

The work described in this document was performed by Transportation Technology Center, Inc.,
a wholly owned subsidiary of the Association of American Railroads.

Analysis of Residual Stresses on High Performance Wheels

F. C. Robles Hernandez*, Satima Anankitpaiboon, and Scott Cummings

Summary

As part of the Association of American Railroads' Strategic Research Initiatives Program to improve the fatigue and wear resistance of wheels, Transportation Technology Center, Inc. engineers measured residual stresses of eight high performance wheels and one AAR Class C wheel with a saw cut technique using both strain gage rosettes and a clip gage.

The residual stresses of the high performance wheels are considered acceptable for controlled testing on a revenue service train. All wheels showed compressive principal residual stresses on the wheel tread in the range -3 ksi to -78 ksi. In the flange root, all but two of the high performance wheels had higher magnitude compressive residual stresses compared to the AAR Class C wheel. On the field side of the tapeline, where most shelling is observed, only three of the high performance wheels had higher magnitude residual stresses as compared to the AAR Class C wheel.

Circumferential residual stresses closely mirrored the principal stresses. The circumferential residual stresses provide the most direct comparison for the clip gage data and are useful for a comprehensive understanding of wheel fatigue behavior. Good trend agreement was observed between the results from the rosettes and the clip gage, thereby increasing confidence in both methods.

Residual stresses in wheels are the result of heat-treatments. Water quenching is applied to develop the desired microstructure and mechanical properties as well as beneficial compressive circumferential (hoop) residual stresses. These stresses play a major role in protecting the wheel tread from fatigue damage, especially when wheel temperatures are substantially elevated under severe braking conditions.

*Former TTCI employee



INTRODUCTION

This *Technology Digest* (TD) describes the results of residual stress measurements conducted on eight high performance wheels and one AAR Class C wheel. Griffin, Lucchini, OneSteel (formerly Smorgon), Standard Steel, Sumitomo and Valdunes donated the wheels for this project. The results of the high performance wheel developed by TTCI, referred to as the SRI wheel, are also presented. OneSteel has participated with two steel compositions. The AAR Class C wheel was tested for comparative purposes.

BACKGROUND

Residual stresses in wheels are the result of heat treatments. Heat treatments are applied to develop the desired microstructure and mechanical properties. Quenching (a common heat treatment for wheels) is applied to create a rapid cooling on the wheel rim, which allows the development of the desired microstructure and helps refining it. This results in compressive circumferential (hoop) residual stresses. Compressive residual stresses are desired since they improve fatigue related properties.¹

Experimental Procedure

To determine circumferential residual strains, a wheel is cut with a band saw along the radial plane, as Figure 1 shows. Using the residual strain results and the methodology described in this TD, it is possible to assess residual stresses. Historically, the AAR has used a clip gage (Figure 2) mounted on the wheel flange to determine whether the wheel has residual tensile strain (saw cut opens) or residual compressive strain (saw cut closes). This methodology allows for a determination of stress sense (tensile or compressive) and a relative magnitude in relation to other wheels tested. For the tests described here, the standard clip gage was used and three rectangular (0°-45°-90°) strain gage rosettes were applied to each wheel at the approximate locations shown in Figure 1.

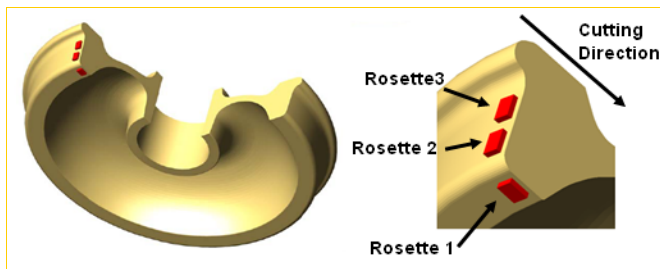


Figure 1. Locations of the Strain Gage Rosettes

The strain gages allow for a quantitative measurement of residual strains, rather than simply a comparative magnitude (as provided by the clip gage).

All wheels were tested in the as-manufactured condition. The convention signs for compressive and tensile stresses are negative and positive, respectively. Cutting fluid was constantly supplied during saw cutting to minimize thermal expansion effects. Figure 2 shows a test setup during the saw cutting operation including the cutting direction and the

location of the clip gage that is used to compare with the data of the strain gage rosettes.

Three 0.5-inch diameter E8-04 standard ASTM tensile test samples (two from the tread, one from the flange) were extracted from each wheel and were tensile tested. The elastic modulus from the tensile test was used to calculate the respective residual stresses on each wheel.

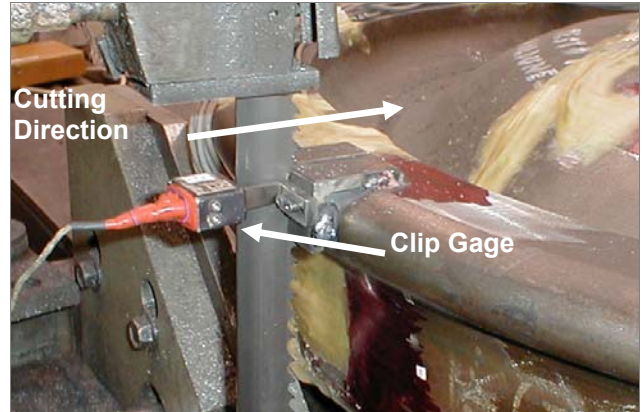


Figure 2. Saw Cutting Operation

Analysis

Figure 3 shows the axes on the rosette(s) and the direction in which each axis was labeled for the respective strains (ϵ_1 , ϵ_2 and ϵ_3).

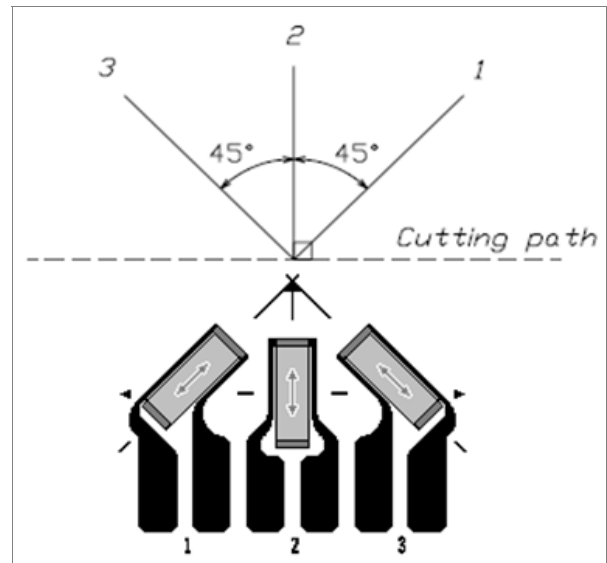


Figure 3. Strain Gage Rosette Orientation

Axis 2 is perpendicular to the cutting path. Principal strains (ϵ_P and ϵ_Q), stress (σ_P and σ_Q) and their directions can then be calculated using well known methods. Figure 4 shows the directions of principal stresses.

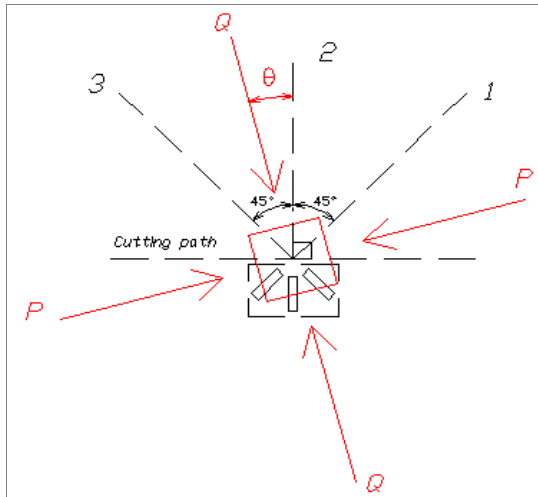


Figure 4. The direction of principal stresses

RESULTS

Table 1 lists the calculated principal stresses and the corresponding directions in relation to the cutting path. The high performance wheels donated by the manufacturers are generically labeled 1 through 7. The residual stresses in the axial direction may not have been completely released by the saw cut. The principal residual stresses range from 2 percent to 71 percent of yield strength for wheels 1 through 7, 12 percent to 22 percent for the AAR Class C wheel, and 3 percent to 8 percent for the SRI wheel. The principal residual stresses on the wheel tread (rosettes 2 and 3) range from -3 ksi to -78 ksi. The range is 30 ksi to -78 ksi when all rosettes are considered.

Table 1. Principal Stresses and Directions

Wheel	σ_P (ksi)			σ_Q (ksi)			θ (Deg.)		
	Rosette Number (1=Rim, 2=Tread, 3=Flange Root)								
	1	2	3	1	2	3	1	2	3
1	0.4	0.3	-0.4	-4.6	-7.6	-16.6	-2	0	12
2	-2.5	1.1	-18.6	-25.5	-21.5	-40.8	3	0	-21
3	-3.9	-9.3	-6.2	-26.0	-36.5	-29.0	-3	-3	-4
4	-2.2	-8.0	-9.2	-23.3	-34.5	-30.3	-1	-2	-1
5	-2.9	-0.1	-7.9	-13.7	-8.1	-20.9	2	1	-24
6	-0.6	-0.1	-0.1	-5.4	-3.1	-3.2	-2	0	8
7	37.4	-28.9	-7.6	30.8	-78.4	-73.6	0	3	12
Class C	-0.3	-4.4	2.2	-19.3	-24.4	-13.4	-5	-4	-30
SRI	-1.1	0.2	-1.6	-8.7	-3.8	-10.8	-5	3	-1

Wheel 7 shows the largest residual stresses in all rosettes. In the flange root (rosette 3), all but two of the high performance wheels (Wheel 6, SRI) had higher σ_Q compared to the AAR Class C wheel. On the field side of the tapeline (rosette 2), only three of the high performance wheels had higher σ_Q compared to the AAR Class C wheel. Most wheel

shelling is observed on the field side of the wheel tapeline,² so the residual stresses in this region may be of critical importance to resisting the damage associated with rolling contact fatigue. Figure 5 graphically displays the σ_Q values.

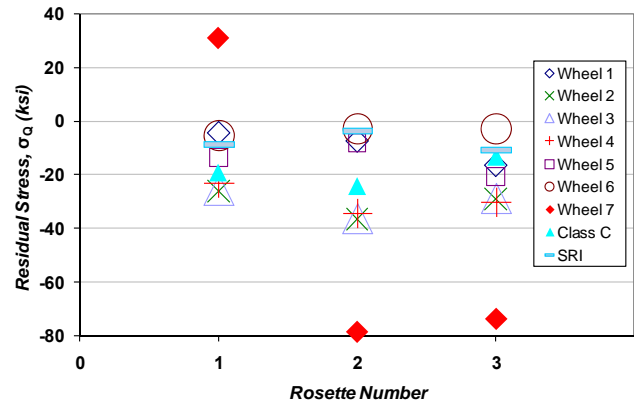


Figure 5. Principal Residual Stress

Circumferential residual stresses were also calculated and are shown in Figure 6. The circumferential (Hoop) stresses are nearly parallel to σ_Q for rosettes 1 and 2. Each wheel had a compressive state of stress at the tread surface (rosettes 2 and 3) in the circumferential direction. With the exception of Wheel 7, compressive circumferential residual stress was also measured on the rim of all wheels (rosette 1).

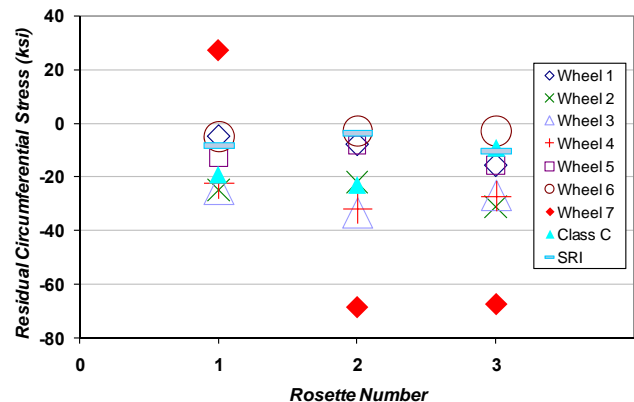


Figure 6. Residual Stresses along Wheel Circumference

Figure 7 shows the results of the clip gage data at the tip of the flanges while the wheels were being cut. The negative displacement measured by the clip gage indicates that all wheels tested have compressive circumferential residual stresses. The data from wheels 2 and 7 are truncated due to the compressive residual stresses causing the saw cut opening to clamp on the saw blade with enough force to stall the band saw — an indication of large compressive residual stresses.

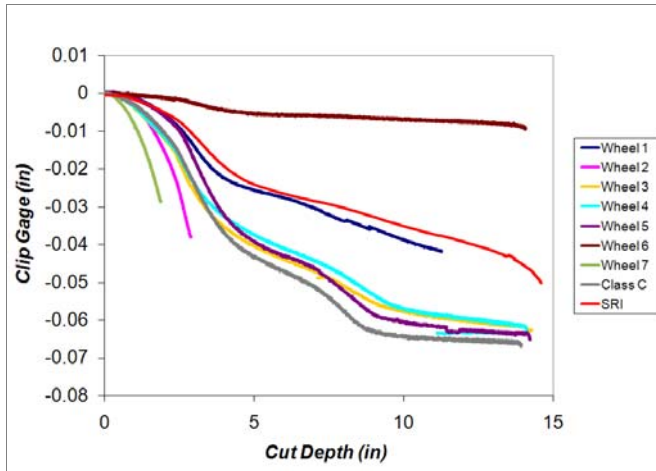


Figure 7. Reading from Clip Gage at the Wheel Flange Tip

Due to the nature of the measurements, an exact relationship between strain readings and clip gage displacement should not be expected. However, the general trends of the two measurement methods agree, particularly when examining the circumferential stress results from rosette 3, which was located nearest to the clip gage:

- All wheels have compressive residual stress on the wheel tread.
- The level of compressive residual stress in the SRI wheel is similar with those of the other wheels tested.
- Wheel 7 shows the largest compressive residual stress.
- Wheel 6 shows the smallest compressive residual stress.

CONCLUSIONS

Residual stresses of eight high performance wheels and one AAR Class C wheel were measured with a saw cut technique using both strain gage rosettes and a clip gage. The residual stresses of the high performance wheels are considered acceptable for controlled testing on a revenue service train. All wheels showed compressive principal residual stresses on the wheel tread in the range -3 ksi to -78 ksi. In the flange root (rosette 3), all but two of the high performance wheels had higher magnitude compressive residual stresses compared to the AAR Class C wheel. On the field side of the tapeline (rosette 2), where most shelling is observed, only three of the high performance wheels had higher magnitude residual stresses as compared to the AAR Class C wheel. Circumferential residual stresses closely mirrored the principal stresses. The circumferential residual stresses provide the most direct comparison for the clip gage data and are useful for a comprehensive understanding of wheel fatigue behavior. Good trend agreement was observed between the results from the rosettes and the clip gage, thereby increasing confidence in both methods.

Acknowledgements

TTCI expresses its gratitude all wheel manufacturers that donated wheels for the present test. Also special thanks to the AAR member railroads and particularly the Union Pacific for its support.

References

1. Stone, D. and S. Cummings. 2008. "Effect of Residual Stress, Temperature and Adhesion on Wheel Surface Fatigue Cracking." RTDF2008-74029, *Proceedings of 2008 Fall Conference of the ASME Rail Transportation Division*, Chicago.
2. Cummings, S., and D. Lauro. 2008. "Inspections of Tread Damaged Wheelsets." RTDF2008-74009, *Proceedings of 2008 Fall Conference of the ASME Rail Transportation Division*, Chicago.

Visit our website at <http://www.ttc1.aar.com>

Disclaimer: Preliminary results in this document are disseminated by the AAR/TTCI for information purposes only and are given to, and are accepted by, the recipient at the recipient's sole risk. The AAR/TTCI makes no representations or warranties, either expressed or implied, with respect to this document or its contents. The AAR/TTCI assumes no liability to anyone for special, collateral, exemplary, indirect, incidental, consequential or any other kind of damage resulting from the use or application of this document or its content. Any attempt to apply the information contained in this document is done at the recipient's own risk.