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Ultrasonic Inspection and Subsurface Cracking of Vertical Split Rim Wheels

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Summary

Ultrasonic test equipment was used to inspect thirty-five wheels with vertical split rim (VSR) or broken flange failures as part of the Association of American Railroads' Strategic Research Initiatives Program to prevent wheel failures.

Shallow subsurface cracks were found in 77 percent of the broken wheels and 51 percent of the mate wheels. Such cracks were far more prevalent than expected. The Federal Railroad Administration (FRA) has since provided cooperative funding for additional analysis and testing of these wheels, to be reported in future FRA reports and *Technology Digests*.

The radial depth range between approximately 0.1 and 0.3 inch below the tread surface appears to be a critical zone for VSR and broken flange wheels. The wheel failure origins, theoretical maximum stresses from contact with the rail, and horizontal subsurface cracks all converge at this depth. Two distinct horizontal layers in the rim can be found in most VSR and broken flange wheels, presumably as the result of shallow horizontal subsurface cracking prior to the failure.

Tread wear, increasing impact loads, material discontinuities, and residual stresses could explain why shallow horizontal cracks turn in a vertical direction and become VSR or broken flange wheels.

Future research work planned for the VSR and broken flange wheels includes optical microscopy evaluation and axial residual stress testing. Radiography and scanning electron microscopy will be used to investigate the horizontal cracks. Transportation Technology Center, Inc. will explore the relationship between shallow horizontal cracks and the VSR failure mode by attempting to create a VSR wheel under controlled conditions using a service worn wheel with a pre-existing horizontal crack.

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INTRODUCTION

This *Technology Digest* (TD) describes the ultrasonic test (UT) results from wheels that failed in service because of VSR or broken flange. This work was conducted as part of the Association of American Railroads (AAR) Strategic Research Initiatives Program to prevent wheel failures. Cooperative funding has been provided by the FRA for additional analysis and testing.

BACKGROUND

VSR and broken flange wheels are thought to be related failure modes, both the result of cracking of the wheel rim. (See Figure 6, page 4, for profile sketches of VSR and broken flange wheels). Cracks develop and propagate in the presence of large stresses. Hamilton[1] developed explicit formulas for calculating the subsurface stress fields due to contact of objects such as wheels and rails. Over the wheel load range of 25,000 pounds to 200,000 pounds and in the absence of tangential forces, the maximum Von Mises stress in the wheel due to contact with the rail is located approximately 0.14 to 0.25 inch deep relative to the surface of the tread. Figure 1 shows the relationship between the wheel/rail contact load and the radial depth of the maximum stress using Hamilton's equations and assuming a new 36-inch diameter wheel in Hertzian contact with a 14-inch crown radius rail. Tangential wheel/rail forces reduce the depth of the maximum stress. Increased contact patch size from causes, such as hollow wheel wear and/or flattened rail crowns, increase the depth of the maximum stress.

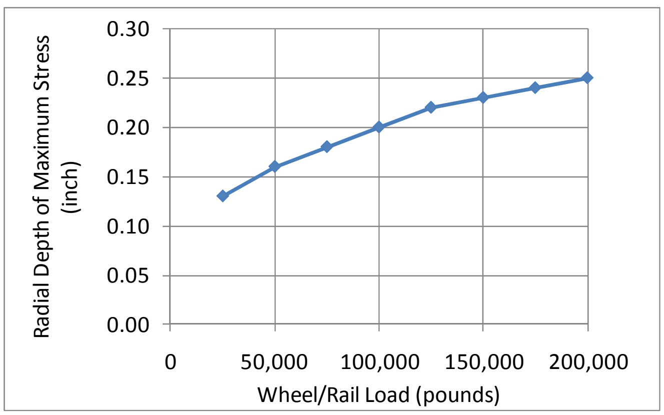

Figure 1. Radial Depth of Maximum Stress Related to Wheel/Rail Load

ULTRASONIC TEST INSPECTIONS

Transportation Technology Center, Inc. received a total of 29 VSR wheels and 6 broken flange wheels from three different railroads to analyze the fracture surfaces and conduct laboratory tests. After analyzing information, such as wear patterns and service life, the failure origin location was determined for each broken wheel by visually examining the failure surface. Origin radial depths were similar for both VSR and broken flange wheels and ranged from 0.10 inch to 0.25 inch below the tread surface with a median value of 0.17 inch.

Cracks in wheels can be found using UT equipment. Each broken wheel and its mate were scanned for horizontal UT indications in the axial-circumferential plane (with the probe on the tread surface aimed radially toward the hub) and for vertical UT indications in the radial circumferential plane (with the probe on the front rim face aimed toward the back of the flange). Dual element probes of 2.25 MHz and 5 MHz were used to detect horizontal indications. A 2.25 MHz standard zero probe was used to detect vertical indications.

A total of 111 horizontal UT indications were found on 27 of the 35 broken wheels. No horizontal UT indications were found on the other 8 broken wheels. The UT indications are considered subsurface cracks rather than manufacturing defects, such as voids or inclusions, because of their large size. The horizontal UT indications ranged in size from 0.1 in^2 to 24.7 in^2 with a median value of 1.3 in^2. The radial depth of the horizontal UT indications ranged from 0.11 inch to 0.60 inch with a median value of 0.21 inch. Figure 2 shows the depth and area of the horizontal UT indications found in the broken wheels. The majority of the horizontal UT indications (83 percent) were found in the same range of radial depths as the expected maximum stress and the failure origins.

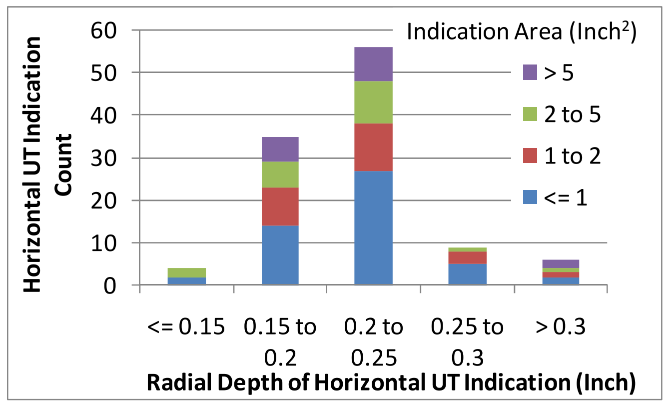

Figure 2. Size and Depth of Horizontal UT Indications

Horizontal UT indications were found in the immediate vicinity of the failure origin on 13 of the broken wheels. Figure 3 shows an example of a broken wheel with a large horizontal UT indication (outlined in white paint) surrounding the VSR origin.

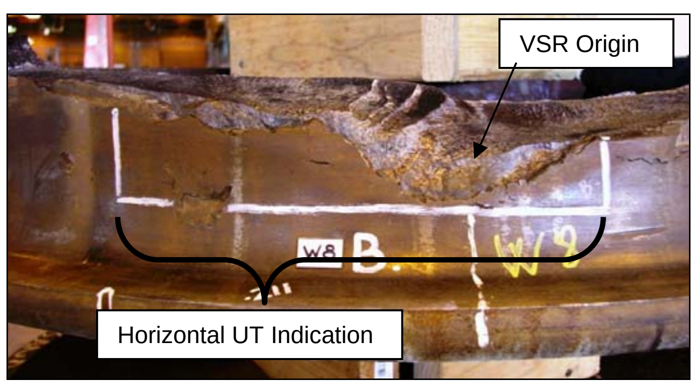

Figure 3. VSR Wheel with a Large Horizontal UT Indication Surrounding VSR Origin

A total of 52 horizontal UT indications were found on 18 of the 35 mate wheels. No horizontal UT indications were found on the other 17 mate wheels. The horizontal UT indications ranged in size from 0.1 in^2 to 28.8 in^2 with a median value of 1.1 in^2. The distribution of indication depths and sizes were similar for both the broken wheels and the mate wheels.

Vertical UT scanning was conducted on the broken wheels and their mates to identify any vertically oriented indications and to determine if the VSR or broken flange crack extended beyond the portion that was visible. Based on vertical UT indications, the failure crack extended beyond the portion that was visible for 16 of 35 VSR and broken flange wheels. Extension of the cracks ranged from 1 inch to 25 inches with a median value of 3.4 inches. No other vertical UT indications were found on the broken wheels or their mates.

SUBSURFACE CRACKING

A common feature found on many of the broken wheels was a horizontal (approximately parallel to the tread surface) separation between two visually distinct layers in the wheel rim. Figure 4 shows examples of two VSR wheels with distinct upper and lower layers in the rim. The upper layer is typically no more than 0.25 inch thick and the lower layer is comprised of the remainder of the rim thickness. The vertical crack does not extend directly across the horizontal separation. In some wheels, the upper layer extends axially past (overhangs) the VSR crack in the lower layer. In other broken wheels, the opposite is found: the horizontal surface of the lower layer is exposed because the upper layer has shelled out or broken off above it. For both wheels pictured in Figure 4, the upper layer overhangs the VSR crack in some circumferential locations and has broken off the lower layer at other locations.

Figure 5 shows a wheel section with a horizontal crack that ranges in radial depth from about 0.1 inch to 0.25 inch below the tread surface and a vertical crack that intersects the horizontal crack at about 0.18 inch radial depth. These dimensions are typical of most of the horizontal UT indications on the broken wheels and the radial depths of the VSR origins (where the horizontal crack turned into a vertical crack). The horizontal crack in this wheel separates the upper and lower layers of the rim.

The horizontal separation of tread layers associated with VSR and broken flange wheels has been shown previously; however, it has typically been attributed to shelling rather than subsurface cracking. Berge[2] sketched the transverse profiles of four broken wheels and each one showed a shallow horizontal component to the vertically broken piece. Figure 6 shows these profiles.

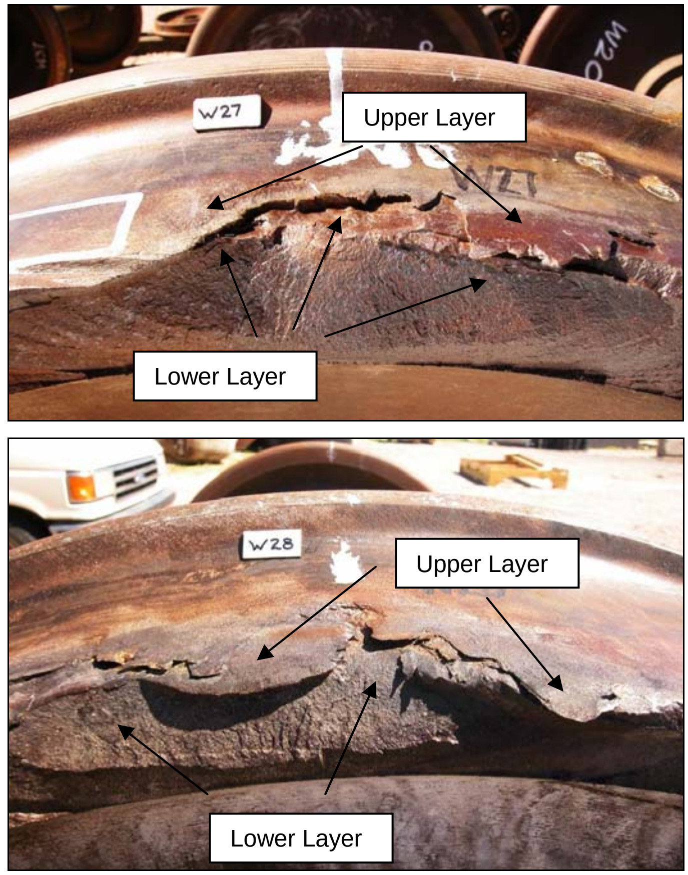

Figure 4. Examples of VSR Wheels with Two Distinct Horizontal Layers in the Rim

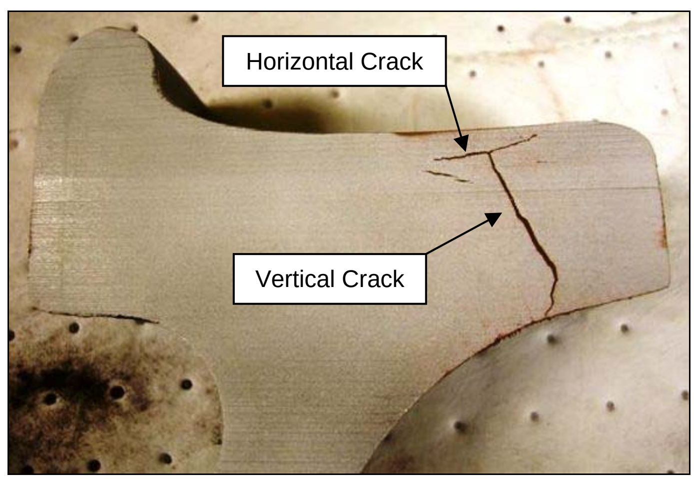

Figure 5. Branching between a Horizontal Subsurface Crack and a Vertical Crack

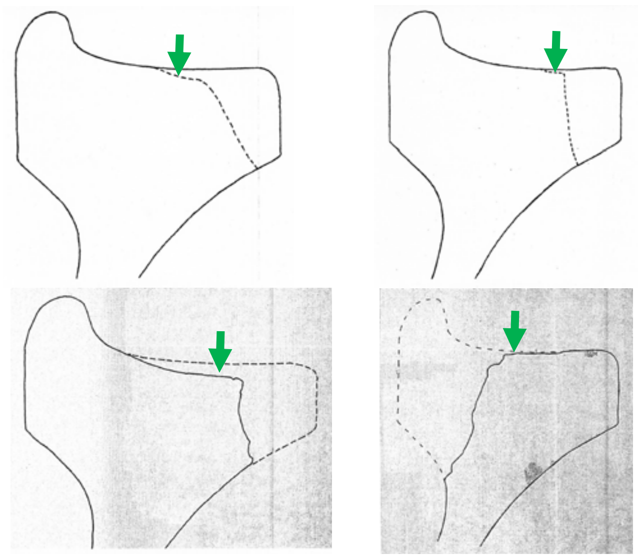

Figure 6. Sketches of VSR and Broken Flange Wheel Profiles Showing the Broken Piece with a Dashed Line.[2] (Green arrows have been added to indicate the shallow horizontal component of the broken piece.)

DISCUSSION

For a VSR or broken flange to develop, it appears that in most cases a horizontal subsurface crack must first be present. This crack could be at least partially visible from the tread surface (shelling) or entirely contained below the tread surface. The orientation of crack growth must then turn from a horizontal direction to a vertical direction. There are multiple reasons, alone or in conjunction, which could help explain why cracks make this turn:

- Increased depth of maximum stress from wheel/rail contact. If the maximum stress is deeper than an existing horizontal crack, the crack may have a tendency to propagate vertically to the depth of the maximum stress. Once the crack has turned in a vertical direction, it can propagate into a VSR or broken flange wheel much more easily.[3] Increased depth of maximum stress could occur because of:
    - Tread wear, which would reduce the radial distance between the tread surface and an existing horizontal crack while the radial depth of the maximum stress remained constant relative to the tread surface. Additionally, hollow tread wear increases the contact patch size, which results in an increase in depth of the maximum stress.
    - Increased vertical loads — the depth of the maximum stress increases as wheel/rail loads increase. Shelled and spalled wheels tend to show a progression of increasing impact loads prior to failure.
- Localized stress concentrations from material discontinuities such as a voids or inclusions. Twenty eight out of 30 VSR and broken flange wheels recently passed the AAR microcleanliness test.[4] 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 origin area that may have caused or contributed to the failure.
- Changes in the residual stress fields. Although computer simulations have suggested that residual stresses are not a critical factor in VSR formation,[3] preliminary results from axial residual stress testing have shown that the axial residual stresses may have larger tensile magnitudes than previously thought. A future TD will describe the full results of ongoing axial residual stress testing.

CONCLUSIONS

UT and visual inspections of 35 VSR and broken flange wheels showed the following:

- Shallow horizontal subsurface cracks were found in 77 percent of the broken wheels and 51 percent of the mate wheels. Such cracks were far more prevalent than expected.
- The horizontal subsurface cracks were typically discovered at the same depth as the failure origins and the theoretical maximum stress: 0.15 to 0.25 inch.
- Most VSR and broken flange wheels exhibit two distinct horizontal layers in the rim, presumably as the result of shallow horizontal subsurface cracking prior to the failure.
- Tread wear, increasing impact loads, material discontinuities, and residual stresses could explain why horizontal cracks turn in a vertical direction and become VSR or broken flange wheels.

FUTURE WORK

An optical microscopy evaluation of the areas around the fracture surfaces and axial residual stress testing are both underway. The horizontal cracks are being investigated with radiography and scanning electron microscopy. TTCI will explore the relationship between shallow horizontal cracks and the VSR failure mode by attempting to create a VSR wheel under controlled conditions using a service worn wheel with a pre-existing horizontal crack.

REFERENCES

1. Hamilton, G. M. 1983. "Explicit Equations for the Stresses Beneath a Sliding Spherical Contact." *Proc. Inst. Mech Eng*, Vol 197 C.
2. Berge, S. 2001. "Wheel Shelling Study Group," Presentation to the BNSF Wheel Shelling Study Group, Topeka, Kansas.
3. Cummings, S. et al. August 2010. "Modeling the Vertical Split Rim Failure of Wheels," *Technology Digest* TD-10-028, Association of American Railroads, Transportation Technology Center, Inc. Pueblo, Colorado,
4. Cummings, S. July 2011. "Microcleanliness and Residual Hoop Stress of Vertical Split Rim Wheels," *Technology Digest* TD-11-021, Association of American Railroads, Transportation Technology Center, Inc. Pueblo, Colorado.