COBEM 99
XV Congresso Brasileiro de Engenharia Mecânica
15th Brazilian Congress of Mechanical Engineering
22 - 26 de Novembro de 1999 / November 22 - 26, 1999 Águas de Lindóia, São Paulo,

APPLICATION OF ACOUSTOELASTIC TECHNIQUES TO RAILROAD WHEELS STRESSES DETERMINATION

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Abstract. *Railroad wheels fails in two main modes: rolling surface defects like spalling, shelling and wear, and internal defects including cracks propagating after the change in the original stress pattern. Although the former is more usual, the effects of the later are almost always catastrophic. The main method of verifying how dangerous it is to leave a stressed wheel in service is the observation of the change in the rim colors, and how much it goes toward the hub. Several researchers have contested this method. Recent researches came along with new applications of the ultrasound in the identification of the dangerous wheels, based on acoustoelastic properties of the materials. Two methods of generating ultrasonic waves have been tested to map the stresses in the wheels, one using electromagnetic acoustic transducers (EMAT) and the other using piezoelectric transducers (PZT). The proposal of this work is to review the previous works, and discuss the state of art in this field. The basic theory is described. The results obtained in the current research are shown and a comparison between the methods is done. The perspectives for the practical implementation of these methods in the field and the difficulties in doing it are pointed out.*

Keywords: *Railroad wheel stress, ultrasonic techniques, nondestructive stress measurements.*

1. INTRODUCTION

Railroad freight cars wheels are subject to mechanical and thermal loads during the normal operation. The main mechanical loads are due to the weight and the driving forces. The great magnitude of the transported weight is one of the main advantages that rail transportation has over the others forms of land transports and the increase in this value has been one of the challenges of the applied research around the world. The driving force is usually lower than the vertical weight force. In extreme situations this load combines with other solicitations given rise to bending stresses in the plate of the wheel. Both loads contribute to the existence of contact failures, the first one can cause shelling on the rolling surface (tread) and the second one can induce the formation of cracks on the wheel flange. Thermal loads arise from the braking process. In freight cars the wheel works as a brake drum. The objective of the braking is to take out the kinetic and potential energy of the train. In this kind of brake system most of the energy is transformed in heat. Part of the heat flows to the wheel rim and creates a temperature gradient in the radial direction. The heated rim tends to expand and the plate, still cool, tends to restrain the rim movement. The difference in deformation between these two parts of the wheel is responsible by the rising of radial stresses in the plate. Also, the constraint causes hoop compressive stress in the rim, because the expansion in the circumferential direction requires an increase in the mean radius of this part. The stresses caused by braking process are called thermal stresses. It's usual to mislead the residual stresses caused by thermal stresses, sometimes wrongly called thermal stresses. The magnitude of mechanical stresses is usually less than thirty percent of the thermal stresses.

1.1. Residual stresses

When the rim is heated by braking loads and its movement is constrained by the cooler parts of the wheel, the combination of the thermal and mechanical stresses can cause portions of it to yield. Usually the thermal stresses alone are required to cause plastic deformation, and the effect is axis-symmetric along the circumferential direction. In this case, a new stress pattern arises when the wheel cools.

Two manufacturing processes are used to make wheels: forging and casting. In the first, a steel block typically is forged by a 6000 ton. weight In the second one, a mold is built to contain the liquid steel until the final form is obtained. In both methods, the wheel tread is quenched to achieve the final surface strength. A posterior finish by machining is required. The quench process creates compressive stresses in the new wheels and virtually all wheels are put on service with a safe stress pattern in the rim.

The sum of the initial compressive pattern and the thermal stresses caused by braking is the actual value of the circumferential stresses in the rim during the braking in new wheels. If this value is high enough for yield to occur, the stresses are relaxed in high temperature and the magnitude of the original compressive stress decrease, and a tensile pattern may arise after cooling. Posterior braking using the same power or lower won't cause further yield. This explains why the wheels usually have the inversion of the original stress pattern in the beginning of their life. The wheel life usually ranges from 400000 to 1.2 million kilometers.

1.2. Problems related to wheel stresses

There are three main problems related to residual stresses in the wheel: spalling, shelling and sudden fracture. Spalling is caused by the change in the material structure in portions of the tread. This change occurs when the hot tread quenched by the cool rail. Only the portion in contact has its structure changed. The original structure in the tread is fine perlite and it can become bainite or even martensite. The movement of the train and the presence of hoop tensile stresses can help small surface cracks to propagate around the new structure formed, causing the piece of the material to fail off.

Shelling is caused by contact stresses. It occurs when a surface check propagates in the direction of maximum shear stress. It happens at 45^o with the normal to the surface. The shells created usually disappear after few wheel revolutions because the checks are in a fine layer near the surface. The propagation of these small cracks depends on the plastic deformation in their tips and it is likely to occur at higher temperatures, like those caused by the braking process. Besides, the presence of a residual tensile stress pattern in the circumferential direction will permit that those cracks to propagate deeper toward the plate, causing greater damage.

Sudden cracking is the most dangerous kind of problem in the wheel. The change in the original compressive stress pattern can lead to a sudden cracking when the train is moving. The effects of the resulting derailment can be catastrophic. It occurs when a crack that originated either in the tread or in another portion of the rim gets in a residual tensile stress field. Preventing this kind of failure is very difficult because there is no easy way to identify highly stressed wheels in the field.

1.3. Identifying dangerous wheels

Most of the Railway maintenance systems identify the overstressed wheels by the change in the color of the outside rim face. When a wheel is overheated, the material oxidation changes the color in the surface of the rim. The deeper the change in colors, the greater the thermal damage. The criteria to take a wheel out of service is that an overheated wheel is overstressed, i.e. it has enough hoop tensile stress to crack suddenly.

Schramm et al. (1995b) showed that about fifty percent of the wheels removed from service in the United States could still continue in use. The criterion causes the loss of money (about 90 million by year at USA) and drives the need for the development of new methods to identify overstressed wheels.

Destructive methods can't be used in this case and a statistically approach can not identify what wheel will fail, even knowing that a certain number of wheels will fail in a predetermined time. A new method to prevent overstressed wheels in service should be developed. It should be economically feasible but reliable enough to be used in this application. Non-destructive techniques have been used to measure stresses since the beginning of 70's. Neutron diffraction, X-rays and ultrasound are the main methods used nowadays. The first one is very expensive and still requires complex instruments and special protection to be used. The X-rays can measure stresses in a short depth below the surface of the material, and also uses a very expensive set of instruments (Kippa, 1998).

Ultrasonic is a non-destructive technique based in the sound propagation through the body where the stresses should be evaluated. It has been used in the determination of rail stresses (Egle & Bray, 1976) for 30 years, but only recent developments in the instrumentation enlarge its field of application. Since 1984, ultrasound has been tested to measure railroad wheel stresses in workshops, and now portable systems are been developed.

1.4. Objective

The objective of this work is to present the state of art in the research in the use of the ultrasound in the stress determination in railroad wheels. The theory of the acoustoelastic phenomenon is discussed and the current development published by all groups that work with this subject around the work is presented. Results are discussed and comparison between them is done. The perspectives for actual and future use of the systems are pointed out.

2. BASIC THEORY

Wave propagation in solids is based in the transmission of the movement between adjacent particles. An impulse can be exited in one surface of material and captured in another surface after going through a path inside the body. Acoustoelastic theory states that the elastic properties of the material are related to the wave speed going from the source of the impulse into the surface of interest. Two kinds of waves are used to stress determination: longitudinal and shear waves. In the former the particle movement is parallel to the wave propagation. It is also called a compressive wave and is used for subsurface stress determination. In the later, the movement of the particles is primarily in the direction perpendicular to the propagation. It is used to bulk stress evaluation.

2.1. Birefringence

The stresses can be evaluated using acoustic birefringence theory. It states that the birefringence is related to the speed of the shear wave propagating inside the material and to the stress field. According to Okada (in Schramm et al., 1995b) its value is defined as:

$$B = \frac{2(V_\theta - V_r)}{(V_\theta + V_r)} = \frac{2(t_\theta - t_r)}{(t_\theta + t_r)} \quad \textbf{(1)}$$

Where: B = Birefringence
V_θ = Velocity of the shear wave polarized in the θ direction
V_r = Velocity of the shear wave polarized in the r direction
t_θ = time-of-flight of the shear wave polarized in the θ direction
t_r = time-of-flight of the shear wave polarized in the r direction

The directions r and θ in the equation 3 are orthogonal and are the principal axes. In this case, the relation between the stress field and the birefringence (B) is:

$$B = B_0 + C_t.(\sigma_\theta - \sigma_r) \quad \textbf{(2)}$$

Where: B_0 = Birefringence, unstressed state
σ_θ = Stress in the θ direction, MPa
σ_r = Stress in the r direction, MPa

Equation 4 shows that the acoustic birefringence is proportional to the difference in the stresses in two orthogonal directions. The unstressed birefringence is related to the material texture and it express the original difference in time-of-flight in the absence of stress in both directions.

2.2. Generation of Ultrasonic Waves

Two main kinds of fixtures are used to generate ultrasonic waves: piezoelectric (PZT) and electromagnetic (EMAT).

PZTs (or PETs) are transducers based in the fact that some crystals generate potential difference between their faces when excited by a pulse and the inverse is also true. A source of high voltage is connected to these transducers and they oscillate in their natural frequency when an electrical pulse is excited. The pulse is transmitted between the surfaces generating the wave when the probe is in contact with the material to be inspected. The wave propagates through the material and can be received by a second transducer on another surface or its echo can be received by the same transducer. A couplant is required to transmit the pulse to the material to be evaluated. The couplant is the most important difficults in the use of PZTs. Air isn't a good transmitter for ultrasonic longitudinal waves and can't be used to shear waves. Couplants to L_{CR} waves transducers are gels or similar substances and for shear waves they have to be denser products, like honey or either synthetic resins. No matter what couplant is used, the change in temperature always influences it in some magnitude. The repeatability of the measurements is influenced by the couplant thickness too.

EMATs generates the wave using induction. A probe is made with coils and the impulse is generated by their excitation. Placed near the surface, the coils can induce the pulse in the specified frequency without contact with the material. No couplant is necessary. The main difficulty in the use of EMATs is to get the electronic instrumentation necessary. The signal attenuation is high and an amplifier is required. The size and weight of the components are a limitation too.

3. STATE OF ART

Five main research groups work in the development of ultrasonic systems to be used in the evaluation of wheel stresses. These groups work basically in the USA and Europe. The objectives and the stage the researches are different. Each one is discussed below.

3.1. EMAT Applications

The researchers around the world have preferentially used EMATs because they have been looking for a system to be used in the field, where couplant could be a problem. As discussed above, EMATs don't require the use of couplant and it is the main reason to choose it. Besides, a number of new EMATs applications have been developed in the last few years, specially in extremely poor conditions. Also it can be used to generate both shear and longitudinal waves (Alers, 1998). The following research groups work with EMATs.

Fraunhofer-institute for nondestructive testing – IzfP (Germany). The IzfP has developed a system able to measure the stress variation along a radial direction in the rim of wrought wheels (Herzer et al., 1994). The system consists in a EMAT transducer, one motor to move the probe along a radial trace in the outside rim face, another motor to turn the probe when changing the plane of propagation for the shear wave and a data acquisition and control set. The probe weights about 12 kg and it's been used in the Austrian, Swiss and German railroad applications. The objective is to evaluate the residual stresses in the whole rim and not only in a specified position.

Figure 1 shows the position of the transducer in two extreme sides of the radial direction (Schneider at al., 1996). In this figure, the internal lines represent the stresses in the rim of a heavily braked wheel. The wheel was tested in a braking test stand. As can be viewed, the maximum stress occurs near the upper corner of the outside rim face. It is a characteristic of the wheels used in Europe. Another special characteristic is the kind of process used in the fabrication. Europeans Railroads usually have only wrought wheels with a special kind of steel (R7). This kind of process leads to a small difference in the grain orientation (texture).

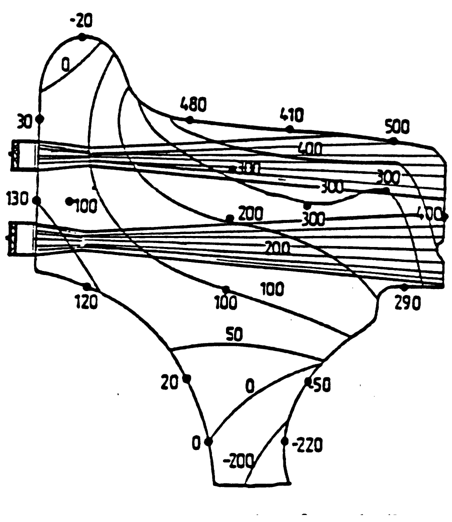

Figure 1 - *Scheme of the extreme positions of the transducer and calculated stresses for heavily braked wheel (Schneider et al. 1996)*

The influence of the texture in the measurement of stresses is significant. Schneider and Herzer (1998) presented the result of a study in 60 wheels were they evaluated the texture in used and new wheels. Also, they evaluate old wheels made with different materials. A modification in the previous control system was done to determine the influence of the texture. The system should be able to evaluate the amplitude of the signals when scanning the rim face. Figure 2 shows the result for two wheels, one of the new type and another with old materials. As can be seen, the amplitude in the new type wheels (solid line) is larger than in the old type (dashed). After the amplitude evaluation, the normal tests to measure the TOF are performed in positions where the amplitude is larger than a specified threshold. The tests can't be performed in cases where no value is greater than the threshold.

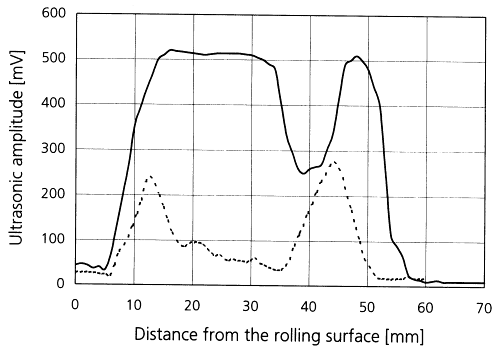

Figure 2 - *Wave amplitude in wheels: new (continous) and used (dashed). (Schneider & Herzer, 1998)*

The result for wheels in similar braking condition is quite equivalent one to another. Figure 3 shows the graph of the results in one wheel after a sequence of braking (Schneider & Herzer, 1994). The lower level of stress is for the new wheel. Posterior applications of brake give rise to higher stresses. No increase in the stress level is expected with the application of any of the previous braking rates after the application of 50 kW for 45 minutes.

The system developed by the IzfP is nowadays the reference for studies in this field. The accuracy is ± 20 MPa and the pulse frequency is 2 MHz. It has been applied in the maintenance shops and in the quality control since 1992. Between 1992 and 1993 about 27000 wheels were tested to verify the accuracy of the method (Schneider & Herzer, 1994). A new portable system has been tested in the field. The main difficult of this method is its use to evaluate cast wheels, because the influence of the texture is greater in this case.

CISE \ Lucchine Siderurgica & Italian Railway FS (Itally). Gori et al. (1998) developed a new kind of EMAT called ECOMAT. It has been developed for industrial applications and adapted for railroad applications. The first objective of this research was to build a system that could be used in the quality control in railroad wheels factories. The transducer is a dual coil 4 MHz probe connected to an AMB100 (100 MHz) board placed inside a PC computer. The dual coil permit the variation in the plane of propagation of the shear waves without turning the probe. The same R7 steel wheels were tested.

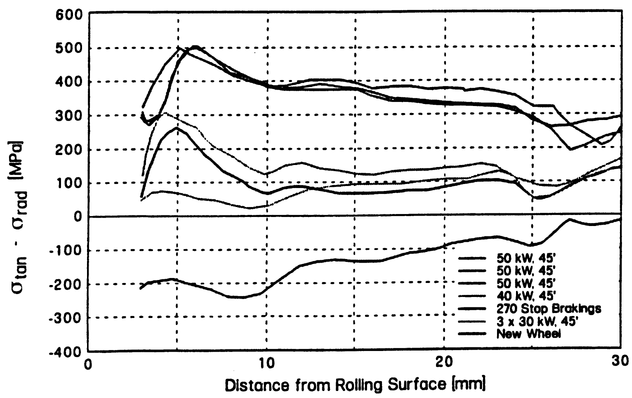

Figure 3 - *Stress in railroad wheel subjects to several sequential brakings. The sequence of the test results is from bottom to top (Schneider & Herzer, 1994)*

Three wheels were cut to determining the influence of the texture (820, 920 and 1240-mm diameter). The results show that the method is sensitive to the release of the initial compressive stress state in all wheels. The stresses calculated using strain gages are in good correlation with the ultrasonic data (± 10 MPa).

Another set of 3-new and 34-used wheels were tested. The results show a short difference between the maximum and minimum values found and the average results for stresses can be related with the wheel age.

AAR - TTCI \ NIST (USA). The National Institute of Standards and Technology (USA) has studied the application of ultrasound in the stress measurement since the middle of the last decade (1986). The objective was developing a system that could be used in the machine shops around the United States. Association of American Railroads - AAR sponsored the work, with a contribution of one-wear cast wheels by Griffin Wheel Company.

The work began with the development of a probe made with EMATs (Schramm, 1998a). Two coils were installed in a case to generate polarized shear waves in radial and circumferential direction. The transducer can be view in the figure 4. The position of the transducer is showed in the figure 5 (EMAT or PZT). It has two magnets to hold the same position during the measurements. The transducer is built to conform to the outside rim face, so it can be placed in the same position no matter what wheel is been measured.

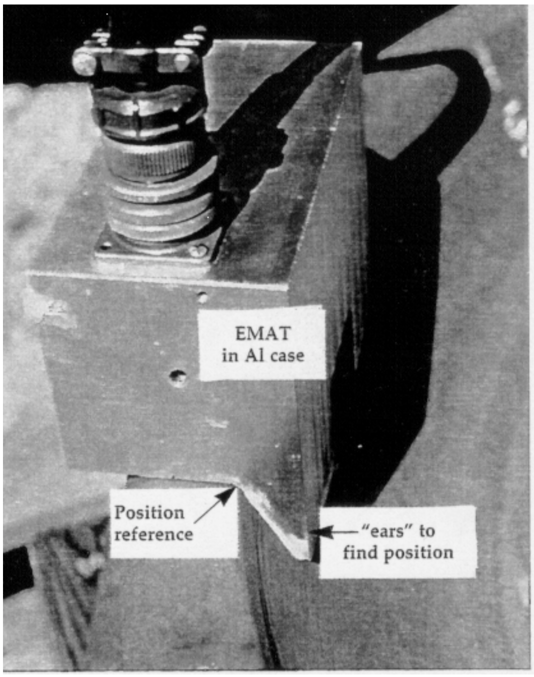

Figure 4 - *EMAT transducer built by NIST (Schramm, 1998a)*

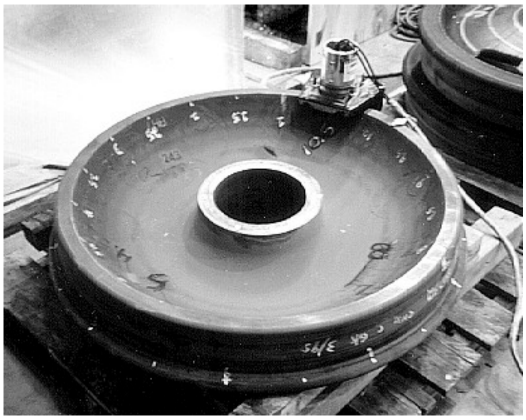
Figure 5 - *Position of the sensors in the surface of the wheel rim*

A personal computer (notebook) controls what plane of the propagation is used through a switch in the same case that contains the pre-amplifier. A pulse-receiver excites the transducer and an eight-bit board (40 MHz) acquires the signal. The computer calculates the stress and shows the value in the screen. The operator can decide if the wheel is overstressed or not comparing the value to a threshold previously defined. .

The first set of wheels tested by the NIST researchers was composed by ten railroad wheels (Schramm et al., 1995a; Schramm et al., 1996). An induction coil fixture was used to heat the wheels: three at 45 kW, three at 42 kW, two at 38 kW and two weren't heated and stay as new. The Transportation Technological Center (TTCI) provided wheel rim slices and those were used to calibrate the birefringence in the unstressed wheel. There was a great dispersion in these values and it stimulates a study about the axis-symmetry of the induction coil heating. The study showed that the heating wasn't symmetric and that the position of the transducer in the circumferential direction was able to detect this non-symmetry. Figure 6 shows the results for as-manufactured wheels and Fig.7 shows those heated at 45 kW. It can be noted that there is a direct correlation between the stresses calculated using acoustoelastic theory and the heating power. Saw-cut tests were performed to verify the calculated stress and they proved the values obtained.

NIST performed the measurement in a second set of wheels heated by constant braking (Schramm et al., 1995b). The tests are described in the table 1 where the terms flange (f) and

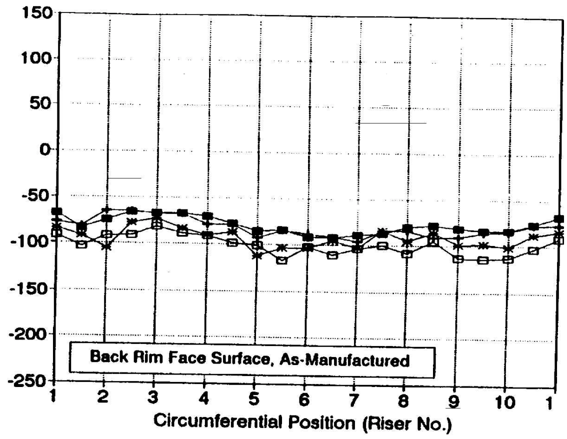

Figure 6 - *Stresses (MPa) measured by EMAT in four new wheels in relation to the circumferential position (Schramm et al.,*

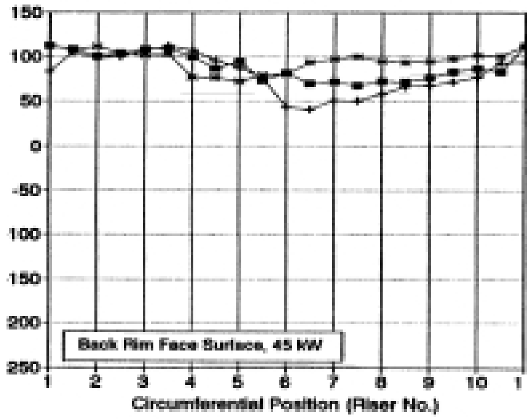

Figure 7 - *Stresses (MPa) measured by EMAT in three wheels after application of 45 kW braking simulation (Schramm et al, 1995a)*

center (c) means the position of the brake shoe in the wheel tread. Figure 8 shows the results of the tests performed according to table 1. Following destructive saw-cut tests confirm the good correlation between the power and the stresses. Although the results are representative of the real condition, the dispersion found due the texture needs to be better studied.

Table 1 Summary of the runs on dymamometer

Kind of Run	Power, kW	Number
	56 (f)	2
	60 (f/c)	4
3 x 30 min	63 (f/c)	4
	67 (f/c)	4
	75 (c)	2
3 (shoe wearout)	63 (f/c)	4

Kristan and Garcia (1998) compared the results obtained by EMATs with a model of finite element in induced heated tests. Figure 9 shows the results. It can be seen that the correlation between the stresses evaluated by both methods is good, although the values differ in about thirty percent. The work was done at Transportation Tecnological Center Inc. and the NIST's system was used. This figure also shows the data obtained for PZT measurements discussed below.

3.2. PZT Applications

The use of PZT is largely known in determination of voids and cracks. The same kind of instrument has been used to measure stresses in wheels (Schramm, 1995b). The stability of the couplant and the required clean surface are the main difficulties to be overcome.

Polish research. By the time the EMAT system was evaluated at NIST, a Polish PZT system was tested too. Professor Jacek Szelazek and fellows built it in the Polish Academy of Sciences. The results obtained with the system were compared to EMATs signals and showed an extremely good correlation with them. Also, the dispersion obtained was smaller than those obtanined with EMAT. Figure 10 showed the correlation with Finite Element Model also. The results for the same condition showed at figure 8, but using PZTs, are showed in the figure 10. These results indicate that there is strong evidence that PZTs can be used since the couplant problem be solved.

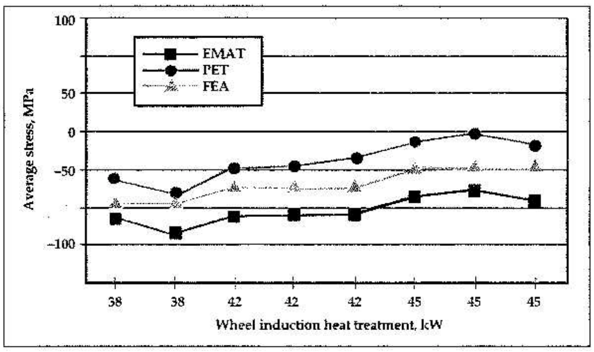

Figure 8 - *Results of the stress measurement by EMAT (Shramm, 1998b)*

Texas A&m University and State University at Campinas (Unicamp). A second research group began to work with PZTs at the end of 1998. This group is composed by researchers from Texas A&M University (TAMU) and State University at Campinas (UNICAMP), both working at TAMU. Griffin Wheel Company provided 10 wheels to be tested at the similar way NIST tested previously. Only two wheels would receive each power level. The remaining two would be cut and used as stress free blocks. The work is been developed since at the beginning of 1999 and at the present time two blocks of wrought steel wheels were tested to identify the texture influence and calculate the birefringence in two orthogonal directions. The values for both measurements are B_2 = $9.398.10^{-4}$ and B_3 = $13.576.10^{-4}$. These results show the difference between the birefringence when the same radial position is tested. There is a strong influence of the radial position of the sensor in the blocks tested (Bittencourt at al., 1998).

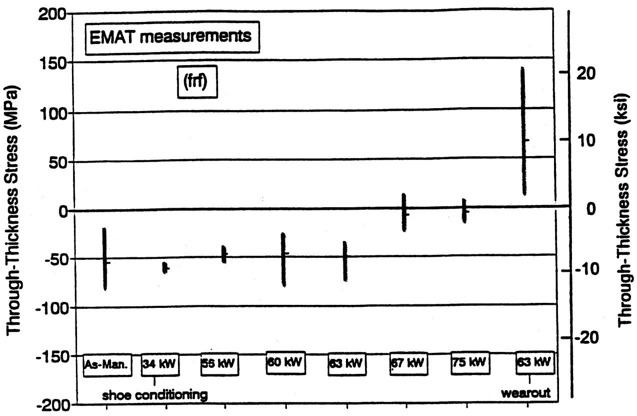

Figure 9 - *Comparision between Finite Element Model and Measured Stresses wit EMAT and PET (Kristan & Garcia, 1998)*

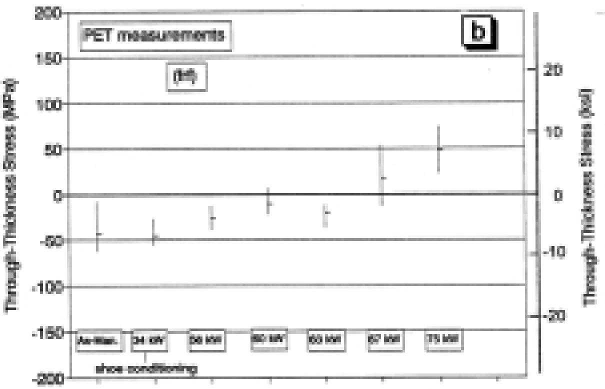

Figure 10 - *Results of the Stress Measurement by PZT (Schramm, 1995a).*

4. CONCLUSIONS

Ultrasonic evaluation is a powerful tool to be used as a nondestructive method of stress determination. Researchers around the world show that it is possible to identify dangerous wheels and take them out of service in a suitable time. Several research groups are still working in the development of new techniques or in the improvement of the existed ones intended to build a reliable and cost-effective system to be applied in maintenance shops.

EMATs are the most used kind of transducer but PZTs can be used too. Both techniques have disadvantages: the former has a small signal-to-noise ratio and the later requires the use of couplant.

This work showed the state of art in the research about ultrasonic wheel stress measurement. Although none of the groups had finished their studies, one of them has applied the initial results in tests at maintenance shops (Germany); Americans are testing the first prototype and Polish already have a commercial system available. The others are still developing their systems but the initial results indicate that they will be useful soon.

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