TECHNOLOGY DIGEST
TD-13-005
©MARCH 2013
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.

Attempt at Creation of Vertical Split Rim Wheel Failure

Scott Cummings and Daniel Szablewski

Summary

Two attempts to replicate the vertical split rim (VSR) wheel failure mode under controlled conditions on a rolling load machine were unsuccessful after approximately 7-million load cycles (equivalent to approximately 13,000 service miles), at wheel/rail loads as high as 90,000 pounds. This work was conducted by Transportation Technology Center, Inc. (TTCI) with cooperative direction and funding from the Association of American Railroads' Strategic Research Initiatives Program and the Federal Railroad Administration Office of Research and Development.

Results of this testing indicate that more research is needed to better understand VSRs and to assess the best potential mitigation methods. Wayside automated detection methods for cracked wheels could potentially provide some reduction in VSRs; however, many questions need to be addressed including the following:

- The relationship between the number of load cycles and the VSR crack size
- The influence on the relationship of parameters such as load magnitude, ambient temperature, and lateral position of the contact patch on the wheel tread
- The influence of wheel microstructure, and microcleanliness in particular, on VSR crack path propagation in the wheel

VSRs are thought to be the result of tread damage on the wheel surface in the form of a shell or spall that initiates cracking in the rim and produces impact loads when it comes in contact with the rail. If the crack propagates vertically into an area of tensile residual stress in the wheel rim, further crack growth is encouraged until a portion of the rim breaks free from the wheel.

Service worn wheels with large naturally occurring subsurface horizontal cracks were used for the testing. These wheels were selected because inspection results of VSR wheels indicate that shallow horizontal subsurface cracks are present in most VSR wheels.

TTCI plans additional testing using the rolling load machine and service worn wheels with machined defects.

INTRODUCTION

TTCI attempted to create a VSR wheel failure in the laboratory under controlled conditions using service worn wheels with preexisting subsurface cracks on a rolling load machine. This work is part of an ongoing study of the root causes of VSR as part of a cooperative research initiative between the Association of American Railroads and the Federal Railroad Administration Office of Research and Development.

BACKGROUND

VSR cracks develop in the wheel rim and usually propagate to the front rim fillet, but can sometimes propagate to the back rim fillet resulting in a broken flange. Two reports describe largely similar theories on the formation of VSR cracks.[1,2] Tread damage on the wheel surface in the form of a shell or spall initiates cracking that propagates into a region of tensile residual stress in the rim. The tensile residual stress encourages further crack growth until a portion of the rim breaks free from the wheel. Figure 1 shows an example of a typical VSR wheel.

Figure 1. Wheel with VSR

One attempt to create a VSR under controlled conditions is described in the literature. A drop hammer machine was used to deliver loads in excess of 200,000 pounds to a service worn wheel that had developed shelling on the tread.[3] The test was not able to produce a VSR failure in the wheel and was halted after 30,000 impact events.[2]

Inspections of 29 VSR wheels and 6 broken flange wheels were conducted to evaluate the appearance of the cracked surface. A VSR origin location was identified for each wheel, and radial depths of these origins were all found in a tight band ranging from 0.10 inch to 0.25 inch below the tread surface with a median value of 0.17 inch.[4] Ultrasonic testing (UT) revealed horizontal cracks at radial depths similar to the VSR crack origins in 27 of the 35 broken wheels and in 18 of the 35 mate wheels.[5] There is 95 percent confidence that more horizontal cracks were present on the broken wheels than the mate wheels. The broken wheel had more cracks than the mate wheel on 80 percent of the wheelsets. No inferences can be made to the general population of wheels at this time. Figure 2 shows a section from a wheel that failed from VSR with a vertical crack branching from a horizontal crack.

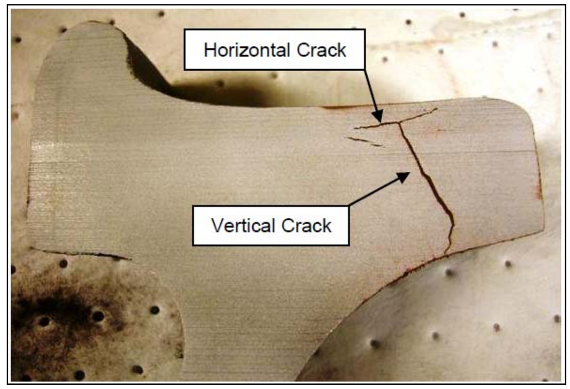

Figure 2. Wheel Rim with Horizontal and Vertical Cracks

TEST

The ability to create a specific failure mode under controlled conditions not only demonstrates understanding of the conditions needed for failures, but also allows for the possibility of parametric testing to better define the relative influence of different conditions. To this end, an existing rolling load machine was modified in an attempt to create a VSR in the laboratory. This machine longitudinally cycles a short piece of rail (approximately 3-feet long) back and forth with a 12-inch stroke underneath a stationary wheel. The machine was modified to allow fine lateral position control for a service worn wheel and to increase the maximum wheel/rail vertical contact force to 90,000 pounds. Figure 3 shows a schematic of the rolling load machine.

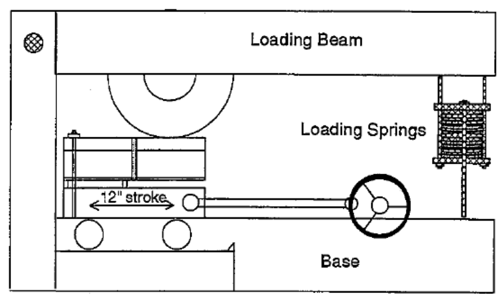

Figure 3. Schematic of TTCI's Rolling Load Machine

A service worn wheel originally mounted on the same wheelset as a VSR wheel was selected as the first test wheel. Based on UT, this wheel was known to have a large subsurface horizontal crack. The wheel was installed on the test machine so that the field side edge of the horizontal crack was approximately in the center of the contact patch between the wheel and rail. Computer modeling had shown this positioning to produce the maximum stress condition. The vertical load was set to 60,000 pounds at the beginning of the test. After 4.5-million load cycles, the load was increased by 10,000 pounds approximately every million-load cycle until the maximum load rating for the machine was achieved. The test was intended to force the horizontal crack to turn vertically. Instead, the horizontal crack expanded in area early in the test, and then stopped growing until the vertical load was increased. The initial area of the crack was 1.4 square inches and grew to 3.4 square inches. Crack area was estimated daily by scanning the wheel with a handheld UT device and noting the edges of the horizontal crack compared to a grid overlaid on the wheel with 0.50-inch grid spacing increments. TTCI believes decreases in the estimated crack area are the result of changes in the tread surface condition during the test that at times provided a suboptimal surface for the contacting ultrasonic probe.

Significant radial runout of 0.110 inch developed on the wheel tread from deformation and wear forcing the rolling load machine to work harder on every load cycle. After 6.8-million load cycles, the test was stopped, because the machine was no longer able to cycle the rail because of the combination of large contact force and radial runout on the wheel. Figure 4 shows the crack area and the wheel/rail contact force from this test as a function of the number of load cycles.

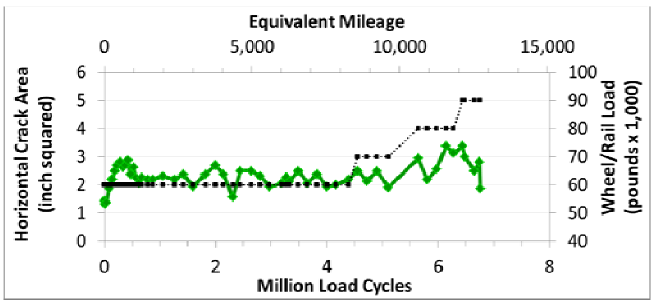

Figure 4. Horizontal Crack Area (Green) and Contact Loads (Black) from the First Rolling Load Test

A second wheel with a 4.3 square inch preexisting horizontal crack was selected (also originally mounted on the same wheelset as a VSR wheel), and testing was resumed. The vertical load was initially set to 50,000 pounds and increased by 10,000 pounds approximately every million-load cycle up to the machine maximum. Again, the wheel developed significant radial runout of 0.120 inch from deformation and wear during the test. After 7.4-million load cycles, the machine experienced a failure in one of the support posts, and the test was stopped. The crack area in the wheel did not change appreciably during this test. Figure 5 shows the crack area and the wheel/rail contact force from the second test.

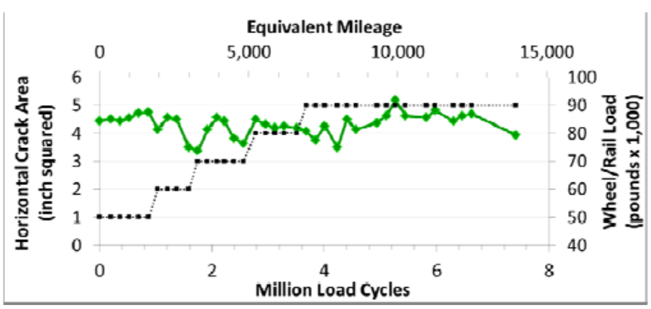

Figure 5. Horizontal Crack Area (Green) and Contact Loads (Black) from the Second Rolling Load Test

ANALYSIS

Following the tests on the rolling load machine, each wheel was sectioned, and the cracks were viewed under a microscope. The horizontal cracks were found to be between 0.08 inch and 0.20 inch below the tread surface with a typical depth of 0.15 inch. Multiple short vertical branches stem from the main horizontal cracks. Figure 6 shows the longest vertical branch found, about 350 µm, at the end of a horizontal crack. This vertical branch is linking a number of small inclusions, and numerous other smaller vertical branches can be seen growing toward the tread surface (top of photo) and further into the rim (bottom of photo). Interestingly, the majority of the vertical crack branches found in these two wheels through optical microscopy were on the flange side of the horizontal cracks, even though the wheel/rail contact during the rolling load test was on the field side of the horizontal cracks. This may be an indication that the bending moment generated in the rim by wheel/rail contact is more important to producing vertical crack branching than localized stresses nearest to the contact patch.

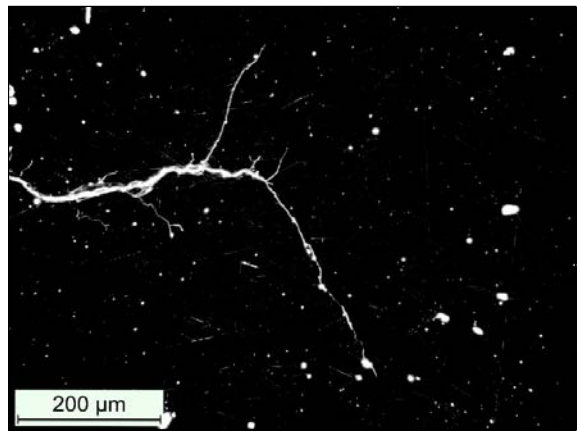

Figure 6. Dark Field Optical Microscopy Shows a Horizontal Crack with Multiple Vertical Branches

Understanding the propagation path of a crack can help define the relative influence of high stress levels and localized material weaknesses. Nonmetallic inclusions act as stress concentrators and tend to segregate out to the grain boundaries as ingots solidify. The crack propagation paths of selected cracked specimens from the rolling load test wheels were further investigated using Norfolk Southern Railway's scanning electron microscope (SEM). The polished samples were etched with a saturated solution of picric acid to show the microstructure including the boundaries between prior austenite grains. The horizontal cracks and the vertical crack branches examined in the samples removed from the two wheels that failed to develop VSR cracks all showed crack propagation through the grains (transgranular cracks) rather than alongside prior austenite grain boundaries (intergranular cracks). This is a strong indication that high stress levels were the main driving force in the crack propagation in these two wheels. If the cracks had followed prior austenite grain boundaries, it would have been an indication that material weakness played a large role in the crack development, because the cracks would have followed paths of least resistance.

Figure 7 shows a typical example of a crack in one of the test wheels as viewed through the SEM using the secondary electron detector.

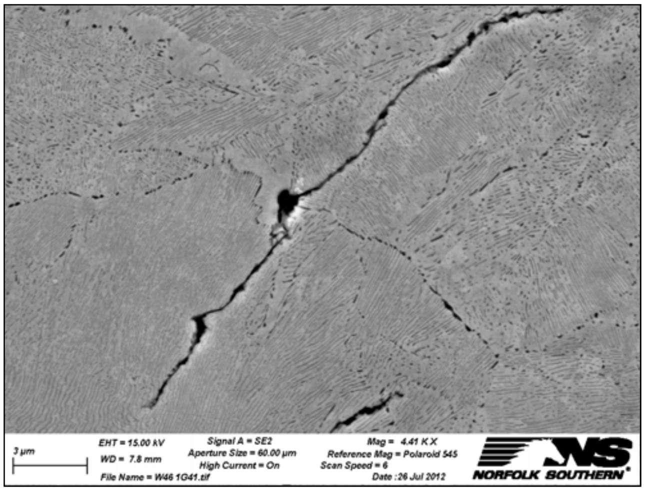

Figure 7. Transgranular Crack Propagation (Image Courtesy of Norfolk Southern Railway)

One of the VSR wheels provided for the inspection was removed from service prior to the crack causing complete separation of the rim. TTCI attempted to analyze both sides of the crack near the VSR initiation site to determine the crack propagation mode. The crack appeared to be transgranular, indicating that high stress levels were likely the main driving force in the crack propagation rather than material weakness. However, during SEM analysis, it was difficult to identify the exact location of the potential vertical crack initiation sites. Once the crack had grown to a sufficient size, the stress concentration created by the crack most likely increased the probability of transgranular crack propagation. Separating the rim material at the crack was necessary to examine the morphology of the crack surfaces to identify potential crack initiation sites. This required that the mating crack surfaces be viewed separately under the SEM, making it difficult to confidently match crack asperities between the two crack surfaces. This further reduced the confidence in confirming transgranular crack propagation with all certainty.

The ideal specimen for this type of analysis would be extracted from a wheel rim at the initiation site of a VSR crack at the initial stage of growth. Unfortunately, identifying such a wheel and extracting a sample at the VSR crack origin location is highly unlikely without being able to successfully generate a VSR failure in the laboratory, because crack origin is rarely preserved in field failures.

It should be noted that VSRs are an extremely rare event in terms of ton-miles carried per wheel, and it make take the intersection of many low probability events to produce a VSR, including the presence of a wheel that is unusual in some way. In other words, it is possible that the perfect test would fail to produce a VSR on the majority of wheels. What can be learned from the results of this testing is that cyclic vertical loads far in excess of the standard vertical load are insufficient to always produce a VSR in service worn wheels with large preexisting horizontal cracks.

CONCLUSION

Two service worn wheels with large naturally occurring subsurface horizontal cracks were cycled on a rolling load test machine at wheel/rail forces as high as 90,000 pounds in an attempt to create a VSR wheel under controlled conditions. In each case, the test machine failed after about 7-million load cycles (approximately equivalent to 13,000 service miles), and the test was stopped. Neither test wheel developed a VSR crack, although post-test destructive evaluation revealed short vertical crack branches in both wheels. The horizontal cracks were found at a typical radial depth of 0.15 inch, which is nearly the same radial depth as the VSR crack origins identified during the wheel inspections. SEM analysis showed that the cracks propagated in a transgranular fashion, indicating that material weakness was most likely not a primary cause for the crack development in these two wheels.

Additional research of VSR failures is needed. Adding or modifying specifications for newly manufactured wheels and/or reprofiled wheels is not recommended at this time based on the current research results. Wayside automated detection methods for cracked wheels could potentially provide some reduction in VSRs; however, many questions need to be addressed including the following:

- The relationship between the number of load cycles and the VSR crack size
- The influence on this relationship of parameters such as load magnitude, ambient temperature, and lateral position of the contact patch on the wheel tread
- The influence of wheel microstructure, and microcleanliness in particular, on VSR crack path propagation in the wheel

FUTURE WORK

Additional testing is planned using the rolling load machine and service worn wheels with machined defects.

REFERENCES

1. Dick, M. et al. 2008. “Characterization of Vertical Split Rim Failures,” Presentation to BNSF Wheel Shelling and Failure Study Group, Topeka, KS.
2. Lonsdale, C. and J. Oliver. 2011. “Wheel Rim Axial Residual Stress and a Proposed Mechanism for Vertical Split Rim Formation,” RTDF2011-76024 *Proc. ASME RTD Conference*, Minneapolis, MN.
3. Lonsdale, C., T. Rusin, and T. Hay. March 2009. “Research to Understand the Effects of Wheel Impact Loads on Wheel Stress Levels,” JRC2009-63026, *Proc. ASME JRC Conference*, Pueblo, CO.
4. Cummings, S. July 2011. “Inspection Results and Impact Load History of Vertical Split Rim Wheels,” *Technology* Digest TD-11-020, AAR/TTCI, Pueblo, CO.
5. Cummings, S. August 2011. “Ultrasonic Inspection and Subsurface Cracking of Vertical Split Rim Wheels,” *Technology Digest* TD-11-023, AAR/TTCI, Pueblo, CO.