Monash University

Monash Institute of Railway Technology

Improving the reliability of rail welds under heavy haul conditions

ICRI-RCF Webinar March 24/25 2021

Peter Mutton, IRT

Group of Eight Australia

Pilbara heavy haul networks

Rio Tinto

FMG

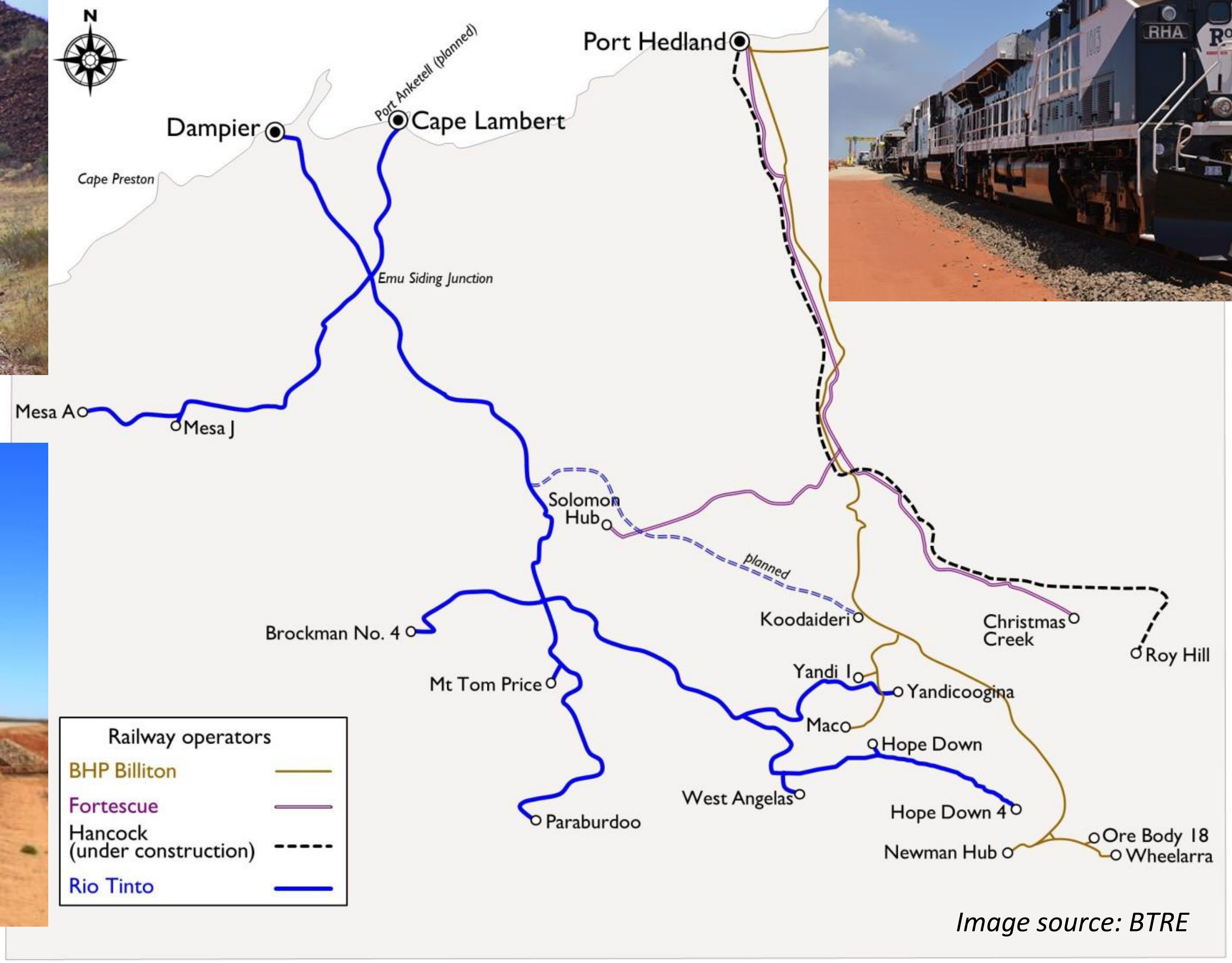
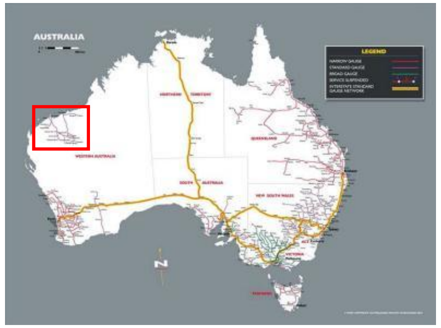


Image source: BTRE

Roy Hill



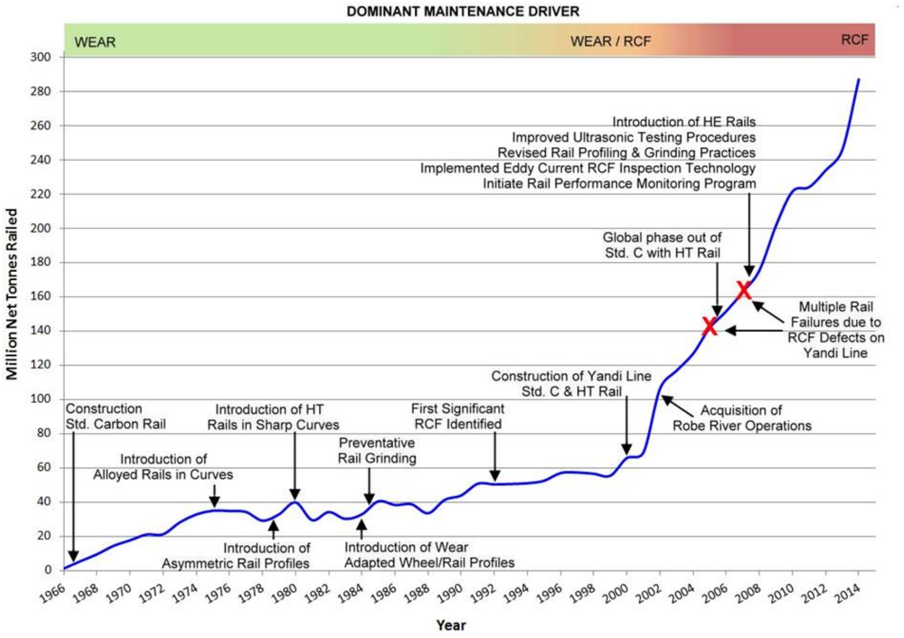
BHP

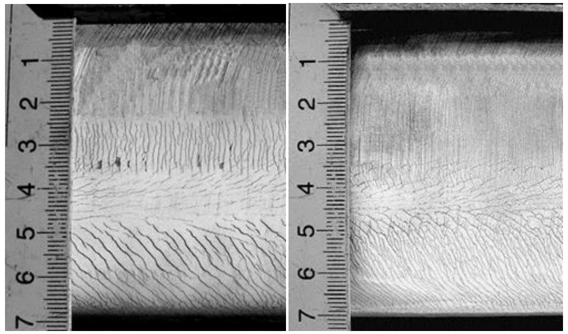
Pilbara heavy haul systems: Rail grades and rail welding

	Then (circa 2000)	Now
Rail networks	BHP, Rio Tinto	BHP, Rio Tinto, FMG, Roy Hill
Axle loads	30 tonnes	35-40 tonnes
Rail grades (68 kg/m)	Head hardened (Low alloy heat treated, 350-380 HB)	Premium heat treated (Eutectoid/hypereutectoid, 370-420 HB)
Plant welds (Long-welded rail - 400 m strings)	Fixed flashbutt welding machines	Fixed and mobile flashbutt welding machines
Field (in-track) welding	Aluminothermic welds	Predominantly mobile flashbutt welding Aluminothermic welding for turnouts and other locations not suitable for mobile flashbutt welders
Aluminothermic welding	Consumables from two manufacturers (Railtech/Pandrol, Goldschmidt-Thermit) Long-life crucibles	Pandrol PLK (single-use crucible) process used across all four systems

Failures in rails and welds

- Failures in parent rail have trended down as a result of:
  - Improvements in rail quality (steel cleanliness)
  - Use of higher strength rail grades
- Rolling contact fatigue (RCF) is now the primary deterioration mode affecting parent rail
  - Managed through rail grinding
- Increasing focus on improving the reliability of rail welds
  - Impact of service failures on haulage rates
  - Higher derailment risks associated with web fatigue failures in both weld types





Head hardened (~360HB) | Hypereutectoid heat treated (~420HB)

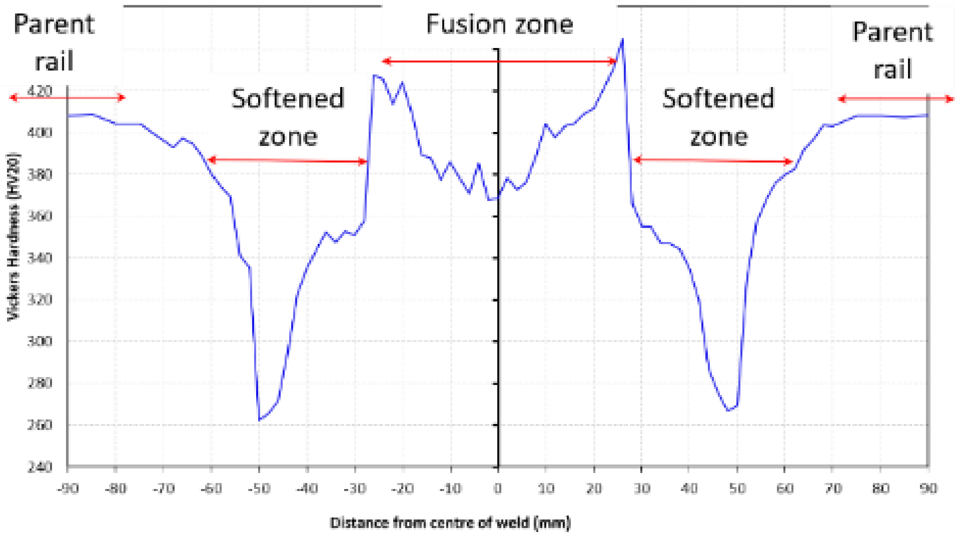
Managing the transition from wear to rolling contact fatigue in a heavy haul environment, L Wessels et al, IHHA 2015

Weld attributes and impact on weld performance

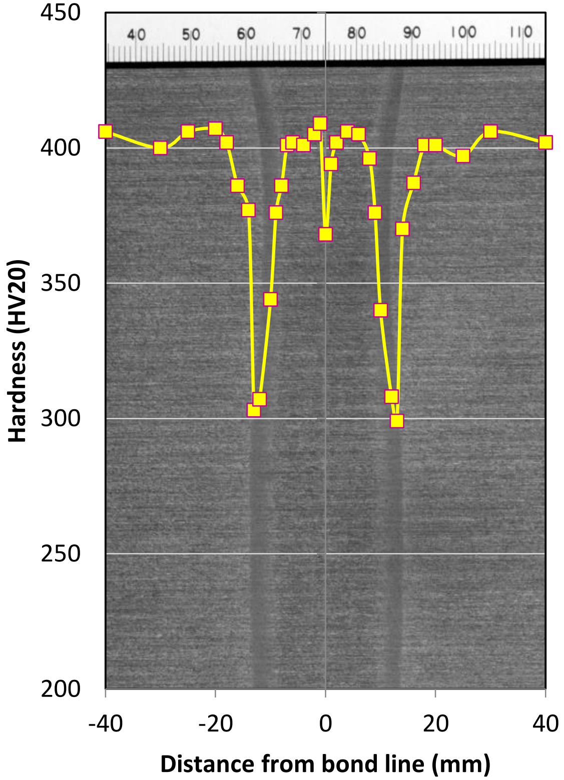
Attribute	Influence of weld type	Influence on weld performance
Variability in microstructure/hardness	Generally more variable in aluminothermic welds May be influenced by parent rail characteristics in flashbutt welds	Localised plastic deformation, wear and RCF compared to parent rail Increased impact loading in dipped welds
Residual stresses	Present on both types; generally higher in flashbutt welds than aluminothermic welds	Increased fatigue crack growth rates and smaller critical flaw sizes
Strength & toughness	Poorer in aluminothermic welds than flashbutt welds	Smaller critical flaw sizes
External dimensions	Larger and more variable in aluminothermic welds due to weld collar Influenced by shearing and weld dressing (grinding) in flashbutt welds	Higher bending stresses relative to parent rail Presence of stress concentrators
Surface condition	Shear drag in flashbutt welds Flashing, cold laps in aluminothermic welds	Fatigue crack initiation
Alignment (vertical and/or lateral)	Can be variable in both weld types	Increased dynamic loads, higher surface traction particularly in curves

Variation in hardness and microstructure from parent rail

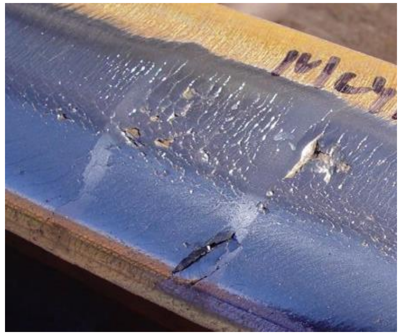
- Material characteristics influence behaviour in wheel-rail contact
- Heat-affected (softened) zones more susceptible to damage



Aluminothermic weld



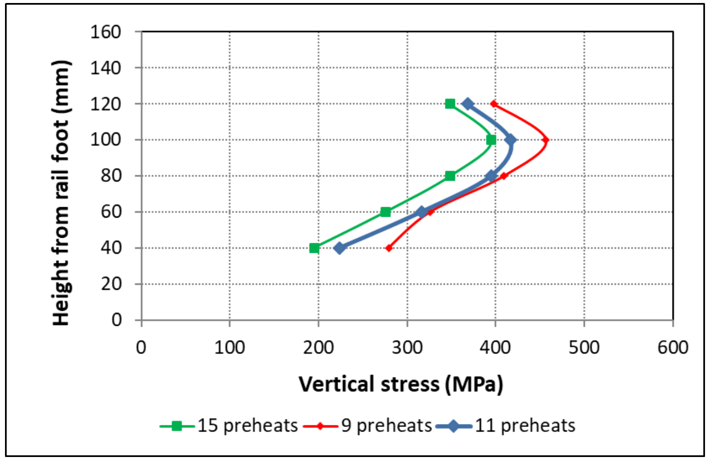
Flashbutt weld

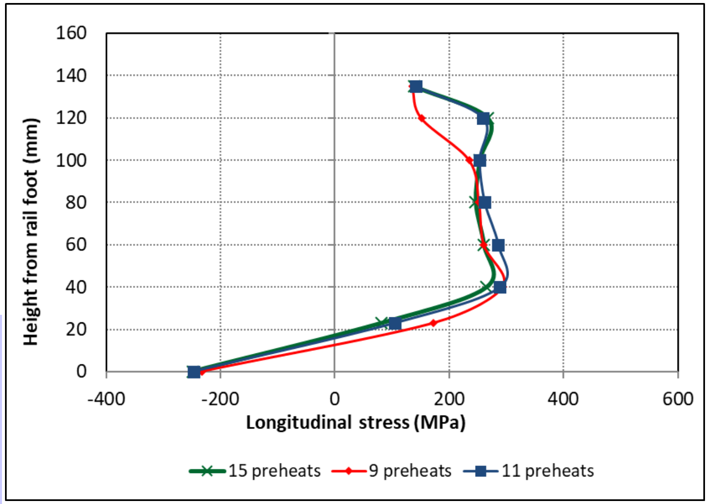


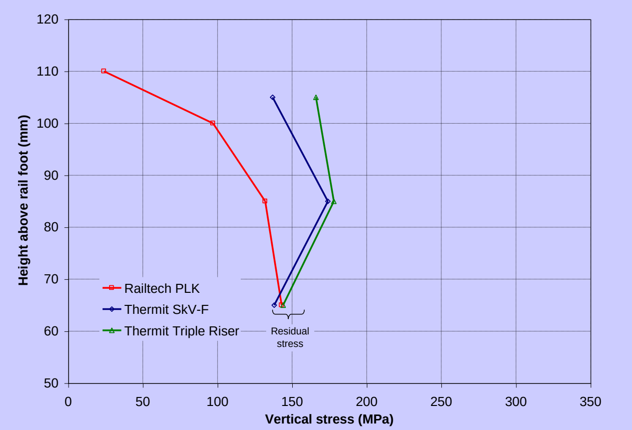
HAZ cracking in flashbutt weld

Residual stresses

- Flashbutt welds
  - influenced by welding conditions (preheat, upset, etc)
  - may vary between welding machines and between rail grades
    - Typically lower in mobile flashbutt welds
  - may be reduced by post-weld treatments (e.g. post-heating, peening)
- Aluminothermic welds
  - generally lower than in flashbutt welds
  - influenced by process type
    - preheating conditions
    - weld collar shape







Aluminothermic welds: Collar designs

Thermit SKV-F
(used till late 1990's)

Thermit Triple Riser
(late 1990's)

Pandrol PLK
(since 2000)

Pandrol PLK aluminothermic welding process

- Improved sensitivity to HSW failures compared to previously used processes
- Single use crucible – improved weld quality

Key aspects which influence weld reliability

Rail metallurgy

Welding equipment
Consumables
Operators

Weld manufacture
- FBW
- ATW

Weld finishing
- Dressing
- Grinding
- PWHT

Process qualification
- Bond strength & integrity
- Weld metallurgy
- Alignment

Fatigue testing and analysis

Production welding

Auditing of welding procedures

Weld inspection/QA

Alternative processes & procedures

Improve or enhance current processes & procedures

Improve quality outcomes from current processes & procedures

Finished welds
- Alignment
- Weld collar shape
- Surface condition
- Residual stresses
- Hardness distribution
- Defects

Service conditions
- **Stresses**
- **Impact loads**

Axle loads

Stress-free temperature

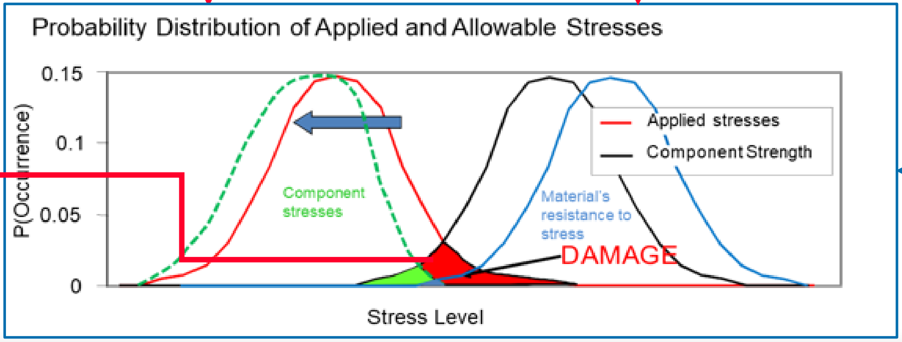
Rail maintenance
- Grinding
- Tamping

Rail Inspection

Failure statistics
- Service period/MTBF
- Failure types
- Root cause analysis

Weld defects & failures

Failure analysis



Key questions in addressing poor service reliability of rail welds

- Do we understand what causes weld failures in service?
  - Weld material characteristics
  - Residual stress levels
  - Weld quality
  - Service loading conditions
- Are we using the best available welding process?
  - Do evaluation and qualification procedures reflect service conditions?
- Are we using the best available welding process *correctly*?
  - Auditing of welding procedures
- Can the welding procedure be modified to improve weld performance?

Weld failure types

Failure modes in flashbutt welds: Horizontal split web

Key issues

- Higher derailment risk due to length of rail affected
- Fatigue cracks small and difficult to detect before weld failure

Contributing factors

- Stress concentrators at weld surface
  - Flow lips from shearing
  - Gouges from poor shearing
- Tensile residual stresses in web
- Reverse bending stresses in web under traffic

Failure modes in aluminothermic welds: Horizontal split web

Contributing factors

- Stress concentrators at surface of weld collar
  - Hot tears and shrinkage cracks
  - Changes in section dimensions in weld collar
- Tensile residual stresses in web
- Reverse bending stresses in web under traffic

Failure modes in flashbutt welds: Foot fatigue failure

Contributing factors

- Stress concentrators at weld surface
    - Flow lips from shearing
- Tensile residual stresses at top of rail foot
- Bending stresses under traffic

Failure modes in flashbutt welds: Fatigue cracking in under-head radius

Contributing factors

- Flow lip from shearing
- Tensile residual stresses
- Longitudinal bending stresses associated with reverse bending behaviour under traffic

Failure modes in aluminothermic welds: Vertical fractures

Fatigue cracking from upper foot surface

Fatigue cracking in under-head radius

Contributing factors

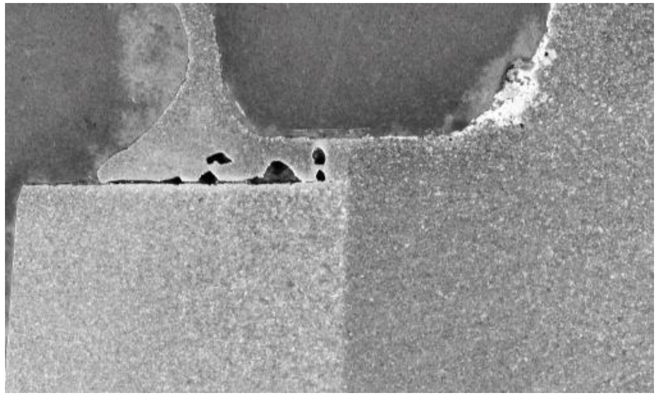
- Stress concentrators at edge of weld collar
  - Flashing and cold laps
  - Changes in section dimensions at edge of weld collar
  - Incorrect position of fusion boundary relative to edge of weld collar
  - Tensile residual stresses

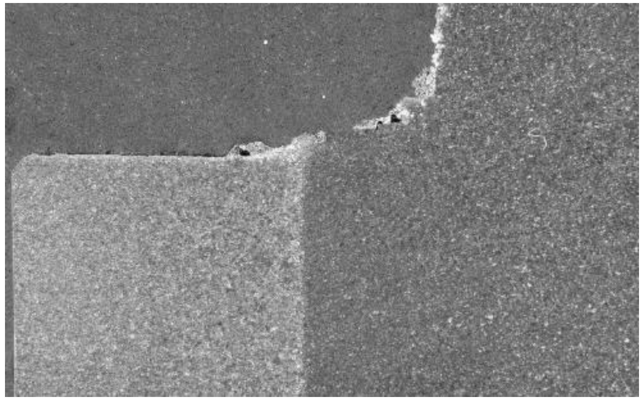
Failure modes in aluminothermic welds: Under-head radius

- Fatigue crack initiation:
  - Poor surface detail at edge of collar or weld defects in head-web radius
- Contributing factors
  - Moulds not fitted correctly
  - Gap between mould and rail surface
    - Defect forms due to reaction between stemming paste and liquid metal
  - Incorrect preheating conditions

Failure modes in aluminothermic welds: Rail foot

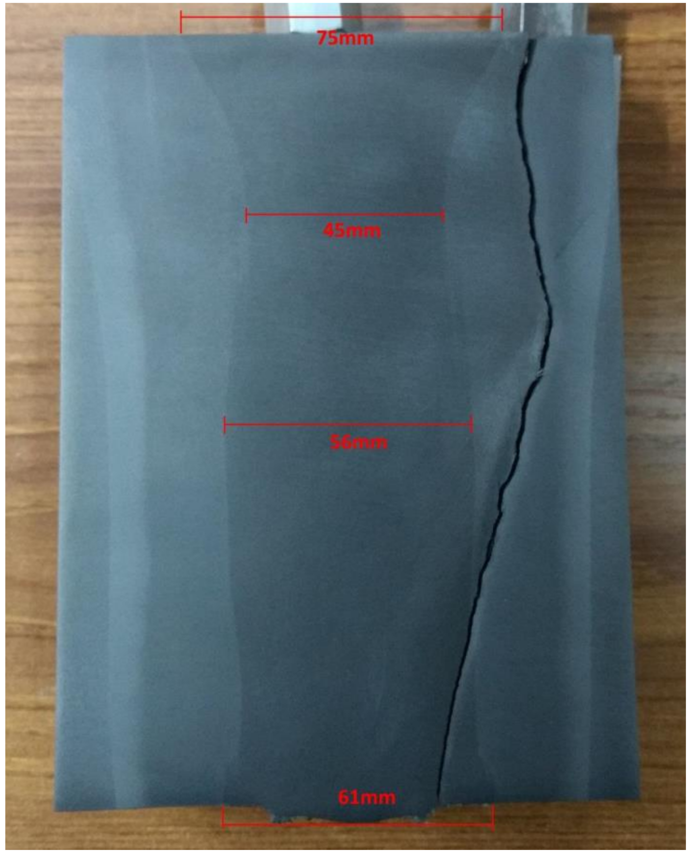
- Fatigue cracking initiates at top of foot, at edge of weld collar
- Contributing factors
  - Gap between mould and rail surface
    - Poor detail on upper surface of foot at fusion boundary
  - Fusion boundary position relative to edge of weld collar incorrect

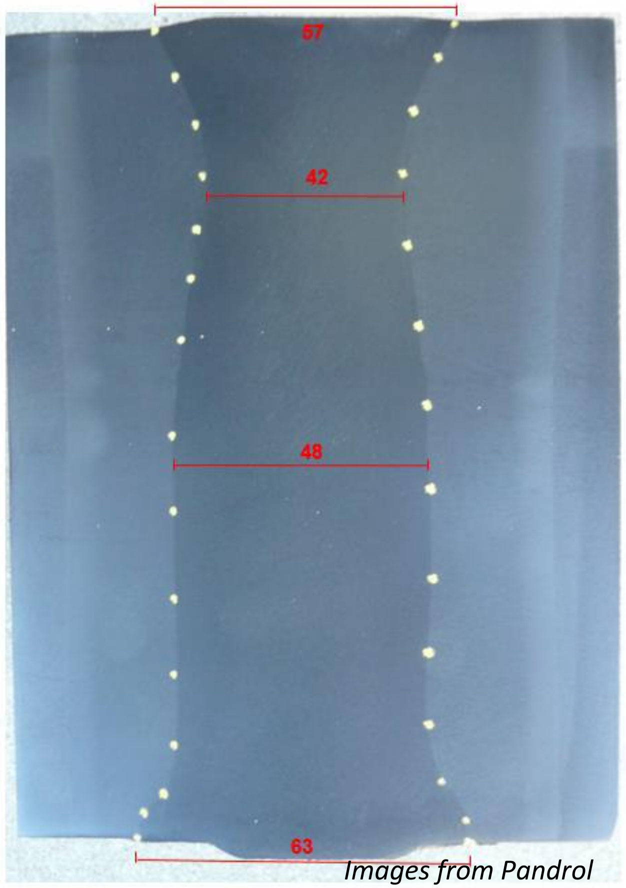




Failure analysis: Aluminothermic welds

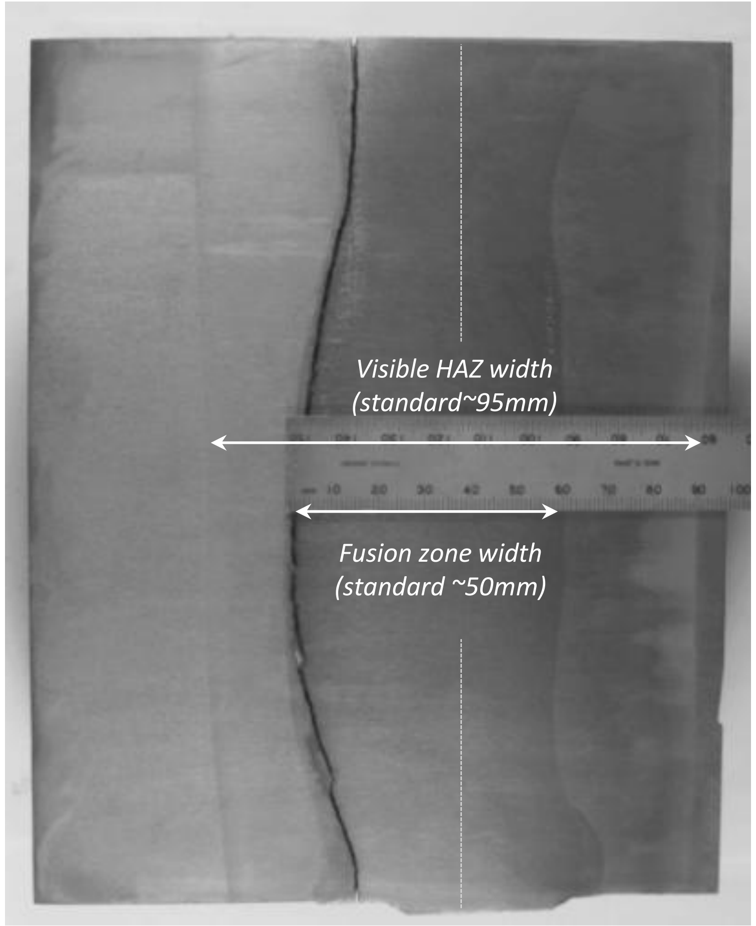
- Macro-sections show width and position of fusion & heat-affected zones
  - Identifies non-compliance with recommended welding procedures





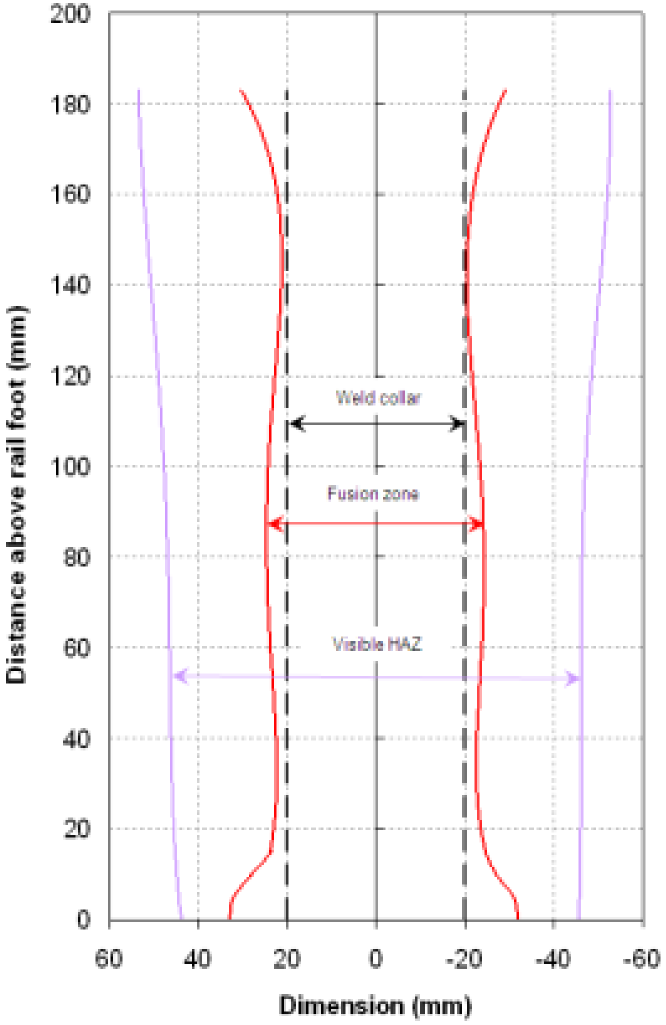
Images from Pandrol

Aluminothermic welds: Appearance of macro-section in failed weld



Failed weld

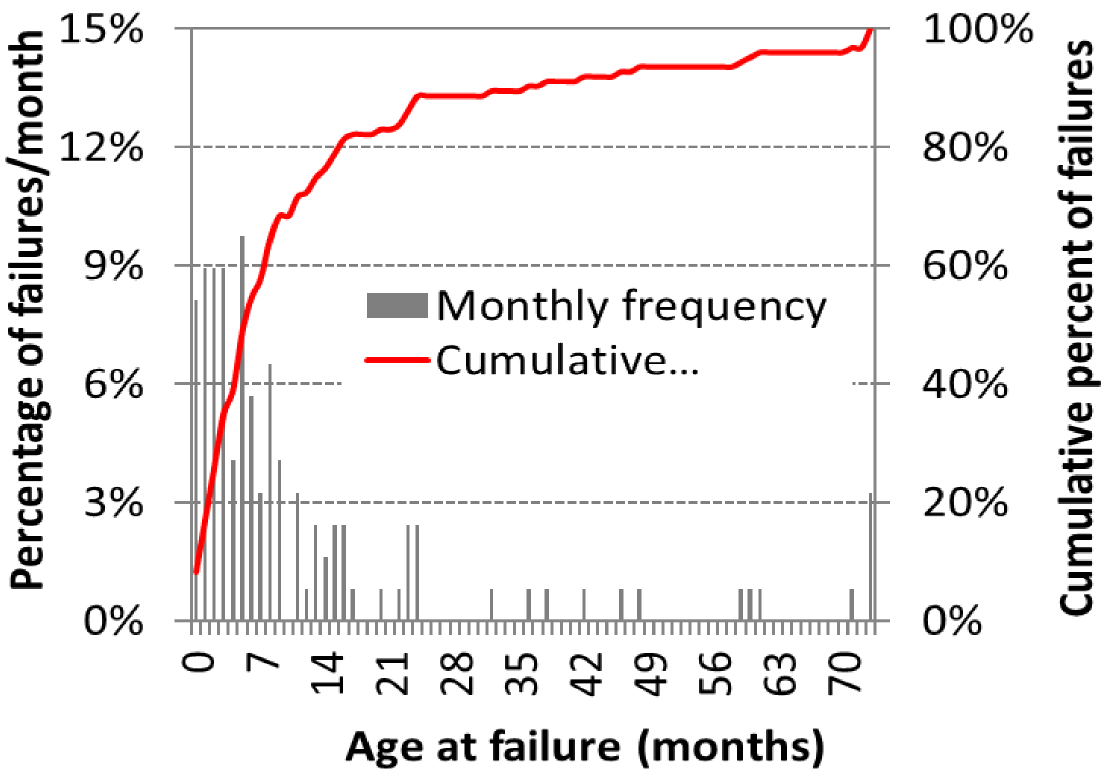
Correctly-made weld



Reliability statistics: Aluminothermic welds

- Failure statistics under heavy haul conditions show a significant "infant mortality" rate associated with poor quality welds

- Defective weld conditions arise from:
  - Incorrect weld gaps
  - Poor mould alignment, fitting and sealing
  - Incorrect positioning of preheating torches



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Influence of loading conditions on stresses and fatigue performance of rail welds

Influence of loading conditions on stresses in rail welds

Objectives

A. Quantify the magnitude of loads applied to, and the response of, rail welds under in-track conditions

B. Can be used to determine the influence of:
   - Weld type (including collar shape in aluminothermic welds)
   - Track conditions
   - Wheel & rail profiles
   - Impact loads (dipped weld/high impact wheels)

   on stresses in rail welds

C. Establish loading conditions for fatigue testing of welds for qualification purposes

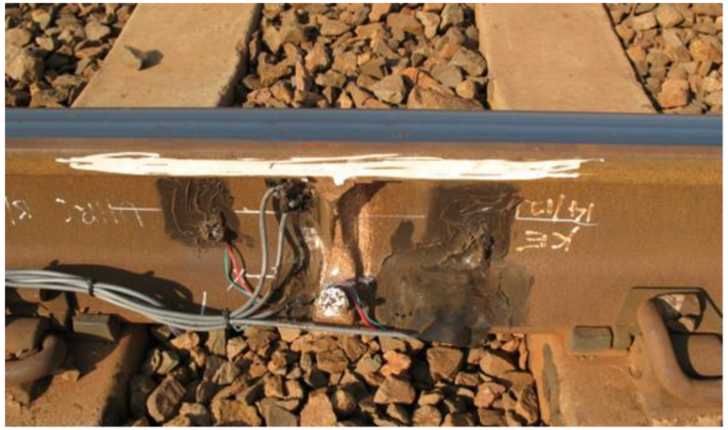
Influence of loading conditions on stresses in rail welds

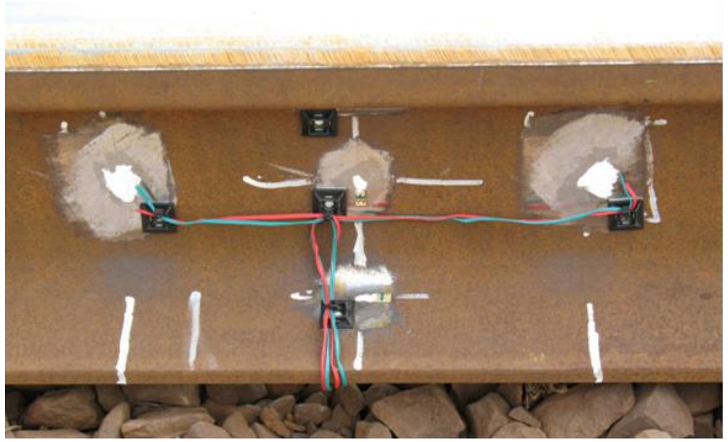
Typical instrumentation approach

A. Measurement of vertical loads
   - At welds
   - Parent rail on approach side (loaded direction)

B. Measurement of stresses at critical locations in rail/weld section
   - Weld
   - Parent rail on approach side (loaded direction)

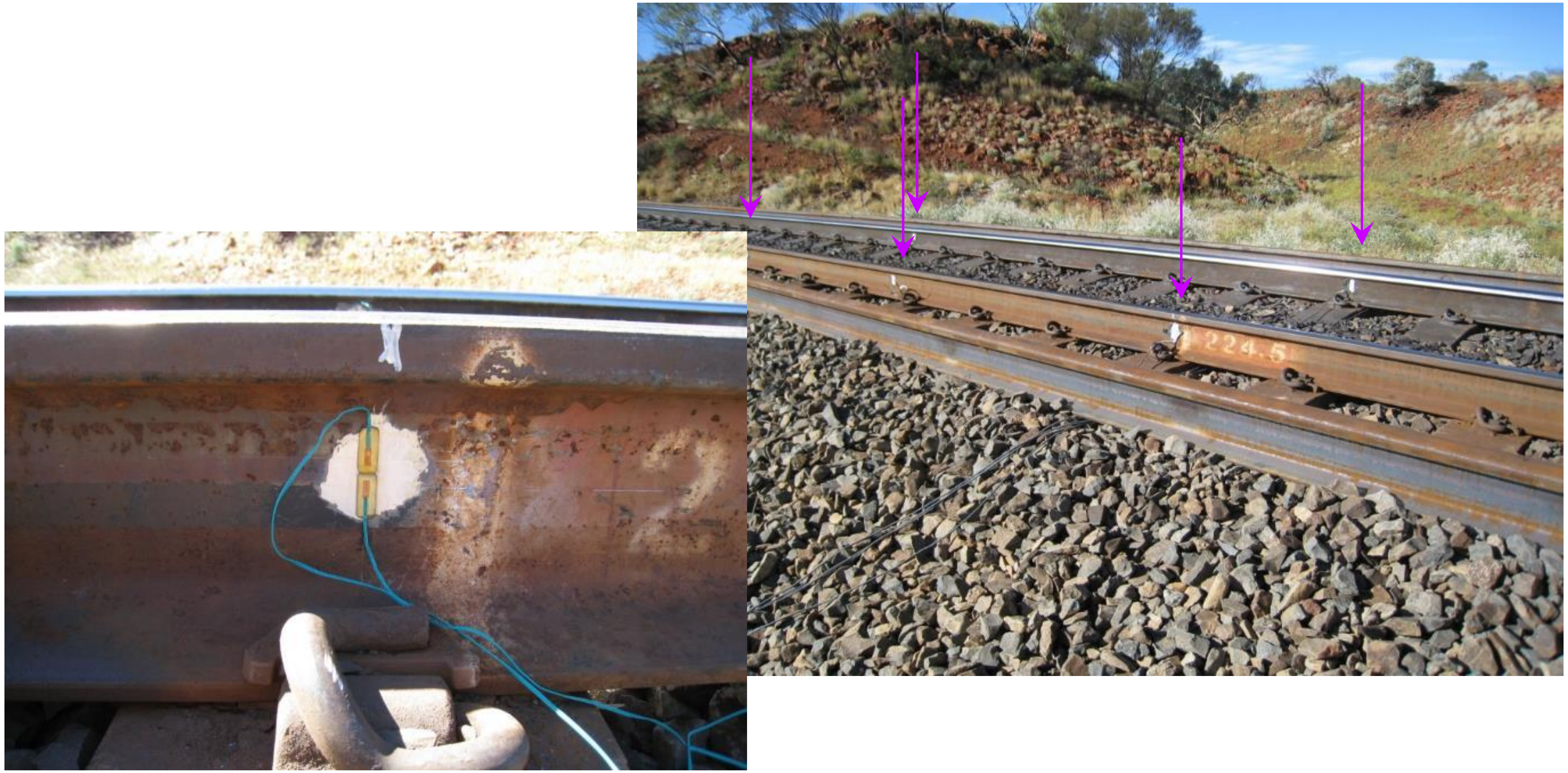
C. Analysis of stresses at weld relative to:
   - Corresponding strain gauge position in parent rail
   - Vertical load





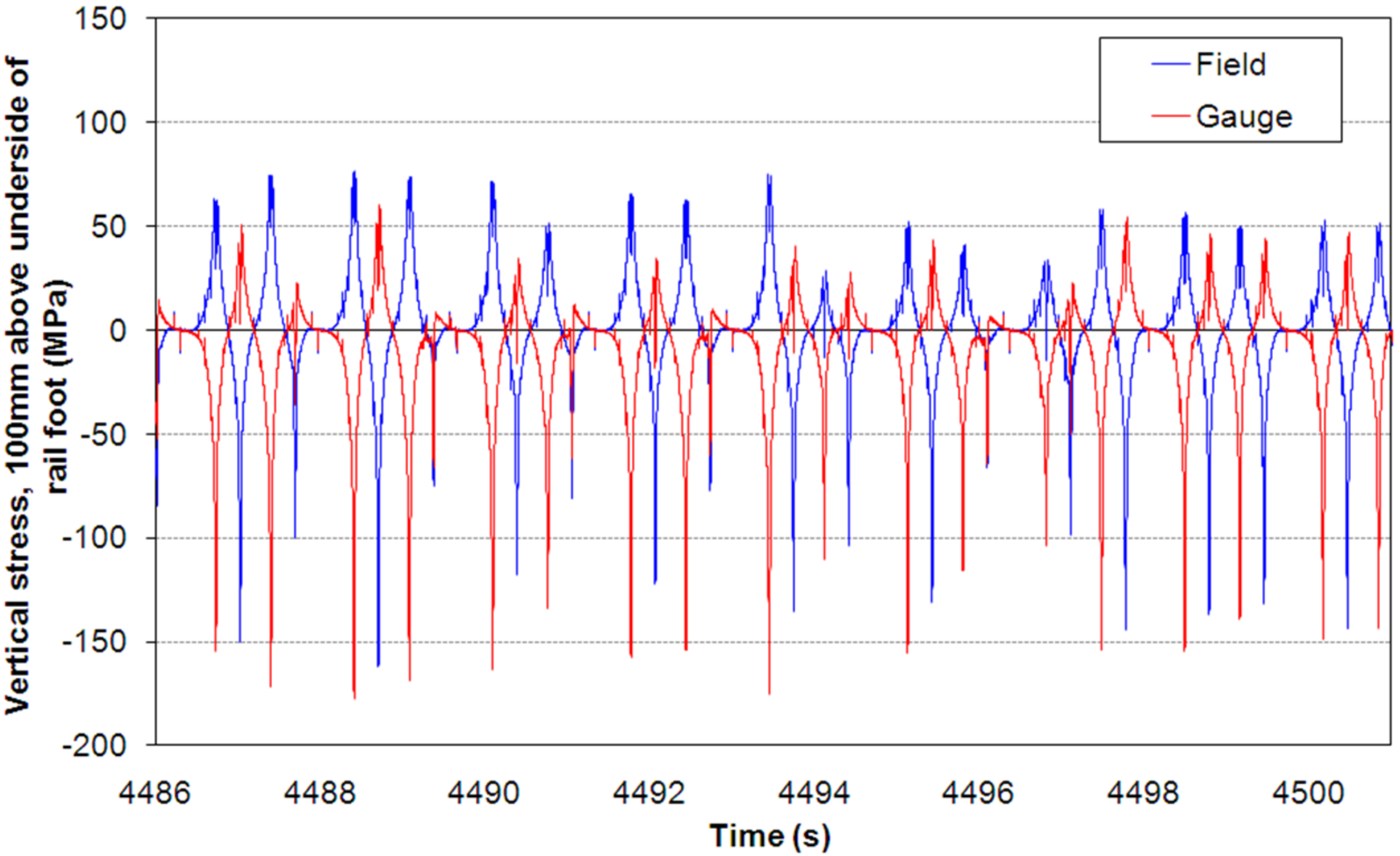
Web stresses in under heavy haul conditions

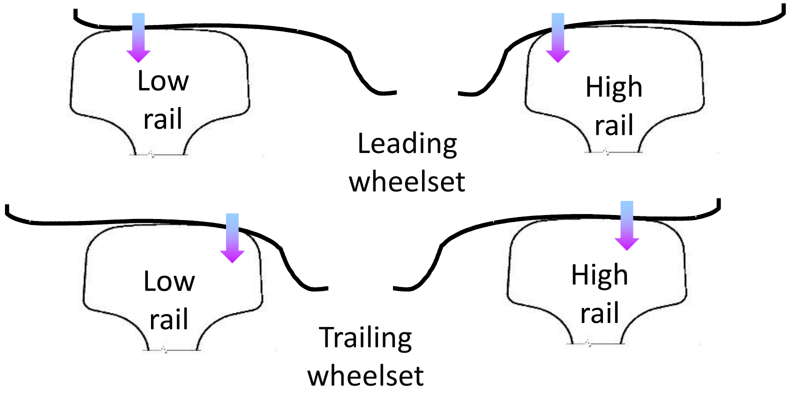
Example from 600m radius curve; flashbutt welds



Web stresses in under heavy haul conditions

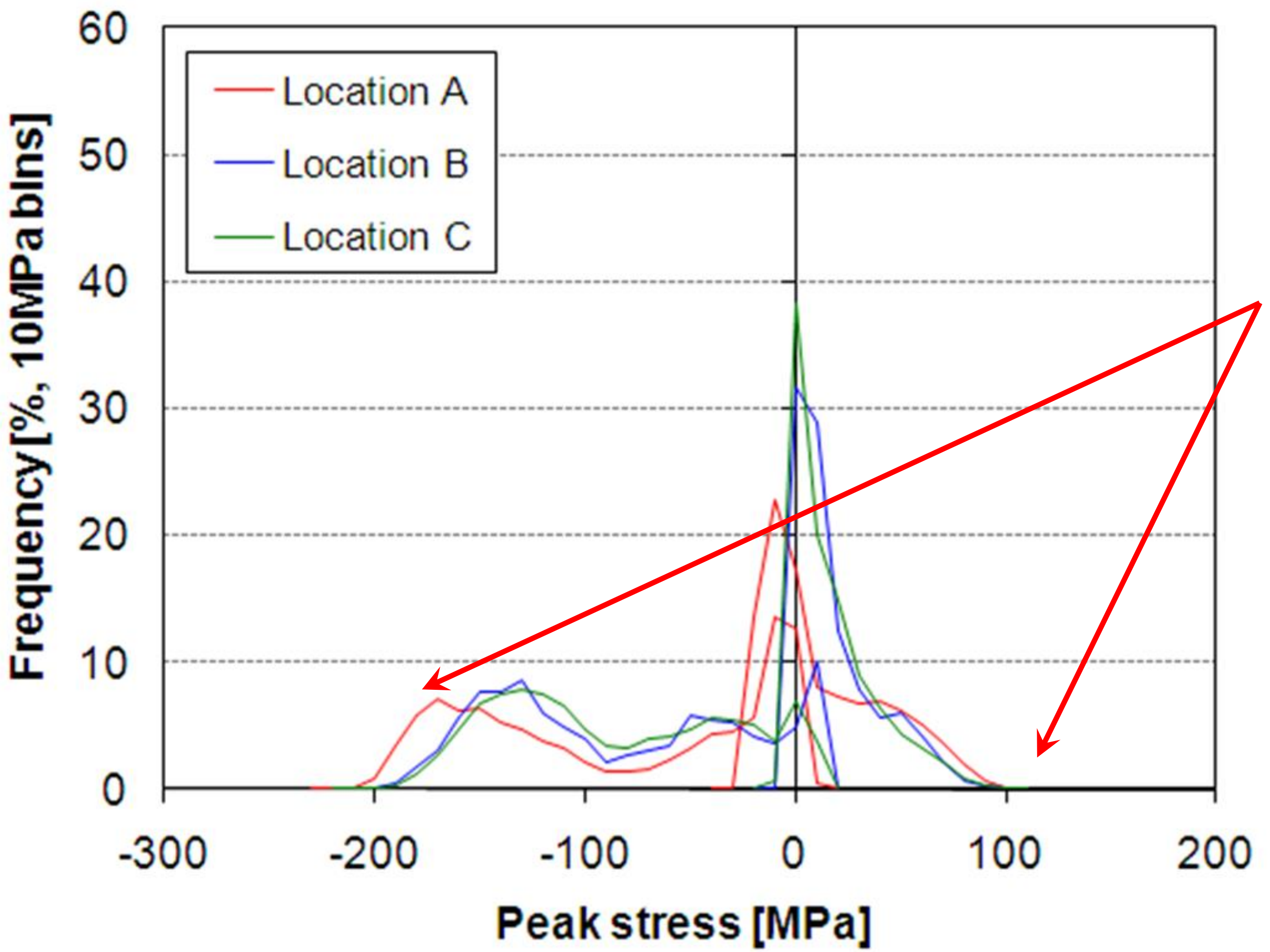
Example from 600m radius curve; flashbutt weld under heavy haul conditions





Web stresses in under heavy haul conditions

Example from 600m radius curve; flashbutt weld under heavy haul conditions



Peak stress levels subsequently used to determine fatigue test conditions

Quantifying stresses under in-service loading: Aluminothermic welds

Critical regions of weld in terms of fatigue failure

A. Under-head radius
   - Edge of weld collar

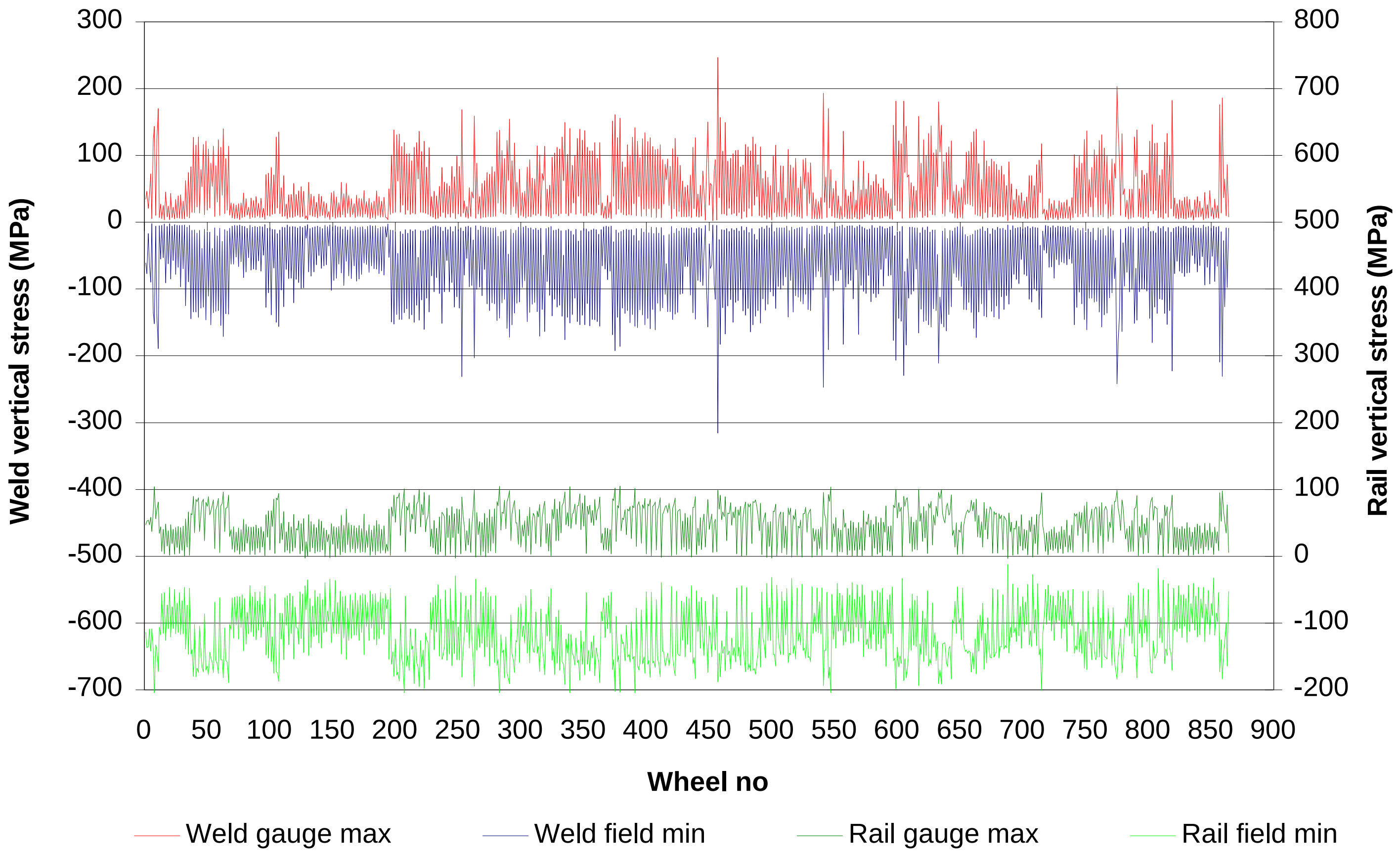
B. Mid-upper web
   - Outer edge of weld collar

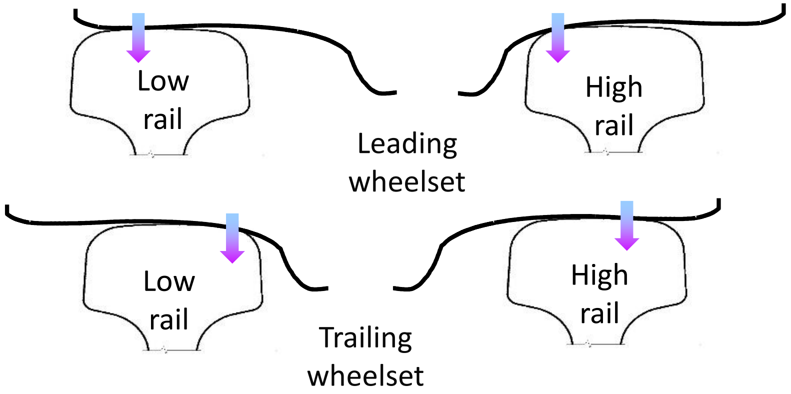
C. Top of rail foot
   - Edge of weld collar

D. Underside of rail foot
   - Edge of weld collar

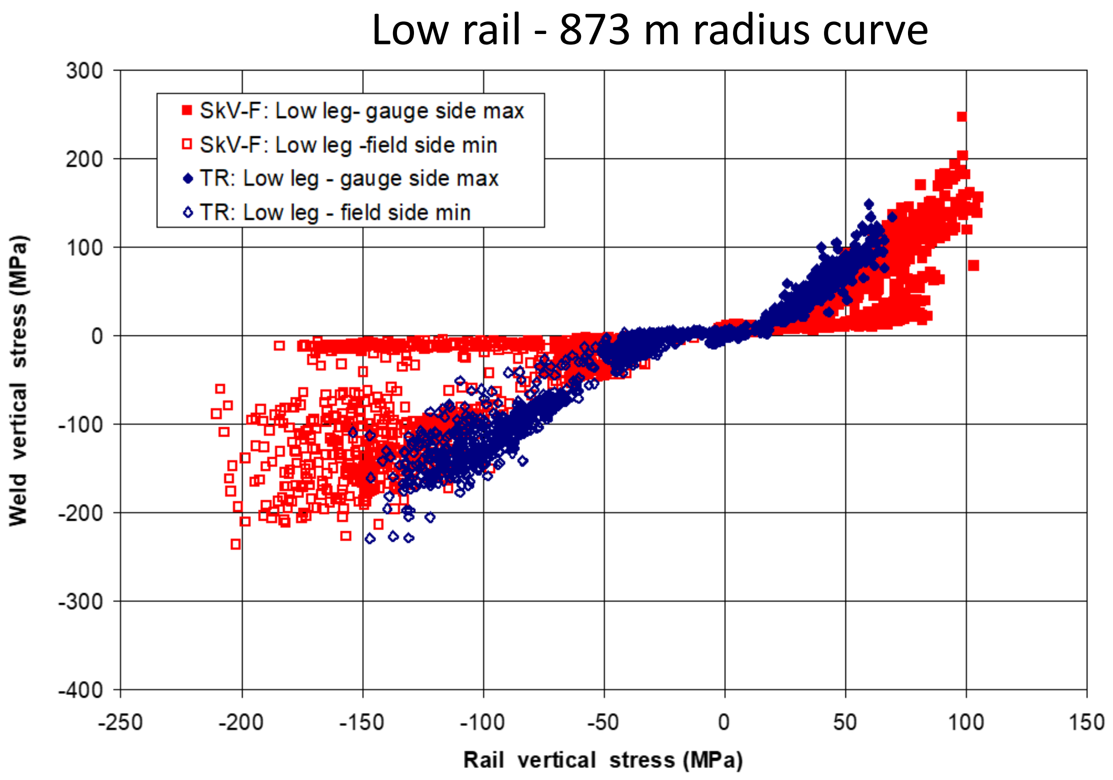
Measurement of web stresses: Aluminothermic welds

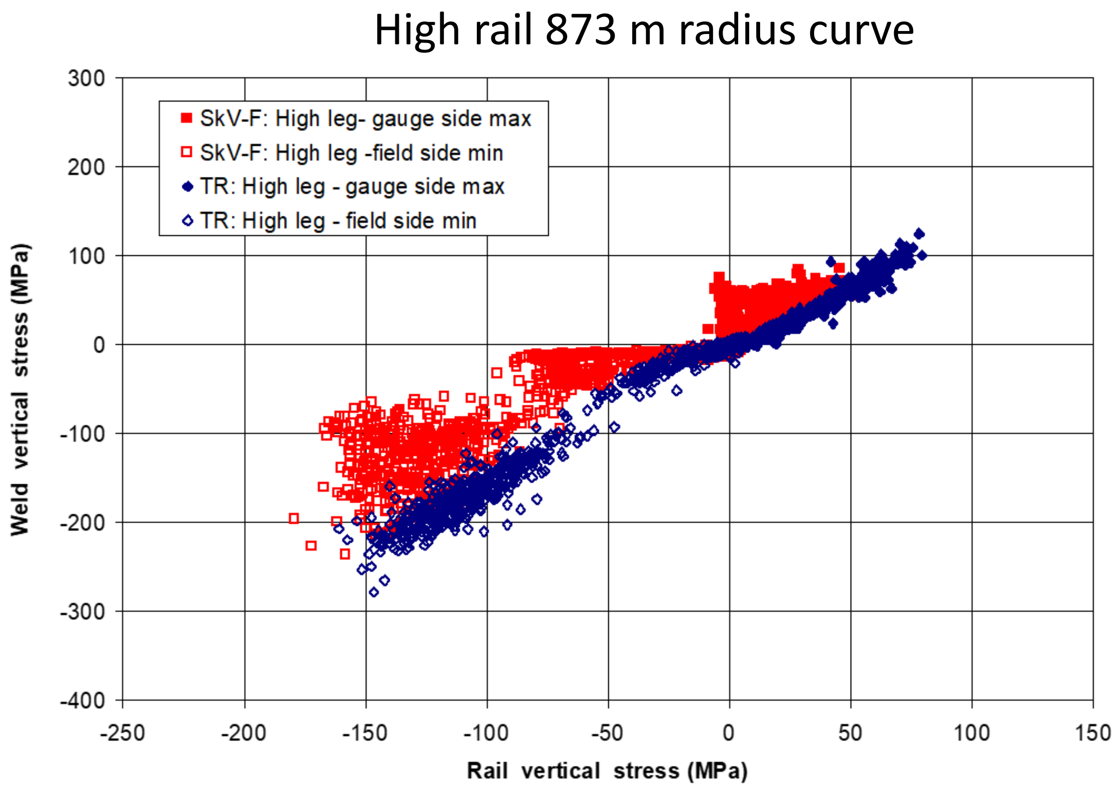
Web stresses in 873m radius curve: Low rail
Response at aluminothermic weld (upper plots) and parent rail (lower plots) during loaded train passage





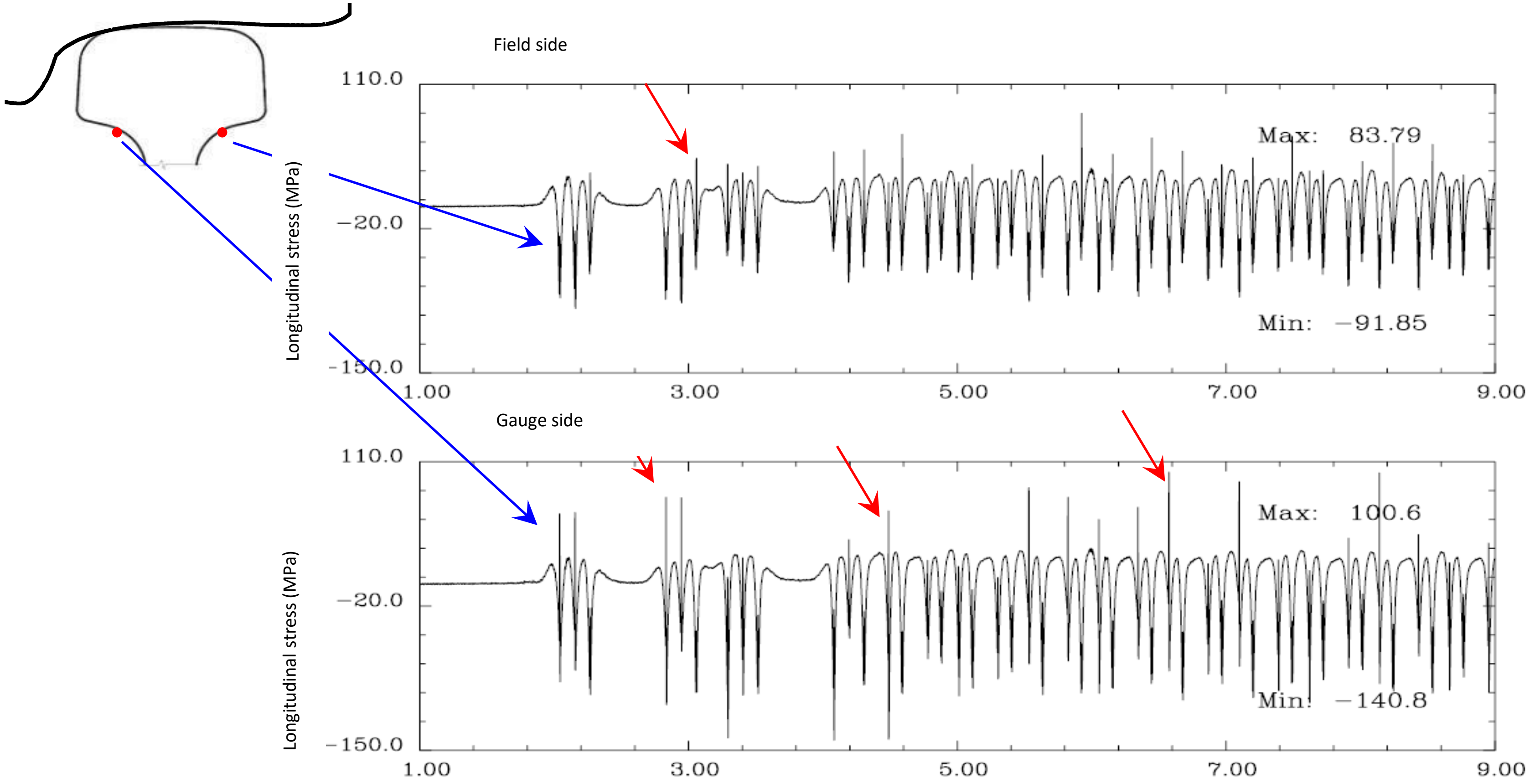
Influence of collar shape on stresses in weld collar: Aluminothermic welds





Rail stresses: Under-head radius

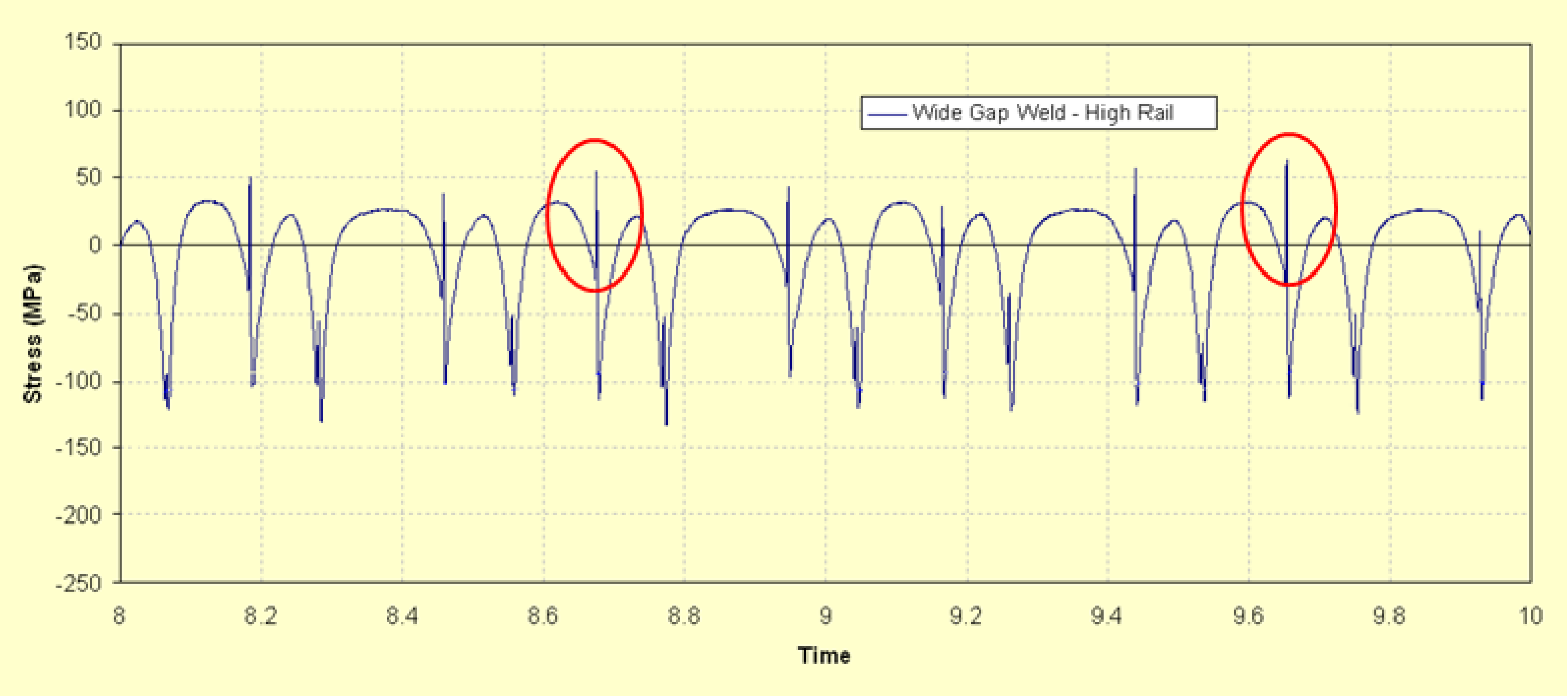
Typical response pattern for longitudinal stresses in under-head radius under loaded traffic



- Small tensile peak due to uplift ahead of and behind wheel passage
- Tension spike associated with local response of head directly under wheel
  - Magnitude varies with wheel-rail contact position and lateral loading

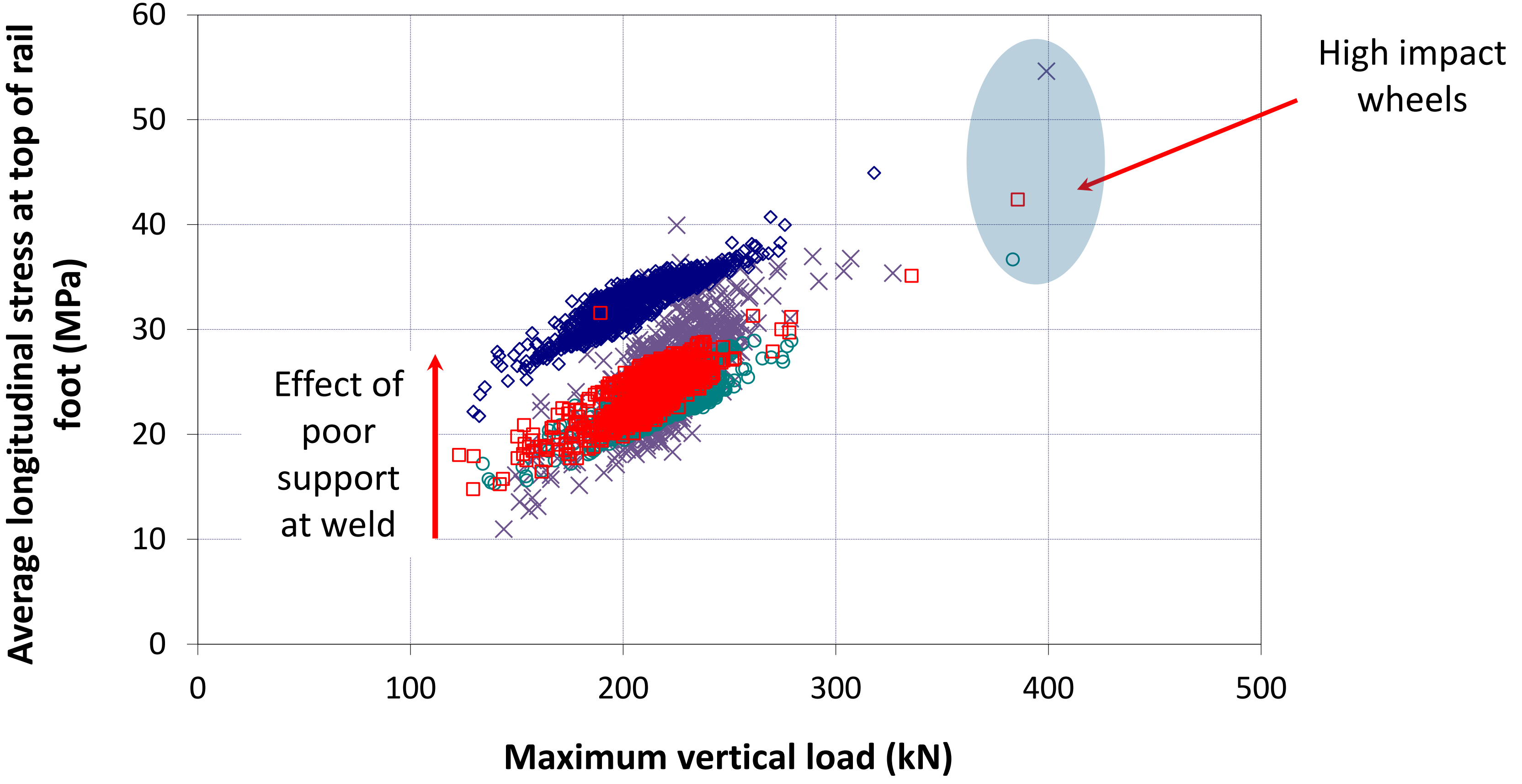
Longitudinal stresses: Under-head radius in aluminothermic welds

Aluminothermic weld, 918m radius curve



Effects of rail support conditions on foot stresses: Aluminothermic welds

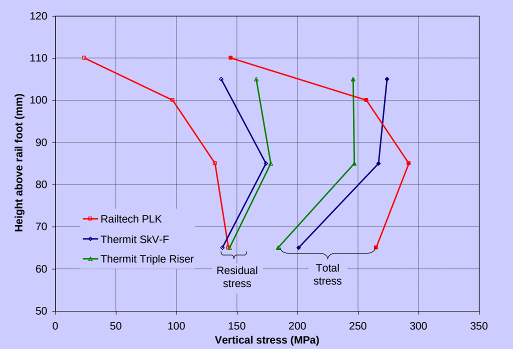
Data for tangent track



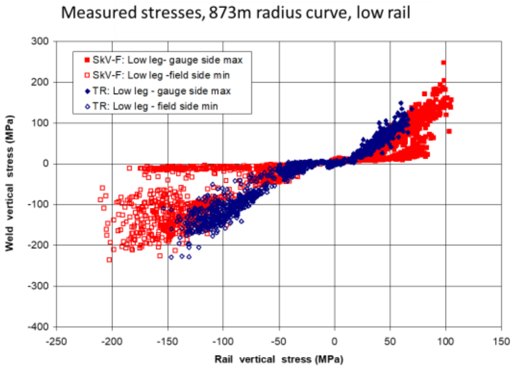
Assessing fatigue performance of rail welds

Assessing fatigue behaviour of aluminothermic welds

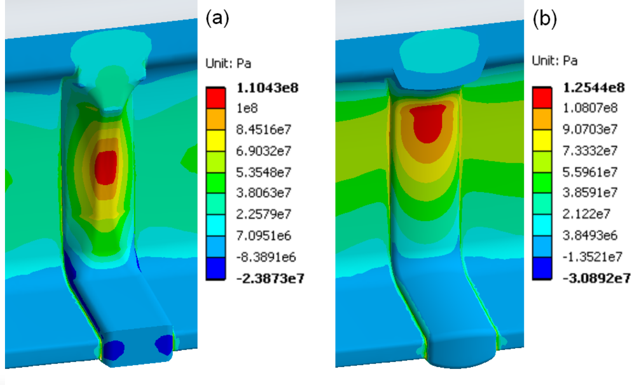
- Determination of stresses in weld relative to parent rail
  - Measurement under simulated loading conditions
  - Measurement under actual service conditions
  - Finite element analysis under simulated loading conditions



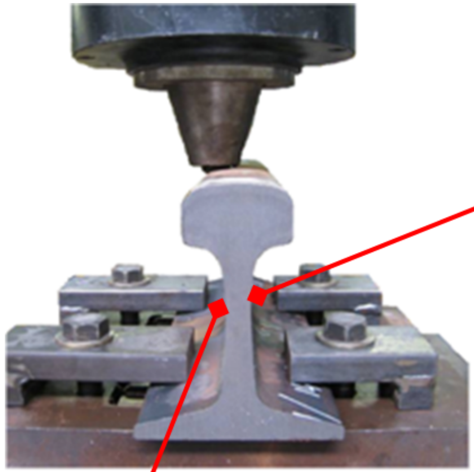
- Fatigue testing under simulated service conditions
  - Loading conditions need to reproduce key aspects of in-service loading

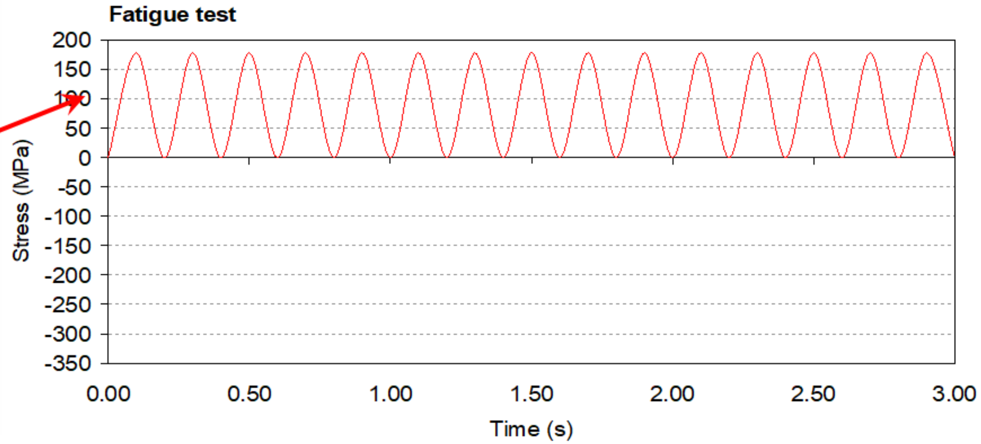


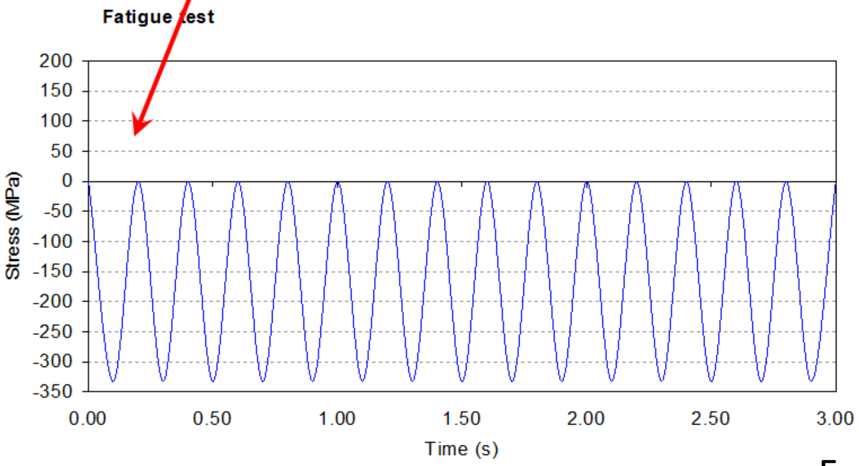
- Fatigue behaviour using multi-axial critical plane criteria
  - Influence of collar shape
  - Damage tolerance using linear elastic fracture mechanics



Fatigue testing of welds: Horizontal split web fatigue behaviour





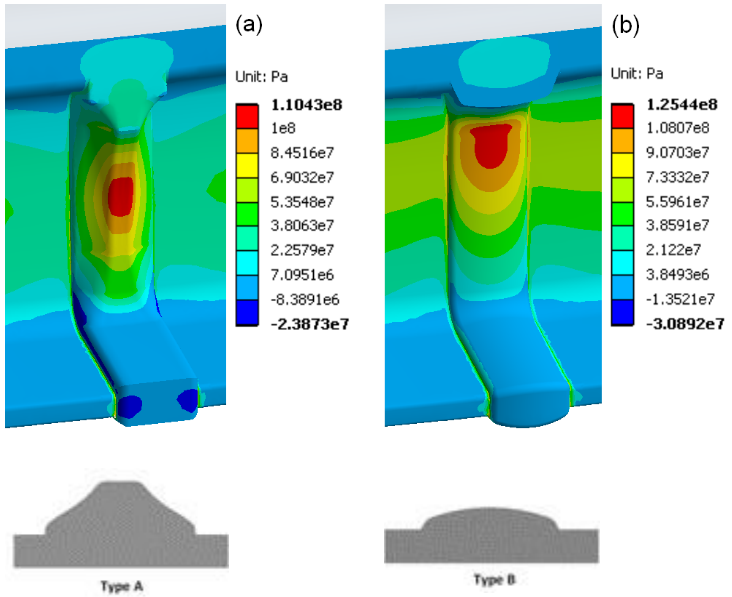


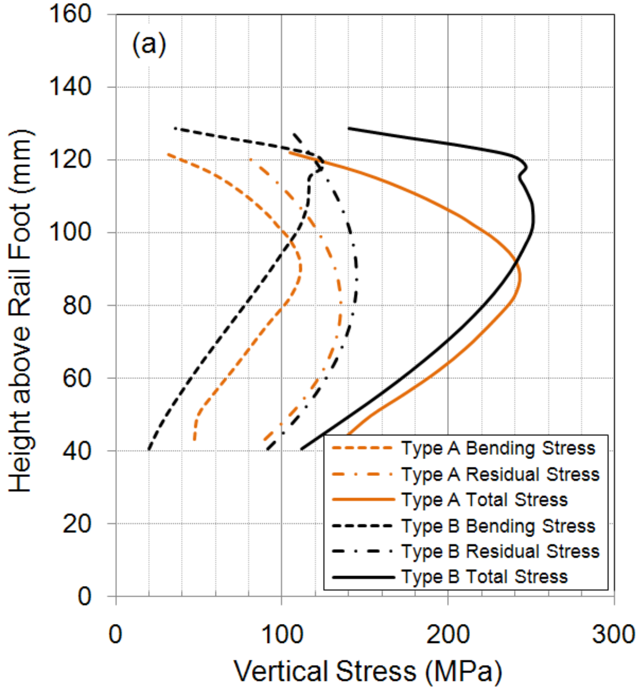
Failure mode in flashbutt welds identical to those under service conditions

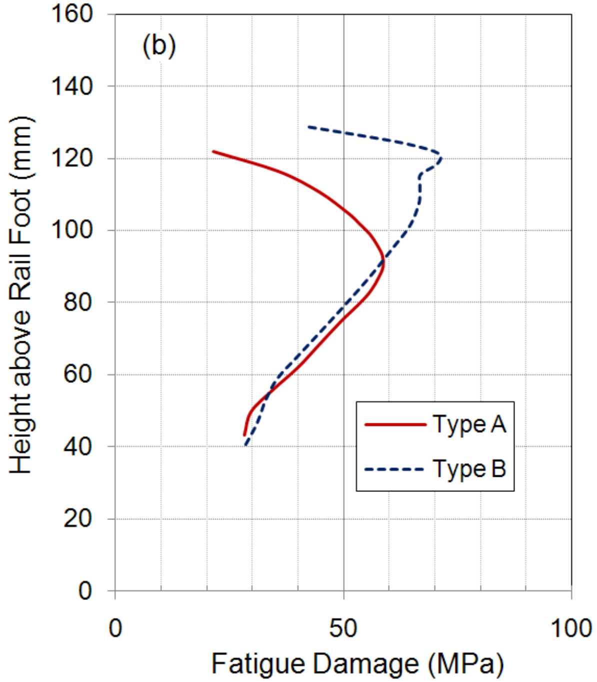
Assessing fatigue response of aluminothermic welds: Analytical approach

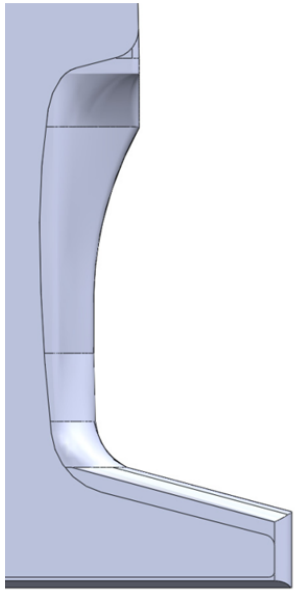
Influence of weld type on fatigue behaviour

- Loading conditions based on measured stresses under service loading
- FEA predicted stresses under simulated loading conditions
- Measured residual stresses
- Multi-axial fatigue analysis based on Dang Van criterion







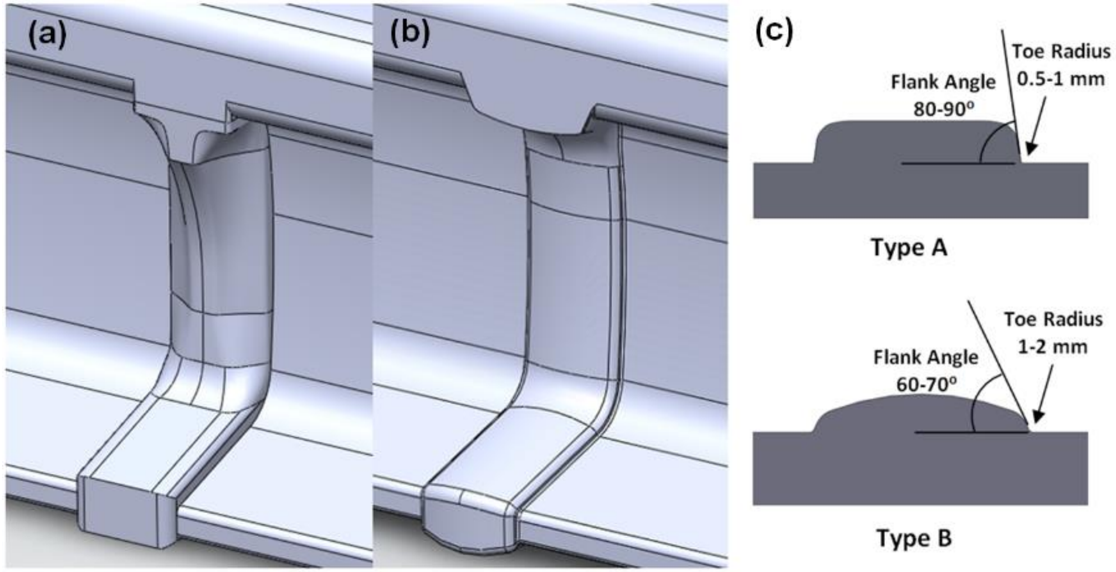


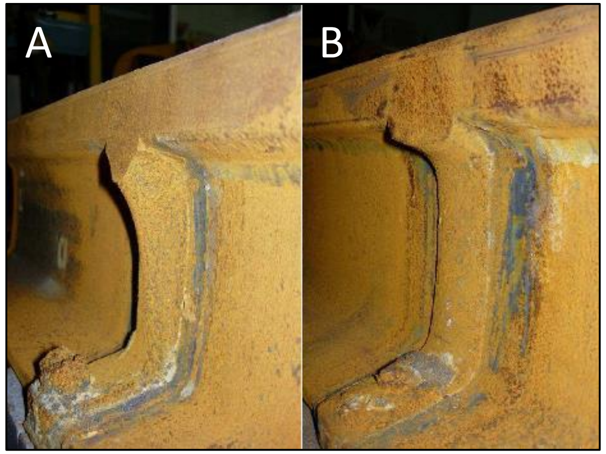
I. Salehi, P. Mutton and A. Kapoor, Analysis of damaging factors in thermite welds through multi-axial fatigue criterion, Proc. International Heavy Haul Association Conference 2011

Influence of weld collar shape: Aluminothermic welds

- Collar design and associated geometrical features
  - *flank angle*
  - *toe radius*
  - *surface irregularities*

  are important factors in the aluminothermic weld process design

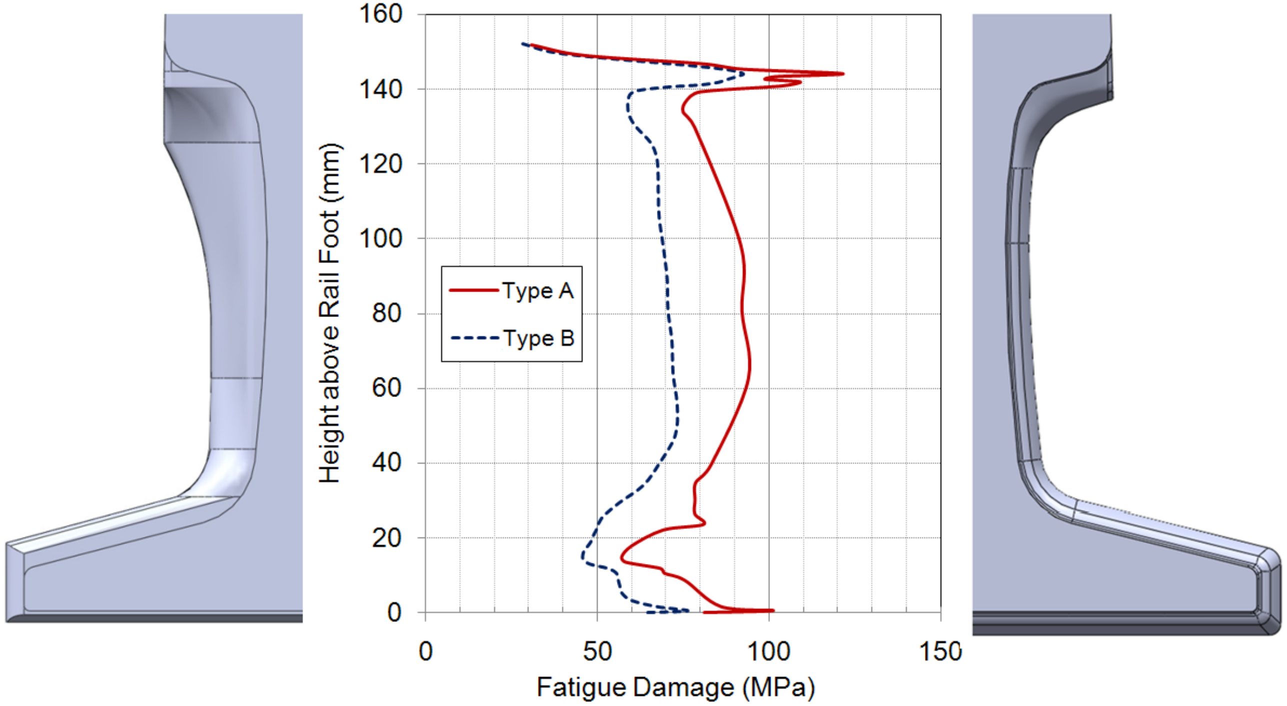




I. Salehi, P. Mutton and A. Kapoor *International Heavy Haul Association Conference 2011*

Fatigue damage in aluminothermic welds: Tangent track

- Higher fatigue damage at the under-head radius
- Reduced damage at the base region (due to compressive residual stress)
- Geometrical features in Type B weld results in lower damage compared to Type A weld



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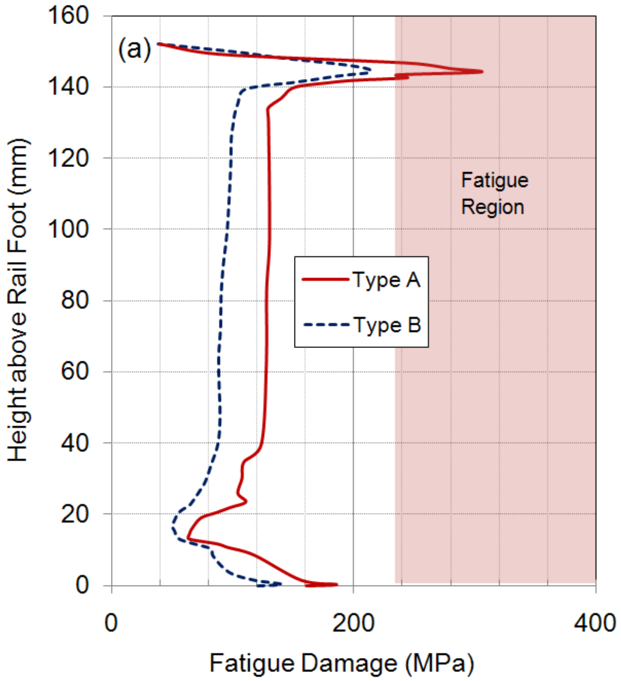
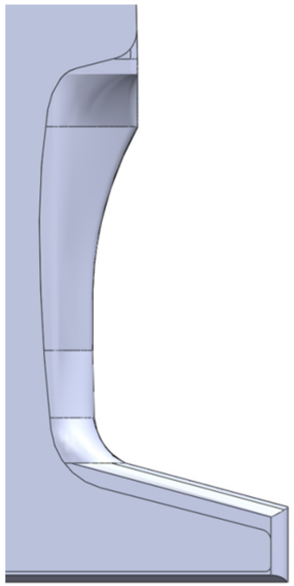
Fatigue damage in aluminothermic welds: Effect of lateral traction

- Substantial damage at the under-head due to cyclic and residual stresses
- High possibility of fatigue crack initiation at the under-head in Type A weld
- Safer performance of Type B weld (under defect free conditions)





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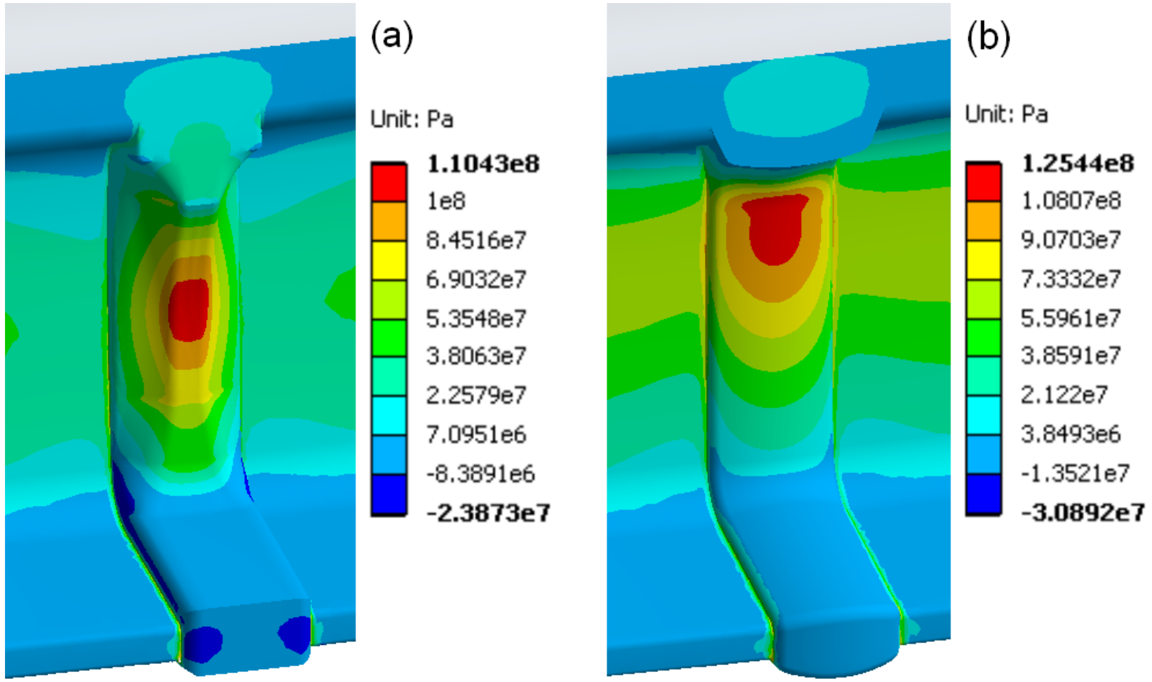
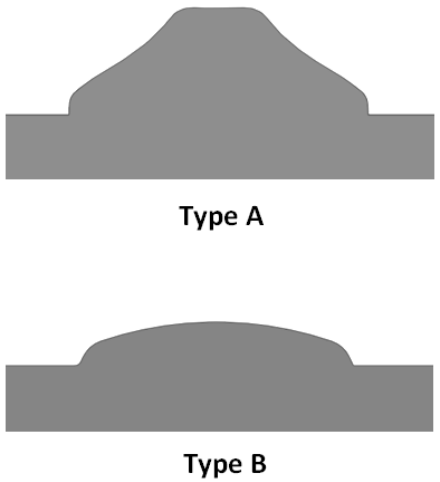
Web bending, vertical stresses in aluminothermic welds

- Difference in maximum vertical stress location due to collar reinforcement
- Lower maximum stress and higher localization in Type A compared to Type B





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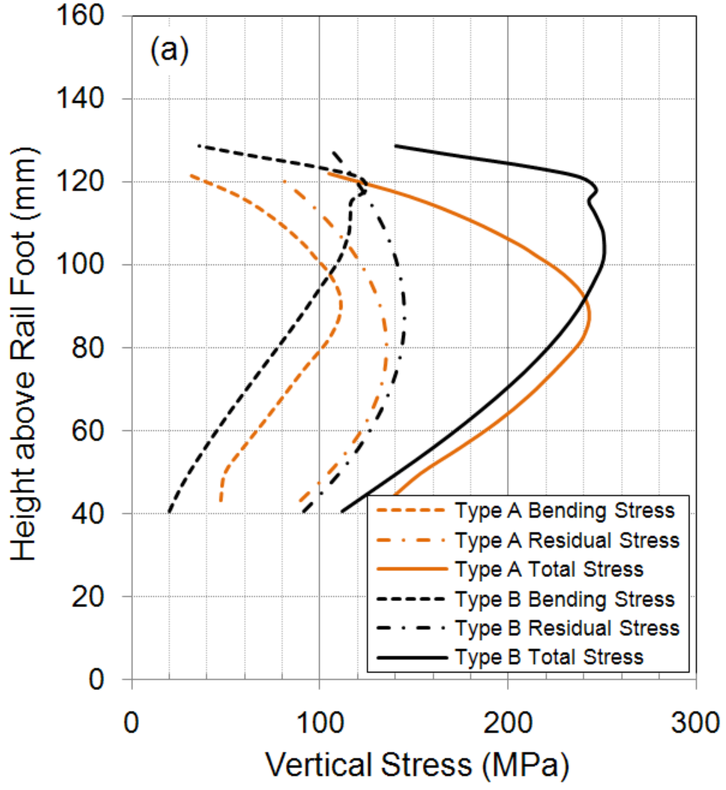
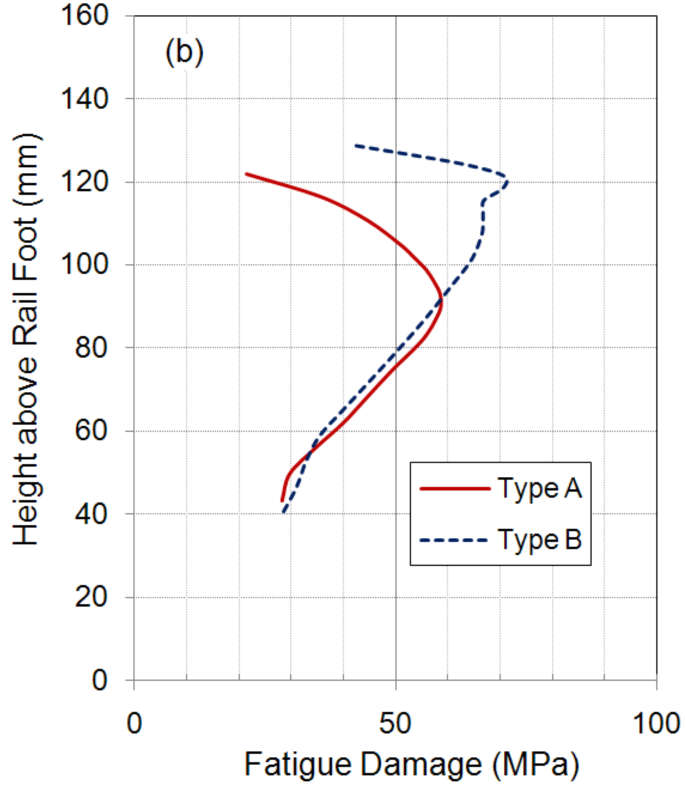
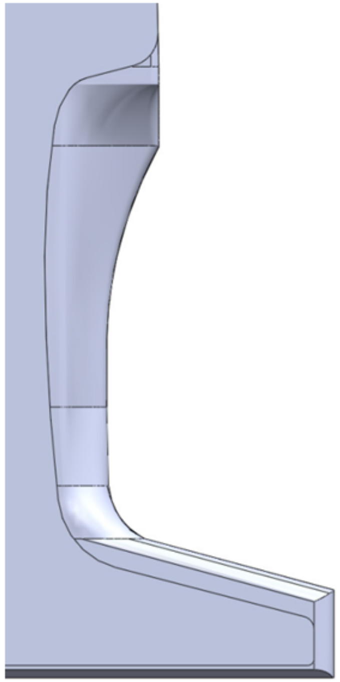
Web fatigue behaviour of aluminothermic welds







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Improvements in welding procedures

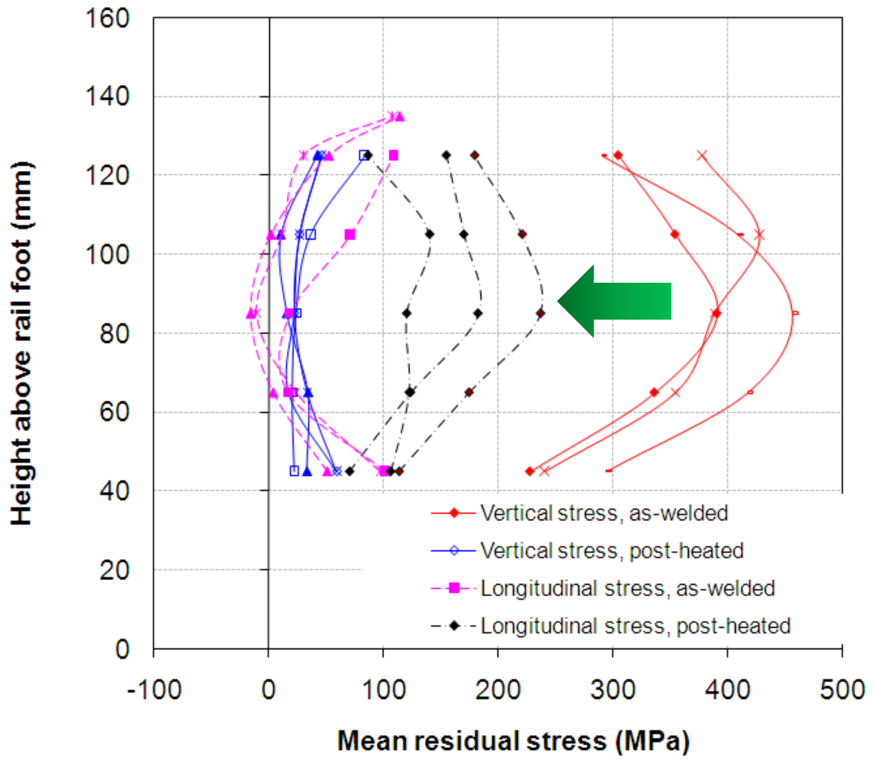
Horizontal split web failure of flashbutt welds: Options

Option 1: Improved surface condition

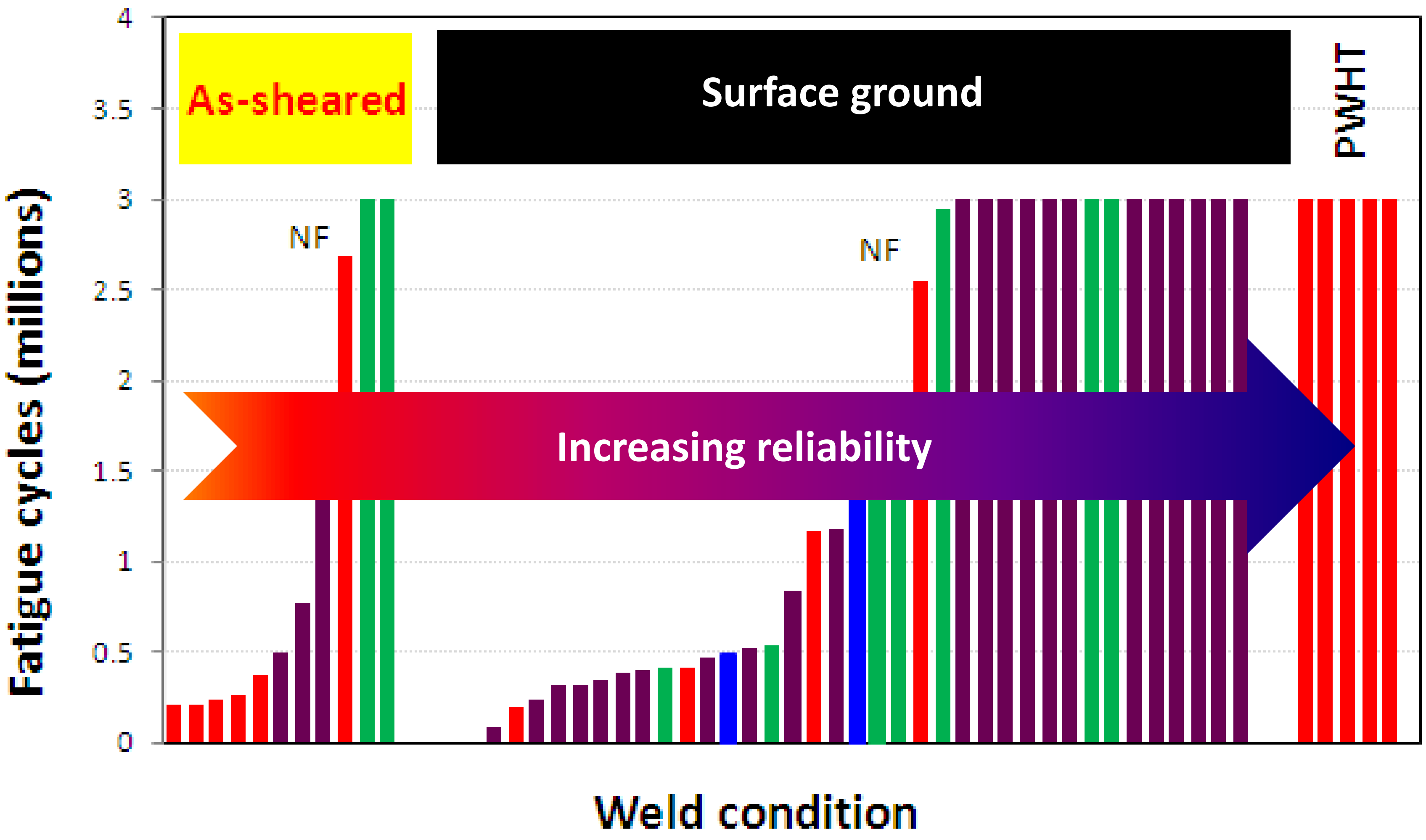
- Cleaner shearing
- Surface grinding

Option 2: Lower residual stress levels

- Rapid post-weld heat treatment



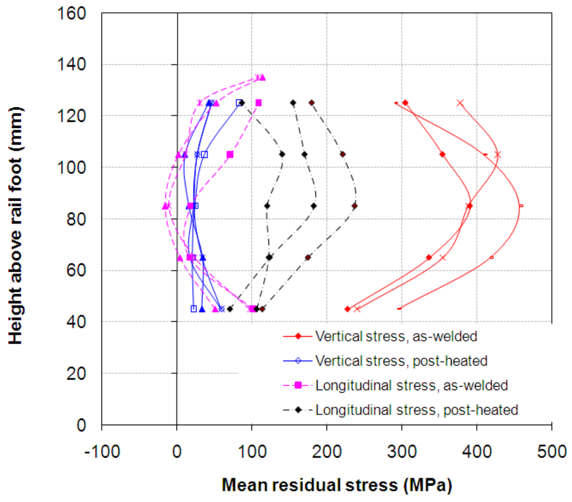
Horizontal split web failure of flashbutt welds: Fatigue test results



Rail grades:
Green: HH
Brown: HE1
Blue: HE2
Red: HE3

Improved reliability of flashbutt welds: Web fatigue failures

- Reducing residual stress levels
  - Application of rapid post-weld heat treatment
  - Most effective method of reducing risk of web fatigue failures
    - Reduced risk of fatigue crack initiation
    - Lower fatigue crack growth rates
    - Larger critical crack size at failure
    - Increased probability of detecting fatigue cracks prior to failure
  - Suitable for use with fixed welding facilities (plant welds)
  - Not currently viable for field welding (mobile flashbutt welds)



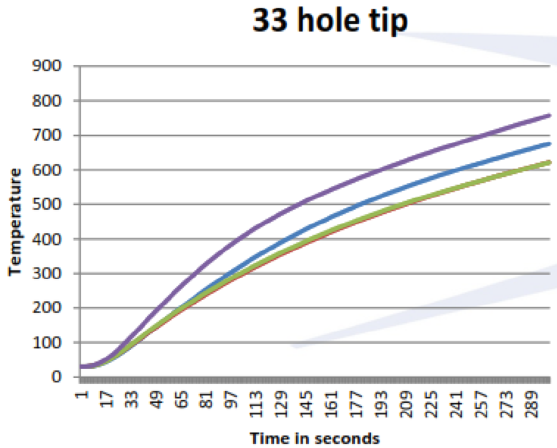
- Web grinding
  - Effectiveness can be more variable, depending on as-ground surface condition
    - Operator dependent
  - Applicable to both plant (fixed) and mobile flashbutt welds
  - Now used across all four Pilbara heavy haul systems to improve reliability of flashbutt welds

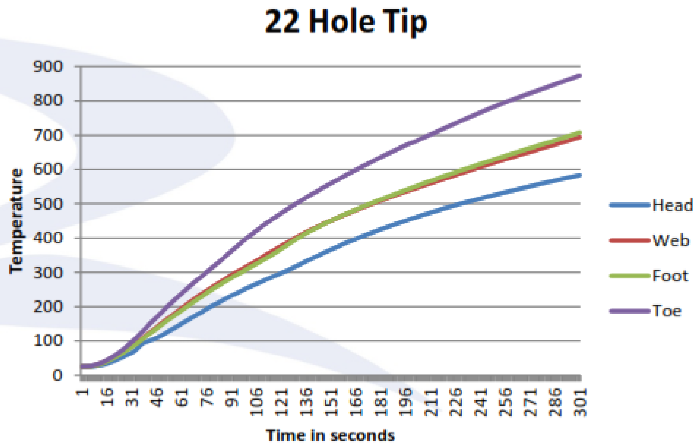
Critical issues in achieving reliable aluminothermic welds

- Welding procedures
  - Weld gaps
  - Mould fitting
  - Preheating
- Welder competency
  - Welders must be trained and competent in the process that is selected
  - Auditing and competency assessment *must* be ongoing
- Welding equipment
  - Inspection and maintenance of preheating torches, mould shoes, etc
  - Adequate supply of gases for preheating
- Monitor weld failure rates, identifying and addressing early failures
- **Above all else, minimise use of aluminothermic welds!**

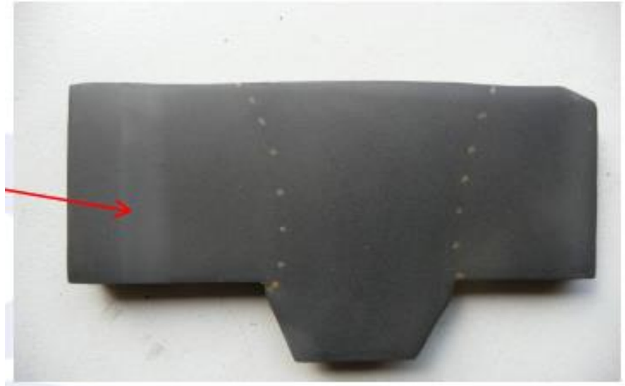
Improvements in aluminothermic welding procedures

- Improved preheating conditions (Pandrol PLK process)
  - Improved temperature distribution in under-head region
  - Wider fusion zone
  - Position of fusion boundary relative the edge of weld collar more favourable
  - Reduced residual stresses





Images from Pandrol



Improvements in aluminothermic welding procedures

- Peening of weld collar
  - Increased resistance to fatigue crack initiation in critical zones at edge of weld collar

Images from Pandrol

Summary

Key aspects in achieving weld reliability under heavy haul conditions

- Understand the rail grade to be welded – particularly important for flashbutt welding
- Aluminothermic welding – select the most suitable process for the service conditions
- Welding equipment – in good condition and reliable
- Operator training and competency – particularly important for aluminothermic welding
- Qualification of welding procedure and ongoing QA during production welding
- Regular auditing of welding procedures
- Tracking early defects and failures
    - Identify root causes of failures and close the loop to the welding process
- Keep abreast of new developments in welding procedures and inspection methods

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  - Stephen Oswald (ret.) – formerly of Rio Tinto and BHP
  - Iman Salehi – Swinburne University
  - Tony Paroz – Pandrol
  - Paul Radmann – Goldschmidt Thermit
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