Non-destructive Evaluation of Residual Stresses in Railway Solid Wheels by Non-Contact EMAT Probe

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Abstract. Adverse service conditions and malfunction of shoe brakes can induce dangerous tensile stresses in the rim of railway wheels. Solid wheels for freight cars are subject to “rim chilling” to induce compressive stresses in the rim; such stresses are beneficial to the wheel safety as they avoid the sudden propagation of potentially evolving defects. Non destructive measurement of residual stresses in a wheel rim is carried by ultrasounds, via the acoustic birefringence effect. The test detects the anisotropy induced by the residual stresses, from the speed of two shear waves with cross polarization. The method was set as a standard for re-qualification of used wheels (UIC 510-5) and accepted as a quality test for evaluation of 100% production (European standard EN13262:2004).

The paper shows a solution developed for stress testing by a non-contact EMAT probe embedding two superimposed sensors that generate shear ultrasonic waves with cross polarization, thus providing the required measures without probe rotation. The dedicated electronic hardware is suited to implement manual or automated test applications. The accurate and reliable measure of wave travel time enables residual stress evaluation accuracies up to 10 MPa in lab conditions. The system has been improved to meet increasingly requirements on test speed, flexibility, and error detection without operator intervention. A mechanical rig with a motorised actuator has been developed to ensure scan and stress tests in a portable set-up. Synchronisation to external manipulators allows in-shop wheels/wheelsets automated tests with existing mechanised systems. The paper will show the system proposed to exploit EMAT stress evaluation in the qualification of wheels operating in a mine district, for iron ore cars subject to load per axis exceeding 32 tons.

Introduction

Thermomechanical stresses in the rim of solid railway wheels can adversely affect the safety of freight transports. An overstress condition, though infrequent, can compromise the integrity of a wheel and, in case of rupture, cause damages and particularly make the infrastructure unavailable to the railway traffic for a period.

In new forged wheels compressive stresses added in the rim by heat treatment hinder the propagation of potential defects, and prevent sudden wheel ruptures. In freight cars, however, the stresses induced by the shoe brakes pressing on the tread surface can progressively reduce the initial compression.

Some years ago railway operators thus called for a test solution to periodically check the stress condition of solid wheels. The method known as "acoustic birefringence" of ultrasound waves was eventually selected and approved for application. Such nondestructive measure can be exploited in a "no-contact" fashion when using an EMAT (ElectroMagnetic Acoustic Transducer) probe, that ensures accurate and reproducible measures of travel times, and an evaluation of the rim residual stress reliable, and suited for testing applications in shop and in field.

1. Controlling residual stresses periodically along the wheel life

Residual stresses in railway wheels can be a serious concern for railway cars mounting block (shoe) brakes. In consideration of the actual operational conditions, shoe braking can induce severe thermomechanical stresses over the tread, which may eventually turn into potentially dangerous hoop tensile stresses in the rim. The stresses built under each single event shall be rarely of considerable magnitude, nevertheless, accumulation of such tensile stresses can eventually bring the wheel rim to a hazard condition.

In fact, an increasing level of residual tensile stress, also combined to operational fatigue conditions, may make a defect quickly propagate and lead a wheel to rupture. To prevent sudden failures solid wheels are submitted in fabrication to rim chilling, a specific quenching treatment, inducing in the rim compressive stresses, in the hoop direction, so as to prevent the propagation of axial/radial defects [1].

In addition to test operated wheels and detect potential defects, railway operators have now a mean to evaluate residual stresses in the rim of wheels, and increase their reliability even when operated under severe conditions. The test can be run in accordance to the standard UIC 510-5 [2] for used wheels; recently the same tests was included in standard EN 13262:2004 so that customers can require stress evaluation in addition to conventional tests to asses the quality of new wheels [3]. Thus the noninvasive measure of residual stresses by the acoustic birefringence of ultrasound waves is increasingly being exploited in industrial conditions.

2. Assessment of residual stresses in solid railway wheels

The methodology included in the above said standards is the result of a joint effort started in the 90' when European Rail Research Institute coordinated a joint project that eventually could demonstrate the effectiveness of the acoustic birefringence to detect and evaluate the magnitude of residual stresses in the rim of solid railway wheels [4].

The acoustic birefringence is the phenomenon - discovered in 1959 by Benson and Raelson [5] - that affects the speed of a linearly polarized shear wave due to the anisotropy of the material elastic properties. When such wave travels along the thickness in a steel block, highest and lowest wave speeds, respectively minimum and maximum travel times, occur when wave polarization is aligned to each principal direction of the anisotropy field.

Such anisotropy can arise not only from residual or applied stresses, but in addition from material texture. Texture orientation can be known according to the manufacturing process, e.g. forging, and thus tested for each new wheel material. However, exploiting the relation between birefringence and an arbitrary combination of texture and stress, in a highly and/or unknown textured block, to detect stress principal directions and provide some estimation of the stress magnitude, is going to be a very difficult objective.

Luckily railway wheels are easier to deal with: texture anisotropy (even though its magnitude can be unknown) shall be aligned to radial and hoop directions, the initial compressive stress is set in the hoop direction, which is also the principal direction of the tensile stress expected from the shoe brake action. While texture will only set the behavior of the initial residual stress pattern embedded in the rim of a new wheel, the operational residual stresses will change the wave speed along the said principal directions. Monitoring the speed of such waves shall thus provide a mean to periodically check each wheel internal stress, before such stress exceeds a safe threshold.

3. Acoustic birefringence and residual stress evaluation

The birefringence B is the relative speed change of wave V_H and V_R propagating along the thickness T of a component with flat and parallel faces. B is evaluated according to (1) where suffix H and R correspond to cross directions hoop and radial:

$$B = \frac{V_R - V_H}{V_R} = \frac{T_H - T_R}{T_H} \qquad \textbf{(1)}$$

and where times of flight T_H and T_R are used to replace speed, since in principle waves start exactly at the same point and travel exactly the same distance. As the difference at the numerator will be very small, typically tens of nanoseconds, the measure of the time of flight must be extremely accurate. B is the sum of the anisotropy from texture B_0 and from (residual or applied) stress $B\sigma$. As it is shown in (2), this last contribution depends linearly, through the acoustoelastic coefficient *A*, from the difference of the principal stresses, whose components we expect aligned to H and R directions:

$$A \cdot B_\sigma = A \cdot (B - B_0) = (\sigma_H - \sigma_R) \qquad \textbf{(2)}$$

A and B_0 can be characterized by means of a tensile test, linearly fitting the data set of actual and estimated stresses, at increasing uniaxial load. Texture B_0 can be better evaluated also on stress-free wheel samples of real thickness. This is an easier task on new wheels, but can be a problem for testing old operating wheels.

Equations (1,2) also show that birefringence will average along the thickness, and measure the difference between the principal stresses of a biaxial stress field. As a fact, the method can only provide a thickness-averaged and relative stress magnitude. It is also worthwhile repeating that texture is not negligible a priori, however its influence will not prevent railway users from tracking the stress of their operating wheels, in order to point out tensile stresses that are about to exceed the safe stress threshold.

4. Measuring stresses in solid wheels

Stress evaluation needs the accurate and reliable measure of the times of flight of the ultrasound waves, with 1 nsec resolution along a 140 mm rim thickness. Once assessed the stress sensitivity corresponding to the calibrated acoustoelastic constant A, it comes clear that the best nominal stress accuracy one can expect shall be ±10 MPa.

Texture could be carefully evaluated on a set of new R7 forged wheels. It was found that texture behaves much like an "equivalent stress", whose contribution was estimated in ±55 MPa, based on constant *A* calibration. Provided that a fixed texture contribution should be suited for testing similar materials only, the said magnitude shall be not so relevant in comparison to the maximum stresses allowed for some operating wheels, for example in the range 200÷400 MPa according to the specific wheel material.

Tab.1 summarizes the main parameters for a typical evaluation of the stress in the rim of solid railway wheels (forged wheels, material R7).

Tab.1 - Parameters relevant to the reliable evaluation rim residual stresses

Parameters	Typical values
Shear wave velocity (v)	3.2 mm/µsec
Rim thickness (t)	140 mm
Time of flight (v/2t)	81.25 µsec
Acoustoelastic coefficient (A, wheel material R7)	~140 10^3 MPa
Resolution in the measure of the time of flight	0.001 µsec
Typical accuracy of the time of flight measures	0.003÷0.005 µsec
Typical accuracy expected for stress evaluation	± 10 MPa
texture (B^0) on typical samples of R7 forged wheels	± 0.4 * 10^{-3}
Stress equivalent texture effect (wheel material R7)	± 55 MPa

5. Development of the application

The exploitation of the stress evaluation with the no-contact EMAT approach has been carried with the support of railway users. The main development steps are below reported.

- Non destructive evaluation of the beneficial residual stresses embedded in the rim of new solid wheels R7, calibration of acoustoelastic coefficient, comparison with strain gauge data (Fig.1). This work carried at the Lucchini plant in Lovere - Italy [6]
- Qualification of the test procedure to evaluate stress on operated wheels with different levels of wear (Fig.2). This work carried at the Trenitalia NDT Lab in Florence [7].

As a tentative procedure to exploit the birefringence for a stress survey of operating wheels, and prevent that a wheel is kept in operation due to a texture oriented so as to reduce the actual stress evaluated by the test method, the allowed stress threshold was decreased by 55 MPa in accordance to the texture contributions gathered from new wheels.

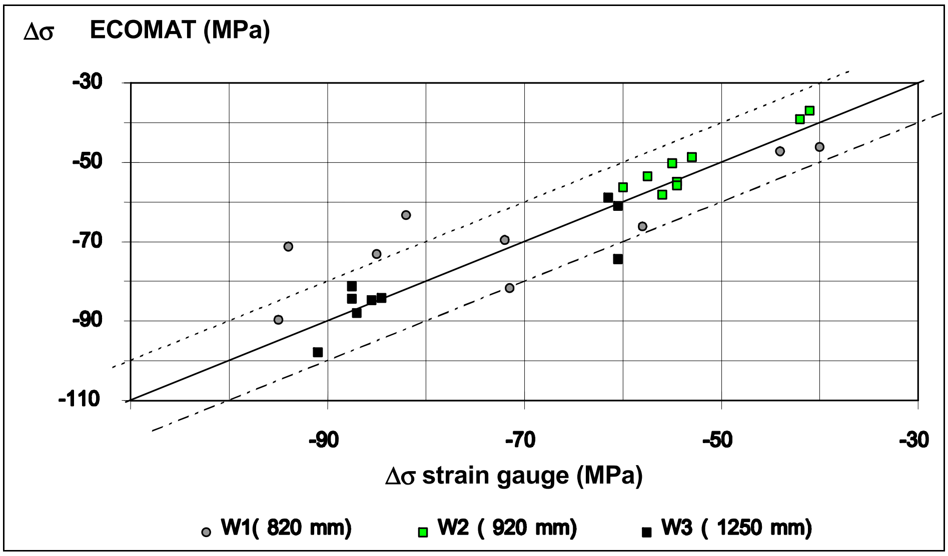

Fig.1 – Comparison between Ecomat-ST and strain gauge during the sectioning test of new wheels

Also the ultrasonic equipment was improved to better support the application development. Design and implementation of a high gain - low noise programmable receiver helped to automate the ultrasound signal acquisition at each measure point, for the exploitation of the dual sensor arrangement of the EMAT probe. In addition to Trenitalia and Lucchini in Italy, Ecomat-ST has been exploited in France at SNCF and Valdunes [8]. In Valdunes (now Standard Steel) an automated system for inspection of new single wheels was developed based on the Ecomat-ST hardware. Recently the EMAT based system was supplied in Australia to the car shop of the mining company BHP Billiton Iron Ore [9].

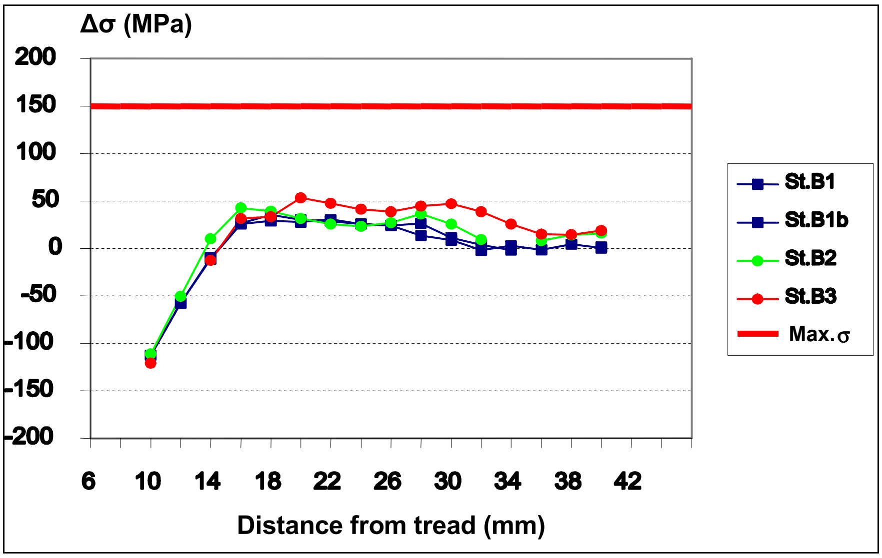

Fig.2 – Operated wheel. The compressive stresses are compensated at about 15 mm from the tread

6. Characteristics of the system

Ecomat-ST is a computer based system; it can be portable or stationary, manual or automated when synchronized to a scanning equipment. The main components are below listed.

- The EMAT-DC probe, two linearly cross-polarized shear waves, frequency 3-4 MHz
- Two pulser/receiver modules each interfacing a single probe sensor: tone burst pulser, high sensitivity and very low noise receiver
- A main analog/digital conversion card to drive the sensors and sample the incoming signals, via the dedicated pulser/receiver modules
- Software to set the system parameters, visualize and analyze the signals, record and document each wheel stress test

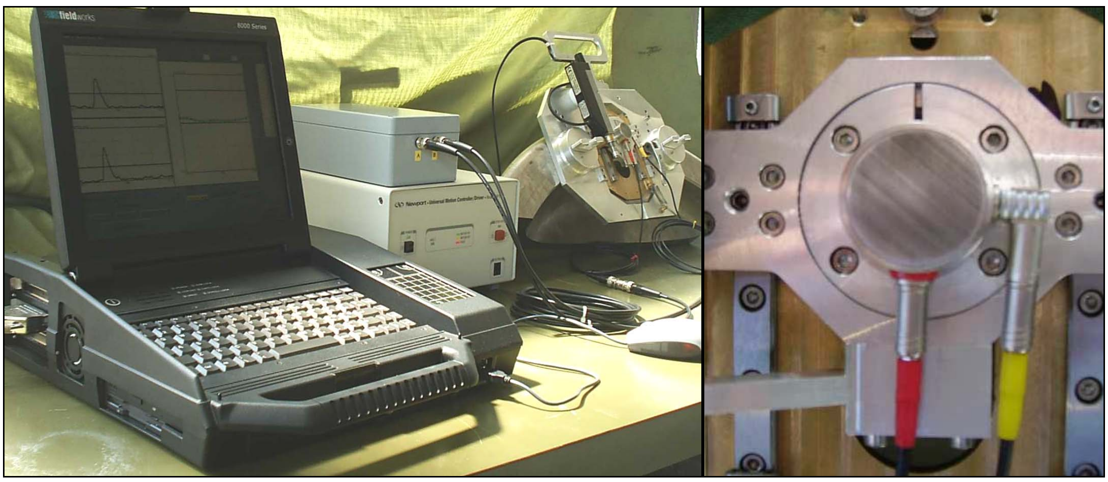

Fig.3 – Ecomat-ST: portable manipulator and dual sensor EMAT probe for shear waves of cross polarization

Fig.3 shows the portable system eventually settled to measure residual stresses in railway wheels, exploiting a EMAT probe for "no-contact" generation and detection of ultrasonic waves, without coupling means. The special probe incorporates two identical sensors so arranged to provide two waves of cross polarization. As compared to conventional contact probes, the EMAT probe prevents the inaccuracy due to fluctuations of the thickness and the temperature of the coupling mean. In addition, the dual sensor architecture ensures both cross polarization are provided without probe rotation, simplifying the test system without affecting its reliability and productivity.

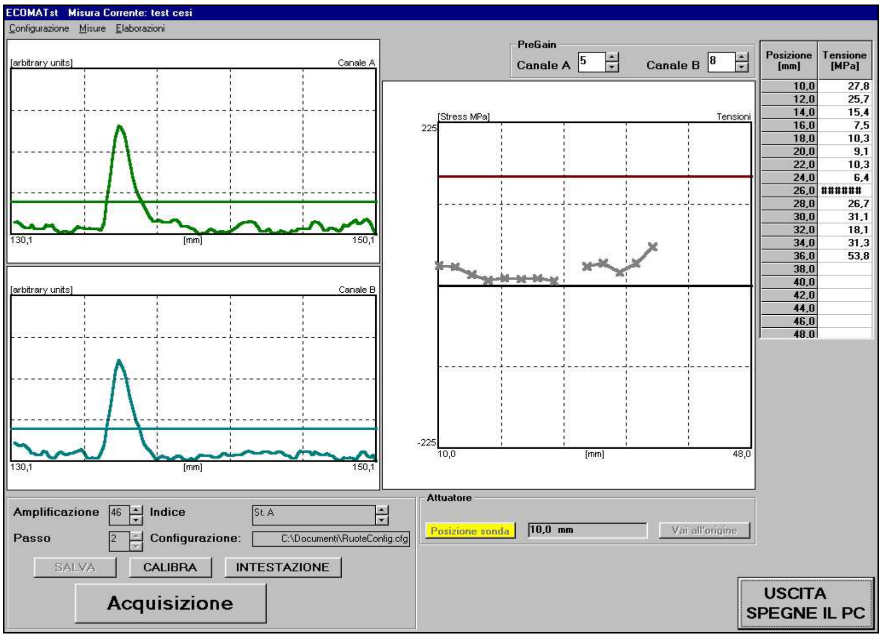

Fig.4 – User interface of the Ecomat-ST system exploited at Trenitalia

The software to perform the wheel stress test allows the set up of the ultrasound parameters, and to visualize the detected signals, evaluate the time of flight, record and document the results of each wheel test. Fig.4 shows the user interface with signals gathered from the EMAT-DC probe, the stress data along the scanning direction, the "stress vs. position" of each scanned line and of the stress data for the line presently under scanning. The commands allow to optimize the sensitivity for the receiver, using a gain specific to each channel, and a common gain to adjust the actual sensitivity of the sampling card according to the amplitude on the incoming signals. The probe position is controlled by the motorized actuator.

7. Further development

Automation of the algorithm to analyze each gathered waveform, check the calibration required to the reliable evaluation of the stress condition, measure the time of flight of each polarized wave, and evaluate the residual stress condition, were the main improvements of the system. Further development of the system performance has been particularly focussed on the following objectives settled according to each end user's specifications.

- Flexible design, allowing easier system customization, providing different system options from the same ultrasonic hardware, and form the same customer: single manual, single automated, twin stationary automated. Fig.5 outlines the twin system designed for BHP-Billiton Iron Ore, where two single Ecomat-ST can be synchronized to a scanning equipment for evaluation of wheelsets in the car maintenance shop. Fig.6 shows the user interface implemented to monitor a wheelset inspection.

- Design and manufacture of the scanning devices to increase the automation of the stress test. The mobile manipulator in Fig.3 was designed to implement a portable automated application for exploitation by Trenitalia in its car maintenance shops.

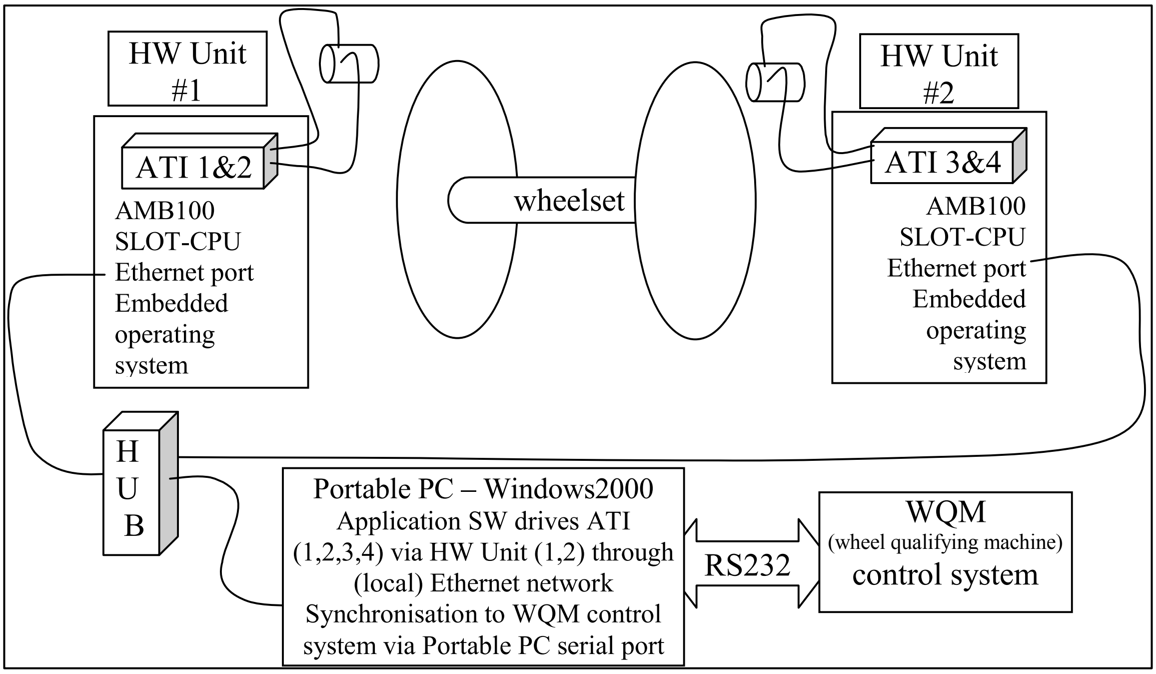

Fig.5 – Architecture of an Ecomat-ST synchronized to the machine allowing wheelset qualification.

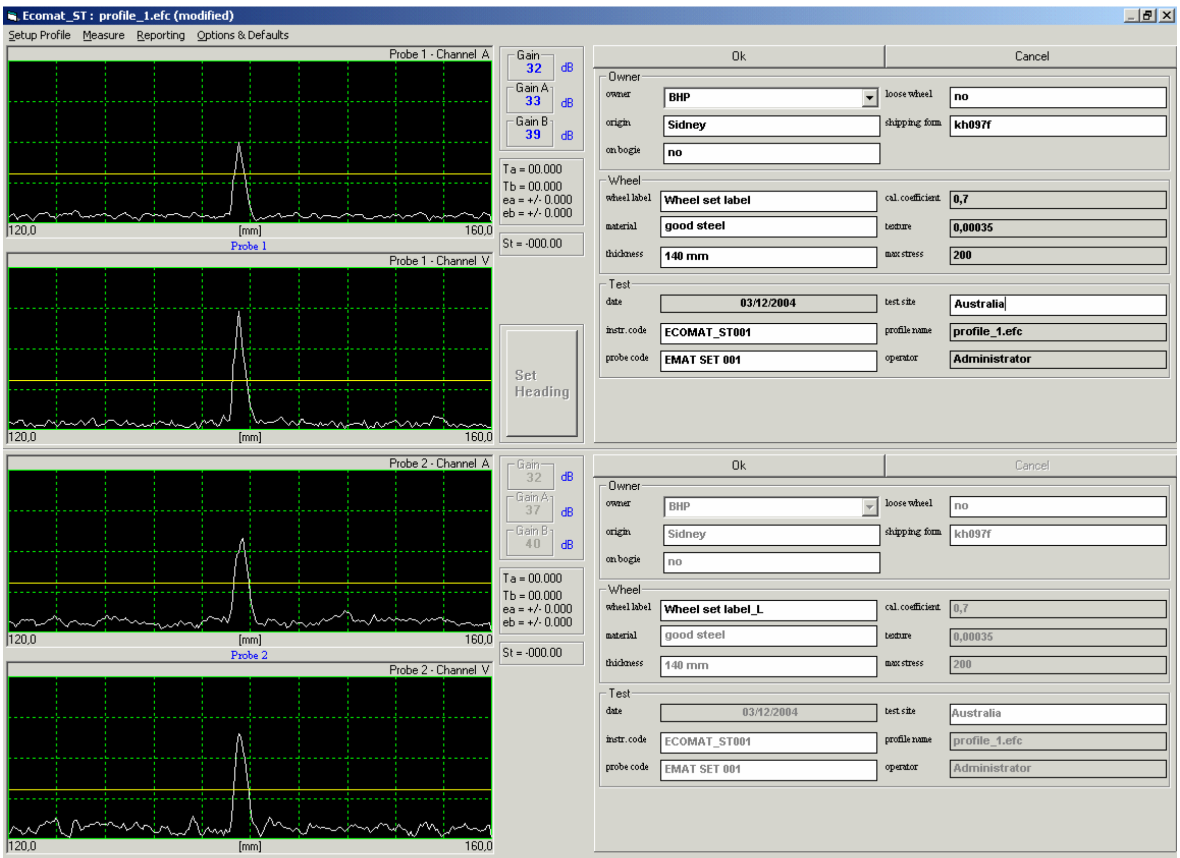

Fig.6 – User interface of BHP-Billiton system: two EMAT units can jointly operate to test a wheelset

Conclusions

Ecomat-ST allows the evaluation of residual stresses in the rim of railway solid wheels. The test can increase the reliability of the rolling stock material, the safety of freight transports, and the overall reliability of the railway network. The exploitation of a stress test system can be particularly useful for railways that move iron ore from the mining areas to transformation facilities.

Ecomat-ST is based on the "no-contact" EMAT sensor approach and exploits the acoustic birefringence of linearly polarized waves with crossing polarization. The dual sensor assembly of the EMAT probe enables both polarizations without any probe rotation. During lab tests the system demonstrated to ensure a stress accuracy of 10 MPa.

In the recent development phase the objective was to integrate and improve the performance of the system, particularly the automation and speed of the test process, the design of motorized scanning manipulators to increase the productivity, with the aim to optimize the reproducibility and objectivity of the test.

For the further exploitation of the system, the size and the weight of the overall equipment is of prominent importance, especially for portable applications; a system customizable in terms of performance and price will help broadening the exploitation of the railway wheel stress evaluation, from institutional railways to private railway users and independent car maintenance shops. The improvement of digital electronic components is monitored as it should provide in the next future standard devices useful to design compact and cheaper stress evaluation systems for the railway users.

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