of material and on the state of the particular material. For the material R7, R8, and R9 a *K*-value of 135 MPa/‰ and for the material R1 and BV2 a *K*-value of 150 MPa/‰ is in use. Using samples delivered by different Russian wheel set manufacturers (material T) *K*-values of 153MPa/‰ and 165MPa/‰ have been evaluated (figure 7, [2]).

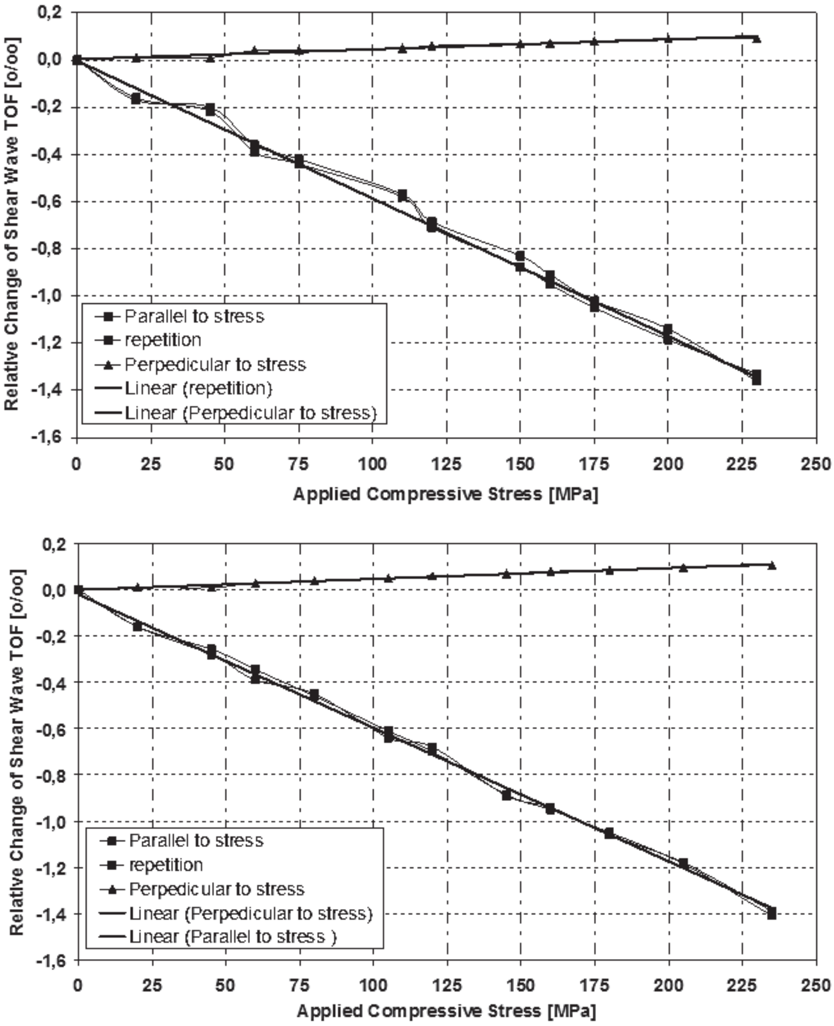


Fig. 6. Relative change of the shear wave time-of-flight (TOF) as function of the applied compressive stress on sample 1 (top) and sample 2 (bottom) cut from the same wheel set

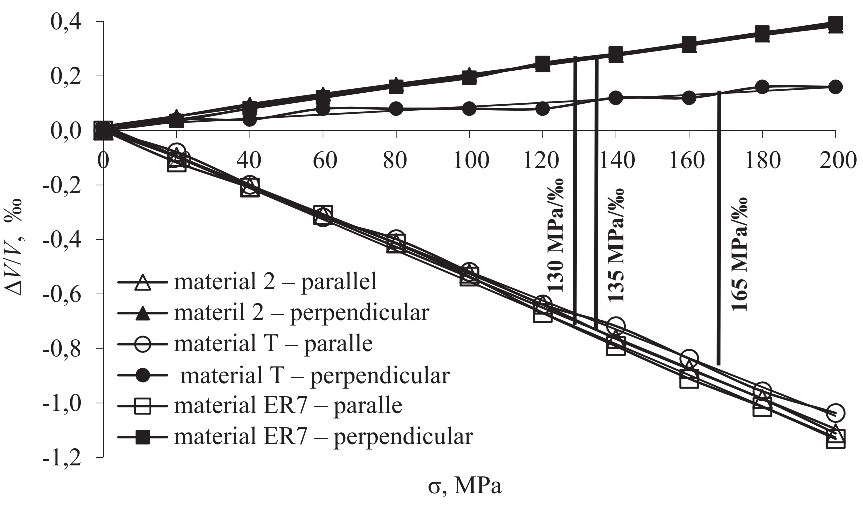


Fig. 7. Relative change of the shear wave TOF as function of the applied compressive stress on samples from wheels of materials 2, T, R7 [2]

3 Characterization of Texture and Stress Analysis on Textured Wheels

The advantageous application of the birefringence technique by the UER systems to evaluate the stress state of the rims is only allowed if the wheel rims have no texture. Texture is a preferred orientation of the single crystals in the polycrystalline steel. Texture is mainly caused by the forging process. Ideally the subsequent heat treatments cause a reduction of the lattice defects, a recovery of the material and a reorganization of grains in such a way that their orientation is statistically distributed in all directions. The mentioned recovery and improvement of the material state is more or less achieved by the heat treatment, the rims of the wheel sets are more or less free of texture and hence, the elastic properties as well as the strength values are more or less direction dependent.

A very simple and easy check on the texture can be performed using a sample cut from the wheel rim or cut from the sample used for the experimental evaluation of the K-value. It is recommend to machine cubes of about 20 mm side length out of the sample which can be regarded as free of residual stress. Ultrasonic longitudinal and/or shear waves propagating and vibrating along the three principal directions of the sample are applied and their propagation velocities are evaluated. If there is no texture the 3 values of the longitudinal wave velocity are the same as the six values of the shear wave velocities are the same within the measuring error which is typically about ±0,1 ‰.

In case of texture, the velocity values are different and depending on the direction of wave propagation and vibration. Since shear waves are used by the UER systems as well as for the evaluation of the K-value, it is convenient to use shear waves for the evaluation of the texture influence also. The time-of-flight of a shear wave propagating along one of the three directions of the cube, let´s say direction 1, is measured in case the vibration of the wave is oriented along direction 2 and along direction 3. The velocities v_{12} and v_{13} are evaluated using the appropriate ultrasonic path length. Here, the first index of v represents the direction of the wave propagation, the second the vibration direction of the wave. And 1, 2, 3 are the principle directions of the sample according to length, width and thickness. The value of the relative change of velocity $(v_{12} – v_{13}) / v_{13}$ or of the times-of-flight $(t_{13} – t_{12}) / t_{12}$ is a direct measure of the texture. As larger the value as higher the degree of texture, the more grains are orientated along a preferred direction of the sample.

The evaluation of the shear wave velocities has an additional advantage. As shown e. g. in [3] the forging texture causes the same influence on the velocity of a shear wave propagating along direction 1 and vibrating along direction 2 as on the velocity of a shear wave propagating along 2 and vibrating along1, hence $v_{12} = v_{21}$. The same holds for the velocities of the other shear waves propagating the textured sample $v_{23} = v_{32}$ and $v_{31} = v_{13}$. And $v_{12} \neq v_{13}$, $v_{21} \neq v_{23}$ and $v_{31} \neq v_{32}$.

In case the relative difference of the times-of-flight or of the velocities of the two shear waves propagating along the same direction but being polarized along the two other principal directions as e. g. $(v_{12} – v_{13}) / v_{13}$ is larger than about 0,2 ‰, the texture influence is regarded as strong and the UER systems should not be applied for stress analysis. The value of about 0,2 ‰ is arbitrarily chosen. Assuming a K-value of 150 MPa/‰ the texture influence of 0,2 ‰ is as strong as a stress influence of 30 MPa. In all samples cut from wheel sets with the material types R7, R8, R9 inspected up to now, the texture influence was found to be smaller than 0,2 ‰ and negligible.

As the forging, the casting of the wheels is also causing a texture and it is again the subsequent heat treatment which reduces more or less sufficiently the degree of texture in the rim.

A particular type of casted wheels, manufactured in the USA, was tested. There was no significant texture found in the upper part of the rim until a depth of about 30 mm. In the area from about 30 mm to 50 mm underneath the tread, the influence of the casting texture was to be measured. The texture was found to be larger in the vicinity of the feeding points, where the material was poured into the mold. The results of the UER-system applied on the casted wheels do not give reliable stress-depth-profiles in the area of more than about 30 mm distance from the tread.

In forged wheels manufactured in Russia, it has also been found [2] that there is a texture only in the deeper part of the rim, whereas there is no texture influence measured in the upper two third of the rim. This type of wheels has been heat treated in order to get the requested hardness of the tread area. In order to minimize the stress along the circumferential direction two saw cuts were made along the radial direction from the tread until the blade of the wheel. A full piece of the rim was cut out of the wheel. The length of the rim sample along the circumferential direction was 200 mm. The residual circumferential stress is assumed to be small and negligible. Hence, the stress influence on the measured times-of-flight and on the relative time-of-flight difference $\Delta a = (t_{circumferential} - t_{radial}) / t_{radial}$ can be regarded as negligible. The measured times-of-flight and the values of Δa are a measure of the texture of the rim sample. Time-of-flight measurements were performed every 2 mm along the radial trace starting at 8 mm underneath the tread. Figure 8 shows a representative result. The values of the relative difference Δa scatter between 0 and 0,2 ‰ in the upper part of the rim until a depth of about 40 mm and systematically increases to about –0,6 ‰ in the deeper part of the rim. The result can be regarded as representative for all wheels of this particular type.

According to the above mentioned criteria, the texture influence of less than 0,2 ‰ in the upper part of the rim is negligible. The linear increase of the texture influence with increasing distance from the tread allows for a modification of the usual evaluation equation (1) used by the UER systems:

$$\sigma_{circumferential} = K\,(t_{circumferential} / / (t_{radial}\,(1 + \Delta a) - 1)). \quad (4)$$

It has to be kept in mind: in order to perform a stress analysis using wheels with the particular kind of texture, the Δa-depth-profile has to be measured in advance and the texture influence has to be taken into account according to equation 4 with the corresponding Δa-values. The Δa-depth data as shown in Figure 8 are stored and used during the evaluation of the stress at each measuring position along the radial measuring trace. Figure 9 shows results of the stress analysis on one of the other surface hardened wheels. The dotted line displays the stress-depth-profile as evaluated applying the usual equation (1) and the full black line shows the stress profile according to the modified equation (4) taking the texture influence into account [2].

Stress Analysis on New Wheels

The UER-set-ups have been designed and mainly been applied to evaluate the stress state of the rims of used wheels. In recent years the

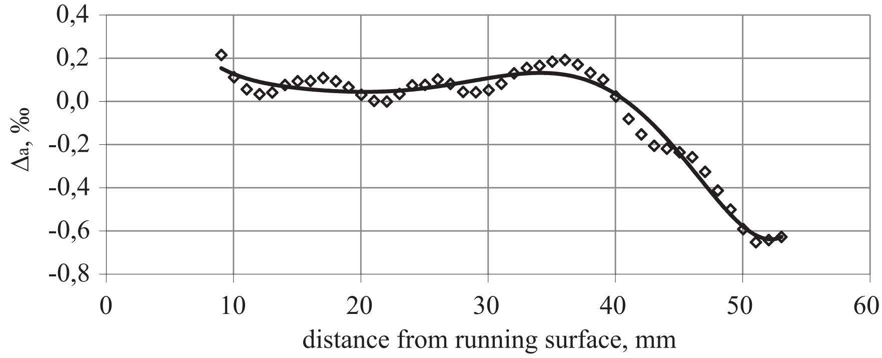


Fig. 8. Relative difference Δa of the times-of-flight of the two shear waves propagating a rim sample versus increasing distance from the tread [2]

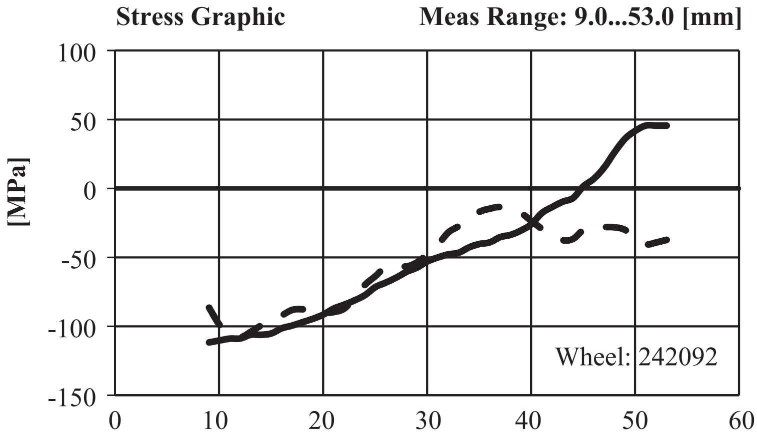


Fig. 9. Stress-depth-profile of a hardened wheel as evaluated using the usual UER evaluation (dotted) and taking the texture influence into account (black) by using the representative change of texture influence as shown in figure 8 [2]

systems are also applied for the stress analysis on new wheels. Among other tasks, EN 13262 Standard [4], also requests a certain stress state of new wheels, characterized by the three properties:

- depth areas close to the tread have to have a compressive stress state with a circumferential stress between –80 MPa and –150 MPa;
- the stress-depth-profile is not allowed to change more than 100 MPa around the mean value of the circumferential stress;
- the circumferential stress has to be zero in a depth of 35 mm till 50 mm underneath the tread.

Requirements of Russian Standards [5], [6] are:

- depth areas close to the tread have to have a compressive stress state;
- the stress-depth-profile is not allowed to change more than 100 MPa around the mean value of the circumferential stress;
- the circumferential stress has to be zero in a depth of more than 40 mm underneath the tread.

The three characteristics of the stress state of new wheels can be determined from the stress-depth-profile as it is routinely displayed by all UER and УКОН systems. In order to facilitate the monitoring of the requested characteristics, a software module is available, which analyses the measured data and indicates by colour written comments and signals whether each of the three criteria is fulfilled or not. The situation is illustrated in figure 10.

These new software modules, adopted for UER and УКОН systems, respectively [7], [8] evaluate the fulfilment of the above mentioned requests taking into account the scatter band of the stress results and their measuring accuracy.

Recommendation for Future Adaptations

Up to now, all European Railroad authorities use a maximum allowable stress value as a quality and safety criterion. In the case of one particular wheel type the maximum value of the allowable stress is 300 MPa. Based on that criterion, a wheel with a stress state as shown in figure 3 is not allowed to be used again and a wheel with a stress-depth-profile as shown in figure 2c will be used again.

It seems to be very obvious that the wheel with a stress profile as shown in figure 2c has a higher risk for crack growth and wheel breaking than the wheel with a profile as shown in figure 3, since small cracks in the tread are more likely to grow under the influence of the higher tensile stress in the surface near part of the rim (figure 2c). In case of the profile shown in figure 3 there is a small tensile stress in the surface near part, where small cracks are often found. The higher tensile stress in a distance of about 18 mm from the tread is not likely to generate the growth of the cracks in the tread zone.

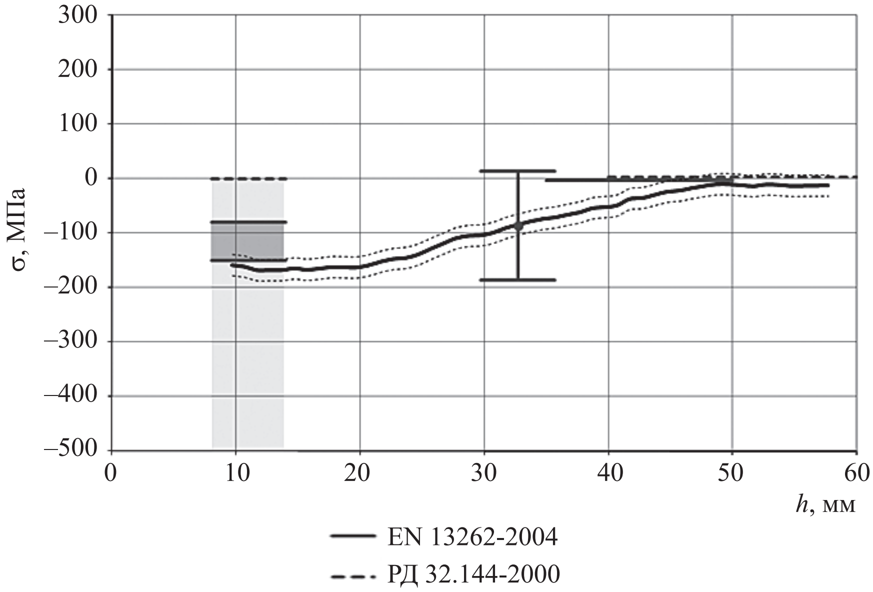


Fig. 10. Evaluation of the fulfilment of the stress-depth-profile to the requirements of Standards taking into account the measuring accuracy

It is suggested to develop another criterion to separate the wheels with a high tensile stress along the circumference and hence a higher risk for wheel breaking from those with a lower stress state. The integration of the stress values along the measuring trace, that is the area underneath the stress-depth-profile, seems to be a meaningful measure. It represents the elastic energy stored in the rim. Based on fracture mechanical calculations and on experimental results, allowable values should be determined for at least two different areas of the distance from the tread, e. g. for the area until about 20 mm of distance from the tread and for remaining part of the rim thickness.

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