Measurement methods for residual stresses in CWR

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Abstract: Continuously welded rails are a part of the track structure since the 1950s. Total stresses in continuously welded rails include residual stresses generated during the manufacturing process as well as the service life of rails. The control of rail stresses is very important for traffic safety. Measurement methods for residual stress in rails are presented in this paper. Since destructive measurement methods are unsuitable for use in the railway track, the modern non-destructive methods were particularly presented and discussed. The advantages and disadvantages of X-ray diffraction, ultrasonic, magnetic and electromagnetic methods are particularly explained and considered.

Keywords: Railway, Residual Stress, Strain Gauge, X-ray Diffraction, Ultrasonic Measurement, Magnetic Measurement.

1 Introduction

Residual stresses exist in rails regardless of the external influence (temperature changes, railway traffic load, track/bridge interaction etc.). The residual stresses in new rails are generated during the manufacturing process of hot-rolled steel, including the uneven cooling, roller straightening and leveling rail profiles. The manufacturing technology directly influences the residual stresses in the new rails [1]. The mass of Vignole rail is concentrated in the rail head and the middle of the rail foot (Figure 1), affecting the cooling speed of rail profile and uneven distribution of residual stresses in rail profile. The amount of the residual stresses in the rails can be reduced by the modifications in the manufacturing process.

The residual stress changes during the rail life cycle [2]. The complex distributions of residual stresses in used rail according to [3] and in new rail according to [4] are

shown in Figure 2. During track laying and rail maintenance, the rail welding process (the both flash butt and aluminothermic welding) induces additional residual stresses (due to differential expansion and contraction in metal) which contribute to the total level of tensile and pressure stresses in continuously welded rails (CWR).
Furthermore, the actual value of the residual stress depends on the traffic loads and affects the stability of the track with CWR (in particular on the track sections on the bridge and in narrow curves). As shown in Figure 3, the residual stresses are a part of basic tensile stress in used rail during service life of railway track with CWR [5].

Fig. 1. Uneven cooling of rail profiles (left) and bending of the rails in cooling bed (right)

In the engineering calculations, the residual stress value of 80 MPa is commonly used for CWR during railway service life [5, 6]. Given that residual stresses in CWR might significantly influence the traffic safety (risk of the rail break [5, 7], track stability [8], railway superstructure design, and life span of rails in track [9, 10]), determining the current value of the stresses in CWR is of great importance for engineering practice.

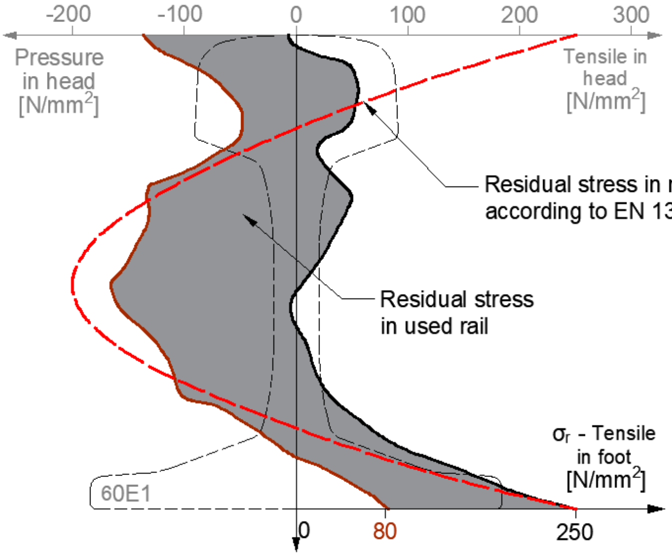


Fig. 2. Complex distribution of residual stresses in Vignole rail profile

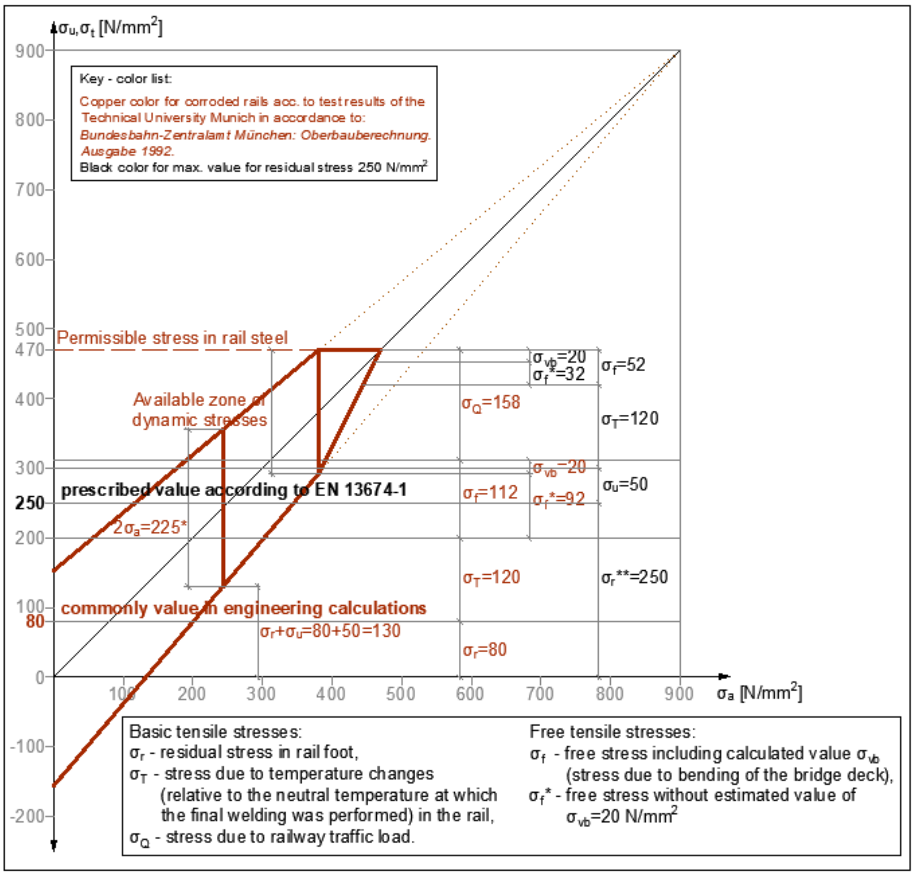


Fig. 3. Residual stress as a part of basic tensile stress in rail foot - Smith diagram for rail 60E1/900 on the track section on the bridge

Figure 4 presents dangerous corrosion-fatigue crack in the middle of rail foot which was developed under the influence of cyclical traffic loads and tensile residual stresses in rail foot.

Fig. 4. Corrosion-fatigue crack in rail foot [11]

Contrary to previous engineering practice, the residual stress in rail foot up to 250 MPa for all steel grades is defined by European standard [4]. Moreover, the same standard prescribes the destructive method using electrical strain gauge for measurement of rail residual stress [4]. This method is presented and discussed in this paper. Since destructive measurement methods are unsuitable for use in railway track with CWR, the non-destructive measuring methods are presented and discussed in this paper.

2 Destructive saw-cutting measurement method

The European standard [4] specifies 23 rail profiles of Vignole railway rails of 46 kg/m and greater linear mass, for conventional and high speed railway track usage. Moreover, nine pearlitic steel grades are specified covering a hardness range of 200 HBW to 440 HBW and include non-heat treated non alloy steels, non-heat treated alloy steels, and heat treated non alloy steels and heat treated alloy steels. This European standard prescribes a destructive measuring method for residual stresses in foot of Vignole rail.

The description of the measurement method is presented in accordance with [4]. The residual stresses are determined on a sample of a rail with length of 1 m. As presented in Figure 5, the electrical strain gauge is attached to the underside of the rail foot: in the middle of the Vignole rail profile, and in the longitudinal direction.

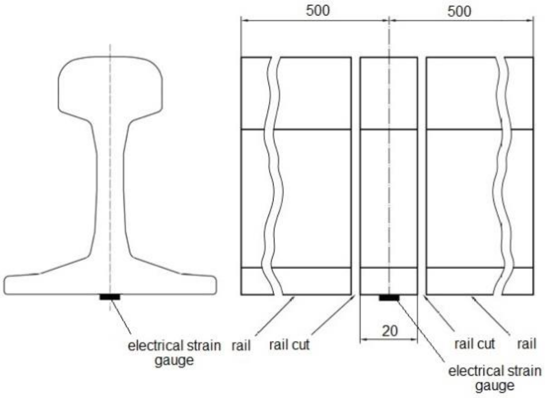


Fig. 5. The one-meter long rail sample and rail slice according to [4]

The gauge is 3 mm long, encapsulated type, and its gauge factor accuracy must be better than 1%. It measures average strain along its length. The first strain measurements are taken in that state. After that, two saw cuts are performed in order to remove a 20 mm thick slice from the middle of the rail (Figure 5). A second set of the strain gauge measurements is taken on that rail slice as relaxed strains. The relieved strain is estimated from the differences between the first and the second sets of measurements. That value, with changed sign, is multiplied by 2.07 x 105 MPa in order to calculate residual stress [4].

However, this measurement method itself may cause the change in the three dimensional residual stress in the rail due to the slice extraction.

3 Non-destructive measurement methods

There are methods for nondestructive assessment of stress in steel. These measurement methods could be suitable for laboratory use only or could be used for in situ measurements.

3.1 XRD method

The most used non-destructive method for evaluating residual stresses is X-ray diffraction (XRD) method. It is based on the interactions of the wave front of the X-ray beam, and the crystal lattice of investigated material. In real ferromagnetic materials, there are domains with different orientation of crystallographic planes. Figure 6 shows principle for measurement of 2θ angle between the directions of incident and diffracted rays.

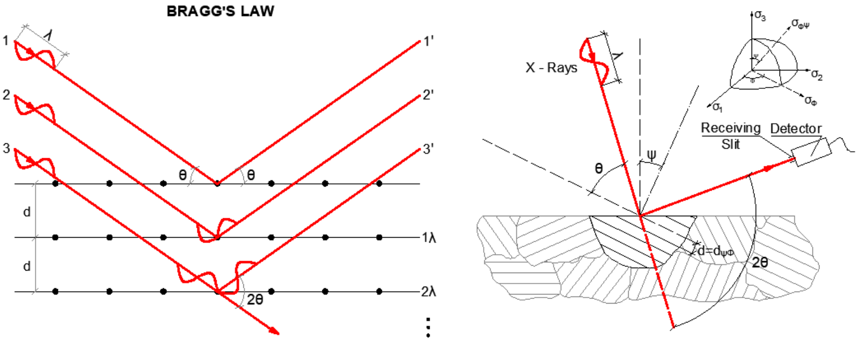


Fig. 6. Principle of measurement by XRD method

When X-ray beam of wavelength λ incidents on the material atoms at angle θ to the atomic planes (Figure 6) the diffracted rays from the different planes at distance $d=d_{\psi\phi}$, will interfere at the detector and thus have maximum values in detected signals for angle θ obeying Bragg's law (1), where z is an integer.

$$2 \cdot d \cdot \sin\theta = z \cdot \lambda \tag{1}$$

The angle equals 2θ between the directions of incident and diffracted rays d can be estimated by practical measuring. Since orientation of crystallographic planes is not parallel to the material surface, angle ψ (between incident ray and a normal to the material surface) and an azimuth angle ϕ have to be measured in order to define the beams directions connected to main coordinates of the material primary strains and stresses σ_1, σ_2 and σ_3 (Figure 4). At XRD graph of signal intensity versus 2θ, maximum values correspond to distances $d_{\psi\phi}$ of various directions [12].

In the case of residual stress, there is a difference between the distance $d_{\psi\phi}$ and corresponding distance d_0 of non-stressed material. By changing the incident angle ψ, wavelength of X-ray or using two detectors, the strain and the residual stress σ_ϕ could be evaluated even without known d_0. This is cheap and quick method for obtaining surface biaxial residual stresses in small measuring volumes. For the high intensity of residual stresses, the nominal accuracy is 20 MPa for steel. The main disadvantage is small penetration depth (up to 30 μm) and unknown elastic constants of steel crystal lattice for all directions. In order to calibrate system and apply appropriate modeling for residual stress estimations, the same slice samples are measured with more accurate and deeper laboratory destructive and non-destructive methods.

Furthermore, Synchrotron X-ray and Neutron diffraction methods are also based on Bragg′s law.

Synchrotron X-ray method

Synchrotron X-ray method provide very intense x-rays beams with million times higher energy than laboratory based x-ray systems and, for that reason, have a depth of penetration about 20 mm in steel components. It enables obtaining 3D maps of the strain distribution to millimetre depth in inspected components. Measurement is fast, and high magnitude residual stresses could be measured with nominal accuracy of 30MPa. However, this technique is strictly laboratory, with limited size of investigated components. Also it does not need stress-free specimen for calibration.

Neutron diffraction method

In 1993, neutron diffraction method was recommended by the European Rail Research Institute (ERRI) as measurement method for residual stress measurements on naturally hard and two head-hardened rails (D 173/RP42 Report, [13]).

Neutron diffraction method is based on larger wavelengthλ, so the penetration depth is larger than in XRD (about 60 mm in steel). This method enables the detection of changes in atomic lattice spacing due to the stress. In order to calculate absolute stress values, stress free sample (″d_0″ sample) should be measured for calibration. With this method, tri-axial residual stress components and stress gradients could be measured. The accuracy for steel is 30 MPa. Unfortunately, this method could only be used in laboratory. Moreover, this method is very expensive and it is not available in all countries.

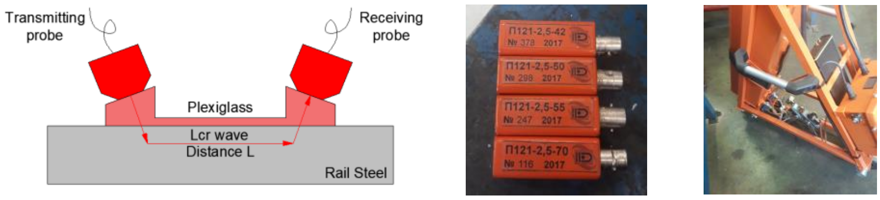
3.2 Ultrasonic method

The speed of ultrasonic waves that travel through a material is affected by the direction and magnitude of the present stresses. Based on this acoustoelastic effect, ultrasonic waves in a frequency range 2 - 10 MHz are used for measurement of applied and residual stresses. The average velocity of ultrasonic waves is measured along the chosen path. This method is most sensitive when the chosen path and motion direction of material particles is parallel to the direction of stress [14].

Different types of waves can be employed, but the most commonly used are the longitudinal critically refracted (L_{cr}) waves [14], which travel just beneath and parallel to the specimen surface. The measurement equipment for the time of flight (TOF) measurement consists of one transmission and one or more receiving ultrasonic probes fitted in the plexiglass wedge at fixed distance is presented in Figure 7. The L_{cr} waves are passing fixed length L for TOF $t=L/v$ in stressed material, and for $t_0=L/v_0$ in stress-free material, where v and v_0 are corresponding wave velocities. In the range of elasticity, the average residual stress along the path compared to stress–free material σ is given by equation (2).

$$\sigma = \frac{1}{K \cdot t_0} \cdot (t - t_0) \qquad (2)$$

The acoustoelastic constant K depends on the type of waves, elastic properties of the material and direction of wave propagation. It should be determined using appropriate calibration tests on the same or similar samples. For increase in stress of 10 MPa, TOF difference is about 10 ns for the rail steel.



Basic principle

Probes in plexiglass wedge

The look of the basic device for rail testing

Fig. 7. Basic principle of ultrasonic method, probes and device for rail testing

The speed of ultrasonic waves also depends upon temperature and microstructure changes in the steel. Changes in temperature can be corrected by simultaneous temperature measurements. The acoustic methods enable accurate tri-axial high residual stresses measurements at penetration depth up to 150 mm. Required stress-free reference, sensitivity to microstructural changes, average stress measuring over relatively large gauge volume and difficulty to specify spatial resolution are disadvantages of the method. It is suitable for in situ stress detection in CWR [15-16]. The total (thermal and residual) stresses could be measured in unloaded CWR at a temperature that is different than the rail neutral temperature. On the other hand, the residual stress in CWR could be measured at its neutral temperature.

3.3 Magnetic and electro-magnetic measurements

The most of the magnetic characteristics of ferromagnetic materials are influenced by mechanical stresses. In the non-stress ferromagnetic material each domain is magnetized in one direction and during magnetizing-demagnetizing process the volume and magnetic orientation of domains are changing. The magnetic flux density or induction vector B in a material is changing under applied magnetic field in cycling process, presented with magnetic hysteresis loop in Figure 8 [17].

The characteristic values on graph B_r (remanence) and H_c (coercivity), permeability $\mu=B/H$ and others could be evaluated as non-stressed material parameters. In case of applied or residual stresses in material, the boundaries between domains called domain walls are moving [17], and the magnetization orientations of the domains are changing. Under tensile stresses, the domains with the same magnetization orientation as stress direction are enlarging and thus increase magnetization in that direction. The compressive stresses enlarge domains with transverse magnetization orientation and increase magnetization in the direction perpendicular to stress directions. So, the residual stresses lead to change in the magnetic characteristics, and the hysteresis loop. This is the foundation of one of mobile type instruments, MAPS (Magnetic Anisotropy and Permeability System), for residual stress measurements [17] designed for manual probe manipulation that measures simultaneously a large number of magnetic parameters from hysteresis loop. The penetration depth of measurements is between 0.1 mm and 5 mm, controllable by the frequency of applied magnetic field. Spatial resolution is between 5.2 mm and 15.5 mm, depending on a probe type. Obtaining complete biaxial stress measurement lasts less than 2 minutes. This system has to be calibrated against known stress levels for the investigated material [17].

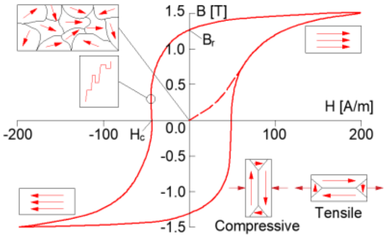


Fig. 8. Magnetic domain alignment during magnetisation and under stress

The MBN (Magnetic Barkhausen Noise) method is based on Barkhausen effect. Figure 8 shows that changing of B is happening in discrete steps (Barkhausen jumps). Those sudden changes in B could be measured with pick up coils above the surface of a material, thus the typical voltage pulses in the signal are obtained. The variation of MBN signals shape, the number and values of peaks, the RMS (root mean square value) of the overall MBN signal over a number of cycles indicate the changes of magnetic material structure due to the stress. If the frequency of applied alternating field frequency is higher than 10 Hz the depth of this measurements is 20 μm, while for low frequency (0.1 - 1 Hz) the penetrating depth is of order of 1 mm, and can be used for evaluation of subsurface stresses.

The ACSM (alternating current stress measurements) technique of stress measurement is based on ACFM (Alternating Current Field Measurement) technique of defect detection. The coil with alternating current induces currents in the metal surface that are unidirectional and uniform in the non-stressed material without defects. These induced currents produce the magnetic field above the surface, which is measured in two directions. Small changes measured in the strength and the direction of those magnetic fields by array of magnetic sensors or sensing coils could be related to changes in stress state of a material and ACSM output signal is almost linear under applied stress. This is non-contact, rapid technique, sensitive to both tensile and compressive stresses and does not need special surface preparation. It is better for stress changes measurements than for absolute stress measurements [18,19].

4 Conclusion

Because of higher speeds, and increased axle and traffic loads, measurement of residual stresses in new rails, as well as in continuously welded rails (CWR), has great importance on modern railways in recent years.

Residual stresses in rails could significantly influence the risk of the rail break, track stability, railway superstructure design, as well as the life span of track with CWR. For now, there is no standard method for testing the residual stresses in CWR.

In accordance with European standard [4], residual stresses in rail shall be estimated by destructive cutting method in laboratory. This method is not applicable to control the rail residual stress in the track with CWR. On the other hand, the prescribed value of residual stress in rail foot up to 250 MPa could adversely affect the traffic safety (especially in CWR on the bridges or transition zones [5]).

If the current residual stress values in CWR could be measured, the level of total stresses in rails and its effects on the traffic safety could be predicted.

This paper presented standard destructive method prescribed in [4]. Unfortunately, this method is not applicable for CWR. Moreover, several non-destructive methods for measurement of rail residual stresses were presented.

The X-ray diffraction method is based on interaction of the X-ray beam and the crystal lattice of the material of the investigated rail. The method is fast, but it lacks higher accuracy. Another limitation of this method is the penetration range, as it is able to identify residual stress only in the surface layer with the thickness of 30 μm. The ultrasonic method is based on measurement of the velocity of ultrasonic waves going through the investigated rail material. Key issues to cope with while using this method are the precise TOF measurement, as the measured times are usually very low on short distances, and extract the influence of the thermally induced stress, as it is a very common factor in field measurements.

Finally, the methods using magneto elastic effect are based on magnetization changes of magnetic domains in the investigated material, which are oriented in various directions.

The changes in magnetization orientation of magnetic domains in the ferromagnetic materials due to presence of residual and applied stresses are the base of various magnetic and electromagnetic methods. Practical portable instruments, based on measuring the changes in hysteresis loop parameters of rail steel or the Barkhausen noise detection and analysis, enable residual stresses mapping. ACFM method is also adapted from defect identification to residual stress measurements in rails. Those methods are very promising for rapid practical measurements and models for interpretation of measuring results and residual stress estimation are constantly improving.

All presented methods have a great potential. However, interpretation and correct evaluation of the results is a subject of ongoing research by the authors.

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