TECHNOLOGY DIGEST

TIMELY TECHNOLOGY TRANSFER

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

Microcleanliness and Residual Hoop Stress of Vertical Split Rim Wheels

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Summary

Thirty wheels with vertical split rim (VSR) or broken flange failures were recently analyzed by Transportation Technology Center, Inc. (TTCI) for microcleanliness and residual hoop stress state as part of the Association of American Railroads' (AAR) Strategic Research Initiatives (SRI) Program to prevent wheel failures. All but two of the wheels met the current AAR microcleanliness limits and most wheels met the current limits by a wide margin. The two wheels that exceeded AAR limits failed due to VSR and were manufactured prior to the AAR microcleanliness requirement. Microcleanliness testing was conducted by a third party laboratory with funding from both the SRI project and the AAR Wheel, Axle, Bearing, and Lubrication Committee. The bulk rim residual hoop stress of all of these wheels was compressive as desired, indicating that none of these wheels sustained extreme heating prior to failure. The Federal Railroad Administration (FRA) has since provided cooperative funding for additional analysis and testing of these wheels, which will be reported in future FRA reports and *Technology Digests*.

The SRI test results show that failure of the AAR microcleanliness test is not a prerequisite for VSR or broken flange failure. However, it is nearly impossible to obtain conclusive evidence about voids or inclusions in the immediate fracture area that may have caused or contributed to the failure of VSR or broken flange wheels due to damage of the fracture surface while in service.

Though relatively rare, VSR, broken flange, and shattered rim remain failure modes of concern to the railroad industry due to potential safety implications. Poor wheel steel cleanliness and tensile residual stress fields are considered to be two potential root causes for VSRs and broken flanges.

Unfortunately, the fracture surface of VSR and broken flange wheels nearly always sustains significant damage while in service, making it nearly impossible to obtain conclusive evidence about voids or inclusions in the immediate fracture area that may have caused or contributed to the failure.

Further analysis planned for the VSR and broken flange wheels includes optical microscopy evaluation and axial residual stress testing. Shallow subsurface horizontal cracks were found on many of the VSR wheels and are being investigated with radiography and scanning electron microscopy. TTCI will attempt to create a VSR wheel under controlled conditions using a service worn wheel with a preexisting horizontal crack to explore the relationship between shallow horizontal cracks and the VSR failure mode.

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INTRODUCTION

This *Technology Digest* (TD) describes the microcleanliness and residual hoop stress test results from wheels that failed in service due to VSR or broken flange. This work was conducted as part of the AAR's SRI to prevent wheel failures. The FRA has since provided cooperative funding for additional analysis and testing of these wheels, to be reported in future FRA reports and TDs.

BACKGROUND

TTCI requested and received a total of 29 VSR wheels and six broken flange wheels from three different railroads to analyze the fracture surfaces and conduct laboratory tests. VSR and broken flange wheels are thought to be the result of related failure modes. Figure 1 shows photos of a VSR wheel and a broken flange wheel.

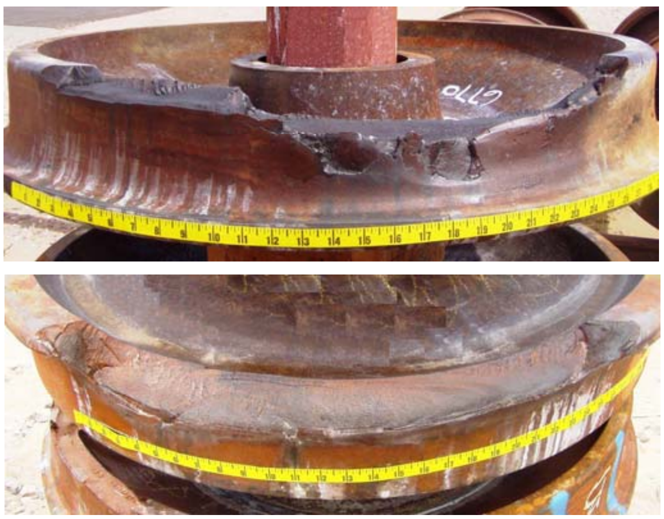

Figure 1. Wheels with VSR (Top) and Broken Flange (Bottom)

In the AAR billing system, VSR wheels are billed as cracked or broken rim (Why Made Code (WMC) 68). Between 2007 and 2010, the AAR Car Repair Billing database showed an average of 224 broken rim wheels (WMC 68) and 101 broken flange wheels (WMC 66) removed per year. During this same time period, shattered rim wheel removals (WMC 71) averaged 64 annually. Table 1 shows that these numbers have improved substantially since the early 2000s. This may be due to changes in AAR rules regarding impact loads produced by wheels (impact loads >= 90,000 pounds are condemnable as of 2004), microcleanliness testing of newly manufactured wheels (first implemented in 2003), and reduced defect size allowed during ultrasonic testing of wheels (changes made in 1999 and 2008 for new wheels, 2003 and 2008 for reprofiled wheels).

Table 1. AAR Car Repair Billing Data

WMC Code	Average Annual Wheelsets Removed	
	2000 to 2004	2007 to 2010
WMC 66 – Flange cracked or broken	155	101
WMC 68 – Rim cracked or broken	393	224
WMC 71 – Rim shattered	164	64

Though relatively rare, VSR, broken flange, and shattered rim remain failure modes of concern to the railroad industry due to potential safety implications. VSR and shattered rims are both considered broken rims (Cause Code E61C) in the FRA safety database, while broken flanges have a separate category (Cause Code E60C). Between 2007 and 2010, the annual average number of FRA reportable accidents was 17 and 1.25 for broken rim and broken flange, respectively. Among all mechanical caused accidents in the FRA safety database between 2007 and 2010, broken rims rank third in terms of the number of accidents and first in terms of reportable damage. Average FRA reportable cost per accident was $594,000 for broken rims and $284,000 for broken flanges.

The current work is focused more on VSR and broken flange, as opposed to shattered rim, due to the relative frequency of each failure mode. Poor wheel steel cleanliness and tensile residual stress fields are two potential root causes for VSRs and broken flanges. Oxide and sulphide inclusions and voids in the steel structure can act as stress risers and are generally undesirable. Tensile residual stresses can become additive to the mechanical stresses developed during wheel/rail contact and increase the probability for crack initiation and propagation. Compressive residual hoop (circumferential) stresses are developed in the wheel rim both during manufacturing and from contact with the rail during service. Heat input from braking can relieve the residual hoop stress or even cause an undesirable tensile state of residual hoop stress in some cases.

MICROCLEANLINESS

Standard AAR microcleanliness testing of a newly manufactured wheel requires the analysis of six metallographic samples taken at equal spacing around the circumference of the wheel (about every 60 degrees). The evaluation surface of each sample is 0.875-inch long in the circumferential direction, located 0.50-inch below the tread surface and 2.5 inches to 3.25 inches from the back rim face.[1] Figure 2 shows the sample location.

Microcleanliness tests were conducted on 25 VSR wheels and five broken flange wheels. Tests were conducted by a third party laboratory with funding from both the SRI project and the AAR Wheel, Axle, Bearing, and Lubrication (WABL) Committee. Because these wheels were service worn and fractured, slight changes to the standard AAR microcleanliness test sample locations were necessary.

Six samples were harvested from each wheel: two samples from each of three circumferential locations, which were spaced about 60 degrees apart on the portion of the wheel that was not fractured. At each circumferential location, one sample was harvested from the flange area and one from the tread area, as Figure 2 shows.

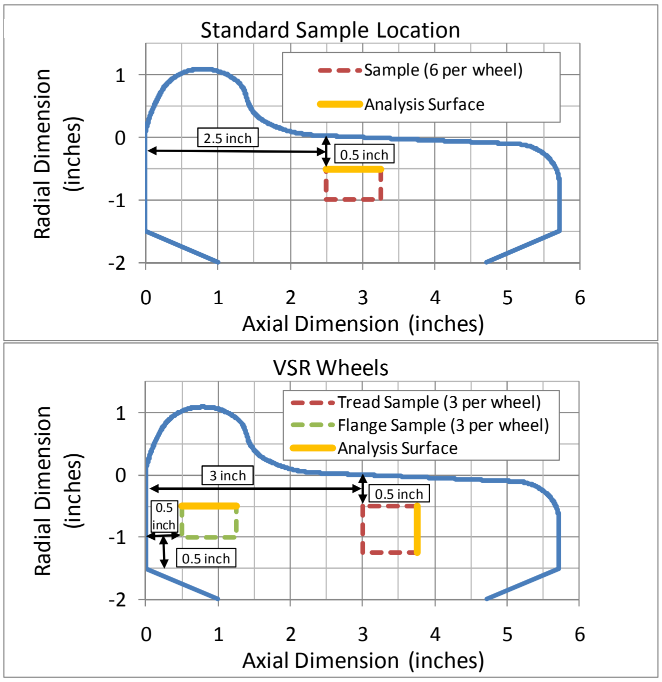

Figure 2. Sample Locations for the Standard AAR Microcleanliness Test (Top) and the VSR Wheels (Bottom)

The analysis surface of the flange sample was perpendicular to the flange back (similar to the standard AAR analysis surface), while the analysis surface of the tread sample was parallel to the flange back (i.e., parallel to the plane of VSR crack growth). The changes to the tread sample were made to try to better assess the microcleanliness in the area and orientation that would be most critical to VSR. Because the microcleanliness test can only evaluate a fraction of a wheel, it is intended to be a general indicator of steel cleanliness. Thus, the flange samples should also provide relevant data about the steel cleanliness even though they are not harvested from the exact same location as the standard AAR test requirements. The AAR WABL Committee approved the sample locations prior to harvesting.

Sample preparation and analysis was conducted according to AAR specifications. Figures 3 and 4 show the microcleanliness results of the VSR and broken flange wheels compared to AAR limits in terms of average volume percent and maximum volume percent, respectively. All but two of the wheels met the current AAR microcleanliness limits, and most wheels met the current limits by a wide margin. Both wheels that exceeded AAR limits failed due to VSR and were manufactured prior to the AAR microcleanliness requirement.

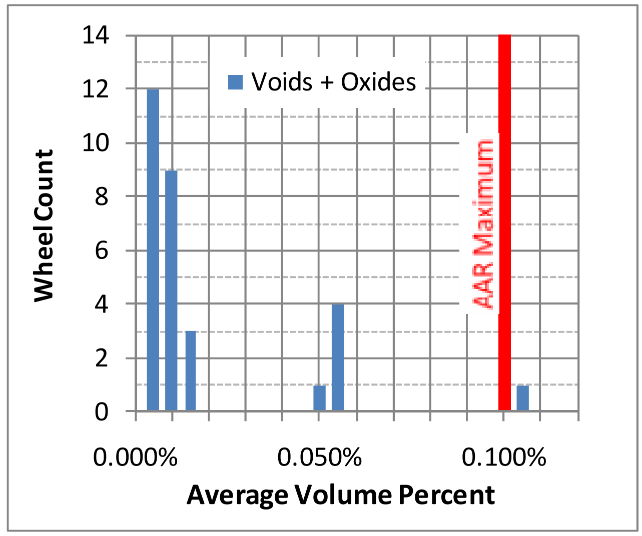

Figure 3. Histogram of Average Volume Percent Microcleanliness Results

These test results show that failure of the AAR microcleanliness test is not a prerequisite for VSR or broken flange failure. In a bulk sense, the steel in the wheels tested appears to be typical of many wheels in service today. Therefore, these results would not provide support for further tightening of the limits associated with the current AAR microcleanliness test. Unfortunately, the fracture surface of VSR and broken flange wheels nearly always sustains significant damage while in service, making it nearly impossible to obtain conclusive evidence about voids or inclusions in the immediate fracture area that may have caused or contributed to the failure. Destructive microcleanliness tests only examine a tiny percentage of the steel in a tiny percentage of the wheels produced. As nondestructive testing methods improve, it may become practicable to substantially reduce the allowable defect size in both new wheels and reprofiled wheels.

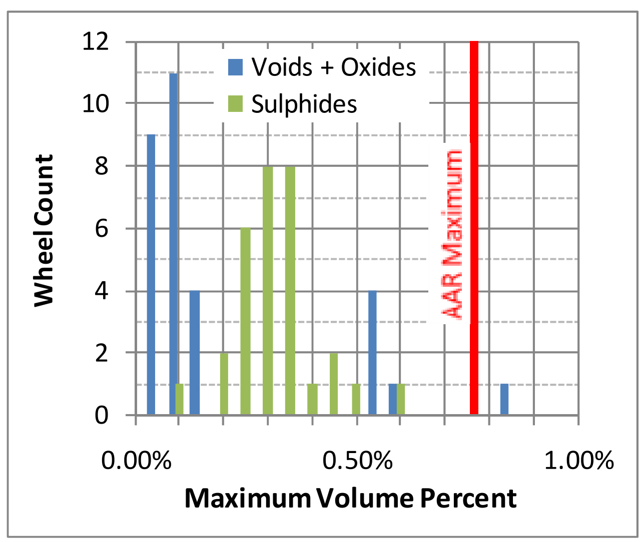

Figure 4. Histogram of Maximum Volume Percent Microcleanliness Results

RESIDUAL HOOP STRESS

While harvesting the samples for the microcleanliness testing, data was collected during the first cut of each wheel to determine whether the wheel was in a state of tensile or compressive residual hoop stress, using a well-established method.[2,3] Each wheel was laid flat on a band saw table and cut along the radial plane at a circumferential location as far as possible from the fracture surface, as Figure 5 shows. A clip gage mounted on the wheel flange was used to determine the changes in the width of the kerf (cut opening) with respect to the radial depth of the cut. A widening kerf (positive slope when plotting cut opening versus cut depth) indicates that the blade tip is cutting through material in tensile residual hoop stress; a narrowing kerf (negative slope) indicates compressive residual hoop stress. Cutting fluid was constantly supplied during saw cutting to minimize thermal expansion effects.

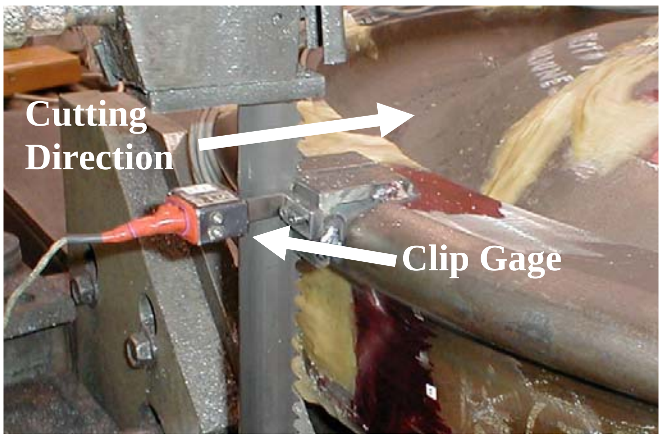

Figure 5. Photo of a Saw Cut Test

Figure 6 shows plots of the changes in the kerf width as a function of the cut depth for each wheel. A new single wear wide flange wheel is also shown on the figure to give visual reference to the cut depth.

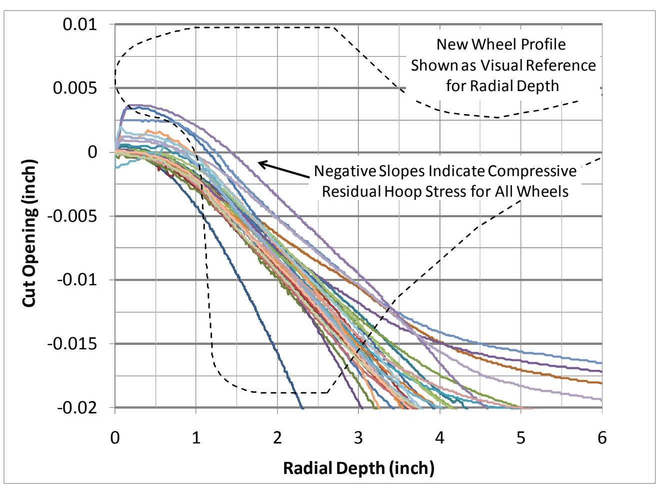

Figure 6. Saw Cut Results Showing Compressive Residual Hoop Stress for All Wheels Tested

For many of the wheels, the kerf increased in width during the initial 0.25 inch of the cut depth indicating tensile residual hoop stress in the outermost tip of the flange. However, the kerf decreased in width for all wheels as the blade progressed further into the flange and rim, indicating that all of the wheels were in a state of residual compressive hoop stress as desired. This state of stress would indicate that none of these wheels had been exposed to extreme heating prior to VSR or broken flange failure. Any tensile residual hoop stress in the tip of the flange should not have a significant effect on VSR or broken flange failures that initiate near the tread surface.

CONCLUSIONS

Microcleanliness and residual hoop stress testing of 25 VSR wheels and five broken flange wheels showed the following:

- All but two of the wheels met the current AAR microcleanliness limits, and most wheels met the current limits by a wide margin. The two wheels that exceeded AAR limits failed due to VSR and were manufactured prior to the AAR microcleanliness requirement.
- These test results show that failure of the AAR microcleanliness test is not a prerequisite for VSR or broken flange failure.
- It is nearly impossible to obtain conclusive evidence about voids or inclusions in the immediate fracture area that may have caused or contributed to the failure of VSR or broken flange wheels due to damage of the fracture surface while in service.
- The bulk rim residual hoop stress of all of these wheels was compressive as desired, indicating that none of these wheels sustained extreme heating prior to failure.

FUTURE WORK

Further analysis planned for the VSR and broken flange wheels includes optical microscopy evaluation and axial residual stress testing. Shallow subsurface horizontal cracks were found on many of the VSR wheels and are being investigated with radiography and scanning electron microscopy. TTCI will attempt to create a VSR wheel under controlled conditions using a service worn wheel with a preexisting horizontal crack to explore the relationship between shallow horizontal cracks and the VSR failure mode.

REFERENCES

1. Association of American Railroads. 2011. *Manual of Standards and Recommended Practices*, “Section G, Wheels and Axles, M-107/M-208,” Washington, D.C.
2. Rajkumar, B. and D. Stone. 1987. “Wheel Failure Mechanisms of Railroad Cars,” Research Report R-679, Association of American Railroads, Transportation Technology Center, Inc., Pueblo, Colorado.
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