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METHODS FOR DETERMINATION OF RESIDUAL STRESS IN RAIL

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***Abstract** – The residual stresses in rails are generated during the manufacturing process and have uneven distribution in rail cross section. The residual stress is a part of basic tensile stress in rail foot. For used rail, the residual stress value of 80 MPa is commonly used in the engineering calculations. On the other hand, the standard EN 13674 prescribes residual stress values up to 250 MPa and destructive method using electrical strain gauge for measurement of rail residual stress. Since destructive measurement methods are unsuitable for use in the track, the possible non-destructive in situ methods for measuring of residual stresses in the rails are discussed in this paper. The fundamentals of X-ray diffraction, ultrasonic, magnetic and electromagnetic methods are explained, as well as, their advantages and disadvantages.*

Keywords – railway, residual stress, strain gauge, X-ray diffraction, ultrasonic measurement, magnetic measurement.

1. INTRODUCTION

For conventional and high speed railway tracks, the usage of Vignole railway rails of 46 kg/m and greater linear mass is specified in European Standard EN 13674-1 [1]. This standard applies to rails of 46 kg/m and greater linear mass and specifies 23 rail profiles. Furthermore, nine pearlitic steel grades are specified covering a hardness range of 200 - 440 HBW and including all types or heat-treated and non heat-treated alloy and non-alloy steels.

The destructive method for determination of longitudinal residual stress in rail foot is defined and described in [1]. In accordance with [1], the maximum longitudinal residual stress in the rail foot shall be up to 250 MPa for all steel grades. The maximum prescribed value of residual stress refers to the new or used (corroded) rail. Figure 1 shows the values of the residual stress in the corroded rails.

The residual stresses in rails are generated in the manufacturing processes: during hot rolling, uneven cooling, as well as, roller straightening and levelling. The mass of Vignole rails is concentrated in the rail head and the middle of the rail foot (Figure 1) affecting the cooling speed of rail profile and distribution of residual stresses. Furthermore, Figure 1 presents the distribution of residual stresses in rail head, web and foot for used rails [2].

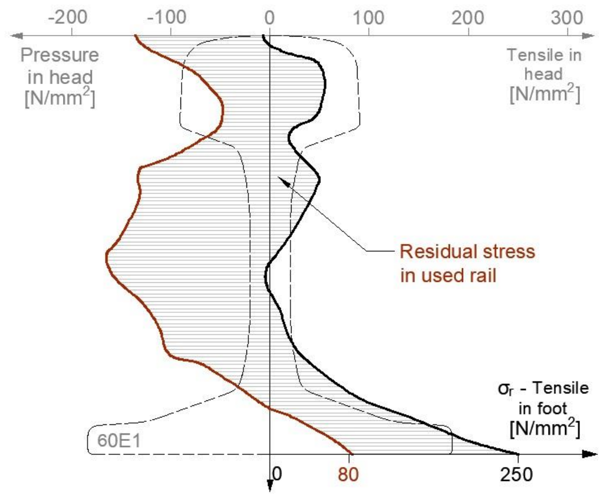

Fig.1. Distribution of residual stresses in rail profile

Residual stress in rail foot is a part of basic tensile stress in rail foot (Figure 2). In the engineering calculations, the residual stress value of 80 MPa is commonly used [3].

In this paper, we present a destructive measurement method in accordance with EN 13674. Non-destructive measurement methods for residual stress measurements that could be applied to rails

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installed in the track are also presented.

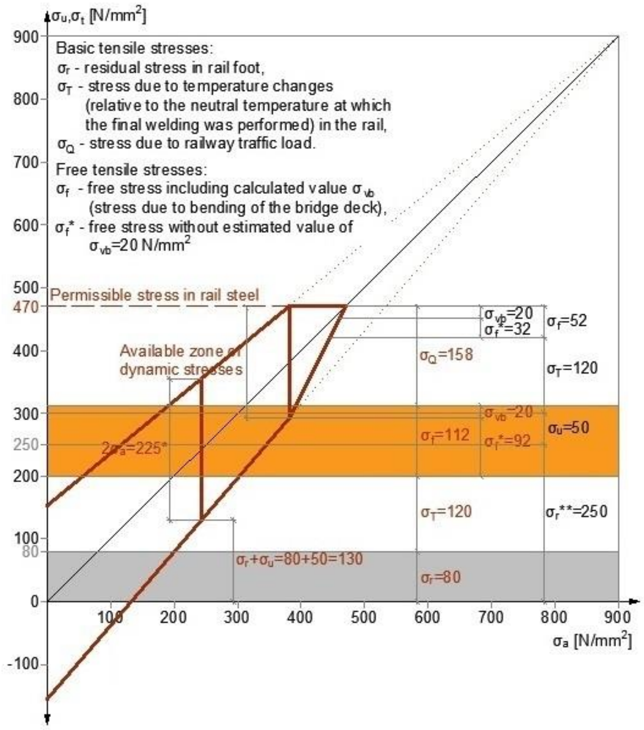

Fig.2. Smith diagram for corroded rail 60E1/900

2. METHOD FOR THE DETERMINATION OF RESIDUAL STRESSES IN ACCORDANCE WITH EN 13674

In accordance with [1], residual stresses are determined on one-meter long rail that is set aside for this purpose. The electrical strain gauge is attaching to the foot surface in the middle of the rail in the longitudinal direction, as presented in Figure 3.

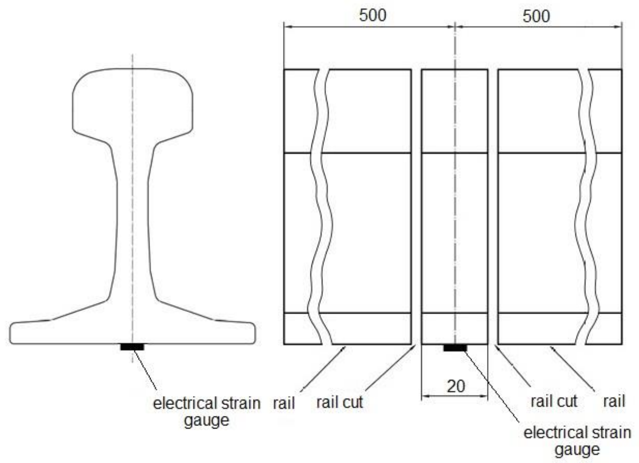

Fig.3. Preparation of rail and rail slice

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 taking in that state. After that, two saw cuts are performing in order to remove a 20 mm thick slice from the middle of the rail. (Figure 3), while cooling the rail to maintain on the constant temperature. A second set of strain gauge measurements is taking on that rail slice as relaxed strains. The relieved strain is estimating from the differences between the first and second sets of measurements. That value with changed sign is multiplying by 2.07 x 105 MPa in order to calculate residual stress.

3. NON-DESTRUCTIVE METHODS FOR THE DETERMINATION OF RAIL RESIDUAL STRESSES

Besides destructive, there are methods for nondestructive evaluations of stress in steel. Some of them like laboratory and synchrotron X-ray diffraction and neutron diffraction are suitable for laboratory use only. Portable instruments based on X-ray diffraction (XRD), ultrasonic, magnetic and electro-magnetic principles could be used for in situ measurements.

3.1. X-ray diffraction

The most used non-destructive method for evaluating residual stresses is XRD. 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 as presented in Figure 4.

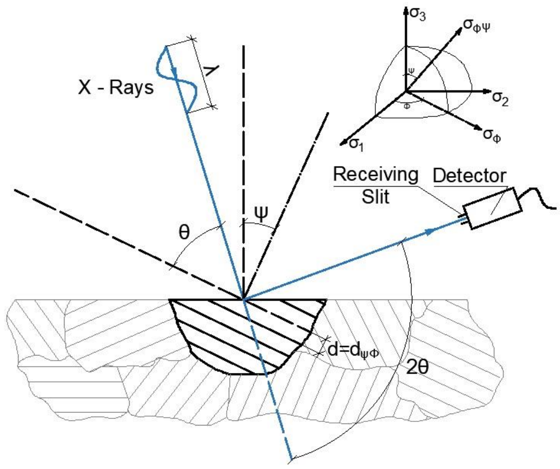

Fig.4. X-ray diffraction method geometry

When X-ray beam of wavelength λ incidents on the material atoms at angle θ to the atomic planes (Figure 4) the diffracted rays from the different planes at distance $d=d_{\psi\phi}$, will constructive interfere at the detector and thus have maximums in detected signals for angle θ obeying Bragg’s law (1) where z is an integer.

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

From practical measuring angle equals 2θ, between the directions of incident and diffracted rays d can be estimated. 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, maximums correspond to distances $d_{\psi\phi}$ of various directions [4].

In a 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, X-ray wavelenth or using two detectors the strain and then residul stress σ_ϕ can 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 residual stresses the nominal accuracy is 20 MPa for steel. The main disadvantage is small penetration depth that is up to 30 μm and unknown elastic constants of steel crystall latice for all directions. In order to calibrate system and apply appropriate modelling for residual stress estimations the same slice samples are measured with more accurate and deeper penetration laboratory destructive and not destructive methods.

3.2. Ultrasonic technics

The speed of ultrasonic waves travelling through a material are affected by the direction and magnitude of the present stresses. Base on this acoustoelastic effect, ultrasonic waves in a frequency range (2 - 10 MHz) are using for measurement of applied and residual stresses. The average velocity of ultrasonic waves is measured along some path and this method is most sensitive when the path and material particle motions are parallel to the direction of stress [5].

Different types of waves can be employed but the commonly used are the longitudinal critically refracted (*Lcr*) waves [5] which travel just beneath and parallel to the specimen surface. The measurement equipment for the time of flight (TOF) measurement consisting of one transmision and one or more receiving ultrasonic sondes connected in plexigal wedge at fixed distance is presented in Figure 5. The *Lcr* 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 constant K, an acoustoelastic constant, depends on the type of waves, elastic properties of material, direction of wave propagation and should be known from some calibrating tests on the same or similar samples. For increase in stress of 10 MPa TOF difference is about 10 ns for the rail steel.

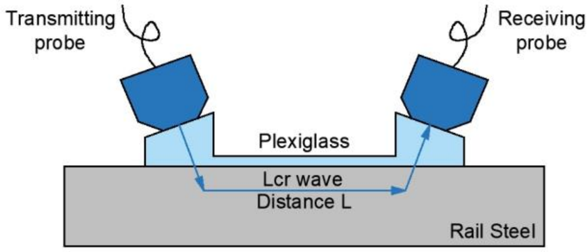

Fig.5. Ultrasonic method

The speed of ultrasonic waves also depends upon temperature and microstructure changes of the steel. Changes in temperature can be corrected by simultaneous temperature measurements. The acoustic methods enables 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 difficult to specify spatial resolution are dissadvantages of the method. It is suitable for in situ residual stress changes detection on the same rail.

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 versus applied magnetic field in cycling procces, presented with magnetic hysteresis loop in Figure 6 [6]. The characteristic values on graph B_r (remanence) and H_c (coercetivity), permeability $\mu=B/H$ and others can be evaluated as a non-stressed material parameters. In case of applied or residual stresses in material, the boundaries between domains called domain walls are moving [6], and the magnetization orientations of the domains are changing. Under tensile stressess the domains with the same magnetization orientation as stress are enlarging and thus increase magnetization in that direction. The compressive stresses enlarge domains with transverse magnetization orientation and increasing magnetization in the direction perpendicular to stress directions. So, the residual stresses lead to change in the magnetic characteristics, and the hystersis loop. This is the foundataion of one of mobile type instruments, MAPS (Magnetic Anysotrophy and Permeability System) for residual stress measurements [6] designed for manual probe manipulation that measures simultaniously a large number of magnetic parametars from hysterezis loop. The penetration depth of measurements is from 0,1 - 5 mm controlable by the frequency of applied magnetic field and spatial resolution is from 5,2 – 15,5 mm depending of a probe type. Obtaining complete biaxial stress measurement lasts less then 2 minutes.. This system has to be calibrated against known stress levels for the investigated material [6].

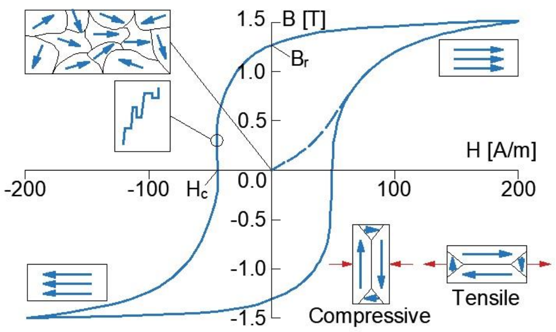

Fig.6. Magnetic domain alignment during magnetisation and under stress

The MBN (Magnetic Barhauzen Noise) method is based on Barkhausen effect. In the insertion in Figure 6 it is presented that changing of B is happening in discrete steps (Barkhausen jumps). Those sudden changes in B can be measured with pick up coils above the surface of a material and 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 stress. If the frequency of applied alternating field frequency is higher than 10Hz the depth of this measurements is 20 μm, while for low frequency (0.1 - 1Hz) 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 defects 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 can be related to changes in stress state of a material and ACSM output signal is almost linear versus 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 [7].

4. CONCLUSION

Because of higher speeds, as well as increased axle and traffic loads, measurement of residual stresses in new and used rails has assumed great importance on modern railways in recent years.

Residual stresses in rails can significantly influence the risk of the rail break, track stability, railway superstructure design as well as the life span of rails in track.

In accordance with [1], residual stresses shall be estimate during destructive cutting method. This standard method is not applicable to control the rail residual stress in the track. There are several non-destructive methods for measurement of rail residual stresses in situ such as X-ray diffraction, ultrasonic, magnetic and electromagnetic methods. The physical principle of each method is presented in order to explain their advantages and disadvantages. All that methods have to be calibrated and compared with laboratory destructive and non-destructive methods.

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REFERENCES

[1] CEN: EN 13674-1: 2011 + A1:2017, Railway applications, Track, Rail, Vignole railway rails 46 kg/m and above, Brussel, 2017.

[2] European Rail Research Institute: ERRI D 202/RP 12: Verbesserung der Kenntnis der Kräfte im lückenlose Gleis (einschließlich Weichen): Schlußbericht, Utrecht, 1999.

[3] DIN: Fachtbericht 101, Einwirkungen auf Bruecken, Deutschland, 2003.

[4] Fitzpatrick M.E., Fry A.T., Holdway P., Kandil F.A., Shackleton J. and Suominen L.: NPL Measurement Good Practice Guide No. 52. Determination of Residual Stresses by X-ray Diffraction, NPL Teddington, United Kingdom, 2005.

[5] Li Z., He J., Teng J., Wang Y.: Internal Stress Monitoring of In-Service Structural Steel Members with Ultrasonic Method, Materials vol. 9, 223-240, 2016.

[6] Buttle J., Moorthy V. and Shaw B.: NPL Measurement Good Practice Guide No.88. Determination of Residual Stresses by Magnetic Methods, NPL, Teddington, 2006.

[7] Lugg M., Topp D.: Recent developments and applications of the ACFM inspection method and ACSM stress measurement method, Proceedings of ECNDT 2006, Berlin, Germany, 2006.