доставки груза железнодорожным транспортом. Определено, что вероятность доставки груза за время большее нормативного времени составляет 0,65.

Библиографический список

1. **Стратегия** развития железнодорожного транспорта в Российской Федерации до 2030 года : утв. распоряжением Правительства Российской Федерации от 17 июня 2008 г. № 877-р. – М., 2008.

2. **Российская Федерация**. Законы. О железнодорожном транспорте в Российской Федерации : федер. закон : принят Гос. Думой 10 янв. 2003 г. № 17-ФЗ (с изменениями и дополнениями). – М., 2003.

3. **Правила** исчисления сроков доставки грузов железнодорожным транспортом от 18 июня 2003 г. № 27. – М., 2003.

UDK 620.179.16

E. Schneider
Fraunhofer Institute for Nondestructive Testing

ULTRASONIC EVALUATION OF STRESS STATES OF RIMS OF RAILROAD WHEELS. PART 1 – PRINCIPLES

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 measuring principle is based on the acousto-elastic effect, which describes the change of the ultrasonic velocity as function of strain or stress. The relative difference of the times-of-flight of the two shear waves propagating the width of the rim and polarized perpendicular to each other is proportional to the difference of the principal stresses along the circumferential and the radial direction, respectively. The factor of proportionality is a material dependent value, most often abbreviated by k-value. The measuring principle has the advantage of easy to perform measurements and enables a robust ultrasonic measuring technique but it had the restriction that the rim had to be free of texture.

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. The second part of the paper informs on the evaluation of the k-value and on a new approach 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.

Introduction

All traffic becomes faster and cargo trains have to fit into time slots between the high speed passenger trains. Most of the cargo trains are braked by pressing brake shoes onto the tread of the wheels. With increasing speed the braking energy increases quadratic and hence the temperature of the upper part of the rim of the block braked wheels sets also increases. Due to the heat put in during the braking period and the subsequent cooling tensile stress in the circumferential direction is developed in the rim of the wheel. Cracks in the tread which are not harmful otherwise, may grow under the influence of the circumferential tensile stress and may even cause the failure of the wheel.

A typical distribution of the circumferential (tangential) stress in a cross section of the rim of a used monoblock wheel is given in figure 1 [1].

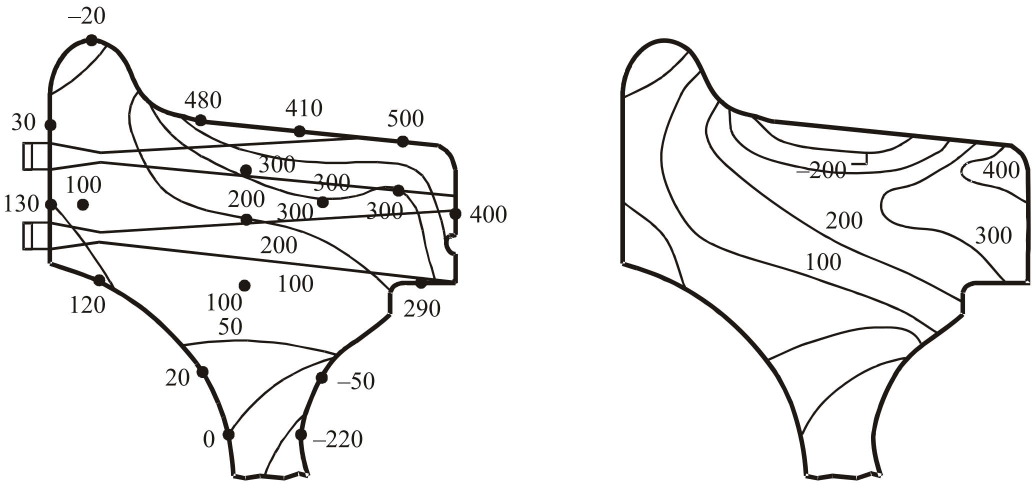

Fig. 1. Distribution of the circumferential stress state [MPa] of a used (left part) and of a new (right part) monoblock wheel

The right part shows a representative stress profile of a new wheel. Figure 1 also displays the ultrasonic field in the uppermost and the lowermost measuring position during the ultrasonic stress analysis.

The highest tensile stress in railroad monoblock wheels has been found in the tread and in the edge area of the tread and the outer side of the rim. The stress values were evaluated using a totally destructive cutting and sectioning technique. The points give the positions and the results of the strain gauge measurements; the lines are numerically evaluated [1]. The results are regarded as representative with respect to the stress distribution; the absolute values are of course strongly depending on the braking conditions.

In order to assure the quality of the wheels and the safety of the traffic, the stress state of cargo train wheel sets needs to be evaluated periodically. With respect to cost efficiency and to the large number of wheel sets to be inspected the inspection has to be nondestructive and fast and easy to apply in daily routines.

Ultrasonic as well as micro-magnetic techniques are already in use in order to evaluate stress states of different automotive, airplane and power plant components. The most significant advantage of these techniques in comparison with the established x-ray diffraction or with the drilling hole or ring core techniques is their high measuring rate and the simple sensor application without any specific preparation of the measuring point. Micro-magnetic techniques analyze a surface near layer of up to about 1.5 mm of depth, ultrasonic techniques allow for the evaluation of surface stress states as well as of stress states in the volume of components. Since the rail-wheel interaction causes surface defects of different nature, size and depth in the tread, only the ultrasonic techniques for volume stress analysis hold highest promise to evaluate the stress state of the rims.

1 Basics of Ultrasonic Stress Analysis

Ultrasonic techniques to evaluate stress states use the acousto-elastic effect; that is the influence of elastic strain states on the propagation velocities of ultrasonic waves. The influence of a strain or stress state on the wave velocities is different in size and sign, depending on the directions of ultrasonic propa-gation and vibration with respect to the principal directions of strain or stress. The acousto-elastic effect is rather small, the relative change of ultrasonic velocities is some per thousands only. That means that the ultrasonic path length and the time-of-flight have to be measured with high precision. Measurement of path length with the required accuracy on a component is at least time consuming. In order to bypass this restriction, two or even three ultrasonic waves are applied in such a way that they propagate the same path, but their vibration directions are along different principal stress directions. This multi-mode application results in evaluation equations for the stress state, in which the ultrasonic times-of-flight are the only measuring quantities. Based on the very well understood acousto-elastic effect, different ultrasonic techniques and set-ups have been developed and introduced to the industry in order to evaluate one-, two- or three axial stress states of components [2, 3, 4].

In order to characterize the stress state of the rim of a railroad wheel, the use of the ultrasonic birefringence effect is of advantage: A shear wave is applied and the time-of-flight is measured. The propagation direction of the wave is along the axial direction, means along the width direction of the rim, as shown in the right part of figure 2. The vibration direction is at first parallel to the circumferential or tangential direction, than parallel to the radial direction of the wheel.

The relative difference of the times-of-flight of the shear wave vibrating along the circumferential direction $t_{circumferential}$ and of the shear wave vibrating parallel to the radial direction t_{radial} is a function of the difference of the principal stresses ($\sigma_{circumferential} - \sigma_{radial}$) along the two principal directions, respectively:

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

It has been found that the principal stress along the radial direction σ_{radial} is small in value and does not change significantly under the influence of the braking. Hence, the difference of the two principal stresses ($\sigma_{circumferential} - \sigma_{radial}$) is mainly representing the circumferential stress component $\sigma_{circumferential}$ and its change caused by the braking:

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

The proportionality is given by K, a material dependent acousto-elastic constant. K is experimentally evaluated using a tensile test sample of the material of interest as described in a later paragraph.

The result of the ultrasonic stress analysis is the mean value of the circumferential stresses, acting in that part of the component, which is penetrated by the ultrasonic beam. That part is shown in yellow in the figures 1 and 2. In order to evaluate the stress state of the rim, measurements are performed along a radial trace at different distances from the tread. For that purpose the ultrasonic transducer is moved along the radial direction from the uppermost to the lowermost position, as shown in the figures 1 and 2.

The advantage of the used birefringence technique is that there is no need to take changes of the thickness of the rim into account. The

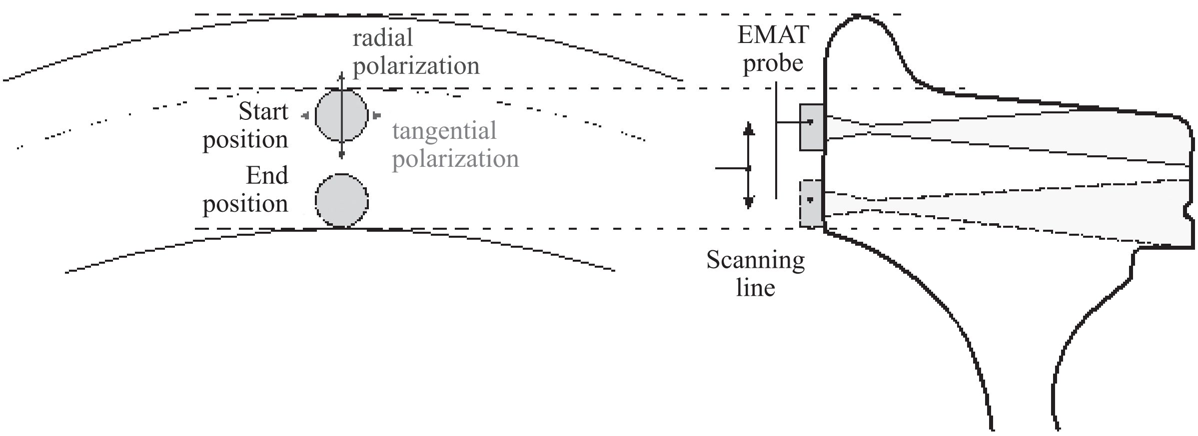

Fig. 2. Sketch of the measuring principle of the ultrasonic technique to evaluate the stress state of railroad monoblock wheels

disadvantage is that there should not be any other reason than the stress state causing the different velocities of the shear wave vibrating along each of the two principal directions. Hence, the rims of the wheels have to be quasi isotropic, means there is no texture. Texture means a preferred orientation of the crystals of a polycrystalline material. The plastic deformation of the wheel during the manufacturing process causes texture; the orientation of the grains is not statistically distributed but has preferred directions. The subsequent heat treatment enables a reorganization of the grain orientations and minimizes the degree of texture. The requirement of no or of a very small texture influence on the ultrasonic wave propagation has been found to be fulfilled in forged wheels manufactured in Western Europe after about 1960. Older types of forged wheels may have texture. In any doubt-ful case, a simply to perform test measurement is recommended to check on the texture influence. The characterization of the texture influence is described in a later paragraph.

The temperature of a component is also influencing the density, the elastic constants and hence the velocities of ultrasonic waves too. Since the measurements of the times-of-flight of the shear waves polarized along the two principal directions are performed immediately one after the other the temperature influence on the calculated time-of-flight difference and hence on the resulting stress value can be neglected [4, 5, 6].

A semi-automated ultrasonic system to evaluate the stress state of the rim of railroad monoblock wheels was developed by J. Deputat and coauthors [7]. They also exploit the ultrasonic birefringence effect and use the same equations as those shown above.

2 The UER Approach

Requested by Deutsche Bahn AG (DB AG) in 1990 the Fraunhofer Institute for Nondestructive Testing (IZFP) developed an ultrasonic technique and set-ups to evaluate the stress state of the rim of railroad wheels, named UER, the German abbreviation for ultrasonic system for stress analysis on railroad wheels.

As to be seen in figure 1, the highest tangential stress values are found in the tread and in the edge between the tread and the outer side of the rim. In order to evaluate the surface stress state in the tread and the edge area, the application of a skimming longitudinal wave or the application of a Rayleigh- or a SH-wave seems to be adequate. But the application of those waves to evaluate the stress state in a surface layer of the tread cannot be recommended because the material is damaged by the wheel-rail contact conditions. The plastic deformation and the different kinds of damages in the tread influence the propagation velocity of ultrasonic waves also, and hence render an automated ultrasonic surface stress analysis on used wheels impossible.

The use of the birefringence effect (equations 1) to characterize the stress state in the bulk of the rims is the best choice towards a reliable measuring technique. But it has to be demonstrated that the braking does not only change the surface stress but the stress state of the volume of the rim as well. It has been decided to perform experimental investigations. For that purpose new wheels produced by different manufacturers were used. The wheels were braked in a braking test stand of DB AG. Different braking conditions were applied and after each of the braking processes, the stress state was evaluated by the ultrasonic birefringence technique using equation 1b.

It has been found, that all inspected new wheels have compressive stress states. The figures 3 and 4 show two representative results. The compressive stress has values in the range of about –100 MPa till –240 MPa in the part close to the tread and decreases in value with increasing distance from the treat. The stress-depth-profiles are shifted to tensile values after the brakings were applied.

As to be seen in figure 3 a tensile stress maximum is developed at a depth of about 7 mm underneath the tread after three brakings with 30 kW and 45 minutes duration were applied. With increasing braking load, the maximum of the tensile stress in the area close to the tread as well as the stress in deeper parts of the rim increase systematically. A significant shift to higher tensile values is found after the 40 kW and after the first 50 kW brakings. A second braking with 50 kW for 45 minutes does not change the profile, already found after the first braking under the same condition. Another wheel of the same material but from another manufacturer was obviously differently heat treated in order to get higher compressive stresses in the new state. As shown in figure 4 the stress difference is found to be about –240 MPa until a depth of 10 mm underneath the tread. The profile goes almost linearly to 0 MPa at 30 mm of depth. After the first braking, the values are smaller than 100 MPa until about 20 mm of depth. The values are smaller than those, found in the first mentioned wheel, and the maximum, shown in Figure 3, is not developed in the second wheel (figure 4). The 270 stop brakings cause a maximum which is at the same position than that

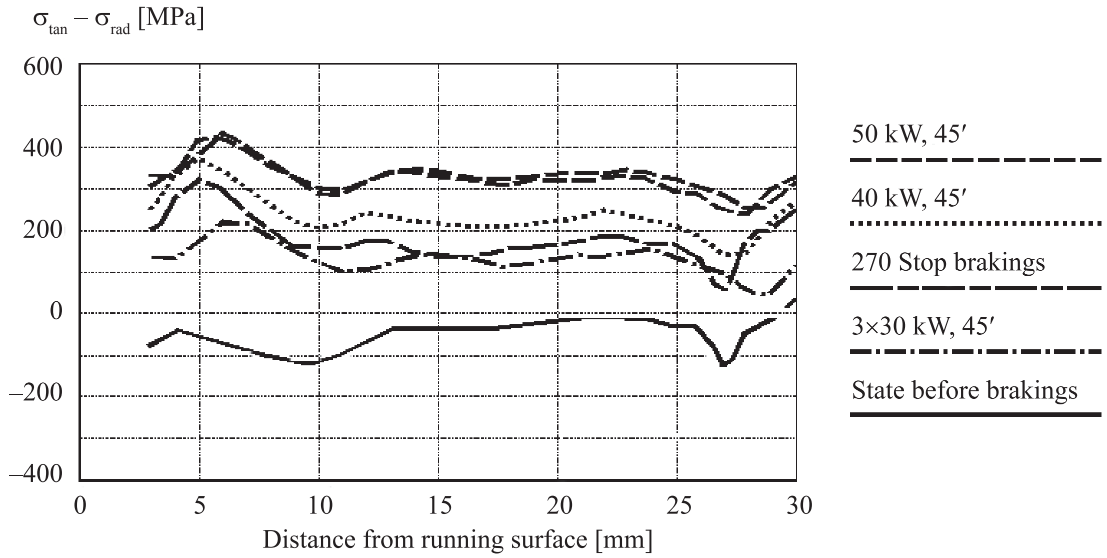

Fig. 3. Change of stress state of the rim of a new wheel after different brakings

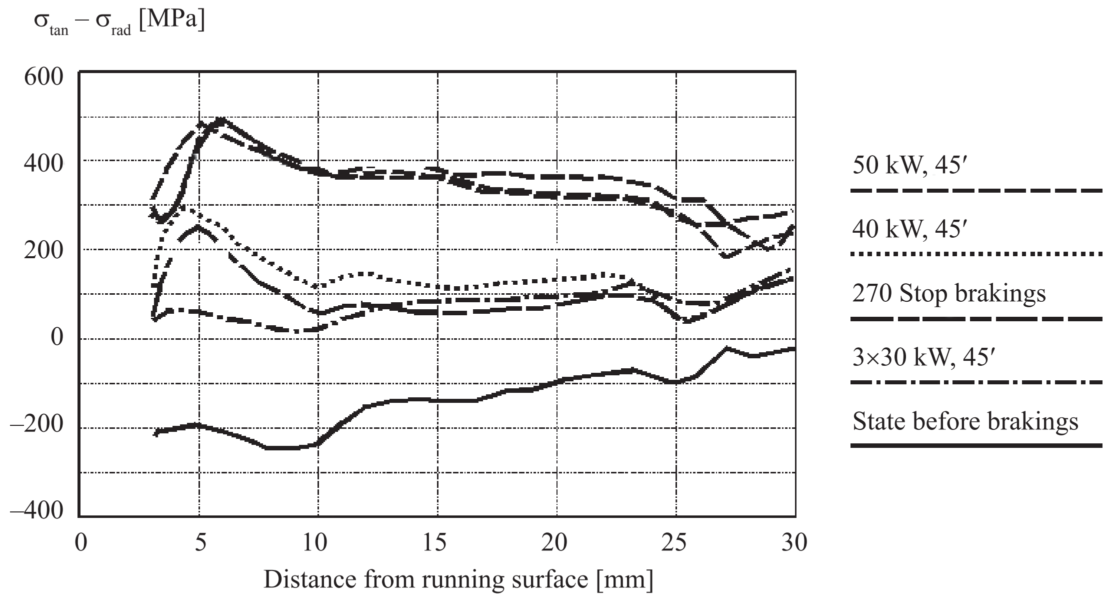

Fig. 4. Change of stress state of the rim of a new wheel after different brakings

shown in figure 3, but about 45 MPa smaller in value. Also after the next braking (40 kW, 45′) the maximum value is lesser than the one in the other wheel. It is also to be seen in figure 4 that the stress-depth-profiles after the first three brakings are more or less of the same level in areas deeper than 15 mm. After the 50 kW brakings maximum values of 500 MPa are evaluated. This is about 80 MPa higher than in the former case. The positions of the maxima are the same. Again, a second and a third braking with the same condition (50 kW, 45′) does not change the stress-depth-profile, determined after the first breaking of that sort.

During the same series of experimental investigations, DB AG cut small notches into the tread and measured the growth of the notches after the different braking sequences. Base on the results, DB AG performed fracture mechanical calculations in order to determine the maximum tensile stress $\sigma_{circumferential}$ which can be tolerated without any risk of wheel breaking. The results of the fracture mechanical calculations as well as the criteria to define the maximum tensile stress values are not available by IZFP. They are private property of the DB AG. It is known by IZFP that the maximum allowable stress value for one type of wheel sets is 300 MPa.

It is known that real brakings cause lower tensile values for $\sigma_{circumferential}$ than those, performed during the test stand experiments. Figure 5 displays the result of the ultrasonic stress analysis on new wheels before and after (dotted line) the application of a braking program as it is usually used during the downhill passage of the south ramp from the alps.

Other series of investigations were performed by applying the ultrasonic stress analysis at different positions around the circumference of the same wheel. As expected, the results are similar, as shown in the figure 6. Since each wheel has a rotational symmetry after the forging process and the heat treatment, and since all treatments of the wheel during its use influence the tread all along its circumference, the change of stress along the radial trace is the same, independent on the particular circumferential position where the measurement is performed. The figure 6 show results of the inspection of a new and a used wheel.

3 UER-set ups

UER and UER-T fulfill all the requirements for ultrasonic systems to evaluate the stress state of the rim of railroad monoblock wheels

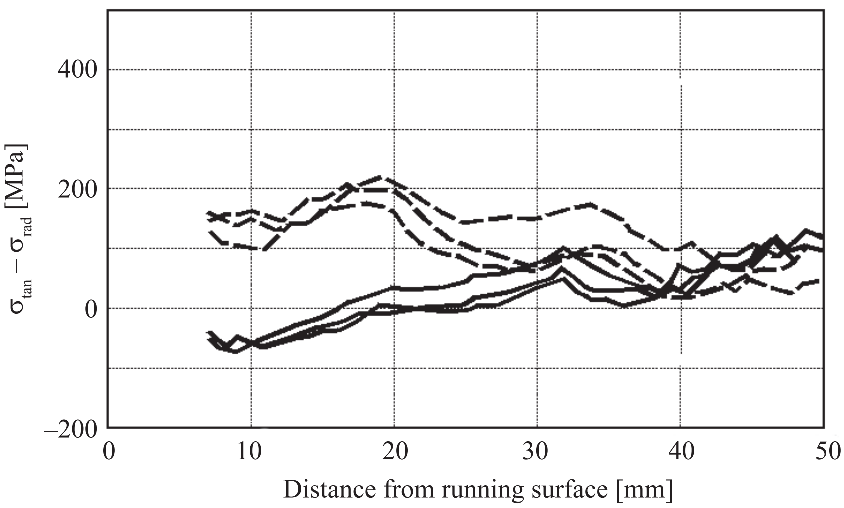

Fig. 5. Result of the ultrasonic stress analysis on new wheels before and after (dotted line) the application of a braking program as used during the downhill passage of the south ramp from the alps

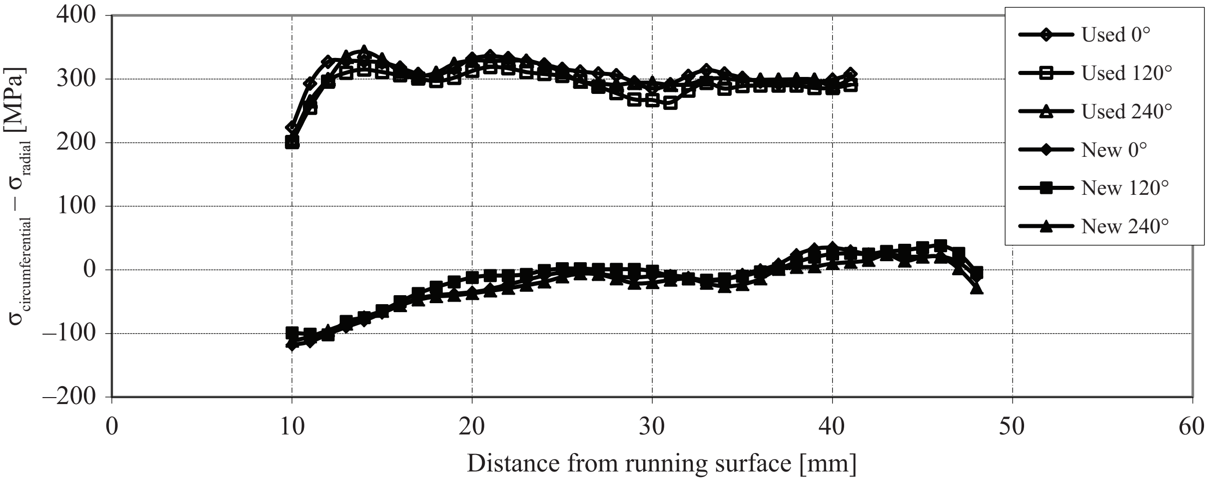

Fig. 6. Stress-depth-profiles of a new and an used wheel evaluated at different positions along the circumference of the wheel

according to DB AG code 907 0801 and UIC 510-2 and DIN EN 13262 Anhang D. The technique is described in the document RP 6 / ERRI B 169 of the European Railroad Research Institute. Figure 7 shows both systems, UER and UER-T as they are built from 1992 until 2012.

UER is designed for the daily use in workshops as part of the requested inspections of wheel sets. The system is housed in a robust, dustproof and air conditioned rack. UER-T is made to be applied in the field in order to inspect individual wheels showing strong heat influence. Both types of systems use the same technique and software packages as well as the same type of manipulator and EMAT transducer for normal incidence linearly polarized shear wave. The manipulator as shown in figure 8 is positioned and fixed by the operator. The total weight of the manipulator is about 10 kg.

Under usual operational conditions the time of a measuring cycle for one wheel does not exceed 3 minutes, including the handling of the manipulator.

The UER and UER-T systems evaluate stress states ranging from –350 MPa to 550 MPa with a resolution of ±20 MPa and an accuracy of ±10 %, assuming the material dependent K value is given with an accuracy of ±5 %. The equipment can be used at environmental temperatures ranging from +5 °C to +40 °C and allows measurements on wheels with temperatures ranging from –20 °C till +40 °C. The set-ups are equipped with a dust and humidity protected drawer keyboard in order to permit a

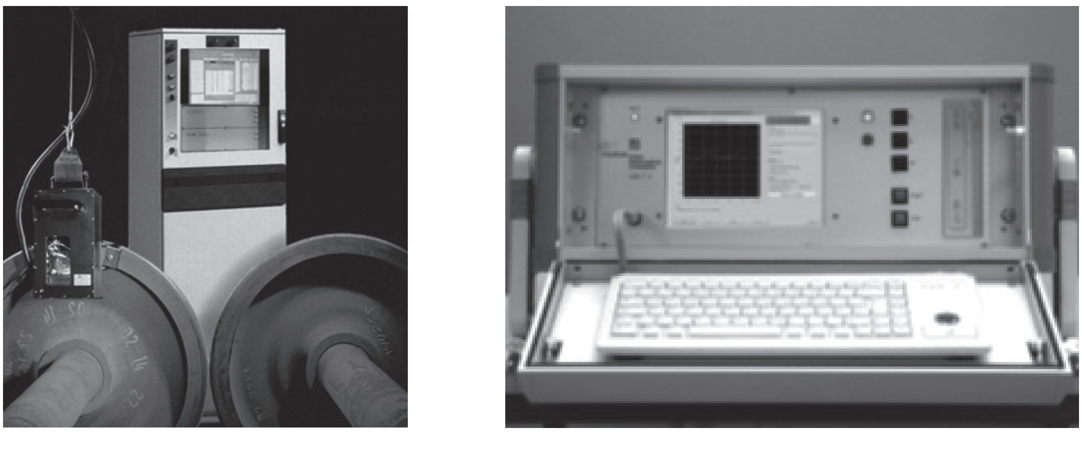

Fig. 7. UER and UER-T systems to evaluate the stress state of the rims of railroad wheels

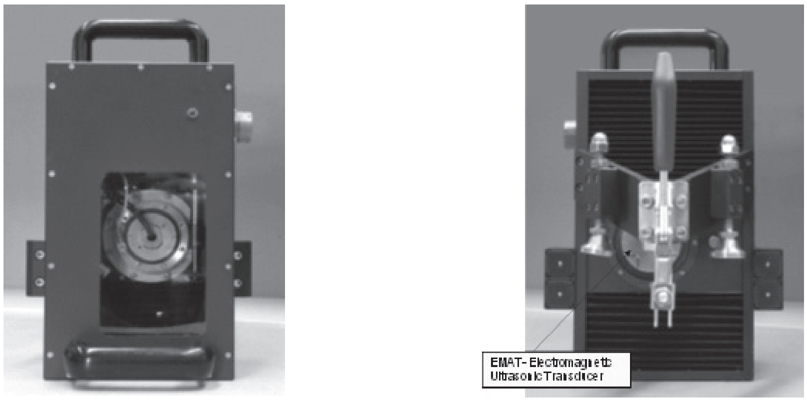

Fig. 8. The manipulator of the UER and UER-T systems

wheel set identification string to be entered by the operator.

The following data are stored for every measured wheel set: wheel set identification string, registration numbers of wheel set; type of wheel set; manufacturer of wheel set; date of measurement; time of measurement; place of measurement; wheel-type dependent K value; threshold for over or under limit evaluation; thickness of the rim; mean value and maximum value of $(\sigma_{circumferential} - \sigma_{radial})$ and comparison with the wheel type dependent and stored value for the maximum tolerable value of $(\sigma_{circumferential} - \sigma_{radial})$; depth position of the maximum value; assessment over or under limit; denotation for the left or ride wheel of the wheel set. The setups allow the storage of wheel type and material dependent data for several hundreds of different types of wheels. The above mentioned data are stored on the hard disk. It is also possible to transfer the data directly to a master PC or workshop master control unit by serial communication link or Ethernet link. The system comprises a routine for a rapid system functionality test using a reference piece of steel. All information given on the screen of the system or on the printer is in the customers language.

The Russian version of UER-equipment – ultrasonic system УКОН-01 as shown in figure 9 [8], is developed in 2008 by Research Institute of Bridges and Nondestructive Testing, Petersburg State Transport University and company «Introtest». The УКОН-01 system [8] is based on the same physical fundamentals as the UER systems.

Also, the new UER-system versions, as shown in figure 10 [9], use the same ultrasonic principle, and can be applied in the same way as the older versions. But they offer some new software features to improve the customer friendliness, the possibilities to store the data and to generate documentation according to the customer's request.

Another new feature is the evaluation of the measured data according to the new requirements of DIN EN 13262 concerning the stress state and the stress-depth-profile of the rim of new wheels (see later paragraph).

The option of a remote maintenance facilitates trouble shooting and repair of the UER and UER-T systems. After the customer gave permission, the status of the system can be analyzed, the measured data can be seen and commented and the state and functionality of the

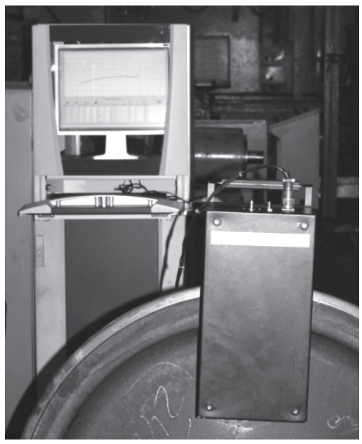

Fig. 9. УКОН-01 system to evaluate the stress state of the rims of wheels

Fig. 10. UER and UER-T system (IZFP, Version 2013) to evaluate the stress state of the rim of railroad wheels

individual modules of the system can be checked on-line by experts from their working place at IZFP as sketched in figure 11 [9].

The ultrasonic technique and the UER-types of set-ups have the following advantages:

The depth-profile of the stress difference ($\sigma_{circumferential} - \sigma_{radial}$) along the thickness of the rim is evaluated. Depending on the particular braking and load situation the extreme values of stress are at different depths from the tread. Those stress-depth profiles give stronger evidences concerning the stress state than any other kind of stress analysis.

The propagation directions of cracks, found in the rims, have also components perpendicular to the radial direction. The principal stress difference ($\sigma_{circumferential} - \sigma_{radial}$) is seen as more suitable for the judgment of the integrity of a wheel than the value of $\sigma_{circumferential}$ alone.

The ultrasonic shear wave is generated by an electromagnetic acoustic transducer (EMAT). No coupling medium is required, and no special

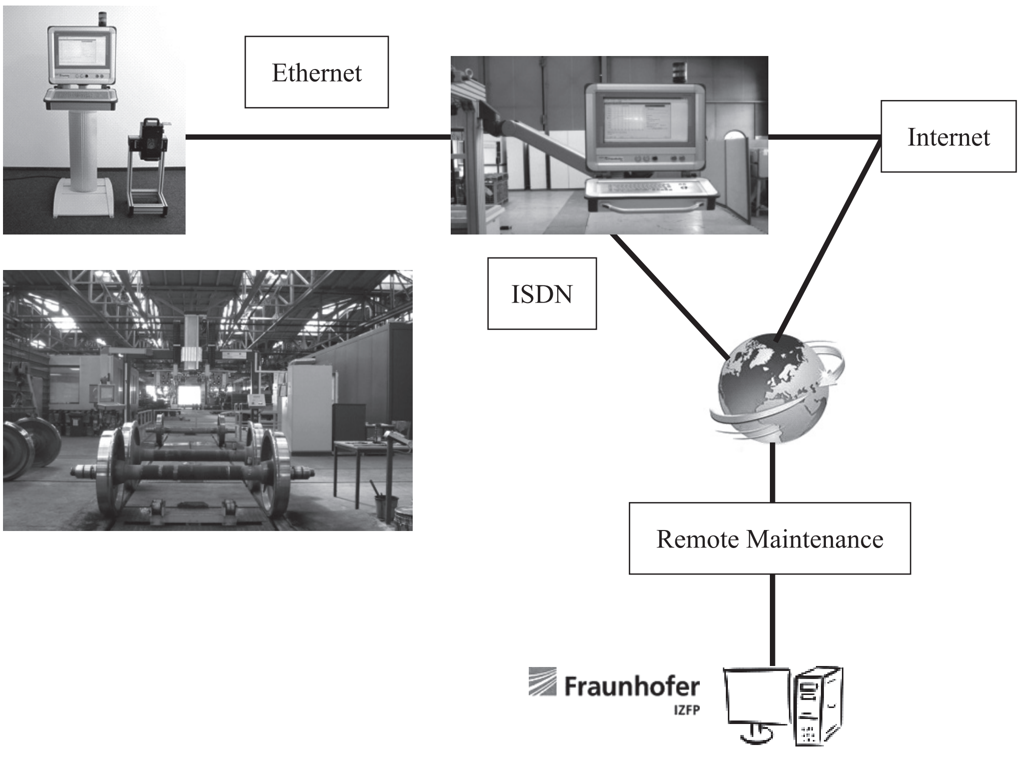

Fig. 11. Sketch of the remote maintenance feature of the UER, UER-T systems

surface treatment is needed. The transducer is automatically manipulated along a radial measuring trace.

The influence of temperature on the ultrasonic time of flight is small and can be neglected. The influence of temperature on the material dependent constant K is also to be neglected. At wheel temperatures between –10 °C and +40 °C, the error due to temperature influences on the final result is within the error, specified for the measuring system.

Automated data acquisition and evaluation; there is no human influence on the result.

References

1. **European** Railroad Research Institute; Document ORE B169/RP2, Utrecht (1989).

2. **Ultrasonic** Methods; Handbook of Measurements of Residual Stresses / R. B. Thompson, W. Y. Lu, A. V. Clark Jr.: J. Lu (ed), Society for Experimental Mechanics Inc.; The Fairmont Press Inc. Lilburn, USA (1996). – Pp. 149–178.

3. **Ultrasonic** Techniques / E. Schneider: in V. Hauk: Structural and Residual Stress Analysis by Nondestructive Methods, Elsevier Science B. V., Amsterdam (1997). – Pp. 522–563.

4. **Untersuchung** der materialspezifischen Einflüsse und verfahrenstechnische Entwicklungen der Ultraschallverfahren zur Spannungsanalyse an Bauteilen / E. Schneider: D 82, RWTH Aachen, Diss 2000; Fraunhofer IRB Verlag, 2000.

5. **Ultrasonic** Characterization of Stress States in Rims of Railroad Wheels / E. Schneider, R. Herzer, D. Bruche, H. Frotscher: Nondestructive Characterization of Materials VI; R. E. Green Jr. et al. (eds), Plenum Press New York (1994). Pp. 383–390.

6. **Ultrasonic** Setup to Characterize Stress States in Rims of Railroad Wheels / R. Herzer, H. Frotscher, K. Schillo, D. Bruche, E. Schneider, ibid. – P. 699–706.

7. **Debby** The fast non-destructive measurement of stress for in service railway wheel inspection / J. Deputat: DEBRO UMS Akademicka 3, 02–038 Warsaw, Poland; 1995.

8. **Ультразвуковой контроль** остаточных механических напряжений в ободьях цельнокатаных колес вагонов / Г. Я. Дымкин, С. А. Краснобрыжий, А. В. Шевелев // Тезисы доклада XVIII Всероссийской научно-технической конференции с международным участием. – Н. Новгород, 2008. – С. 74.

9. **UER-Systeme** der neuen Generation / R. Herzer, E. Schneider, H. Kapitza: 7. Fachtagung «ZfP im Eisenbahnwesen» 20–22.03.2012, Wittenberge.