Quality Assessment of Continuously welded Tracks by Non-destructive Testing of Stress-Free Temperature SFT

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Summary: SFT is one of the key parameters for track safety against buckles, breaks and ride comfort. Track stability assessment must be made including SFT. A new technique enabling the reliable non-destructive determination of the actual SFT under traffic, at any hour without any rail unfastening [1] is available for this purpose. Measurement system capability investigations prove an accuracy of ±3° C enabling SFT control subsequent to cw track production and with regard to possible changes of the actual SFT, due to heavy loading or extreme weather conditions. This also reduces maintenance costs on main-line tracks and interurban railways.

Index Terms: Stress-Free Temperature SFT, Neutral temperature, Longitudinal Force, Track Security

1. INTRODUCTION

Due to temperature changes, longitudinal forces are generated in the rails of continuously welded (cw) tracks. In a welded track, the sleepers prevent displacement of rails through track fastening elements. After the rails have been clamped, any temperature change causes a thermal stress in the rails due to restriction of movement. The temperature at which the thermal stress in the tested cross section of a rail is zero is defined as the neutral or stress-free temperature. It is important that the neutral temperature be in the vicinity of the average of expected highest and lowest rail temperatures. Should the discrepancy from that average be large, rail breaks at low temperatures and buckling at high temperatures may occur (fig.1). This can lead to high tensile and compressive stresses. The Stress Free Temperature (SFT) defines the ratio of these stresses and is consequently the key track parameter for determining its stress properties. Safety against buckles and breaks and ride comfort depend decisively on the SFT. An assessment of the stability of the cw tracks must therefore be made, including the SFT measurement and from this the forces acting on the track. Especially in times of increasing competition from aviation companies, increased prices of raw materials and energy and the greater loading of the tracks, it is important to maximize drive comfort and track safety particularly against excessive stresses and to minimize track maintenance costs with maximum track availability.

Figure 1: Picture of a transverse rail buckle due to inadmissible high longitudinal compressive load stresses.

The task of determining the longitudinal stresses acting on a rail of cw railway track is not a simple technical problem. Destructive methods are not expedient, because they require the cw-rail to be cut. A new technique enabling reliable non-destructive determination of the actual SFT of the track under traffic [1] has been further developed for this purpose. The measurement, to an accuracy of ±3° C, can be made at any hour without any rail unfastening. The control of the SFT is reasonable subsequent to the production of the cw track for checking the correct neutralization and in case of dangers with regard to possible changes of the actual SFT due to heavy track loading or extreme weather conditions.

For a successful SFT management, it is important to maximize driving comfort and track safety and to minimize maintenance costs at maximum track availability. RailScan has been developed for this purpose and offers advantages that cannot be provided by other methods. Table 1 gives a short comparison between the characteristics of current SFT measuring methods. We see that RailScan possesses outstanding properties enabling an unprecedented cost-effective and efficient longitudinal force management. The RailScan technique is offered as a complete SFT inspection service package leading to lower expenditure, high-precision measurements and the complete documentation of track conditions and safety.

The technology is based on a micro-magnetic method where a known interaction between magnetic field and ferromagnetic material to be checked enables the determination of its stress state. This phenomenon, also known as magneto-elastic effect, was published in 1865 by E. Villary and is ideally suited to the inspection of stresses in cw rails. During the measurement the rail microstructure reacts to the applied magnetic field and releases a signal to the probe. This measuring signal named after its discoverer H. G. Barkhausen contains the generated pulses, possesses a noise-like spectrum and is known internationally as Magnetic Barkhausen Noise (MBN). A detailed description of the physical background of the RailScan technique is given in [1]. Further developments of the last years resulted in a light-weighted non-contact measuring device that allows fast measurement and documentation of the actual neutral temperature of most rail types. The longitudinal stress and the SFT are determined evaluating the nd parameters. Inspection results are reliable and have been validated by measurement system capability investigations. Therewith, it is assured that the cw track has been welded within the required stressing tolerance excluding any subsequent re-establishment of required stress conditions. Further examples of inspections on heavily loaded main-line tracks and interurban railways show that track stability can be assured and maintenance costs can be reduced by non-destructive SFT measurements.

Table 1

Properties and characteristic features of essential currently used SFT determination methods (* mathematical correction)

Properties	RailScan	A-frame technique	Cut-&-gap size method	Cut-&-strain gauge method
Measuring accuracy within ±3° C	X	X	X	X
Measurement of tensile and compressive stresses	X			
Reliable measurements at any hour	X			
Reliable measurements under any weather conditions	X			
Non-destructive method	X	X*		
Measurements without any rail unfastening	X			
No SFT modification by means of the measurement	X			
No danger of injury from the sudden buckling	X			
Light weighted and easy to use	X			
No own customer’s staff required	X			
Usable without possession	X			
Usable at short date without any company ruling	X			
Complete track safety documentation	X	X		

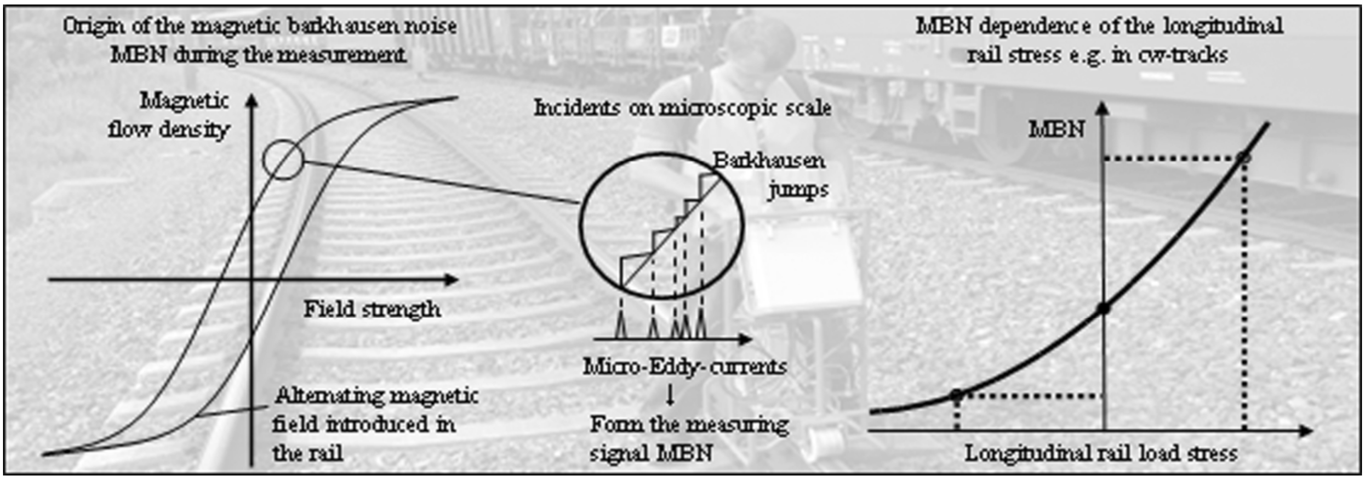

Figure 2: Schematic representation of the elasto-magnetic effect: The magnetic Barkhausen noise MBN is generated during the magnetic measurement by micro-eddy-currents forming the MBN signal. Different longitudinal load stresses in the rail lead to different signal amplitudes. In longitudinal tensile stress direction the signal amplitude increases and follows the function MBN = f (longitudinal load stress) which is determined by means of appropriate calibration.

2. FUNCTIONAL PRINCIPLE

For producing the MBN, the rail is energised in the direction perpendicular to the measured cross-sectional area and the magnetic Barkhausen noise emitted from the surface is measured. The MBN is measured at the surface with a sensor containing a ferromagnetic material which is brought into contact with the surface to be measured. Imperfect matching due to unevenness of surface, scale, rust, contamination or paint coating reduces the magnitude of the detected MBN. In order to eliminate inaccuracies resulting from such conditions, the spacing between the ferromagnetic material and the surface being investigated, known as the air gap, is measured and the magnitude of the detected MBN is corrected according to the measured depth of the air gap. If a longitudinal stress is applied to the measured rail, the permeability for the applied magnetic field changes. Tension leads to an increase of the permeability. The higher the longitudinal stress, the higher the increase of permeability. The rail becomes more and more easily magnetizable. The opposite case applies, when compressive stress is applied. With increasing compression the rail becomes more difficult to be magnetized. The permeability for the magnetic field decreases. The MBN contains the eddy currents of the stress sensitive processes. By reading the MBN for different load stresses a calibration on longitudinal load stress is produced. The readings are stored in the measuring computer. The figure 2 gives a schematic overview of the magnetic processes during a RailScan measurement and the stress dependency of the method.

3. EVALUATION

After completing the measurements, the raw data are exported to a PC and stored for further evaluation. The evaluation is performed using software evaluation tools. Results are obtained by evaluating and plotting the measured values of the magnetic parameter ß and rail temperature versus the longitudinal coordinate and measuring point number and further by depicting the load stress determined by means of the averaged magnetic parameters and the calibration curve. The neutral temperature is calculated by means of equation (1), with the load stress σ, the elasticity modulus E, the thermal expansion coefficient α and the rail temperature T_{Rail}.

$$T_N = \frac{\sigma}{E \times \alpha} + T_{Rail} \tag{1}$$

The results of the inspected locations are summarised in a report containing all relevant track information, i.e. the measured SFT linked to their location and position in the cw-rail.

4. CALIBRATION

Before measurement, the device is calibrated in laboratory or on site using calibration rails. Measurements of the MBN are taken for different longitudinal stresses and used to plot a calibration curve of the MBN as a function of longitudinal stress. Before performing the calibration the excitation parameters are optimized and defined.

5. RAILSCAN APPLICATION FIELDS

Thanks to its accuracy and flexibility, RailScan is versatile and allows widespread use. Examples are the SFT determination for minimizing the areas to be maintained, the detection of locations in which quality and safety are endangered, the determination of zone length affected by rail buckles, fractures and derailment as well as the verification and documentation of cw-rail production.

6. EXAMPLES FROM PRACTICE

During the last years extensive practice experiences could be collected during different inspection and development projects. Regular RailScan inspection works have been performed since 2006. Corresponding detailed measuring results, if not confidential, are available on request. Extensive track inspections have been performed in Australia. Experiences and knowledge resulting of the latter have been presented at the IHHC 2007 [1]. An interesting European inspection project took place during 2006 and 2007 in France on the new Paris – Strassbourg TGV high speed line [2]: Pre-commissioning of track and before speed record of the TGV EST was assured that the continuously welded high-speed track has been welded within the required stressing tolerance. That was made by RailScan-Stress Free Temperature measurements. More than 100 measurements assured the required high quality standards for the TGV line and excluded any subsequent re-establishment of required stress conditions.

On German tracks and construction sites of DB Netz AG as well as tramway operators RailScan measurements provided the supervision of continuously welded rail production. In Dresden [3] and Leipzig [4], Germany, the stress conditions were measured and assessed immediately after the execution of final welds. All results were documented. Furthermore, as a result of long-term stress monitoring, unduly low Stress-Free Temperatures were identified and the re-establishment of required stress conditions was recommended and accepted. The work execution was supervised using RailScan. Thus, track quality and availability could be provided and a contribution to save maintenance cost could be made.

Figure 3: SFT inspector Mayk Hofmann at work during SFT inspections of track renewal in Dresden, Germany.

Track inspections in Denmark started in 2005. In 2007 and 2008, inspections were performed on heavily loaded main-line tracks as well as interurban railways. Stress-Free Temperatures were measured, documented and assessed with regard to their deviation to the required SFT. Knowledge about the state-of-the-art of neutralization techniques and their documentation could be collected enabling a reduction of future maintenance costs. Furthermore it has been determined and documented that for the most part of the measured track the SFT is correct. Thus, the more than 100 measurements enabled a reduction of maintenance activities and costs. Due to the experiences and investigations like capability investigations according to recognized standards [6] and practical comparison measurements, the RailScan technique could be approved as a reliable and satisfactory technique for SFT determination and was admitted in Banedanmarks directives for the production of cw rails end of 2007. The highly detailed investigations were submitted to the institute FORCE, Denmark, and are available for worldwide homologations of the technique. In January of 2009, RailScan SFT inspections could be performed for C.S.X. Transportation in North Carolina, US. All given examples underline the worldwide demand for an economical and effective SFT measuring technique.

7. EVALUATION OF MEASUREMENT SYSTEM CAPABILITY

Requirements for the measurement system capability are well described in DIN ISO 9001 and assure an equipment use with a known and consistent uncertainty. DIN EN ISO 10012 requires e.g. metrological characteristics like accuracy, stability, range and resolution to be appropriate for the intended use and furthermore a documentation of the required performance and measurement uncertainty.

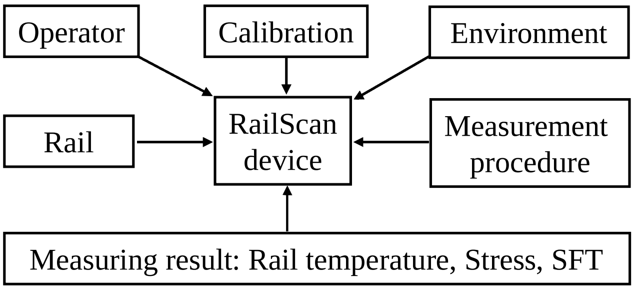

Figure 4: Schematic representation of RailScan process

The total sum of all the factors that can affect the determination of the RailScan SFT measurement value is built by the characteristic operation steps such as calibration, measuring and operation procedure, the measuring instrument itself, used standards, personnel/operators, software used for the measurement and the operation. Fig. 4 depicts a simple block diagram of these influences. For specifying RailScan system capability, the influence of these factors on the measuring result was investigated.

7.1. Resolution of the equipment

The resolution in percent "%RE" of a measuring equipment can be defined following [6] by means of the characteristic's nominal value RE, usually a value of the sensor or display and the reference value, the specified tolerance T and the relation %RE = RE x RF^{-1} x 100, where the required resolution in percent %RE shall be smaller than 5%. For RailScan a consideration of the stress and the temperature measurement is appropriate. The characteristic's nominal value RE for the stress is here defined by the non-linear calibration function and depends on the longitudinal load stress. It is determined by means of the resolution RE of the magnetic parameter ß, and the load stress determined from it in the calibration curve. RE for ß is 10^{-3} and constant for the whole stress range. The resolution for the stress REσ increases with increasing load stress because of the non-linearity of the calibration curve. For -80 MPa REσ is 0.2 MPa and for +80 MPa REσ is 0.01 MPa. The worst case calculation leads to a resolution of %REσ = 4 % < 5% and the best case calculation to %REσ = 0.2 % < 5%. These resolutions are satisfactory. The resolution of the rail temperature measurement is received by calculating %RE = 10^{-2} °C x 1 °C x 100 = 1 % < 5% which is satisfactory.

7.2. Accuracy

Every time a measurement is repeated with a sensitive instrument, e.g. RailScan, slightly different results are obtained. The common and generally recognized model used is that the error has two additive parts: The systematic error which always occurs when the instrument is used in the same way, and the random error which may vary from observation to observation. These error components enter in the absolute observational error also called measurement error that can be described as the difference between the indicated value and the right value. Therefore, statistical evaluations based on the comparison of the indicated and the real values have been performed. One of these tests consisted of 5 repetition measurements on the same measuring spots whereby each measurement consisted of 50 single measurements The accuracy of the system was estimated by calculating the average of the relevant values: The average value of the stress for the 5 measuring series is only 0.25 MPa, the standard deviation of these five repetition measurements are for the stress 0.6 MPa and the SFT 0.25 °C. The mean error of the difference of the SFT between RailScan and required value is 1.1 °C and its standard deviation 0.47°C.

Residual stress changes: It is known that rail residual stress distribution is affected in function of time. Experiments proved long ago that residual stresses changes with time during loading. The basic cause of these changes is that the resultant of stresses originating during loading and residual stresses at certain points of the cross section of the rail reaches the yield point. These changes are extremely large on the running surface of the rail, due to the reforging effect of the wheels and on the edges of the base of rail, specifically on its external side in relation to the axis of the track. In order to exclude that these effects cause errors during SFT measurements on new and old rails, RailScan has been equipped with a special probe. Experience has shown that on the neck of the rail the residual stress state does not change or only to a very slight extent during loading in the range of the zero stress state. It may be explained by the small - the value being about zero - residual stress, the large cross section and the small moments due to their nearness to the inertia axis. The RailScan measurement is therefore performed in this area.

Thermal stresses: In CWR tracks dilation caused by temperature changes is inhibited. Inhibited dilation results in longitudinal tensile or compressive stresses depending on the movement of the rail in the examined section, namely whether it expands or contracts at the examination temperature. According to the principle of equal dilatations, every difference between neutral temperature and existing rail temperature introduces a longitudinal stress in the cw-rail of approx. 2.4 MPa/°C. Even under constant temperature and wind conditions, thermal stresses vary in the longitudinal direction of the rail. Force relations in the joints to different sleepers can be different, so the value of thermal stresses is different for each space between the sleepers. Examination of these differences is possible with RailScan. Variations in the measuring results must not be confused with data scattering.

Temperature gradient in the rails: In reality, the temperature distribution around the circumference as well as in the volume of the rail is rarely constant. The temperature around the circumference is affected by the intensity and direction of sunshine, the force and direction of wind, the temperature of the air and that of the ballast. In the case of strong wind and sunshine the difference between the temperatures measured on the sunny and windless side or on the shady and windy side may be as much as 7°C. As a consequence of the varying temperature distribution around the circumference, the thermal stresses in the cross section are not constant, thus leading to bending effects in the rail. For RailScan SFT measurements the temperature gradient is a negligible error source because the stress is measured only in a surface-near layer of 0-1 mm depth and the rail temperature is measured close to the stress measurement. Consequently in accordance to the principle of equal dilatations the measured longitudinal load stress is always an approx. linear function of the rail temperature and this even if the cw track doesn’t follows this principle due to longitudinal or lateral creep/ displacement effects.

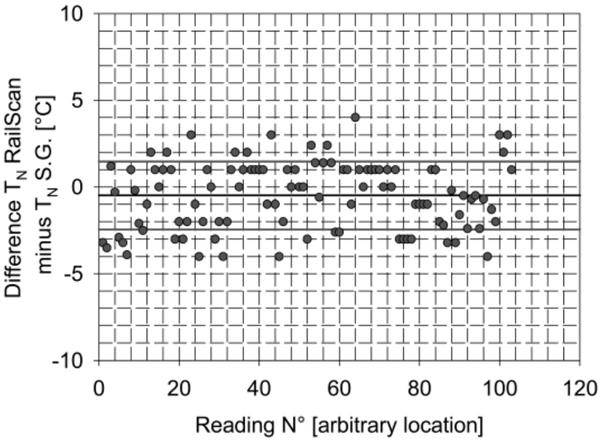

Figure 5: Results of 100 comparison measurements RailScan vs. Strain Gauges (S.G.).

Linearity study near the specification limits: According to [6] the capability of the system is investigated near the limits of the tolerance range of ± 3 °C. For this, comparison measurements between RailScan SFT results and those determined on the same locations by means of strain gages have been performed. Fig. 5 shows the difference between RailScan and strain gauge SFT of 100 comparison measurements. It can be seen in the figure that the calculated standard deviation is less than ± 3°C.

7.3. Reproducibility of RailScan SFT results

The recognized important conditions for the reproducibility of RailScan are the selected RailScan measuring length that can be different, the rail temperature and different stress states. Appropriate tests to study the influences of these conditions on the result are presented below.

Reproducibility at different load levels: Various tests were performed at Elektro-Thermit in order to verify the reproducibility of RailScan SFT results. The test presented here was performed under the supervision of Force Technology, Brøndby, Denmark in Halle/Saale in April 2008. The calibrated RailScan device was used to determine the stress and the SFT on 3m long calibration rails. Different load levels were applied before the measurements. From each RailScan measurement series the longitudinal stress and the SFT was calculated and compared with stress and SFT determined by the strain gages. The maximal deviation between RailScan and strain gage SFT was 1.8 °C, the mean error 0.9 °C and the error standard deviation 0.6 °C. The RailScan results show good agreement with the strain gage method.

Investigation of temperature influence: The temperature influence of the measuring effect was investigated for a temperature range between approx. +5°C and 50 °C. The results show that the average values as well as the standard deviations of the repetition measurements are in the order of magnitude of the resolution of the measuring equipment and are negligible.

Investigations of the transferability of RailScan calibration on long rails also were performed. The measuring values received on long rails were evaluated and compared with the required values. For all measurements the deviation was less or equal than 0.5 °C. In a further step different rail temperatures and their consequences on the measuring result were investigated. For this, a long rail was measured at different rail temperatures. The measurements were taken at a rail temperature of 19.4°C, 19.5°C, 49.77°C and 49.82°C. All SFT deviations were less or equal than 1 °C.

Stability of the measuring system: An ongoing assessment of the measuring stability was performed on calibration rails at Elektro-Thermit. Initially, studies to demonstrate the stability were performed at short intervals. Based on these results an appropriate interval for routine checks was established to demonstrate that the measurement system used retains its suitability over the entire period of use. Repetition measurements were performed with a time interval of several months. The average values and standard deviations are in the order of magnitude of the resolution of the equipment and are negligible.

7.4. Operator influence

The performance of the measurement and some steps of the evaluations are dependent on the correct work of the operator who has to carry out all works in accordance to his working instructions. The results previously given and presented below already include the component of operator influence that is essentially built by the correct coupling of the measuring probe on the rail. Larger errors are avoided by means of an air gap controlled coupling. The occurrence of errors is actually avoided by means of a working instruction and a report creation including the verification by a second technical person.

7.5. System capability

In order to arrive to a general judgment of system capability, a formalism for the estimation of RailScan's uncertainty is required. For this, the generally recognized capability indices Cg and Cgk are introduced /5, 6/, where Cg takes into account the random error and Cgk the systematic error. Cg is given by

$$C_g = \frac{0.1 \times T_{RailScan}}{2 \times (s_g \times RE \times T_{Standard}^{-1})} \qquad (2)$$

where T_{RailScan} is the tolerance for the RailScan SFT measurement and s_g the standard deviation of typical repetition measurement series. Taking the results of the reproducibility tests previously presented Cg becomes 2.4. The systematic error of a measuring system can be expressed by the bias, the difference between the observed average of measurements x_g and the reference value x_m and respecting the tolerance of the standard:

$$Bi = \left| x_g - x_m \right| \times RE \times T_{S\tan dard}{}^{-1} \qquad (3)$$

Using again the results of the reproducibility tests, x_g is represented by the RailScan values, x_m the strain gauge SFT values and Bi is the average value of the SFT difference. Bi becomes then 0.5. The determination of the capability index Cgk enables an assessment of both of the error components, the systematic and the random error. Cgk is

$$C_{gk} = \frac{0.1 \times T_{RailScan} - Bi}{2 \times (s_g - RE \times T_{S\tan dard}{}^{-1})} \qquad (4)$$

With the results T_{RailScan} = 6 °C, sg = 0.25°C and T_{Standard} = 0.2 °C, Cgk becomes 2.2.

The capability indices have been calculated for various calibration measurements as well as for inspection measurements. Therewith could be proved that RailScan is a capable measuring equipment and the SFT results are reliable and satisfactory with regard to their accuracy.

CONCLUSION

The article presents the RailScan non-destructive technology that enables measurement of the stress-free temperature SFT of stressed track during operation without intervention in the track. This obviates the need for time-consuming, complicated and hence expensive alternative methods that necessarily involve intervention in the cw track. Extensive tests on the measuring ability of RailScan, together with a release and inclusion in the Danish technical guidelines for stress equalization, testify to the fact that the system provides accurate and reliable measurements of the SFT. Whereas the SFT was previously a difficult parameter to measure, the introduction of this rapid, flexible and simple technique makes it much easier. By enabling an evaluation of track quality and safety, it contributes to forward-looking and timely maintenance management.

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