WHEEL RIM RESIDUAL STRESS MEASUREMENTS

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ABSTRACT

Beneficial, as-manufactured, residual compressive stresses in wheel rims are introduced during the rim quenching operation. Such compressive stresses are known to help inhibit the formation of rim fatigue cracks and thus are important to wheel safety. This paper describes measurements of stresses in new wheel rims at a wrought wheel manufacturing facility, and also use of rim stress measurement for used wheels on the French National Railways (SNCF) and Belgian National Railways (SNCB). Ultrasonic stress measurements made using commercially available Electro-Magnetic Acoustic Transducer (EMAT) and Piezo-Electric Transducer (PET) systems are described. The implications of wheel rim residual stress on wheel service performance and the potential for use of wheel rim residual stress measurement techniques in North America are discussed.

INTRODUCTION

During the wheel manufacturing process after forging and rolling, wheels are austenitized, the rims are quenched with water spray and wheels are subsequently tempered. The rim quenching process (known as heat treating) results in beneficial circumferential (hoop) residual compressive stresses in the wheel rim. These compressive stresses are useful to help prevent rim fatigue cracks in railroad service and are thus a significant safety benefit for the user.

For residual compressive hoop stresses to result in the rim from the rim quenching operation, plastic (permanent) deformation must take place. When the water spray quenches the hot, austenitic wheel rim, the rim cools and shrinks inwards. However, the steel below the quenched region is still hot (thus larger than at lower temperatures) and has a reduced yield strength at that temperature. The inner fibers of the rim and the plate are upset in compression by the colder, outer rim fibers and yielding occurs. Upon cooling of the entire wheel, the inner rim fibers and plate are now smaller than they were originally due to the compressive yielding. However, such areas try to fit into a larger space. This results in the lower part of the rim and the plate being in tension while the outer portion of the rim is in compression.

In railroad service the wheel acts as a brake drum in addition to supporting lateral and vertical mechanical loads. When brake shoes are applied to the wheel tread the surface is heated due to friction. The steel at the tread surface gets hotter, tries to expand and is constrained by the colder body of the wheel rim and plate. If the tread surface is heated to a high enough temperature by braking, the steel will have a reduced yield strength, and plastic deformation caused by expansion and compressive upsetting of steel in the hot zone is possible. After cooling and shrinking, continuity must be maintained between the locally yielded material at the tread surface and the constraining remainder of the wheel. Therefore, the material at the tread surface is now in tension. In severe cases of braking heating, complete stress reversal of the rim could take place. Both of these situations will allow for propagation of service related fatigue cracks in the tensile zone.

Stone, et al. (1999) reported that the number of wheel-related derailments has decreased by an order of magnitude since AAR required that rim quenched, curved plate wheels be used. Studies have shown that wheel fracture occurs when a service induced crack is exposed to a large enough tensile stress (Opinsky, 1982 and Stone, Pellini and Harris, 1986). Clearly the use of rim quenching to impart beneficial residual compressive hoop stress is an important part of the noted improvement.

Although the number of derailments caused by wheel thermal failures is quite low, use of a nondestructive method to measure the stress state of the wheel rim will have safety benefits for railroads. The traditional saw cut method is able to qualitatively determine if a wheel rim is in tension or compression, but the wheel is destroyed. A simple, practical way to find “problem” wheels with tensile stresses near the tread surface would be useful, particularly if such measurements can be performed in the field or in a railroad car repair shop.

PAST RESEARCH EFFORTS

In recent years there has been considerable interest in use of nondestructive inspection techniques to evaluate the residual stress state of railroad wheel rims. Much research work has taken place around the world and numerous technical papers have been written.

Schramm, Clark and McGuire (1992) presented a paper at the 10th International Wheelset Congress that dealt primarily with the use of birefringence to detect and quantify stress in wheel rims. The paper suggested that Electromagnetic Acoustic Transducers (EMATs) were likely to be useful for field instrumentation. These authors, and others at the National

Institute of Standards and Technology (NIST) in Boulder, CO, performed significant research on the subject of nondestructive testing of railroad wheels and produced many detailed NIST reports during the late 1980's and into the mid-1990's. All of this work was done using cast wheels produced by one North American manufacturer.

Further work by Schramm, Szelazek and Clark (1996) described ultrasonic stress measurements on cast wheel rims using EMATs and more conventional piezoelectric transducers (PETs). Induction heating of the wheels changed the rim stress state from compression to tension and this was noted by the instruments. Agreement between the two instruments was found to be good, and a comparison of the saw cut tip opening displacement (opening increases – tension, opening decreases – compression) with change in average bulk stress found using the PET instrument was also performed. The results showed that nondestructive techniques matched the saw cut opening for 9 of the 10 cast wheels.

A more recent article by Kristan and Garcia (1998) summarizes the work at NIST that had been supported by the Association of American Railroads (AAR). This paper states that the EMAT system has demonstrated accuracy and reliability, and that there is good correlation in measurement trends found using the PET and EMAT system. Good correlation between finite element analysis (FEA) results and PET ultrasonic data was also shown.

German investigators have also studied the use of ultrasonic techniques to evaluate forged wheel rim residual hoop stresses (Schneider et al., 1992). Additionally, this paper presents the results of a European cutting and sectioning technique that allows for creation of a residual stress "profile" for the wheel rim. Residual stress measurements were taken for wheels before and after various braking cycles. Compressive residual stresses became more tensile after the braking cycles.

French researchers investigated the use of residual stress measurements for new wheels as part of the manufacturing process. Del Fabbro and Catot (1995) describe the use of the birefringence technique in an automatic machine that is part of the wheel production line at Valdunes. This machine is therefore able to insure that wheel rims have compressive residual stresses after the heat treating process is complete.

A recent ASME paper by Gordon and Perlman (1998) provides significant insight on the residual stress profile of an as manufactured 32" reverse dish forged commuter car wheel. The authors used computer FEA methods to simulate wheel quenching and tempering processes and were able to quantitatively describe the resultant state of stress throughout the wheel cross section. Parameters used in the computer model including temperatures, quench times, temper times etc., were confirmed with a wrought wheel manufacturer. Simulation results show that there is a residual stress gradient within the rim with the maximum as-manufactured compressive hoop stress found closest to the tread surface. The magnitude of residual compressive stress decreases as the depth below the tread increases and eventually, well down into the rim section below the condemning limit, the residual hoop stresses become tensile. Figure 1 is a schematic of a radial wheel section showing finite element analysis residual hoop stress results for a wheel after quenching, tempering and cooling steps are complete (Gordon and Perlman, 1998). The area near the tread is the most compressive.

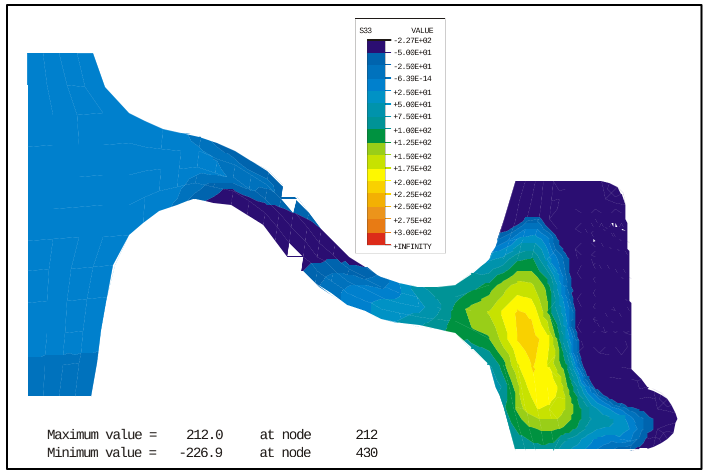

Figure 1. Radial section hoop stress plot for a new wheel.

Another ASME paper by Gordon, Jones and Perlman (1998) describes the effect of passenger car service braking on the residual stress state of the wheel rim. This FEA simulation work showed that predictions of rim stress reversal are possible and that depth estimates of stress reversal agreed well with thermal cracks noted on wheels of certain passenger cars.

THEORY OF OPERATION - BIREFRINGENCE

The principles of birefringence, which allow for measurement of residual stresses in wheel rims, are well known and have been described in the literature. A stress change in a material results in a change in the speed of ultrasonic waves passing through that material. The difference in the wave speeds in the hoop (circumferential) and radial directions allows calculation of the stress state of the rim. For the residual stress measurement systems used by Valdunes (PET and EMAT), the appropriate equations are:

$$B = K(v_r - v_c) \text{ and } B_m = B_o + B$$

B	= the birefringence due to stresses
K	= a proportionality factor in MPa/(m/s)
vr	= wave speed in the radial direction, m/s
vc	= wave speed in circumferential direction, m/s
Bm	= the measured birefringence
Bo	= birefringence due to elastic anisotropy

Since anisotropy means that a material has directional properties, there can be variation in properties within a material due to forging, heat treating, etc. Valdunes found the effect of structural anisotropy to be very slight and they use a proportionality factor K of 1 m/s = 43 MPa for Class C steel (Del Fabbro and Catot, 1995). Normally the K factor must be determined for each different grade of steel. Since there is a gradient of residual stresses within the rim that changes with depth below the tread surface, any nondestructive measurement made from the front or back rim face produces an average of the bulk residual stresses across the rim width.

EMAT vs. PET COMPARISON

Although the EMAT and PET systems owned by Valdunes are quite similar and operate using the same basic ultrasonic principles, there are several advantages to EMATs as follows:

1. No couplant is required.
2. The transducer does not need to be manually turned in the radial and circumferential directions.
3. A stress value is automatically calculated by the computer.
4. The EMAT system is computer based and is easier to use.

Recently comparative testing of new wheel rim residual stresses was conducted at Valdunes using portable EMAT and PET systems. Calibration was accomplished on a stress relieved rim block and the PET system registered 0 MPa while the EMAT calculated a value of +30 MPa. Four different wheel designs were tested, and agreement between the two systems was found to be quite good. All measurements were taken using the front rim face. Photos of the PET system (Figure 2) and the EMAT system (Figures 3 and 4) are shown. Test results are contained in Table 1.

Figure 2. Using the PET system on the front rim face.

A measurement could not be taken using both systems at some matching depth locations (see Table 1). This is due to the large transducer diameter for the EMAT system and problems getting the correct back echo near the witness groove or geometry change with the ultrasonic system. Note that there is good agreement between the two measurement techniques, and that rim stress values become more tensile as the depth below the tread surface increases.

Figure 3. The EMAT transducer on a front rim face.

Figure 4. A photo showing the portable EMAT computer.

Wheel Type	Depth below tread (mm)	PET stress (MPa)	EMAT stress (MPa)
D42	10	-155	-140
	20	-112	-115
	25	-65	---
	35	0	-40
	45	---	16
E40	10	-185	-170
	15	-112	-120
	20	-69	-83
	25	-64.5	-60
H36	15	-164	-140
	25	-108	---
	Near ID	---	-35
32RD	15	-190	-143
	25	-151	-95
	35	-56	-45
	40	-39	-12

Table 1. Comparison of residual stress results using the portable PET and EMAT systems.

If correlation measurements are made on the same wheel using both the front and back rim faces, care must be taken to insure measurements are at the same depth value below the tread surface. For both PET and EMAT systems, measurements were found to be very sensitive to parallelism of rim faces. Testing of a non-machined, as-rolled wheel did not yield valid results. Measurements were also found to be sensitive to the surface condition of the wheel rim face and grime, rust, etc., can affect results obtained.

USE OF RESIDUAL STRESS MEASUREMENT EQUIPMENT AT VALDUNES

Valdunes currently has an automated EMAT residual stress measurement system at their plant in Valenciennes, France. This system takes measurements at 10 different locations on the back rim face of the wheel beginning at 10 mm below the tread surface. Handling equipment automatically brings the wheel in for inspection by the EMAT system and data are collected by a computer. Photos showing the equipment are shown in Figures 5 and 6.

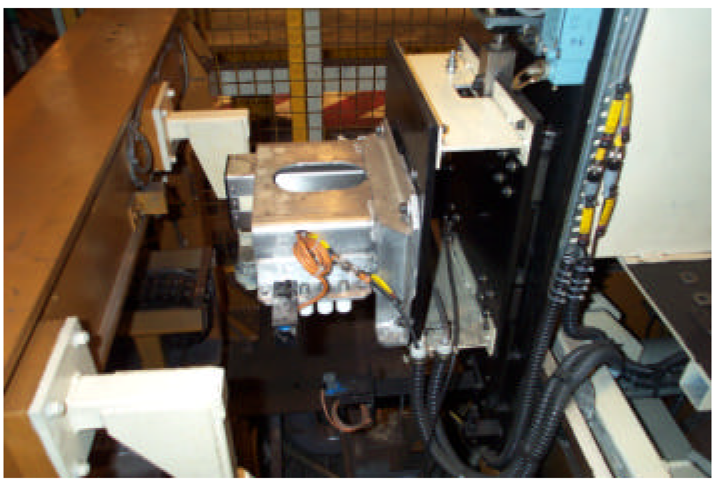

Figure 5. Close-up view of the EMAT device used to measure wheel rim residual stresses at the Valdunes plant.

Figure 6. The computer cabinet for the EMAT system.

For wheels produced for European service using the European Committee for Standardization (CEN) specification, 100% of the wheels are tested for rim residual stresses during the manufacturing process at Valdunes. The residual stress results shown in Table 1 are typical values for newly manufactured wheels.

USE OF RESIDUAL STRESS MEASUREMENTS ON EUROPEAN RAILWAYS

As with other railways in Europe, the French National Railways (SNCF) has experimented with residual stress measurement techniques for many years (Vionnet, 2000). This research began after a number of thermally related wheel failures took place on European freight cars with tread brakes. In 1994 the SNCF purchased a prototype EMAT system and began testing new and used wheel rims for residual stresses in their laboratory. In 1996, use of the system in a SNCF maintenance shop began and continued for about 1-1/2 years. Problems with electrical interference in the repair shop led to development of the improved EMAT system that is now owned by SNCF and Valdunes.

Currently SNCF uses the improved EMAT system to evaluate wheel rim residual stresses for wheels that experience demanding tread braking in mountain territory. This system was installed in a SNCF maintenance shop in the spring of 1999. All tread-braked wheels in selected service lanes are tested based upon the number of kilometers traveled by the wheel. If the wheel does not achieve the requisite number of kilometers within 12 years, it is tested anyway. Since the as-manufactured value of residual stresses is known in Valdunes wheels, SNCF is able to monitor the stress state of the wheel rim over time and mileage in service. The particular type of wheel used in this service is removed if the measured circumferential tensile stress is greater than 400 MPa (58 ksi). During the past year, one such wheel has been rejected for excessive circumferential tensile stresses in the rim.

The ERRI (European Rail Research Institute) has established condemning rim residual stress levels for tread braked wheels in freight service. Such residual stress limits depend upon the steel grade and the properties of that grade. Most wheels are condemned if a 400 MPa tensile stress is found, but some wheels are condemned at 350 MPa (51 ksi).

The German, Swiss and Austrian National Railroads are using the residual stress measurement system developed by German researchers in their repair shops (Schneider, 2000). A reported 30 such systems are currently in use by railroads and other European wheel manufacturers.

MOUNTAIN SAFETY WHEEL DEVELOPMENT

The Belgian National Railways (SNCB) has also benefited from the use of wheel rim residual stress testing. Certain tread braked, container carrying flatcars travel in a service lane from Belgium to Italy that passes through France and over the Alps. These cars travel loaded from Brussels or Anvers, Belgium to Milan over mountainous terrain from St. Jean De Maurienne, France to Bussoleno, Italy. From St. Jean De Maurienne to the summit near Bardonecchia the rail line ascends from 535 meters to 1,258 meters elevation in about 44 kilometers. Then, the line descends from 1,256 meters to an elevation of 441 meters in approximately 40 kilometers. Clearly, tread braking on this section is demanding. Figure 7 shows the route used by these cars and Figure 8 is a photo showing one of the flatcars.

Figure 7. Map showing the general route of tread-braked flatcars over the Alps from Belgium to Milan, Italy.

Figure 8. One of the Belgian tread braked flatcars.

Wheels on these flatcars have painted plates, as do many wheels in Europe, so that evidence of overheating from tread braking can be seen. If the paint is burned/discolored, the wheel has been subjected to severe braking. Residual stress measurements made using the EMAT system confirmed that the ORE wheels used under the cars had developed tensile stresses. ORE wheels are those freight wagon wheels originally designed by the European railroads, and such wheels have a relatively straight plate. As a result, Valdunes worked to develop and produce the Mountain Safety Wheel (MSW), which is a specially designed S-plate wheel with better stress response under tread brake loading.

Periodic measurements were made by Valdunes personnel at the railway shop in Belgium to determine the effect of service braking on VMS and ORE wheel rim stresses over time. Figure 9 is a photo showing measurements being made at the SNCB railway shop.

Figure 9. Residual stress measurements at SNCB.

Table 2 shows the data for ORE and VMS wheels after 150,000 km of railway service. Residual rim stress data are shown, along with deflection data. Axial rim deflection (outward bending of the wheel plate) occurs as a result of brake heating on the tread. Note that deflection for VMS wheels is lower than for the ORE wheels.

Values after 150,000 km	**ORE Wheels, %**	**VMS Wheels, %**
Residual Stress		
0 to 100 MPa	11	54
100 to 200 MPa	32	38
200 to 300 MPa	43	8
300 to 400 MPa	14	0
Deflection		
Over + 1.5 mm	87	0
Over + 2.0 mm	11	0

Table 2. Wheel residual stress and deflection data.

Figure 10 is a graph showing the residual stress measurement results for ORE and VMS wheels. Note that both VMS and ORE wheels start out with beneficial compressive residual stresses in the wheel rim. However, as mileage in service increases, the wheels are tread braked and wheel rim stresses become tensile. Note that the ORE wheels have higher maximum and higher average tensile residual stresses than the VMS wheels.

Figure 11 is a bar graph of the Table 2 stress data showing the levels of wheel rim residual stress in VMS and ORE wheels after 150,000 km of railway service. Figure 11 clearly shows that VMS wheels have lower levels of residual tensile stress in the rim. A system to measure rim stresses in severely tread-braked wheels has important safety benefits for railroads.

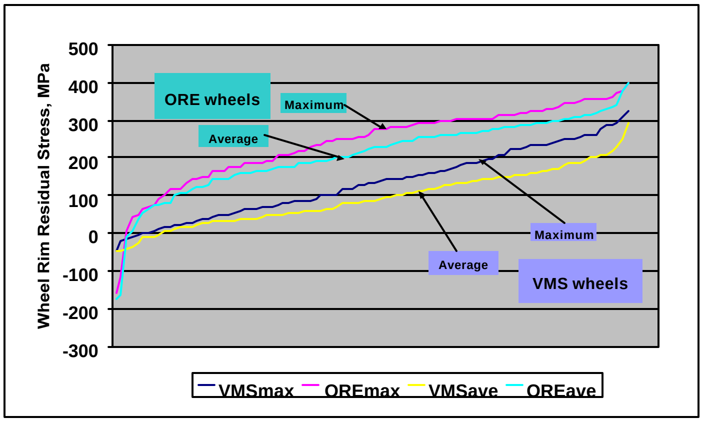

Figure 10. ORE and VMS wheel rim residual stresses.

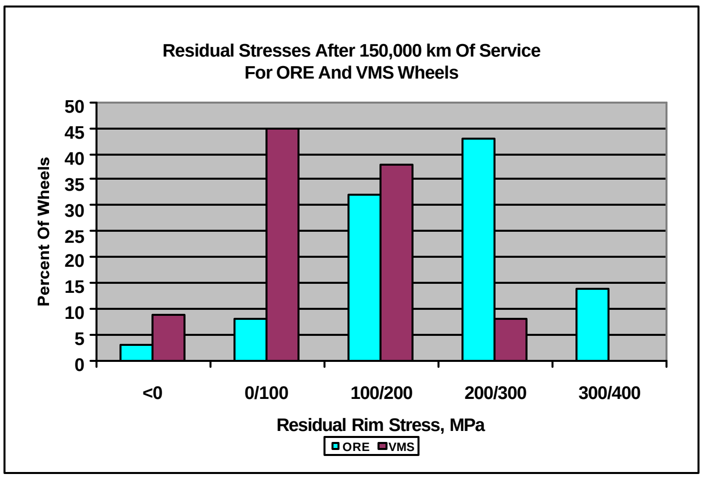

Figure 11. ORE and VMS residual stresses.

POTENTIAL FOR USE OF NONDESTRUCTIVE RESIDUAL STRESS MEASUREMENTS ON NORTH AMERICAN RAILROADS

Current use of nondestructive residual stress measurement techniques by European railroads shows that such work can be performed quickly and easily in car repair facilities. Quantitative information on the stress state of wheel rims is obtainable and decisions on wheel removals can be based upon data rather than more subjective methods.

Recent EMAT measurements of wheel rim stresses took place at a North American railroad and helped that company evaluate locomotive wheels with thermal cracking. 11 wheels that had been removed from service were tested using the Valdunes portable EMAT system and then were subjected to saw cut testing. The EMAT system determined that 9 of the 11 wheel rims were in compression while 2 were slightly in tension. The saw cut test showed that all 11 wheels were in compression since the saw cut tip opening closed.

The EMAT system also was used to measure rim stress in a locomotive wheel that failed due to a radial crack extending from rim to hub. This wheel was found to have very tensile rim stresses, as was expected, thus lending credibility to the EMAT method.

CONCLUDING REMARKS

Nondestructive techniques to measure the stress state of wheel rims have been shown to be a viable method of improving railroad safety. These techniques do indeed work and are being used in Europe on freight cars. Much research has been performed over the years and commercially available portable systems, such as the EMAT system owned by Valdunes, are now in use.

Although nondestructive techniques provide an average of bulk stress values across the wheel rim section, further work should be performed to correlate nondestructive testing methods with established saw cut procedures. This will add additional credibility to the use of nondestructive residual stress measurements in North America.

North American railroads should consider using EMAT rim stress measurement systems on freight cars that are in service lanes with severe braking. Frequencies of wheel inspection and shop locations for stress measurements are important issues. Also, condemnable levels of wheel rim residual stresses should be considered and established, as has been done in Europe. Residual stress measurement systems will also have safety benefits for North American passenger car wheels with tread braking.

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