Handheld Solution for Measurement of Residual Stresses on Railway Wheels using EMATs

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Abstract. The braking process used on railroad cars is known to create tensile stresses in the circumferential direction due to the thermal expansion and subsequent cooling of the wheel rim. This tensile stress can significantly accelerate the growth of small cracks on the rolling surface which can cause a spall or catastrophic failure of the wheel under load. By periodically evaluating the tensile stress, railroad companies can prevent wheel failures and derailments that can be extremely dangerous and costly. Innerspec Technologies has developed the first, portable, battery-operated handheld instrument that can be used to provide rail-side inspections and facilitate operation in any environment. The instrument is coupled with a proprietary, patent-pending, dual-channel sensor that does not need to be rotated during inspection thus simplifying the operation, increasing the reliability and accuracy of results, and reducing complexity and inspection cycle time.

1 Introduction

Residual stresses are generated during most manufacturing processes involving material deformation, heat treatments and machining or processing operations that transform the shape or change the properties of a material. These are originated from a number of sources and can be present in the unprocessed raw material, introduced during manufacturing or arise from in-service loading.
In rail wheels, the presence of tensile residual stresses is generally harmful since they can contribute to, and are often the main cause of fatigue failure and cracking. Compressive residual stresses are generally induced by different means in the wheel material during manufacturing process as these are beneficial since they prevent origination and propagation of fatigue cracks and increase wear and corrosion resistance. It is also important to maintain compressive stress levels within specific safety limits in order to avoid compression stresses in excess of yield limit which would lead to inhomogeneous plastic deformations.

2 Brief overview of non-destructive stress measurement techniques

There exist several destructive or semi destructive methods for measuring residual stress levels on materials. [1] In contrast with these, the non-destructive residual stress measurement methods have the obvious advantage of specimen preservation, and they are particularly useful for production quality control and in service inspection of valuable assets. The diffraction methods such as X-ray and neutron diffraction can be applied for the polycrystalline and fine grained materials including metallic or ceramic. The advantage of the neutron diffraction method in comparison with the X-ray technique is its lager penetration depth as x-ray method is limited for the measurement of residual stresses on the surface of materials, with a penetration of only few microns. [2] However, the relative cost of application of neutron diffraction method, is much higher compared to X-Ray making it not extensively used for routine process quality control in engineering applications. Alternatively, the magnetic Barkhausen noise method [3] has the advantages of being rapid, requiring no direct contact with the part and offering a penetration depth 100 times greater than that of X-ray diffraction.

2.1 Stress measurements on rail wheels

For wider specimen sections such as rail wheels, the use of ultrasonic waves for residual stress measurements is advantageous as these provide an average stress level of the complete wheel rim profile. The ultrasonic method is based on the generation of two ultrasonic elastic waves with different orientation which propagate through the thickness of the wheel rim and whose speed vary depending upon both texture and material stress levels. There exist a variety of applications where Piezoelectric (PZT) transducers are used for generating ultrasonic waves on materials, however, EMAT (Electro Magnetic Acoustic Transducers) have been the most widely used and are best suited for this application due to a variety of technical advantages. Standard Ultrasonic transducers make use of the piezoelectric effect of certain materials to generate a mechanical vibration that is transferred into the specimen under test by means of a coupling fluid or under high pressure levels. In comparison with Piezoelectric transducers, EMAT, or Electro Magnetic Acoustic Transducers offer the advantage of generating the sound in the component inspected instead of the transducer [4].

3 Ultrasonic EMAT stress measurement technique

3.1 Ultrasonic EMAT technology

EMAT generates ultrasonic waves into the test object using electromagnetic induction with two interacting magnetic fields. A relatively high frequency (RF) field generated by electrical coils interacts with a low frequency field generated by magnets to produce a Lorentz force in a manner similar to an electric motor. This disturbance is transferred to the lattice of the material, producing an elastic wave. In a reciprocal process, the interaction of elastic waves in the presence of a magnetic field induces currents in the receiving EMAT coil circuit [5] [6].

Because the sound is generated in the part inspected instead of the transducer a liquid couplant is not required when using EMAT transducers.

3.2 Stress measurement technique

Ultrasonic bulk waves are used to determine the presence and degree of stress in metal samples (e.g. rail wheels). In a stress-free metal that does not appear to have any crystallographic texture or anisotropy due to the average alignment of grains within that metal, horizontally polarized shear waves will pass through the material with a constant velocity regardless of the direction of polarization. The application of in-plane stress will however make the metal behave anisotropically. For an in-plane stress in one particular direction, shear waves propagating normal to the surface of the metal will be forced into one of two polarizations, either polarized along or orthogonal to the stress direction. Each

polarization will have a slightly different velocity and by measuring the difference between these velocities, the stress can be obtained.
Temperature variations will change the velocity of both polarizations by the same amount to a first order approximation, and so by measuring the relative difference of the shear wave velocities, the stress measurement is not significantly affected by variations in temperature or even sample thickness.
EMATs are especially well suited for this application because they can generate shear waves with different polarizations and do not mechanically load the surface under test allowing a greater precision of measurement of ultrasonic arrival time variation. Furthermore, EMATs do not suffer from "beam steering" errors caused by misalignment of the transducer with the surface because they electromagnetically couple energy into and out of the material under test.

3.3 Ultrasonic birefringence measurement

The principle of birefringence, which allows for measurement of residual stresses in wheel rims, is well known and has been described in previous publications [7]. A stress change in a material results in a change in the speed of ultrasonic waves passing through that part. The difference in the wave speeds in the hoop (circumferential) and radial directions allows for calculation of the stress state of the rim.
The technique requires using two linearly polarized shear waves oriented orthogonally from each other as presented in Figure 1 .

$$\sigma \cdot K = B - B_0 \tag{1}$$

$$(\sigma_c - \sigma_r) \cdot K = \frac{(T_{Sc} - T_{Sr})}{\left\{\frac{(T_{Sc} + T_{Sr})}{2}\right\}} - B_0 \tag{2}$$

Where T_{Sc} and T_{Sr} are the arrival times of each of the orthogonally polarized shear waves, σ_c and σ_r are the corresponding stresses in circumferential and radial directions, and K is a constant of proportionality which can be determined empirically.
B_0 represents the unstressed state birefringence due to material texture.

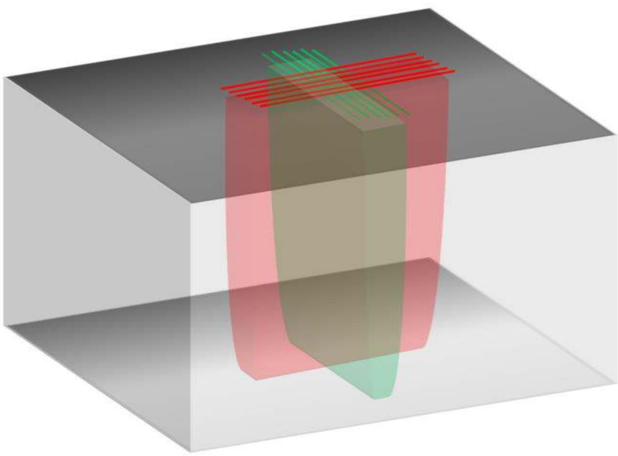

Figure 1 Disposition of the orthogonal wave beams

3.4 The acousto-elastic constant

The acousto-elastic constant, K, is a parameter which is function of the elastic constants of the wheel material. The standard procedure for obtaining K consists on evaluating a sample of the same material and thermal treatments of the rail wheel under known stress levels (on a tensile tester or similar, Figure 2) in order to evaluate the ultrasonic time of flight (TOF) variation versus applied stress. Normally the K factor is determined for each different grade of steel. Since there is a gradient of residual stresses within the rim that changes with depth below the surface, an ultrasonic measurement made from the front or back rim face produces an average of the bulk residual stresses across the rim width. K provides an indicator of TOF variation vs a given circumferential stress.

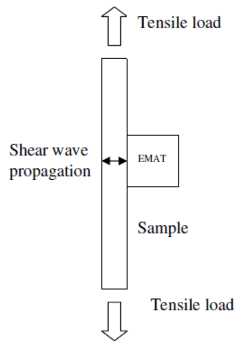

Figure 2 Test description

4 Innerspec PowerBoxH hand held stress measurement system description

4.1 Hand held solution vs stationary advantages

Alternative ultrasonic-based stress measurement systems are used to ensure wheel quality control after manufacturing process [8] [9]. These instruments generally comprise heavy industrial equipment requiring continuous connection for energy supply. Portability and stand-alone battery powered operation become a requirement for in-service wheel inspection. EMAT transducers are energy consuming circuits thus requiring the use of High Power instrumentation which has to provide instant currents in the range of 100A. Such demanding tasks have historically put a barrier on the development of stand-alone EMAT pulse-receivers. Recent advances in efficient energy management systems and low consumption EMAT electronics carried out by Innerspec Technologies have made possible the development of the first hand-held battery powered EMAT residual stress measurement system, the Innerspec PowerBoxH.

The Innerspec PowerBoxH is the only EMAT portable instrument capable of generating up to 1200V with 8kW of peak power at speeds of up to 300Hz, making it ideal for Stress Measurement on in-service rail wheels. The device contains a built-in transmitter/receiver switch which permits pulse-echo operation required for TOF measurements. Furthermore, an embedded signal multiplexer allows for coil selection enabling switching from one coil to its orthogonal one in order to make readings at 90 degree without moving the stress measurement transducer. A setting of 600Vpp (approx. 3kW) is also available to maximize battery life if the application does not require full power. Figure 3 shows the device performing stress measurements on a sample test rail wheel.

Figure 3 Innerspec PowerBoxH performing stress measurement on rail wheel

4.2 EMAT stress measurement sensor

Innerspec Technologies has developed a proprietary sensor design that permits generation of two, orthogonal, linearly polarized beams without moving the sensor from the surface. This novel approach allows not only for more accurate and repeatable readings but also reduces cycle time and mechanical complexity, making the system more reliable. In order to study EMAT ultrasonic beam characteristics, Innerspec has carried EMAT signal propagation Finite Element Analysis. Figure XXX shows the beam energy distribution for the stress sensor EMAT coil. In order to measure residual stress, only one of the two orthogonal sensor coils is used at a single time. Therefore, the ultrasonic beam modelled does only consider the propagation of the elastic wave generated by one of the coils.

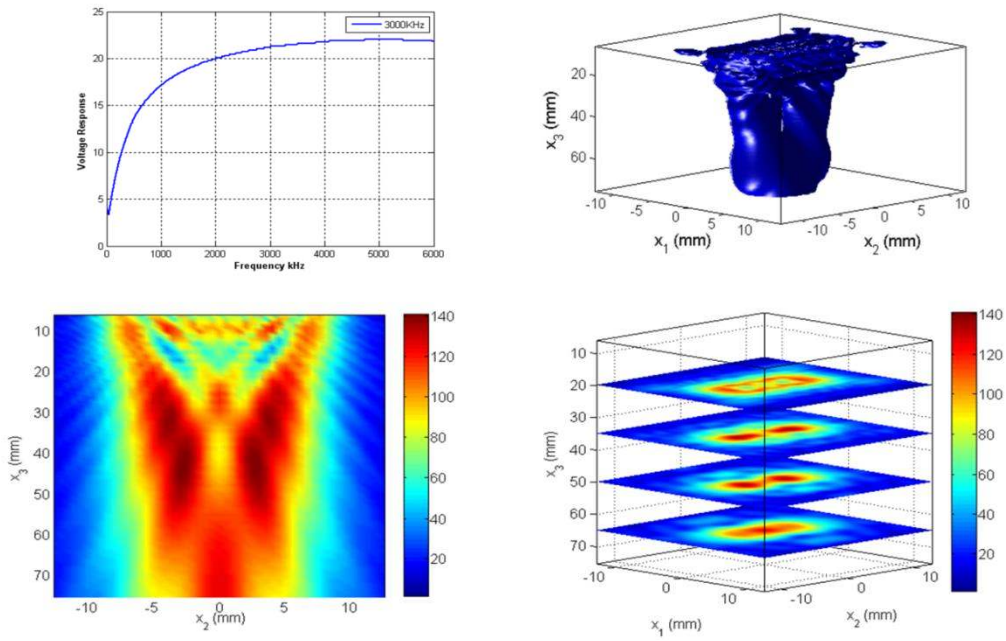

Figure 4 Frequency Spectra & 3dB Beam Profiles for one coil (sensor contains two orthogonal coils)

Transducer external design work has been focused on dimensions optimisation in order to allow encapsulation of the required magnets to generate strong enough ultrasonic waves while keeping sensor footprint at minimum levels. With external dimensions of 47 x 60 mm, the dual EMAT coil transducer has been designed to withstand operational environment conditions and can be utilised at temperatures up to 80 ºC.

5 Stress measurement procedure using Innerspec PowerBoxH

Innerspec PowerBoxH system allows for storage of wheel specific configuration parameters which facilitate user intervention. In addition, inspection results are reported automatically and linked to the used configuration parameters for data reporting.
When using Innerspec´s Stress Measurement system, the acousto-elastic constant, K, can be either entered manually or calculated empirically by performing TOF measurements for a range of known load values introduced into a table as described in Figure 5. In the last case, a step-by-step process allows data entering into the Innerspec PowerBoxH stress calculation software.
Once this process is completed the stress measurements can be performed on the different sections of the wheel rim and the stress calculations are performed as described in equation (2). In contrast with alternative systems, the dual EMAT sensor allows for instant acquisition of stress values avoiding transducer rotation and facilitating user intervention.

	Stress	S1:TOF1	S2:TOF2	Birefringence
1	0	-	-	0.04
2	10	-	-	0.05
3	20	-	-	0.06
4	30	-	-	0.07
5	40	-	-	0.08
6	50	-	-	0.09

Figure 5 Innerspec PowerBoxH TOF, stress and Birefringence data table.

5.1 Sensor wheel positioning

Before starting measurement process it is necessary to ensure that the ultrasonic EMAT signals can propagate through the wheel rim. Furthermore, measurements can be performed only in the areas where the rim faces are parallel, starting from the rolling surface up to the inner rim diameter. Measurement area ends in the areas where ultrasonic signals scatter or diffract due to varying geometry as described in Figure 6.

Figure 6 Rail Wheel rim stress measurement area description

5.2 Mechanical sensor positioner

Although manual sensor positioning can be performed using Innerspec´s system, the use of a mechanical sensor positioner (Figure 7) is desirable to guarantee accurate inspection results. Innerspec´ s rail wheel sensor positioner guarantees extended accuracy (0.1 mm) in comparison with manual handling which helps to comply with the requirements set by the European Norm EN13262:2015.

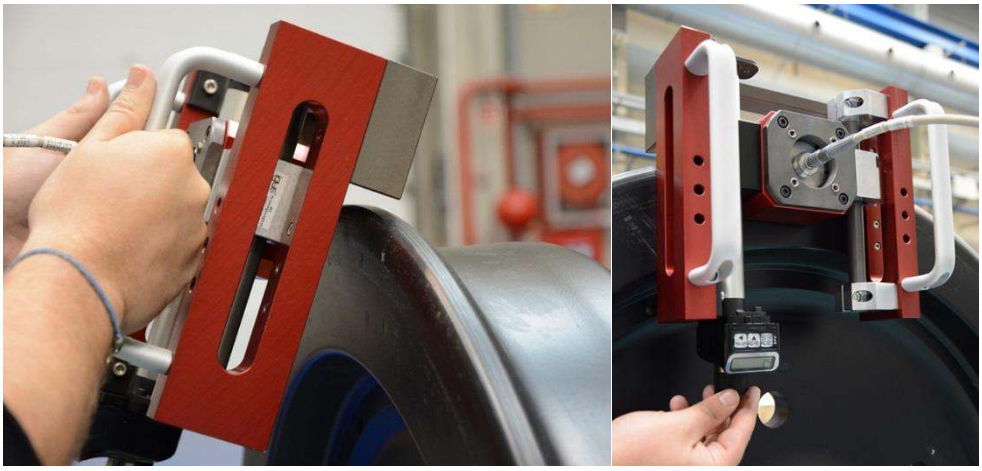

Figure 7 Stress sensor mechanical sensor positioner

6 Results and further work

The Innerspec PowerBoxH residual stress measurement system performance has been validated on sample cast steel rail wheels after manufacturing process. These wheels had not been used in operation and therefore presented stress values within the standard margins. For this test, the K parameter used was directly provided by the wheel manufacturer instead of calculated experimentally. Figure 8 shows the stress profile including measurement errors for this test.

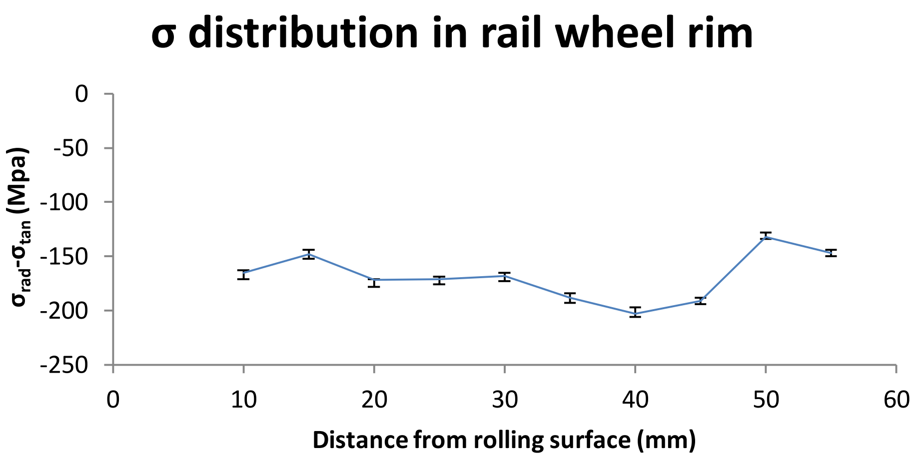

Figure 8 Residual stress distribution and measurement error in sample rail wheel

These results show good correlation with those provided by similar existing commercial instruments, therefore validating the developed solution.

As further steps, Innerspec is working on the development of standard calibration blocks in order to guarantee that system stability is ensured complying with all the requirements set by the European Norm EN13262:2015. Other future developments under consideration include manufacturing smaller sensors maintaining the same capabilities and improving the software of the portable EMAT system according to the user needs.

7 References

[1] N. Rossini, M. Dassist, K. Benyounis and A. Olabi, “Methods of measuring residual stresses in components,” Elsevier Materials & Design, vol. 35, pp. 572-588, March 2012.

[2] M. Fitzpatrick, A. Fry, P.Holdway, F.A.Kandil, J. Shackleton and L.Suominen, “Determination of Residual Stresses by X-ray Diffraction,” September 2005.

[3] P. Wang, S. Zhu, G. Y. Tian, H. Wang and X. Wang, “Stress Measurement Using Magnetic Barkhausen Noise and Metal Magnetic Memory Testing,” in 17h World Conference on Nondestructive Testing, Shanghai, China, 2008.

[4] Innerspec Technologies Inc, “www.innerspec.com,” [Online]. Available: http://innerspec.com/knowledge/emat-technology.

[5] B. López, A. Syed and V. García Benavides, "Surface and thin volumetric inspections with EMAT," in 11th European Conference On Non-Destructive Testing, Prague, 2014.

[6] C. Boyero Molina and V. García Benavides, “Inspección bajo soportes mediante ondas guiadas generadas por EMAT,” Spanish Congress of NDT, Seville, May 2015 .

[7] A. V. Clark, H. Fukuoka, D. V. Mitraković y J. C. Moulder, «Ultrasonic Characterization of residual stress and texture in cast steel railroad wheels,» de Review of Progress in Quantitative Nondestructive Evaluation, 1987, pp. 1567-1575.

[8] C. Gilardoni, M. Gherbin, M. Carboni and A. Gianneo, “High-performance methodology for residual stress measurement in railway wheels,” in 11th European Conference on Non-Destructive Testing (ECNDT 2014), Prague, Czech Republic, October 2014.

[9] E. Schneider and R. Herzer, “Ultrasonic Evaluation of Stresses in the Rims of Railroad Wheels,” in 7th European Conference on Non-Destructive Testing, Copenhagen, 1998.