Railroad Wheel Design Considerations, Service Defects and Failure Modes

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Presentation Outline

- North American Railroad Wheel History
- Wheel Design
- Shelled Tread Condition (Shelling and Spalling)
- Other Tread Defects
- Microalloy wheels
- Wheel Failures (Shattered Rims and VSRs)
- Axial Residual Stress Testing

North American Railroad Wheel History

- North American Railways had to import rolling stock and components from Europe at first.
- 1856, first steel tyres manufactured by predecessor to Standard Steel in PA.
- Domestic forged tyre and monobloc wheel development followed.
- Domestic cast wheel development followed.

North American Cast Wheel History

- Early North American railroads faced steep mountain grades and rapidly expanded westward.
- Original cast wheels were cast “chilled iron” wheels.
  - First manufactured in Maryland in 1829
- 1868 - “Master Car Builders Association” standardized wheels at 33 inches diameter.
- “Double plate design” 1838-1928, 2 parallel plates and cooling fins to increase convection.
- Griffin Wheel Company – Detroit, Michigan, 1877.
- Several plants around North America by early 1900’s.
- Griffin patented the single plate chilled iron wheel in 1924, and AAR adopted the single plate wheel in 1928.

North American Cast Wheel History

- Needed: A wheel to withstand heavier loads, speeds, braking forces without cracking, with greater wear resistance.
- 1940's – Griffin began experimenting with graphite molds to provide near net shape castings with excellent rotundity, surface finish and balance.
- Controlled pressure pouring to reduce air entrainment and allow for production of cleaner steels.
- Service testing showed that new cast steel wheels lasted 3x longer than chilled iron wheels.
- Last chilled iron wheels produced by Griffin in Chicago – 1963.
- 1960's - Superior thermal performance of 28 inch Griffin cast parabolic plate wheel was noted vs. forged straight plate wheels.
  - **Significantly fewer failures**

Wheel Design

- In 1989 AAR required that wheels must be rim quenched and have a low stress plate. Rim quenching imparts beneficial hoop compressive residual stress, and higher hardness.
- Parabolic curved plate, and s-plate wheels, have lower resultant stresses when exposed to tread braking in service.
- Wheels are analyzed using AAR S-660 Finite Element Analysis to determine the stresses at various plate locations.

Wheel Design

- Manufacturers have different plate shapes.
- Straight plate wheels have much higher stresses in the front hub-plate fillet and in the back rim-plate fillet.
- Straight plate wheels failed more often.
- Thermal failures have largely disappeared due to the design change.
- However, about 1-2% of freight wheels in service are still straight plate wheels!

Wheel Profiles

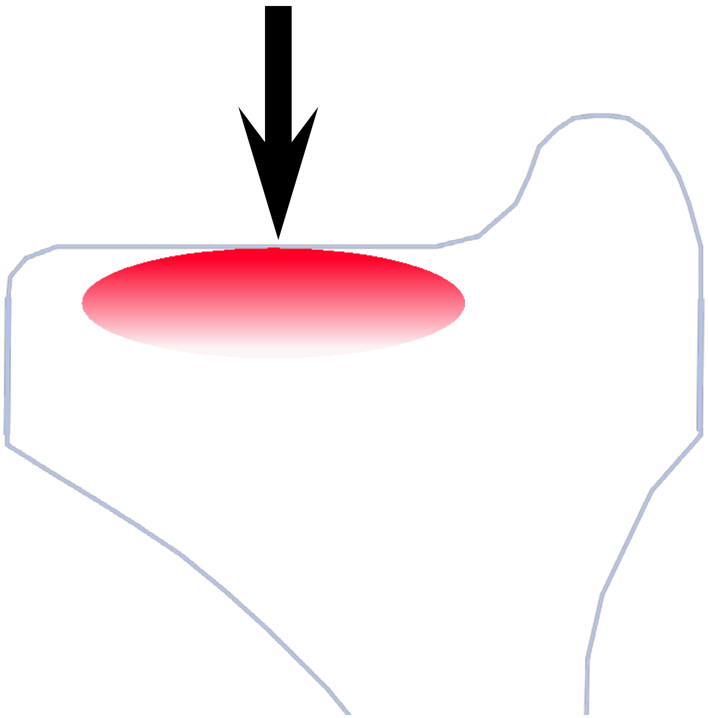
- 1:20 tread profile for freight
- 1:40 tread profile for Amtrak
- 1:40 has a more gentle slope that “corrects” less aggressively, meaning a smoother ride

Shelled Tread Conditions

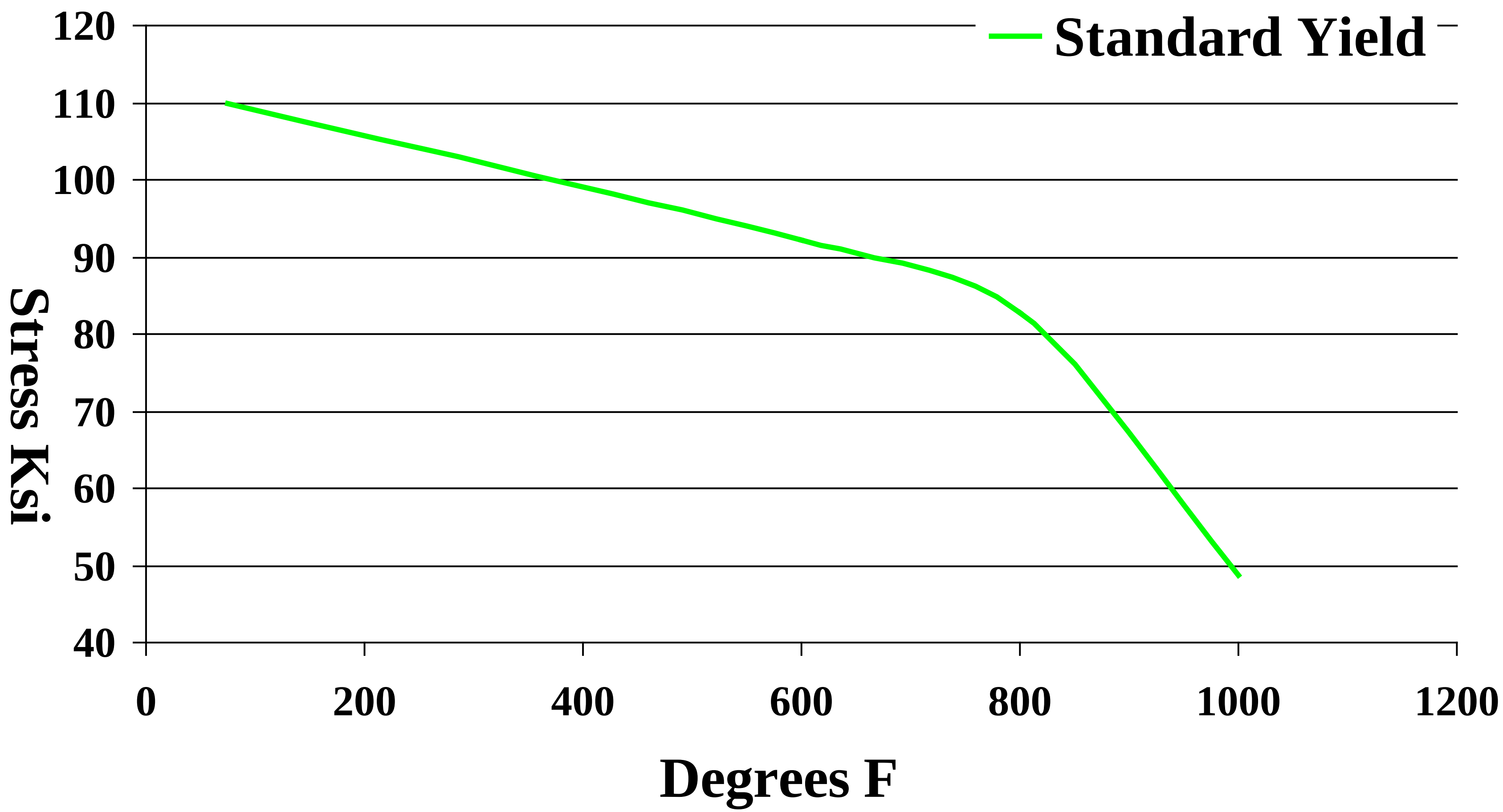
Shelling and Spalling

Thermal Mechanical Shelling

- Thermal Mechanical Shelling occurs when the stresses from rolling contact exceed the thermally reduced material strength.



Strength vs. Temperature



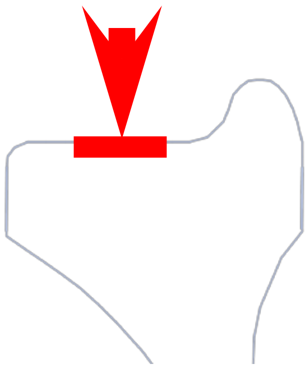
Thermal Mechanical Shelling

The rolling contact fatigue cracks initiate at either side of the contact patch then propagate parallel to the tread beneath the surface. These cracks join and pitting results.

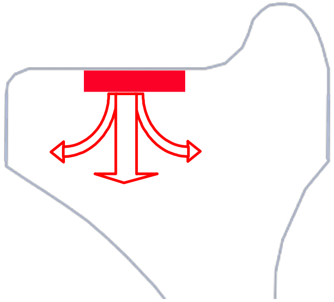
Thermal Mechanical Shelling

Spalling

A high thermal input followed by rapid cooling forms martensite. This brittle material then cracks under normal rolling loads.



Localized Heating Above 1350 Deg F

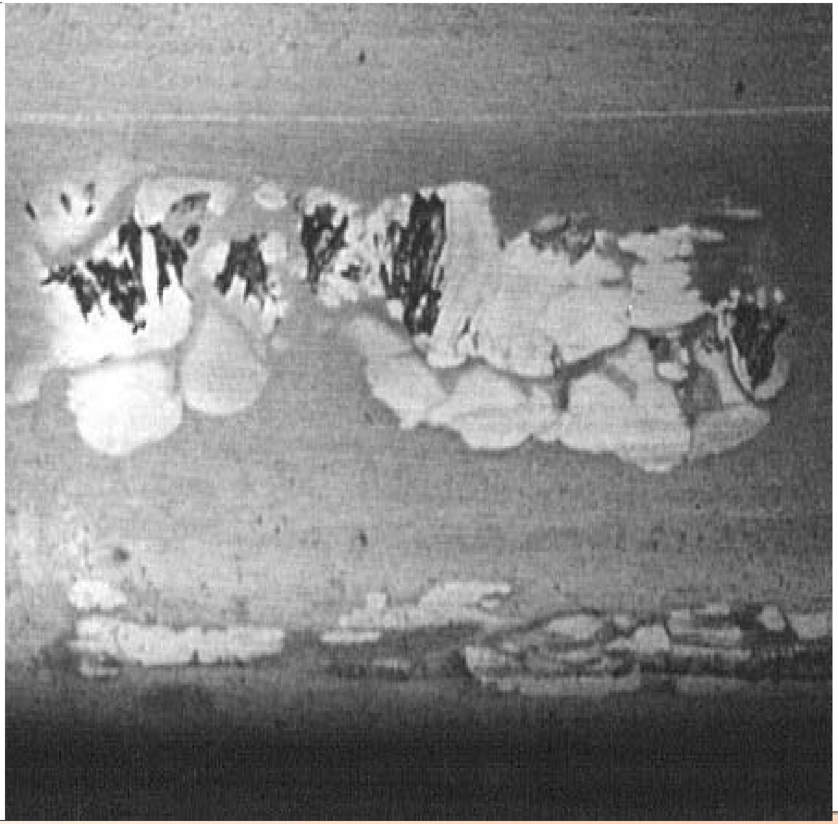


Rapid Cooling

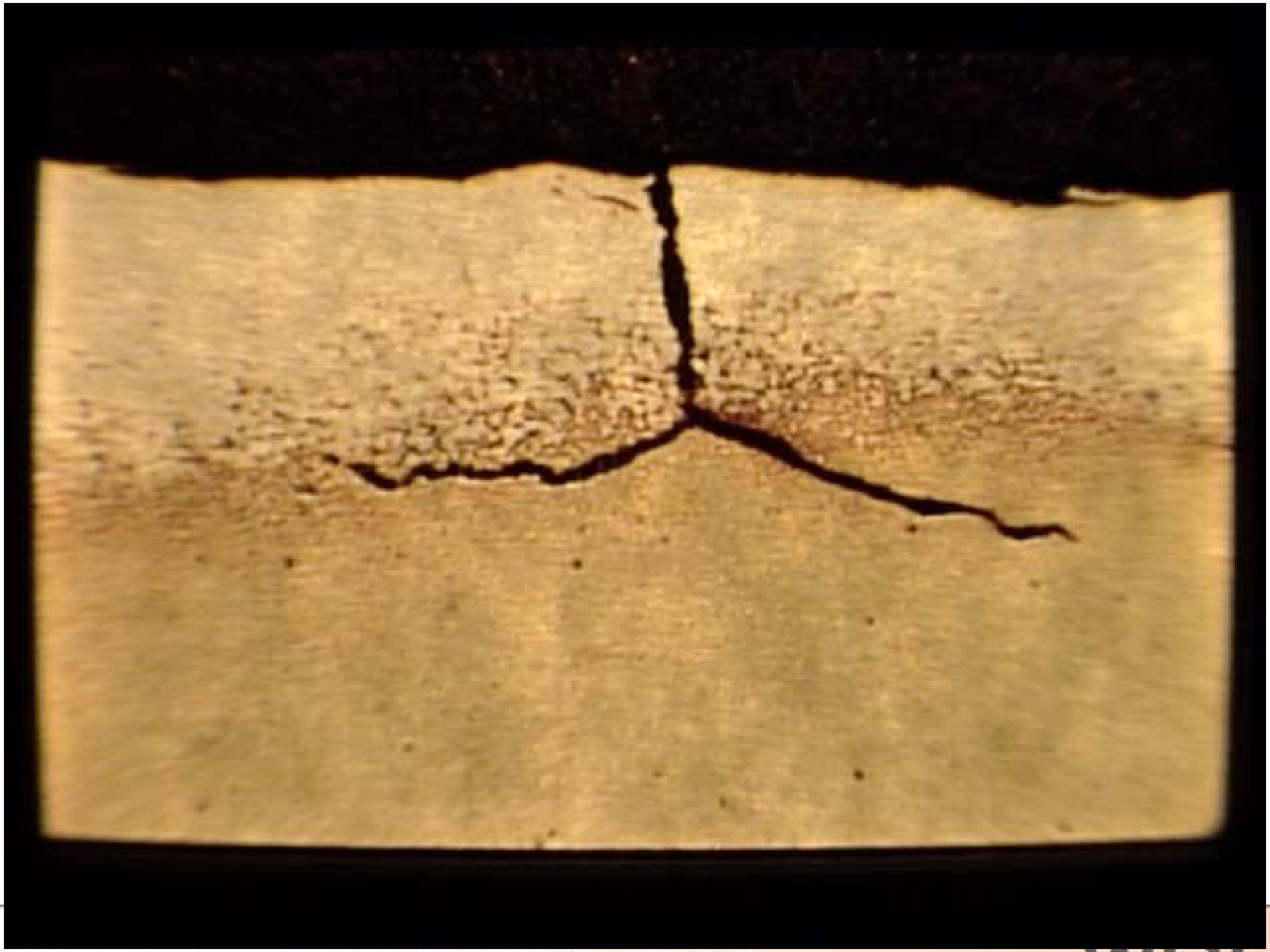
Spalling

The cracks propagate through the martensite perpendicular to the tread then turn and run in the circumferential direction in the base metal. Several of the cracks link up and pitting results.

Spalling

Martensite and Crack



Thermal Shelling vs. Spalling

- Thermal mechanical shelling - created by elevated tread temperatures and rolling contact stresses.
  - Thermal mechanical shelling is seen in heavy grade braking service
  - Can be caused by stuck brake or hand brake left on resulting in "warm wheel"
- Spalling - due to generation of martensite on tread surface from wheel sliding.

Effects of Shelled Treads

- Shortened wheel life.
- High impact loadings which:
  – Damage track and car equipment.
  – Originate cracking at the tread damage on an axial plane resulting in vertical split rim fractures.
  – Damage wheels, contributing to sub-surface originated, shattered rim fractures.

Microalloy Wheels To Combat Tread Damage

- Spalling – wheel sliding and martensite formation
    - Seen generally on mixed freight cars
- Shelling – rolling contact fatigue
- Thermal-Mechanical Shelling – RCF, heavy loads, with elevated temperature from braking
    - Seen generally on unit coal trains
- Griffin "Class D" microalloy - targeted to help solve Thermal Mechanical Shelling
- Higher strength than Class C at elevated temperatures

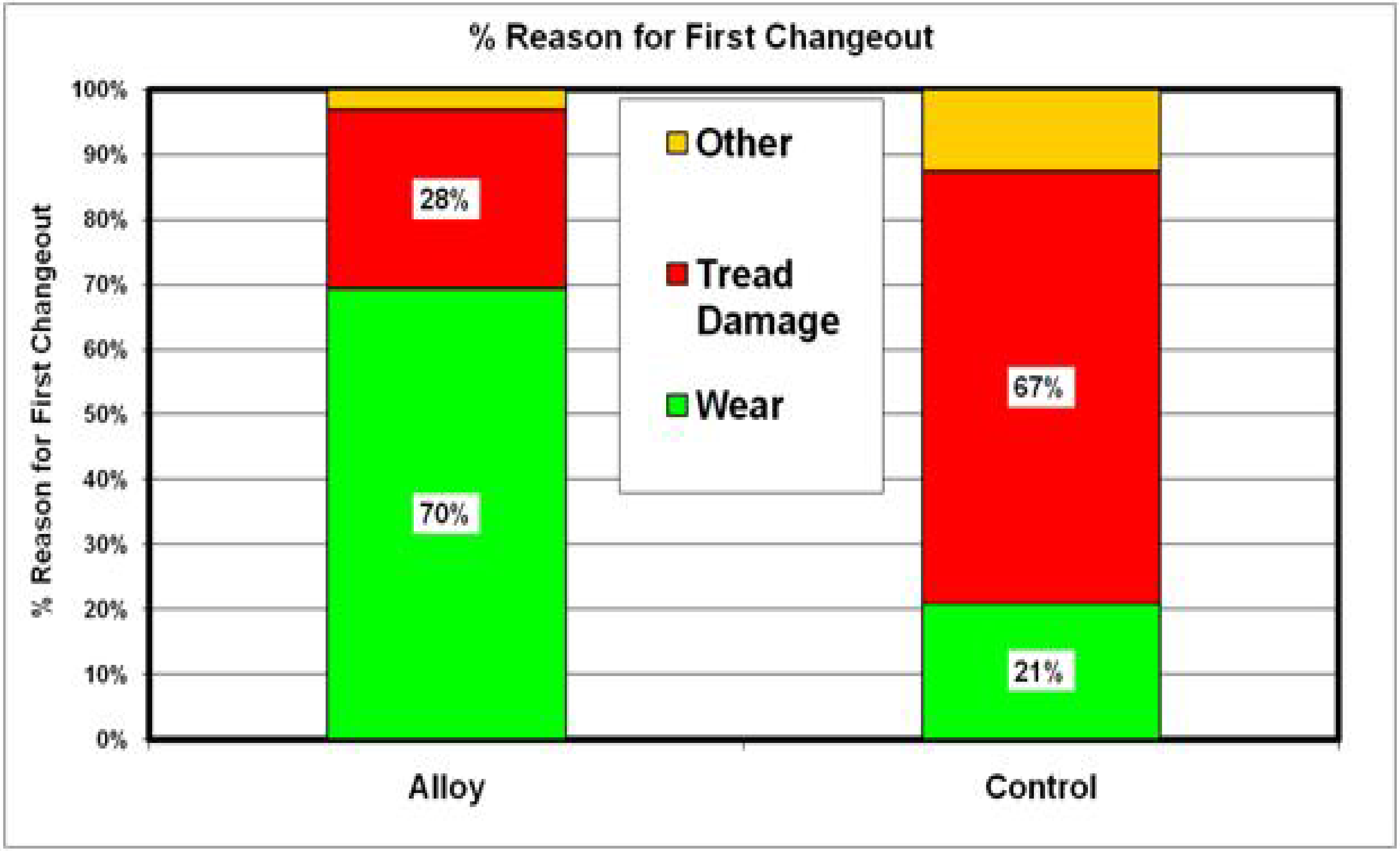
Microalloy Wheels To Combat Tread Damage

- Cr, Mo, Si additions
- At 1000F, Class D has 25% higher yield strength than Class C
- Microalloy wheel has 30% higher fracture toughness than Class C
- Ductility also significantly improved
- Griffin alloy is patented

Microalloy Field Tests

- Canadian National Railway, Quebec Cartier Mining, etc.
- 930 wheels total in all field tests
- CN Tests – Griffin Class C and 400 Griffin Microalloy wheels under 2 sets of 100 new aluminum coal cars
- Average mileage to first reprofile:
    - Class C = 213,600 miles
    - Microalloy = 368,150 miles
    - 72% improvement in wheel life
- QCM Tests – 198 wheels tested, 40-50% improvement in wheel life due to decrease in thermal-mechanical shelling

CN Microalloy Wheel Field Test



Broken Wheels By AAR Why Made Code

- 66 Flange cracked or broken
- 68 Cracked or broken rim
- 69 Thermal crack extending into plate
- 71 Shattered rim
- 72 Spread rim
- 74 Thermal cracks
- 83 Cracked or broken plate

Other Tread Defects

- WM 76 Tread built-up tread (1/8” or higher)
- WM 78 Tread slid flat (2” long , or 2 adj. at 1.5”)
- Past air brake testing on steel coal cars at Conrail showed high brake cylinder pressure in:
  - 80% of cars with built-up tread
  - 72% of cars with slid flats
  - 38% of cars with shelled tread

❖Now we have pressure taps to help detect leakage into the brake cylinder

Wheel Impacts

- 90,000 pounds, can remove wheelset
- Many causes of tread damage – stuck air brakes, hand brakes left on, etc.
- Role of hand brakes:
  – 294 tank cars, truck mounted brakes
  – Impact load levels consistent with tread damaged wheels for 139 wheels located in B-end trucks and only 7 wheels on A-end
  – 95 percent of the wheels with tread damage on only truck affected by handbrakes

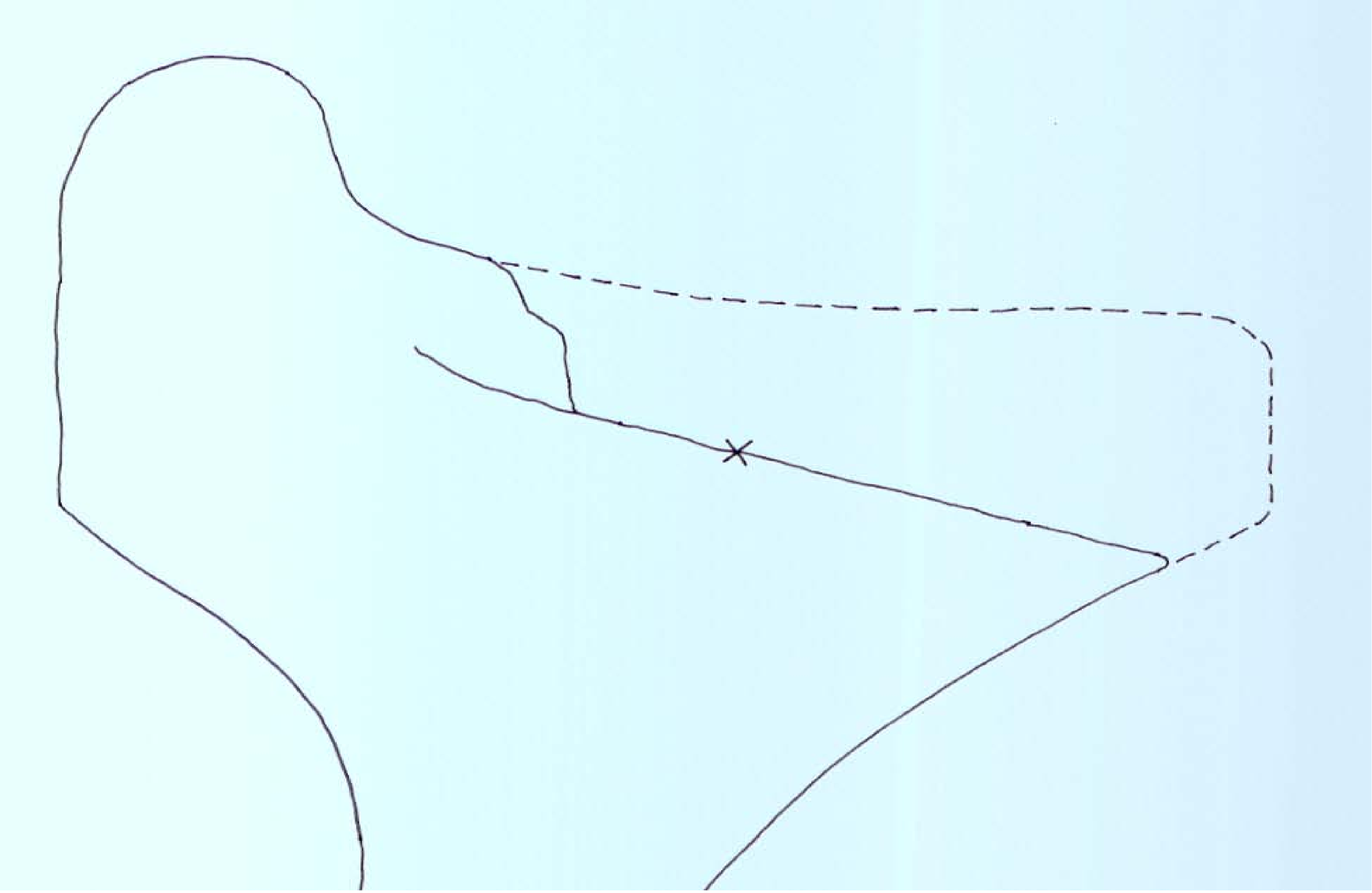
Broken Wheels

- Shattered Rims: Sub-surface fatigue initiating from a stress raiser such as porosity or inclusions. Fracture surface almost parallel to tread surface.
- Vertical Split Rims: Rapid cyclic overload initiating from tread damage. Fracture surface parallel to front rim face.

Shattered Rim Fractures (AAR Why Made Code 71)

Shattered Rim Fracture
AAR Why Made Code 71

Shattered Rim Profile



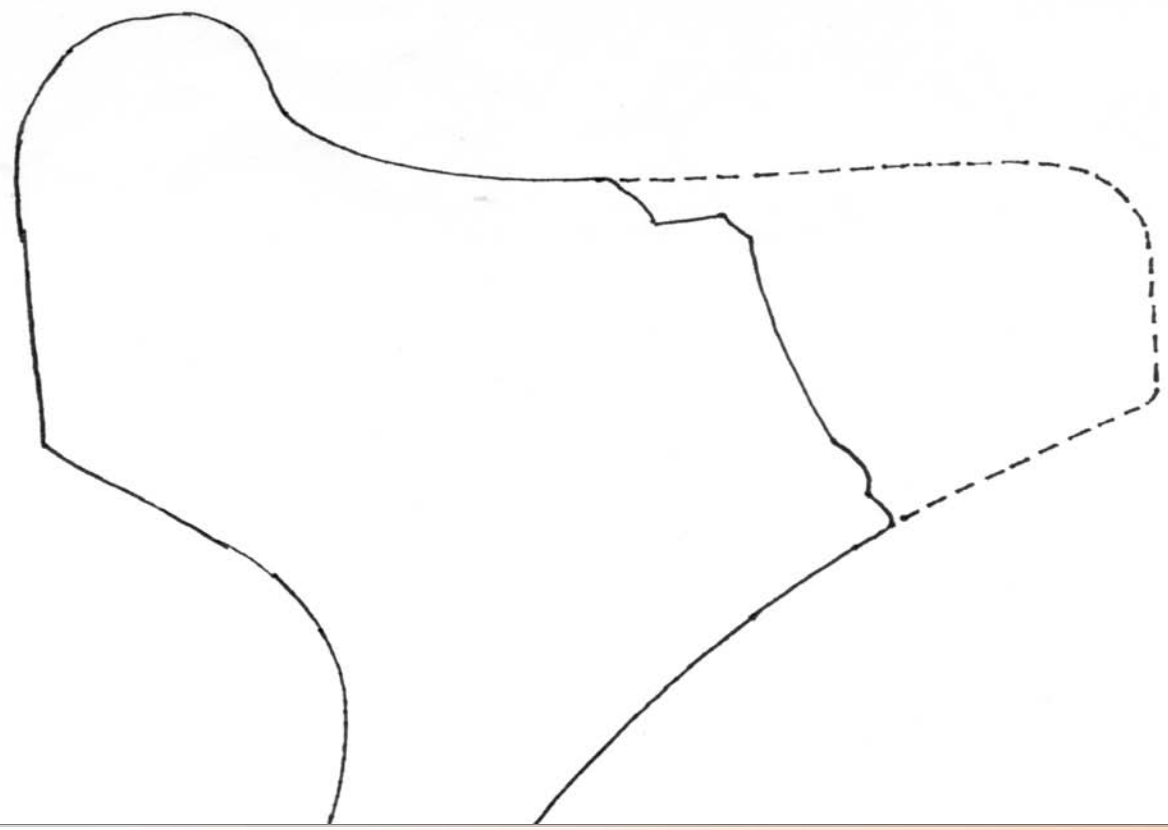
Shattered Rims

- Caused by inclusions in forged wheels and porosity in cast wheels
- AAR UT requirement was tightened 2 x – 1/8” FBH prior to 1999, 50% of 1/8 FBH in 1999, 25% of 1/8” FBH in mid-2000’s
- Also additional riser added to Griffin wheels in mid-1990’s to reduce porosity
- Shattered rim failures are quite rare today

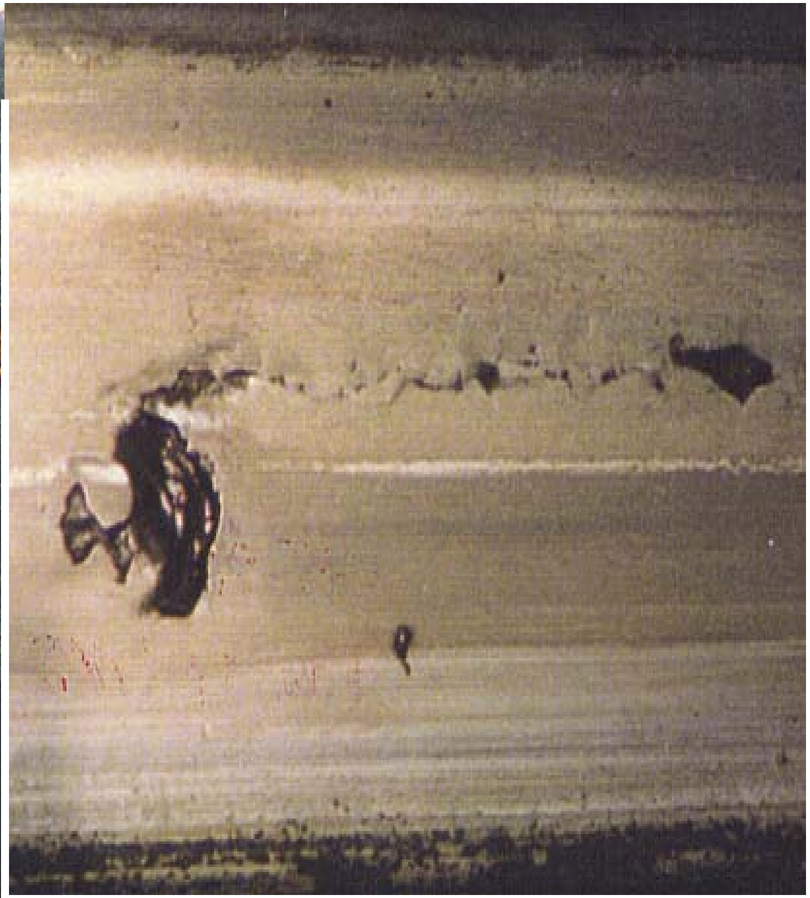
Vertical Split Rims
(AAR Why Made Code 68)

Introduction and Background

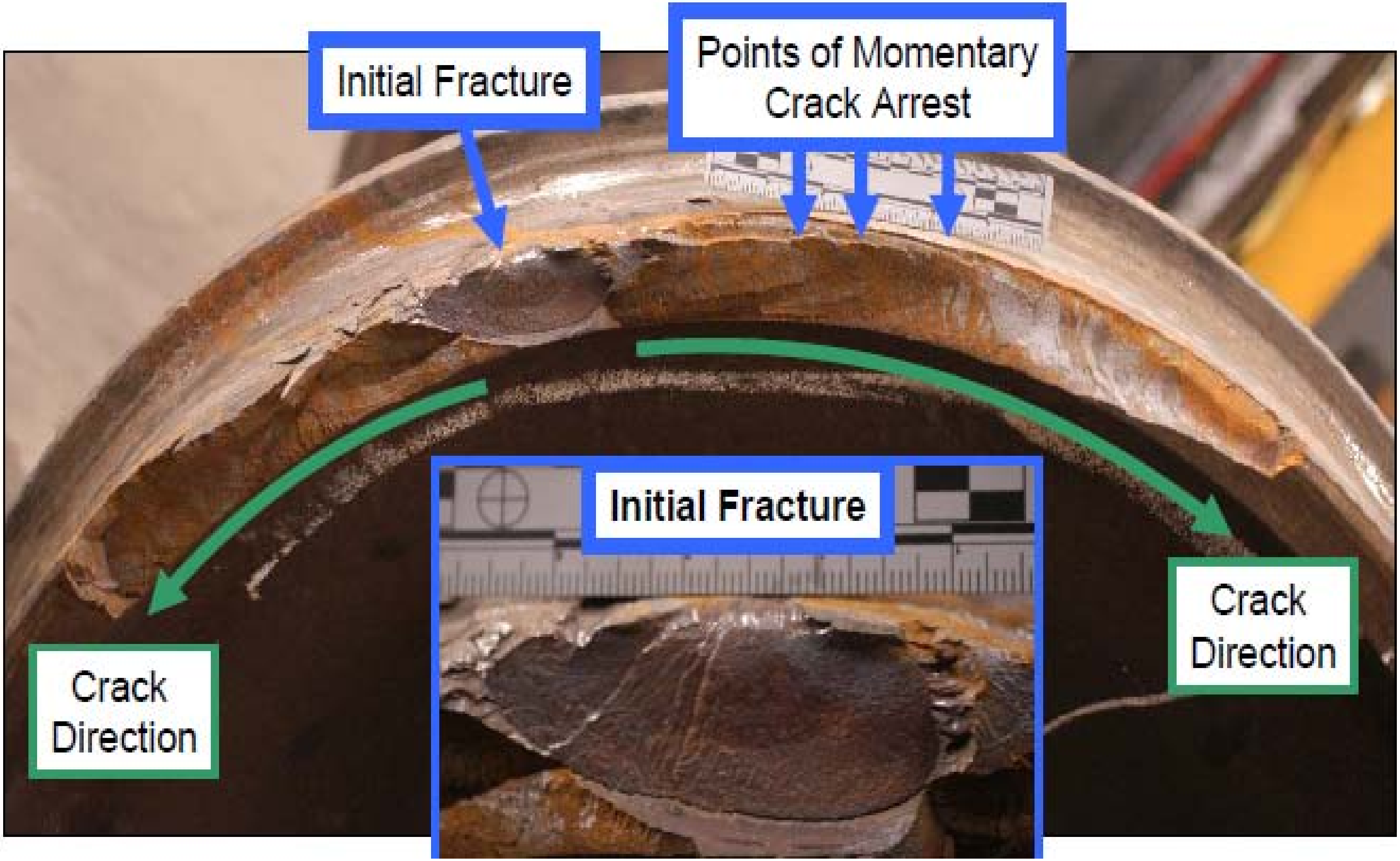
- VSRs start almost exclusively at tread damage
- Typically, a circumferential section of the front rim face breaks off, and wheel can drop into gage



Vertical Split Rims Start at Tread Damage



VSR Image, Courtesy of Dick, et al.



Introduction and Background

Observations by Dick, et al. on 68 wheels

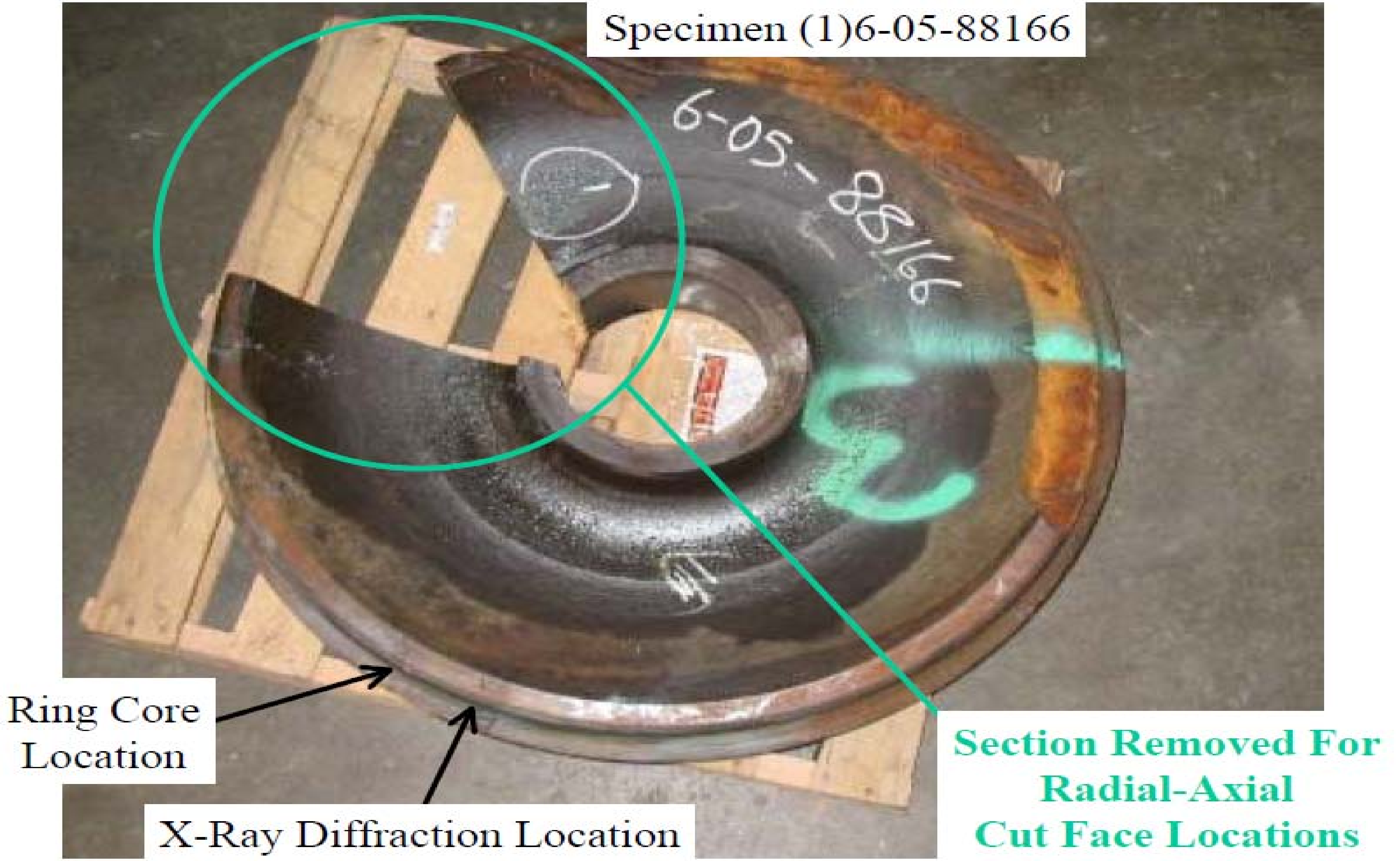
- VSRs length is typically 15 cm to entire circumference
- Typically VSR is 25 to 70 mm from wheel's front rim face
- 263K GRL and 286K GRL cars have similar number of VSRs
- Covered hoppers had most VSRs with 15/17 on B end
- 62/68 wheels were 36" or 38", only 6/68 were 33"
- Not all were thin rimmed wheels
- Most VSRs had hollow tread wear
- VSRs more common in winter months
- Most VSRs were impacting before failure

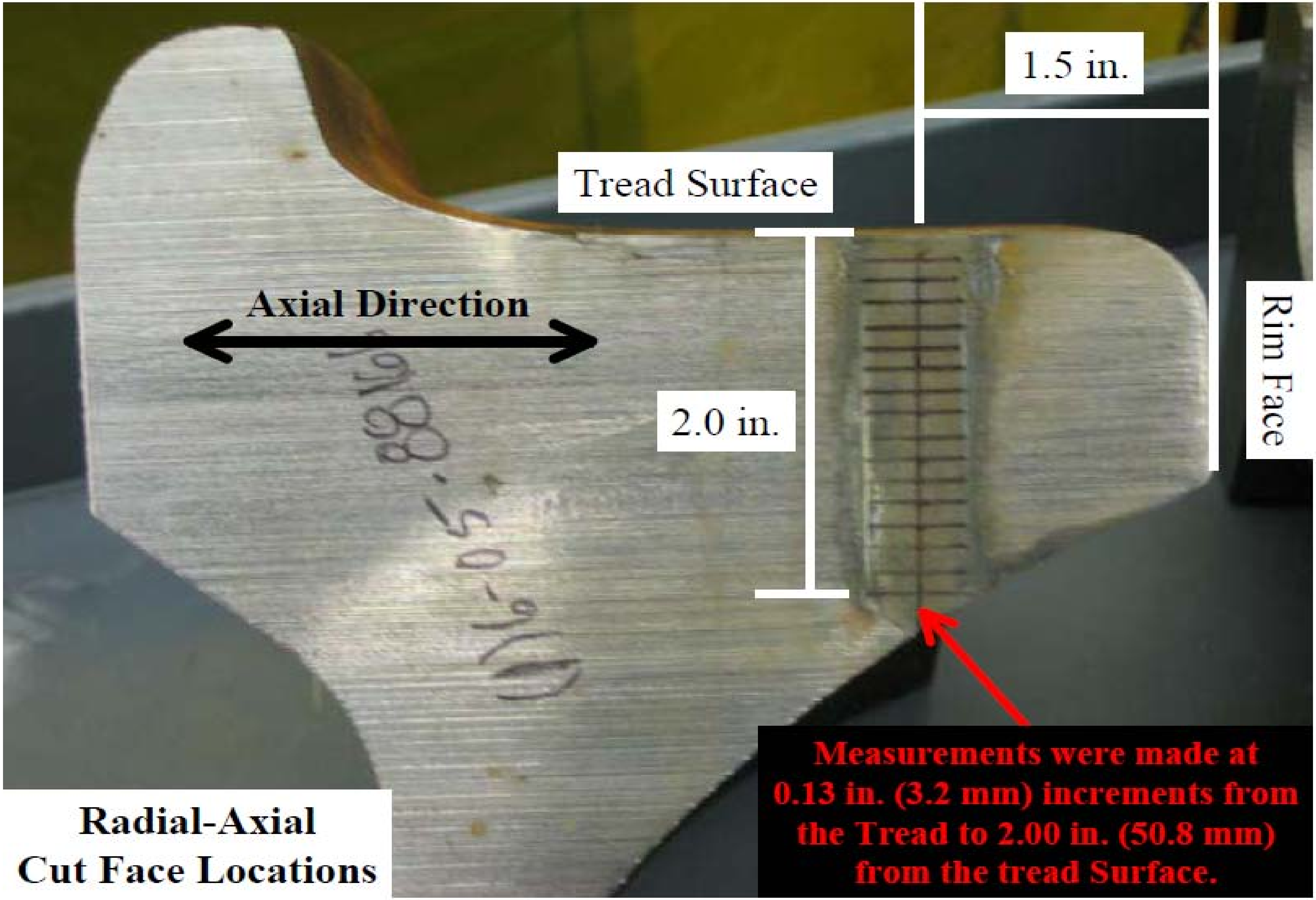
The VSR Puzzle

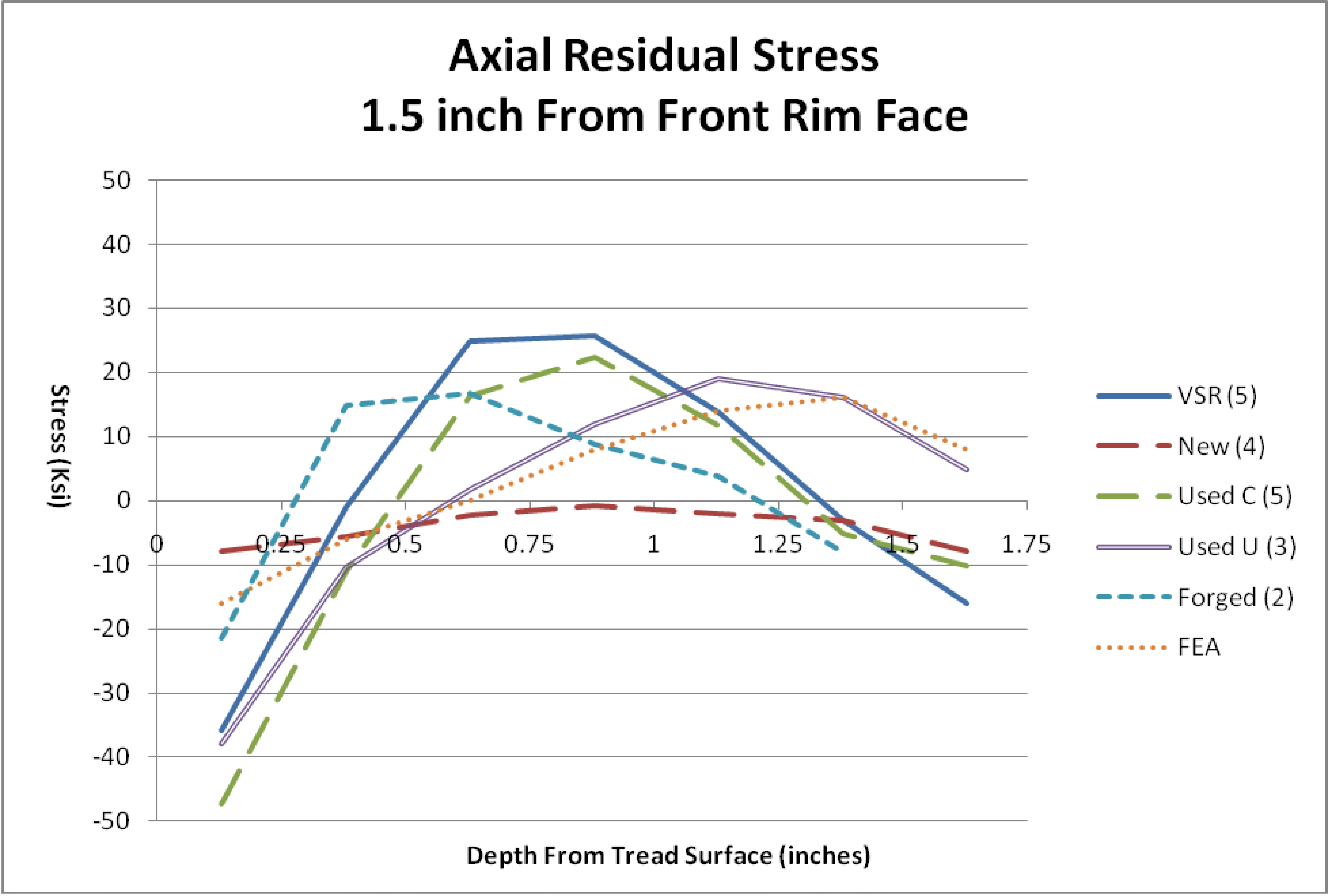
- No reports of VSR elsewhere in the world
- We did not seem to have them with Class U wheels?
- VSRs were not common before mid-1990's and 286K GRL?
- No difference in chemistry from non-VSR wheels, in fact S and P values LOWER (thus MnS inclusions also) for VSRs
- Saw cut testing – no evidence of thermal overload
- No microstructural anomalies
- Recent TTCI microcleanliness testing showed that 28/30 VSRs passed the AAR test – the only 2 that failed were manufactured before the test was adopted
- Impact, bending loads are insufficient for VSR to form
- Drop hammer tests (250 kips, 30,000 x) did not create VSR

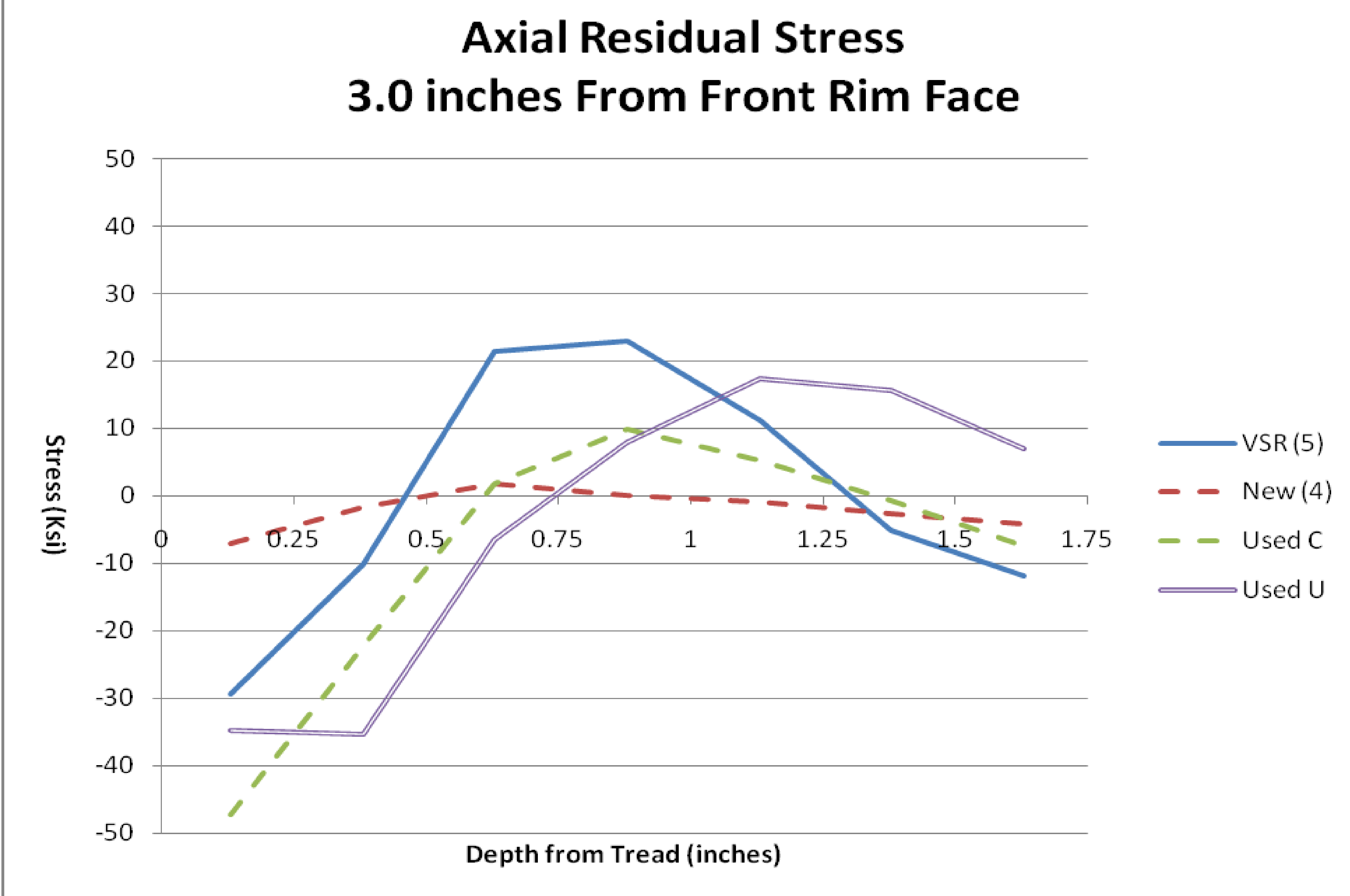
Radial slices – X-ray diffraction

- Core drill and x-ray diffraction from tread surface only provided residual stress measurements up to a depth of 1/3 inch
- Needed to determine stresses at locations below tread surface in the wheel rim
- Asked Lambda Research for assistance
- Focus on axial residual stress measurements
- Did we need to strain gauge wheel every time before cutting slices, or can relaxation effect be ignored?
- Also used American Stress Technologies, Pittsburgh

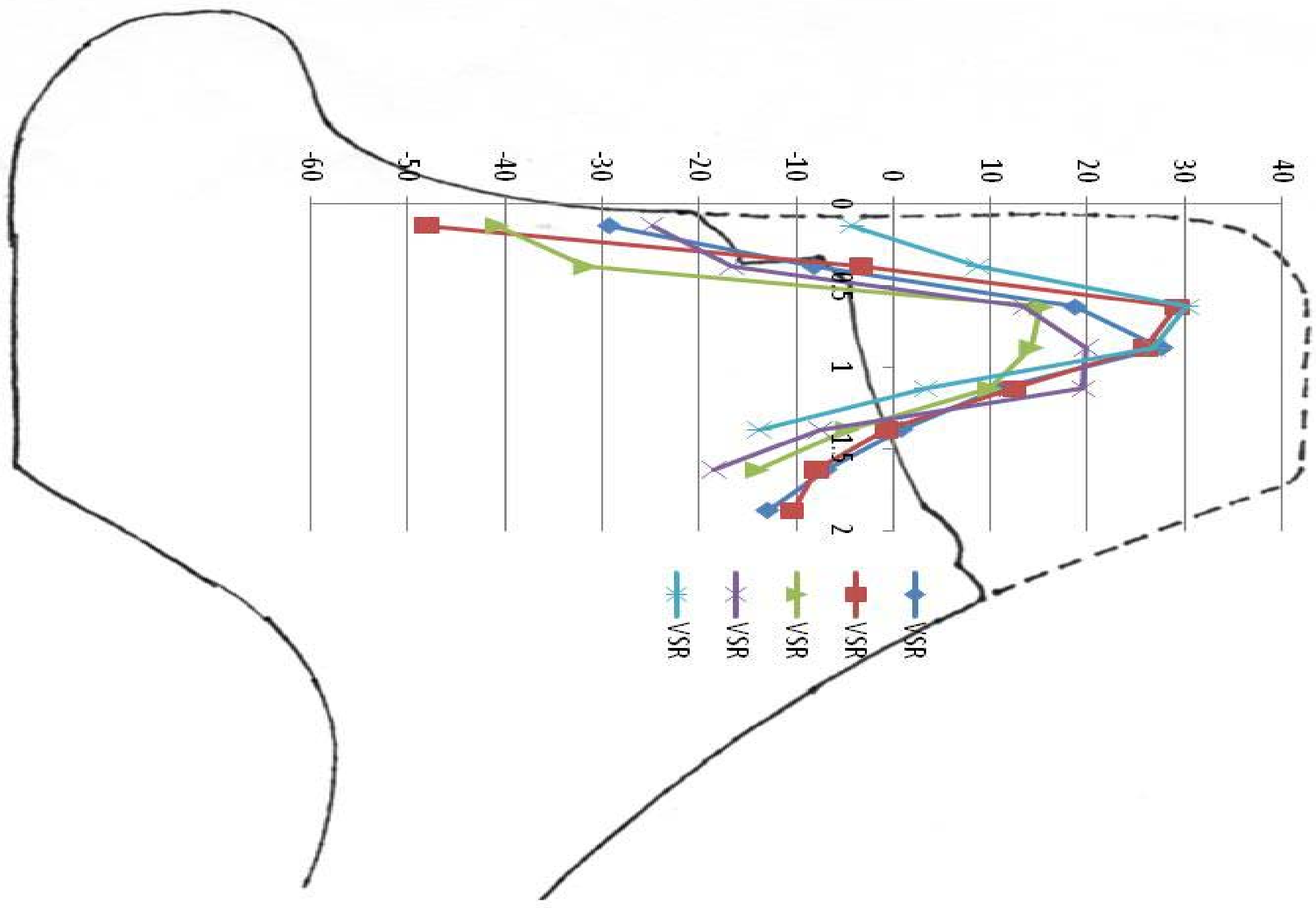

Specimen (1)6-05-88166
6-05-88166
Ring Core Location
X-Ray Diffraction Location
Section Removed For Radial-Axial Cut Face Locations


1.5 in.
Tread Surface
Axial Direction
2.0 in.
Rim Face
Radial-Axial
Cut Face Locations
Measurements were made at 0.13 in. (3.2 mm) increments from the Tread to 2.00 in. (50.8 mm) from the tread Surface.


Axial Residual Stress
1.5 inch From Front Rim Face
Stress (Ksi)
50
40
30
20
10
0
-10
-20
-30
-40
-50
0
0.25
0.5
0.75
1
1.25
1.5
1.75
Depth From Tread Surface (inches)
VSR (5)
New (4)
Used C (5)
Used U (3)
Forged (2)
FEA


Axial Residual Stress
3.0 inches From Front Rim Face
50
40
30
20
10
0
-10
-20
-30
-40
-50
Stress (Ksi)
0
0.25
0.5
0.75
1
1.25
1.5
1.75
Depth from Tread (inches)
VSR (5)
New (4)
Used C
Used U

VSR Profile With Results Superimposed



Proposed VSR Failure Mechanism From Previous Work (ASME RTDF 2011)

- Tread damage occurs due to shelling (RCF/thermal-mechanical shelling) or spalling (wheel slides)
- Cracks propagate under rolling and pounding loads
- Highly compressive layer at tread surface must be balanced by tension deeper below the surface
- When cracks propagate into this tension zone, cracks can rapidly change direction in service, making VSRs more likely
- Class U wheels had the tension zone much deeper below the tread surface – this, and lower loads, meant that U wheels did not often suffer VSRs

Questions?