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Axial Residual Stresses in Vertical Split Rim Wheels

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Summary

Transportation Technology Center, Inc. recently commissioned measurements of the axial residual stresses of wheels that failed from vertical split rim (VSR) and compared the results to other service-worn wheels and a new as-manufactured wheel. Additional axial residual testing was conducted and funded independently by Amsted Rail, beginning in early 2009.¹

Comparisons showed that the large axial residual stresses developed during service in AAR Class C wheels could be an important factor in the VSR failure mode. At approximately 0.4-inch radial depth, axial residual stress in service-worn AAR Class C wheels transitions from compression that impedes VSR crack growth to tension that encourages crack growth. Anecdotal evidence suggests that VSR failures first started appearing in the mid-1990s when the use of heat treated AAR Class C wheels became widespread and axle loads were on the rise to accommodate more cars with 286,000 pounds gross rail load.

Work commissioned by Amsted Rail using x-ray diffraction has revealed that the transition from compressive to tensile axial residual stress occurs at a radially deeper location in AAR Class U wheels compared to AAR Class C wheels. This is likely the result of differences in yield strength between the wheel types and the plastic deformations from wheel/rail contact. The deeper transition forces a vertically oriented crack to have to propagate farther in a compressive stress field before entering a tensile stress field where crack propagation could be accelerated. This could help explain the increase in the VSR failure mode associated with AAR Class C wheels.

Residual stress measurements on 10 AAR Class C wheels showed dramatically different results depending on whether the wheel had experienced service loading or not. Residual stresses were much larger in service-worn wheels compared to a new as-manufactured wheel. Residual stresses were similar between wheels that had failed from VSR and other service-worn wheels.

To further investigate the root cause of the VSR failure mode, service-worn AAR Class C wheels with existing subsurface cracks will be repeatedly loaded on a laboratory rolling load machine with the goal of producing a VSR failure. The internal cracks will be monitored with nondestructive methods to quantify crack growth and orientation as a function of load magnitude and number of load cycles.

Federal Railroad Administration funded the test as part of a cooperative effort with the Association of American Railroads Strategic Research Initiatives Program to prevent wheel failures.



INTRODUCTION

This *Technology Digest* (TD) describes axial residual stress test results from wheels that failed in service from VSR. Comparisons are made with unfailed service-worn wheels and a new as-manufactured wheel. Federal Railroad Administration (FRA) funded the test as part of a cooperative effort with the Association of American Railroads (AAR) Strategic Research Initiatives Program to prevent wheel failures. Additional axial residual testing was conducted and funded independently by Amsted Rail.

BACKGROUND

Wheel stresses can be described in three directions: circumferential, radial, and axial. Circumferential stresses are also referred to as hoop stresses and are commonly investigated using saw cuts along radial lines. This TD describes work related to the axial stresses rather than the circumferential stresses. VSR and broken flange wheels are the result of cracks in the wheel rim oriented approximately in the axial plane. The axial plane of a wheel is parallel to the roller bearing end cap. Because VSR cracks propagate in the axial plane, tensile axial residual stresses will encourage crack growth and compressive axial residual stresses will impede crack growth. Figure 1 illustrates the principal directions associated with wheels, and Figure 2 shows a wheel with a VSR failure.

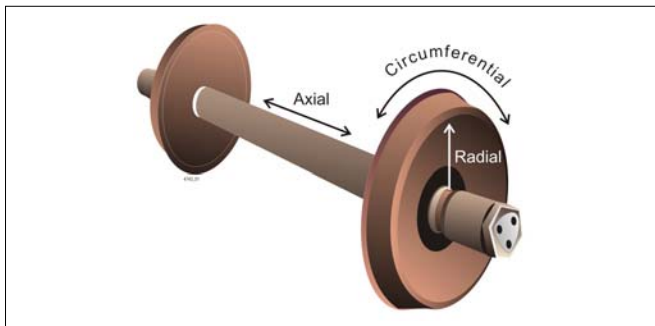


Figure 1. Wheel Principal Directions



Figure 2. Wheel with VSR Failure

Anecdotal evidence suggests that the VSR failure mode as seen today was extremely rare or nonexistent prior to the mid-1990s. In this general timeframe, axle loads were increased to accommodate cars with heavier capacity (263,000 pounds GRL compared to 286,000 pounds GRL). The AAR required that all new wheels be heat treated starting in 1989. Prior to this, new, nonheat treated AAR Class U wheels could be applied. Unfortunately, it is difficult to verify the general association of VSRs and AAR Class C wheels using safety or repair data. The FRA safety statistics have a category for

broken rim wheels, but this quantifies the number of reportable accidents (not the number of wheel failures), includes failures from root causes other than VSR such as shattered rim, and does not track the wheel class. The AAR uses a why made code for cracked or broken rim, but this also includes rim cracks other than VSR, and therefore does not allow an accurate historical count of VSR failures.

An AAR Class C wheel is essentially an AAR Class U wheel that has been heat treated during the manufacturing process. The heat treatment produces many benefits including beneficial compressive circumferential residual stresses, increased yield strength, and increased hardness. The increased yield strength improves resistance to rolling contact fatigue and shelling, and the increased hardness improves wear properties. AAR Class C wheel steel yield strength has been reported at 113 ksi² and the AAR allows a hardness range from 321 to 363 HB. AAR Class U wheel steel yield strength has been reported at 66 ksi.³ No hardness range was specified for AAR Class U wheels, but measured values throughout the rim ranged from 254 to 277 HB.³

AXIAL RESIDUAL STRESS

Axial residual stress measurements were made on 10 AAR Class C wheels. Test specimens encompassed at least 3 inches in the circumferential dimension and were extracted from the wheels using bandsaw cuts. Axial strain readings were recorded by Transportation Technology Center, Inc. engineers on two of the wheels before and after extraction of the test specimen to verify that the extraction method did not produce significant changes in residual stress. Six of the wheels failed in service because of VSR, three of the wheels were unfailed service-worn wheels, and one wheel was in the new as-manufactured state with no service loading. The specimens from the three unfailed service-worn wheels were free of subsurface cracks or large defects based on ultrasonic testing results. Table 1 contains additional detail about the wheels and the results of the axial residual stress measurements including the maximum tensile and compressive residual stresses and the radial depth at which the axial residual stress transitioned from compression to tension. The “Highest Impact Load” values in this table are the largest wheel impact load detector reading for each wheel for up to 18 months prior to the date the wheel was removed from service.

Residual stress measurements were conducted by Hill Engineering, LLC using the slitting method. Two strain gages were installed on each wheel section — one on the tread surface and one on the front rim fillet. An incremental slit was cut into the specimen using wire electrical discharge machining (EDM). Wire-cutting EDM is commonly used to minimize residual stresses imparted by the cutting process. The slit was located 2 inches from the wheel front rim face and cut through the wheel rim at 0.05-inch radial increments. The released strains were recorded at each incremental cut depth. A finite element model was then used to generate geometry specific coefficients relating the experimentally measured strain to residual stress. Figure 3 shows a wheel specimen after the slit has been cut. More detail on this measurement technique can be found in the literature.^{4,5}

Table 1. Axial Residual Stress Results

TTCI Wheel ID	History	Years in Service	Design	Rim Thickness (inch / 16)	Highest Impact Load (pounds * 1000)	Max Compression (ksi)	Max Tension (ksi)	Radial Depth of Transition (inch)
14	VSR	7.5	CH36	14	57	-47.7	35.3	0.41
9	VSR	2.1	CH36	23	138	-54.9	21.7	0.42
69	VSR	7.0	CH36	25	69	-57.0	35.1	0.49
30	VSR	1.3	CH36	23	70	-65.5	33.3	0.43
35	VSR	4.1	CH36	18	114	-52.1	60.7	0.54
36	VSR	1.3	H36	27	85	-51.4	37.9	0.45
54	Worn	2.1	CH36	23	79	-55.4	29.0	0.38
41	Worn	3.5	CH36	18	50	-67.7	29.8	0.36
37	Worn	1.3	H36	27	75	-52.2	38.5	0.47
N1	New	0.0	CH36	Nominally 24	N/A	-11.3	2.6	0.56

Figure 4 shows the average composite axial residual stress as a function of radial depth for the VSR wheels, the service-worn wheels, and the as-manufactured wheel. A radial depth of 0.0 inch indicates the tread surface.

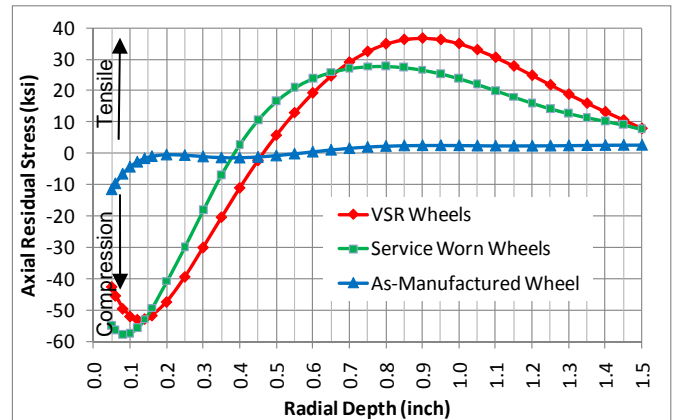


Figure 4. Composite Results of Axial Residual Stress Testing of Class C Wheels

DISCUSSION

The most striking observation from the results is the overwhelming influence the service load environment has on the axial residual stress in AAR Class C wheels. While the heat treatment during manufacturing imparts a relatively small compressive residual stress near the tread surface, the service load environment produces much larger compressive and tensile axial residual stresses from the plastic deformations associated with rolling contact. The VSR wheels and the service-worn wheels show similar trends: large compressive residual stress near the tread surface transitioning to large tensile residual stress at approximately 0.4-inch radial depth.

When failed and unfailed parts both show similar results in a laboratory test, there is a tendency to exclude the property under test as a critical factor in the failure mode. However, the axial residual stresses in AAR Class C wheels should be viewed as a clue to the VSR failure mode. As reported previously, the VSR initiation sites from 35 broken wheels have a median value of 0.17 inch radially below the tread surface.⁶ This means that a VSR crack need only propagate approximately 0.23 inch deeper, radially, from point of maximum stress before entering a tensile residual stress field that would encourage rapid growth. The difference between the VSR wheels analyzed and the unfailed service-worn wheels is the presence of a VSR crack that propagated to the depth of the tensile axial residual stress field. The conditions necessary to form and propagate such a crack are under investigation.

Beginning in early 2009, Amsted Rail independently commissioned axial residual stress testing of VSR wheels, newly manufactured wheels and service worn AAR Class C and AAR Class U wheels using x-ray diffraction techniques.¹ The x-ray diffraction and slitting method results and trends compared well for AAR Class C wheels, thereby providing an added measure of confidence in both measurement techniques. The service worn AAR Class U wheels showed a transition from axial residual compression to axial residual

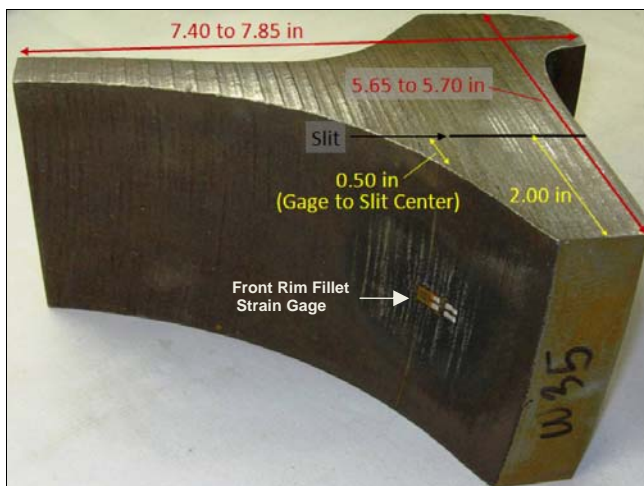
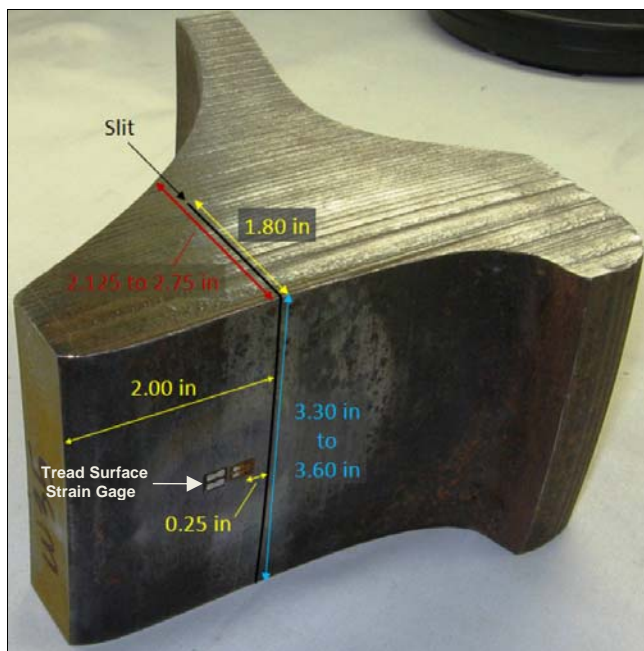


Figure 3. Wheel Specimen after Slitting Operation Showing Typical Dimensions (photos courtesy of Hill Engineering, LLC)

tension approximately 0.15 inch deeper, radially, compared to service worn Class C wheels.¹ This result corresponds well with the lower yield strength of AAR Class U wheels compared to AAR Class C wheels. Figure 5 shows the calculated stress from wheel/rail contact as a function of radial depth into the wheel. This stress curve is based on Hamilton's equations for contact between spherical bodies.⁷ The calculated stress exceeds the yield strength of an AAR Class C wheel to a depth of 0.17 inch, and it exceeds the yield strength of an AAR Class U wheel to a depth of 0.40 inch. This plastic deformation creates the compressive axial residual stress, which must be reacted at a deeper radial location with a tensile axial residual stress. Deeper plastic deformation will result in a deeper transition from compressive residual stress to tensile residual stress. Hence, a VSR crack would need to propagate farther in a compressive residual stress field before reaching a tensile residual stress field in an AAR Class U wheel compared to an AAR Class C wheel. This may help explain why VSR failures are more commonly associated with AAR Class C wheels compared to AAR Class U wheels.

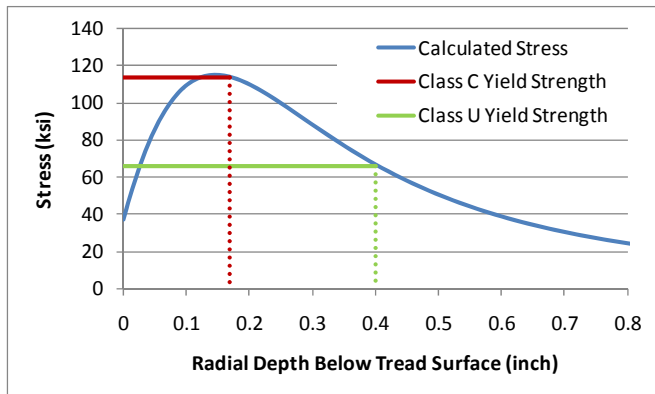


Figure 5. Radial Depth of Expected Plastic Deformation in AAR Class C and U Wheels

Wheel/rail contact forces can be increased statically, through the use of heavier axle loads, or dynamically, through impact loads from tread surface discontinuities such as shelling or spalling. Wheel tread damage and increased wheel impact loads are common features of wheels that fail from VSR.⁶ Increased wheel/rail contact force not only causes an increase in the magnitude of subsurface stress in wheels, but it also increases the radial depth at which the maximum stress occurs. Higher stresses occurring at a radially deeper location could propagate existing cracks (such as from shells or spalls) to radially deeper locations and possibly into the axial tensile residual stress zone. The farther a crack propagates into the axial tensile residual stress zone, the higher the probability that the crack would continue propagating parallel to the front rim face and form a VSR.

CONCLUSIONS

The rise in VSR failures is commonly associated with the mid-1990s, a time when the industry began widespread use of increased axle loads and heat treated AAR Class C wheels. These wheels develop large axial residual stresses during service presumably from plastic deformation as a result of rolling contact. The axial residual stresses are compressive near the tread surface and transition to a tensile stress state near 0.4 inch below the tread surface. The presence of a large axial tensile residual stress field relatively near the tread surface could encourage VSR crack growth once a crack in the tread reaches the depth of this tensile field and is a likely contributing factor to VSR failures in AAR Class C wheels.

FUTURE WORK

Service-worn AAR Class C wheels with existing subsurface cracks will be repeatedly loaded on a laboratory rolling load machine with the goal of producing a VSR failure. The internal cracks will be monitored with nondestructive methods to quantify crack growth and orientation as a function of load magnitude and number of load cycles.

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