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Developments in Rail Metallurgy & Rail Welding

Swedish Welding Institute
12th November 2009

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Corus Rail

Agenda

- **Rail Metallurgy and Implications for Welding**
- **Corus Steel Developments**
- **Corus Developments in FB Welding Technology**
  - **Weld Degradation Mechanisms & Required Improvements**
  - **Narrow HAZ FB welding**
- **Corus Developments in Weld Repair Technology**
  - **The Metallurgical basis**
  - **A pictorial tour of the developed process**
  - **Technical validation of process integrity**

Rail Metallurgy & Implications for Welding

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Steel grade [a]		Hardness range (HBW)	Description	Branding lines
Steel name	Steel number			
R200	1.0521	200 to 240	Non-alloy (C-Mn) Non heat treated	No branding lines
R220	1.0524	220 to 260	Non-alloy (C-Mn) Non heat treated	
R260	1.0623	260 to 300	Non-alloy (C-Mn) Non heat treated	
R260Mn	1.0624	260 to 300	Non-alloy (C-Mn) Non heat treated	
R320Cr	1.0915	320 to 360	Alloy (1 %Cr) Non heat treated	
R350HT	1.0631	350 to 390 [b]	Non-alloy (C-Mn) Heat treated	
R350LHT	1.0632	350 to 390 [b]	Non-alloy (C-Mn) Heat treated	
R370CrHT	t.b.a.	370 to 410	alloy (C-Mn) Heat treated	
R400HT	t.b.a.	400 to 440	Non-alloy (C-Mn) Heat treated	

- Increasing carbon equivalent & Hardness
- In all, but R350HT, increasing inherent hardenability

- **FB Welding challenges:**
  - **Matching weld region- parent rail hardness**
  - **Avoiding hard microstructures in critical HAZ**
- **Industry response:**
  - **Post weld accelerated cooling**
  - **Reduce segregation levels**
- **Weld Repair challenges**
  - **Increased risk of hard microstructures**
- **Industry response:**
  - **High pre-heat**
  - **Post weld treatments**
- **Corus response:**
  - **Rail steel development to address the dominant degradation mechanisms**
  - **Supporting welding developments**

A Summary of Key Rail Degradation Mechanisms

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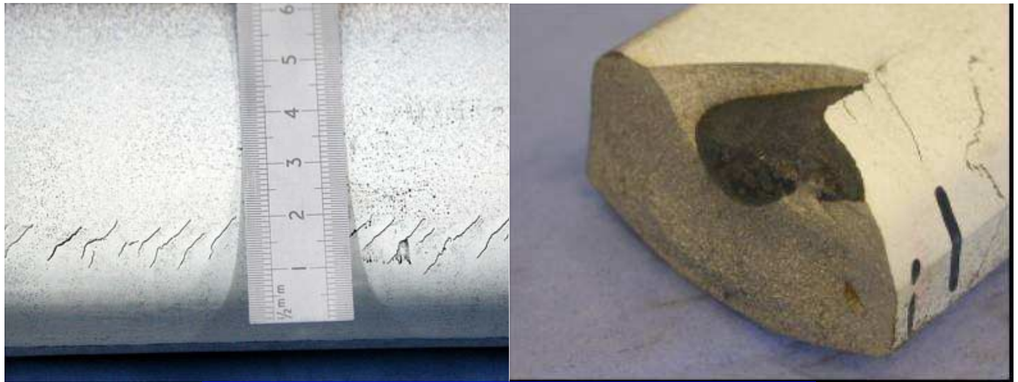
Wear



Rolling Contact Fatigue

Deformation

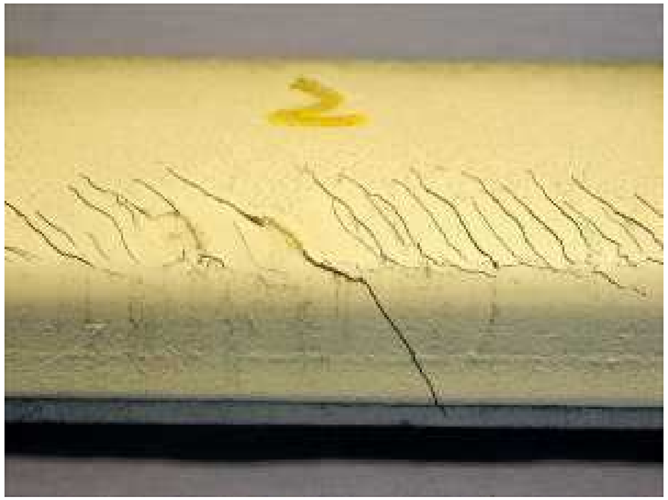
- Factors Limiting Rail Life
  - Wear: Vertical & Side
  - Rolling Contact Fatigue: Head checks, squats
  - Plastic Deformation
  - Corrugation
  - Rail Grinding: Frequency & Metal removal
- Duty Conditions
  - Vehicle Type & Traffic Density
  - Increasing Freight Traffic on Passenger Routes
  - Variability in Track Support

Grinding

Corrugation

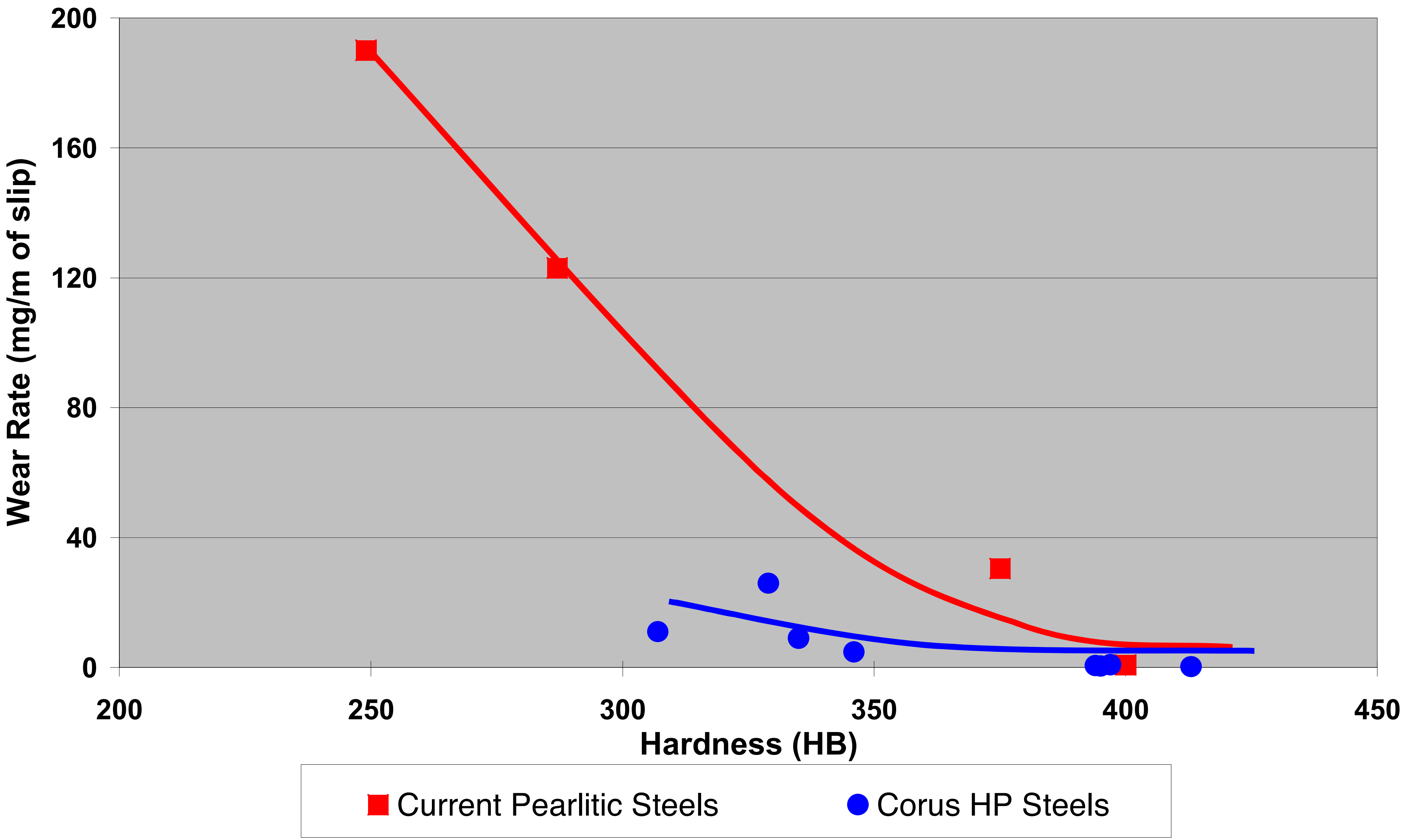
Corus Rail's Response to the Increasing Demands

- Special HT 400 MHH Grade (very hard & improved RCF resistance)
  - Eutectoid carbon & Chromium microalloying
- Metallurgically Engineered UHC Steel (Engineered microstructure for high wear and RCF resistance) – Corus HP Steel
  - Hypereutectoid Steel
- Bainitic Steels (High RCF resistance)
  - Low carbon with significant alloying



- In a welding context, the key points of note are:
  - High hardness of parent rail that needs to matched across the HAZ
  - Inherent high hardenability of composition
  - Effect of alloying elements in the case of Bainitic Steels

Corus HP Steel – Wear Resistance



Corus HP Steel – RCF Resistance

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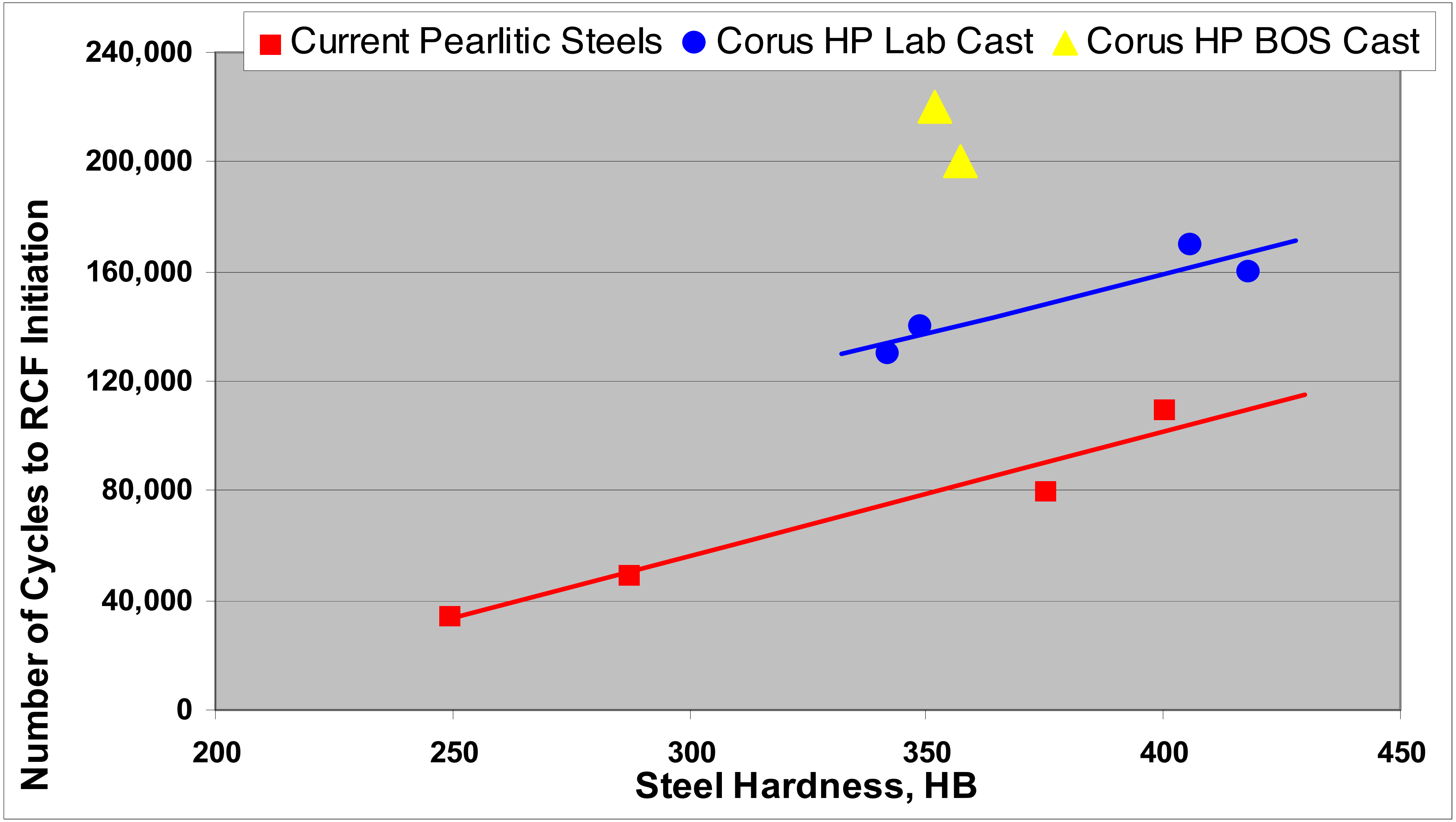

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Corus Developments in FB Welding Technology

Addressing Weld Degradation

1. **Running Band Deviation at & following FB Welds**
2. **Weld Breakage Risk**
   a. **Rail manufacturing flaws**
   b. **Welding flaws**
   c. **Potential of fatigue failures**
3. **In-service Degradation**
   a. **Weld "Cupping" & Dips**

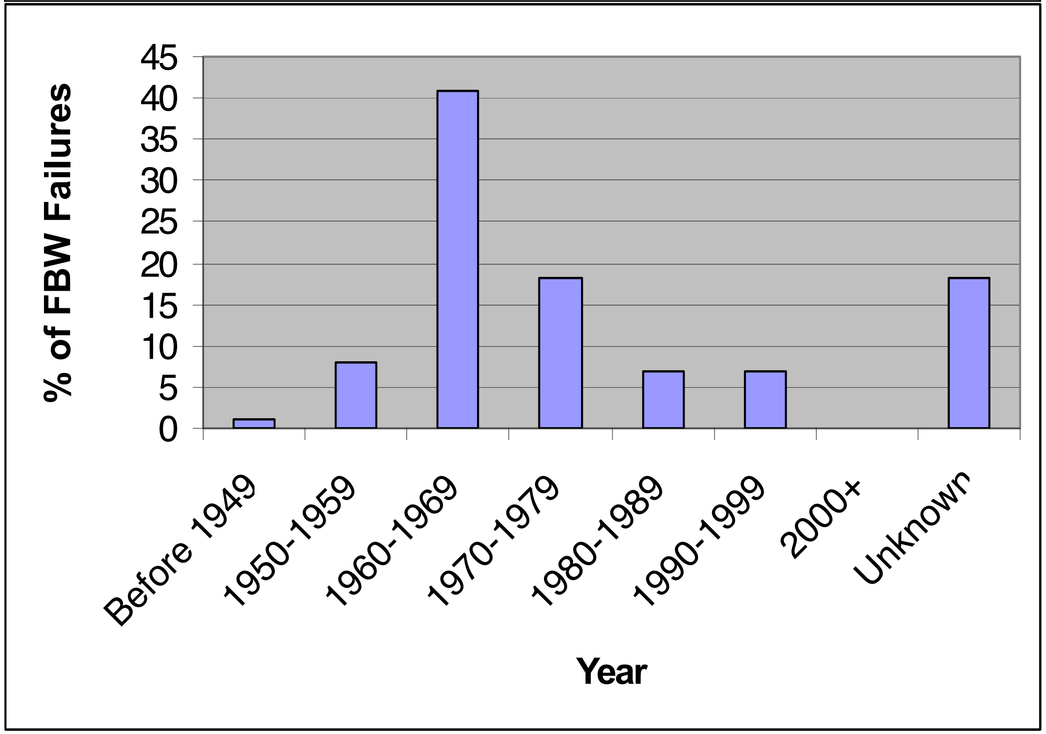
Weld Degradation – & Required Improvements (1)

Running Band Deviation

- Running band deviation is considered undesirable for the effective management of Wheel-Rail Interface
  - Some evidence that such running band deviations can contribute to the development of RCF
  - Can ground transverse weld profile contribute to squat formation on the weld itself?
  - However, factory FB welds are profile ground using dedicated "semi-automatic" grinders and longitudinal & lateral profile checked using laser. How does the transverse weld profile compare to that of ground rail?
  - Technology exists to mill welded region to original rail profile – would involve increased cost
    - Needs to be balanced against reliable data of in-service performance issues arising from current ground profiles

Weld Degradation: & Required Improvements (2)

Failure Statistics
Age profile* of flash butt weld failures 1994-2003.



- **Majority of welds >25yrs life**
- **‘Youngest’ recorded weld failure 1993**

* assumes recorded rail age = weld age

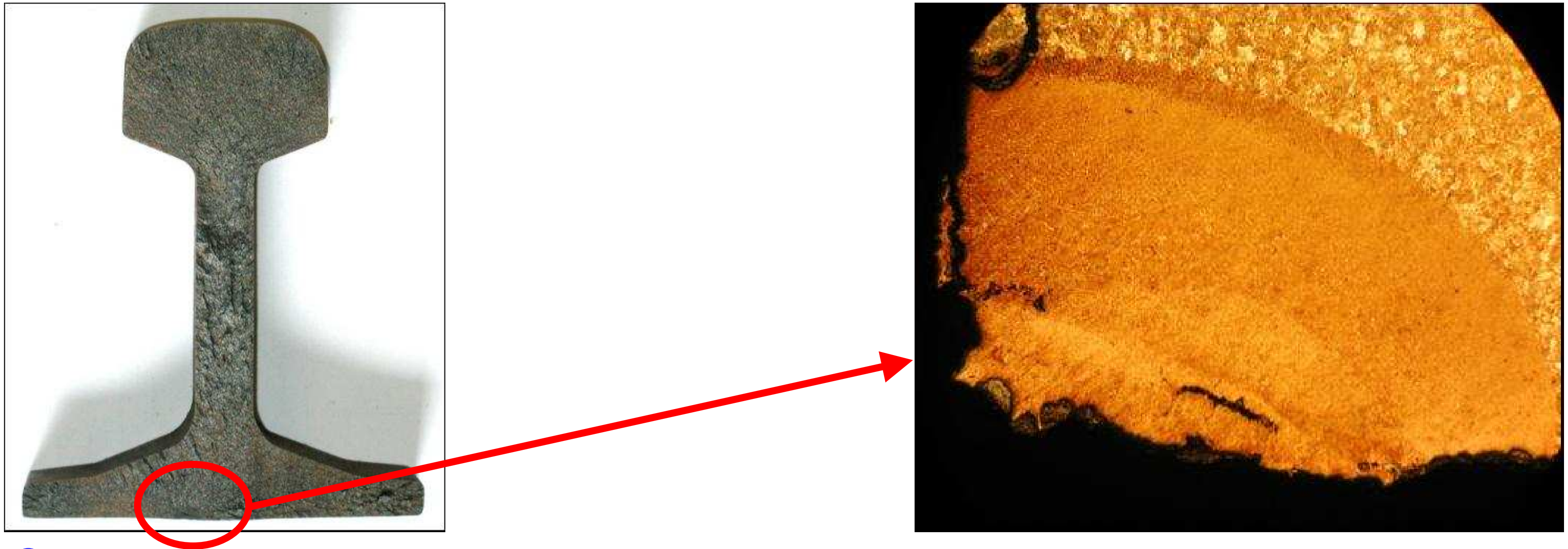
Weld Degradation: & Required Improvements (3)

Any Lessons from Past FB Breaks?

- Unusual fatigue crack on one side of web-foot transition radius
  - Difficult to detect with conventional UST
  - Oxide inclusions
  - Parent rail defect (piping) - 1972 BS11:Normal Grade rail
- **Modern rail manufacturing has eliminated such defects**

Weld Degradation: & Required Improvements (4)

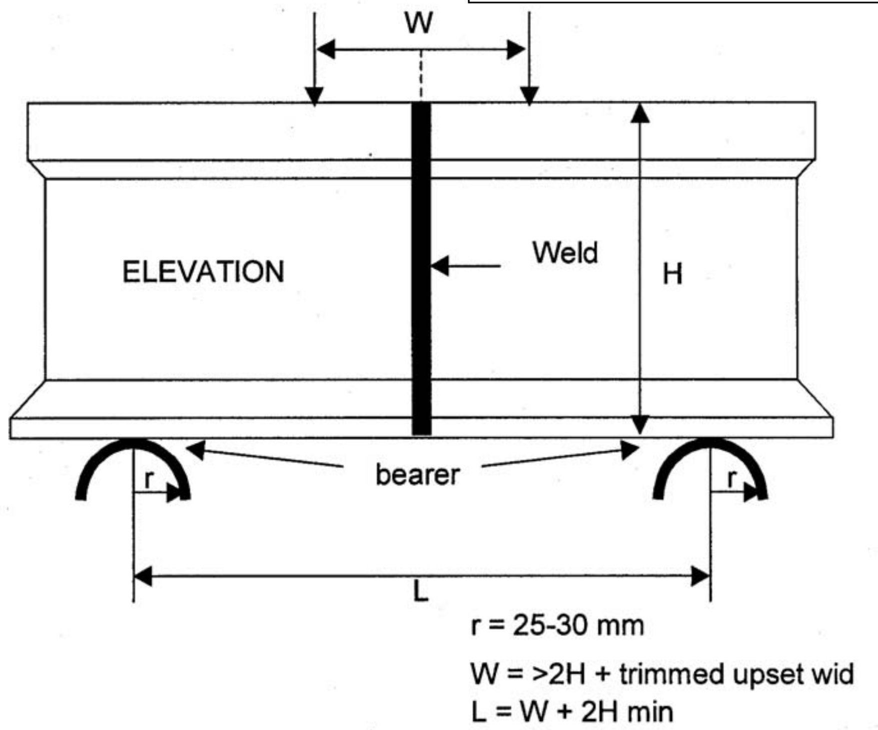
Any Lessons from Past FB Breaks?

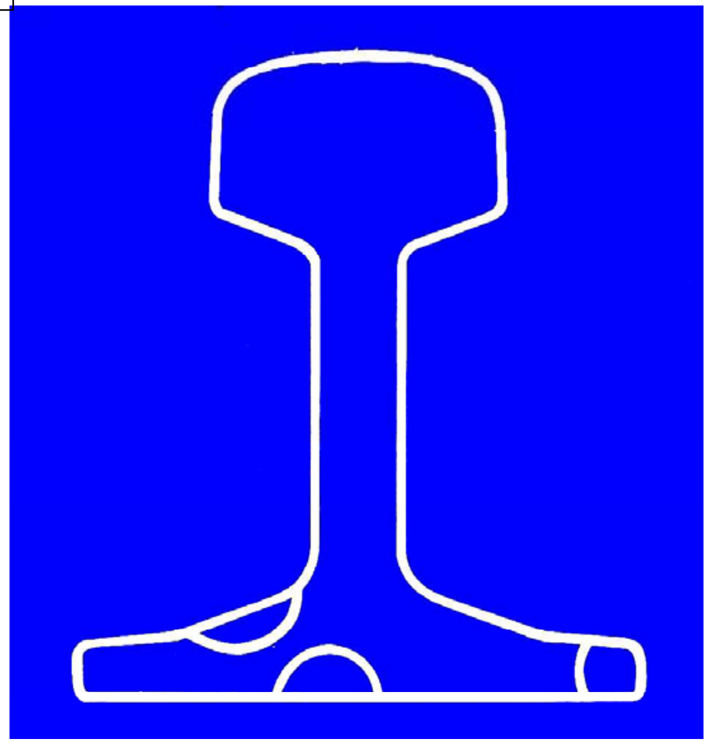


- **Weld Failure from Die Burn**
  - **1991 350HT rail**
  - **Die burn – pitting on bottom of foot**
  - **Also brittle microstructure (martensite and bainite)**
- **Better awareness of operators & maintenance of machine ensures such welds do not leave factory**

Weld Degradation – & Required Improvements (5)

Potential of Fatigue Failure?





- **Determining the fatigue strength (staircase method) of FB welds is a key requirement in NR specifications but reduced emphasis in EN 14587-1 2007**
- **Note potential sites of fatigue initiation (based on laboratory tests) & hence the importance of the quality of upset stripping**

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Weld Degradation – & Required Improvements (6)

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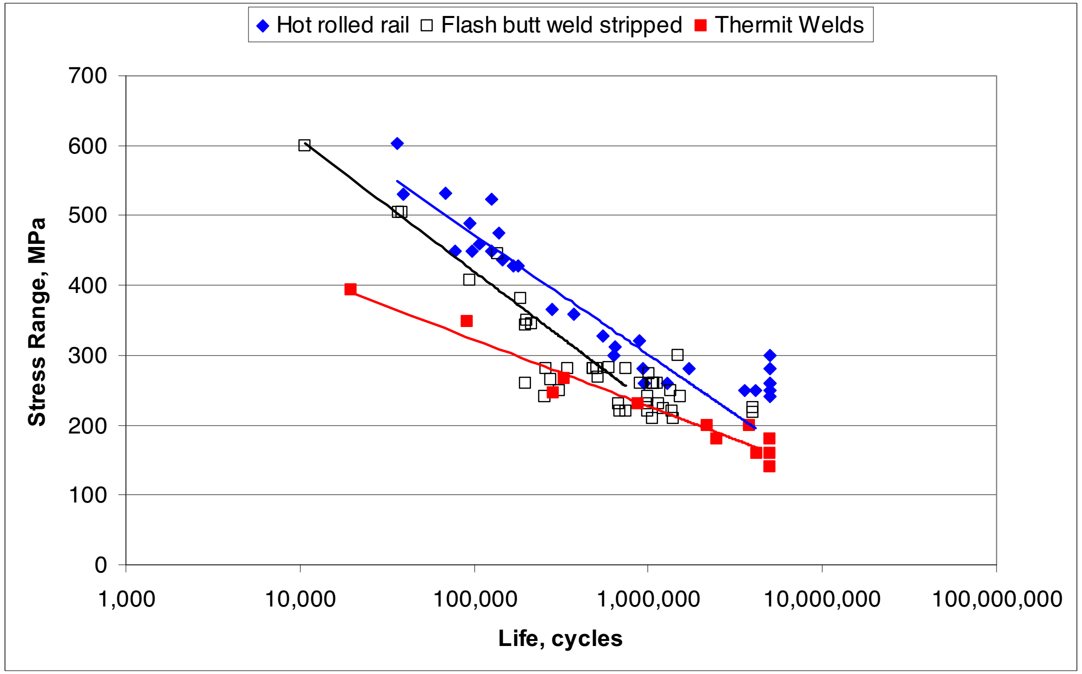
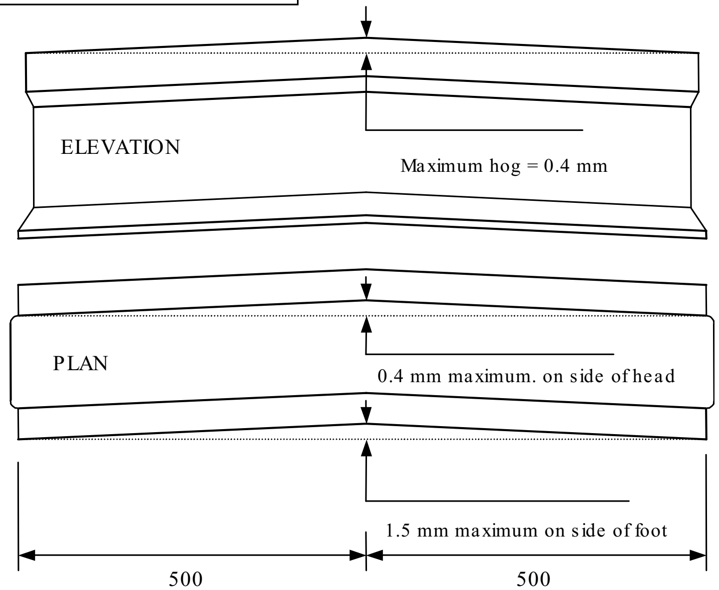
Potential of Fatigue Failure?



- **Extensive laboratory tests demonstrate that the fatigue strength of Factory FB welds is slightly below that of parent**
  - **Fatigue Strength of Factory FB welds in UK of >250 MPa is significantly above the stresses experienced by welds in service**
  - **Fatigue strength matching parent rail (~270 MPa) can be achieved – is it required?**
  - **Failure statistics confirm that fatigue failure is not an issue for Factory FB welds**

Weld Degradation – & Required Improvements (7)

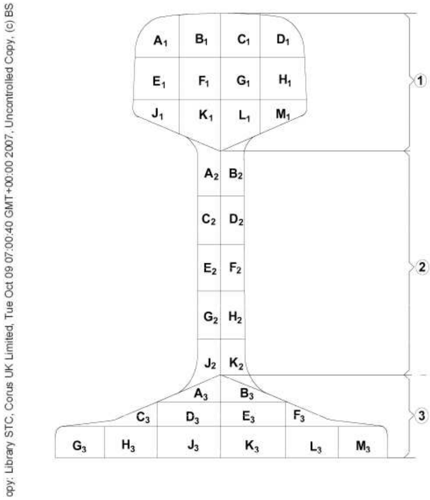
Potential of Fatigue Failure? - Effect of Geometry

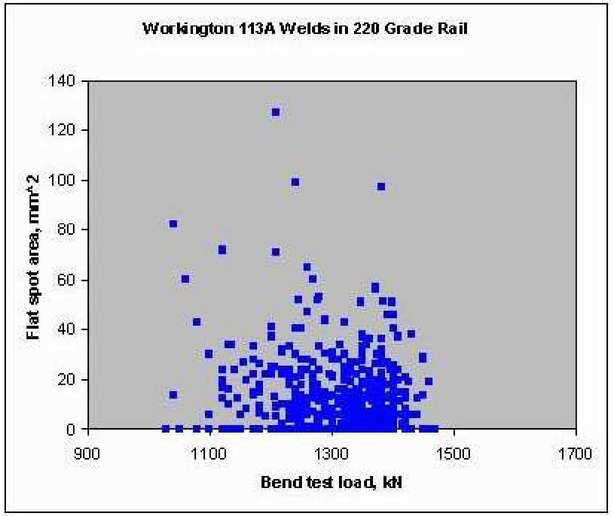


- **Deviation from Straight at foot tips can give rise to stress raisers to lower fatigue resistance**
  - **Where step arises from differences in rail dimensions, BSEN14587-1 2007 permits local dressing but does not specify how**
  - **Care is taken to ensure dressing is to reduce stress raiser and not just compliance with specification limit**

Weld Degradation – & Required Improvements (8)

Potential of Fatigue Failure - Effect of Flat Spots?

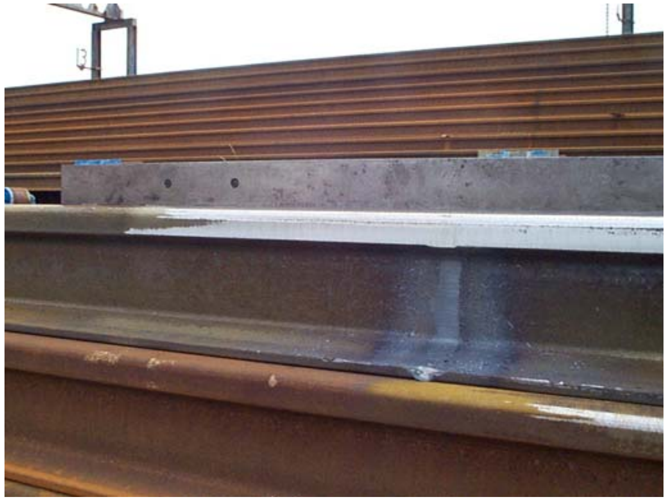


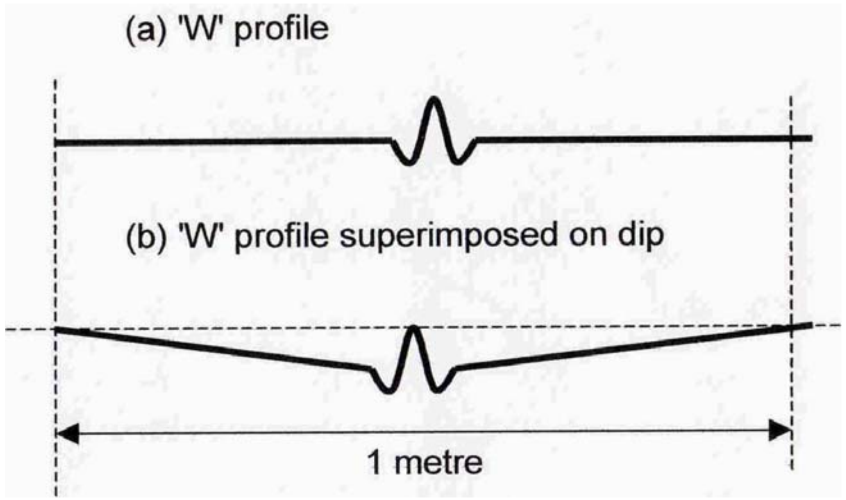


- The causes of Flat Spots in FB welding have been extensively researched
  - A key cause generally acknowledged is the failure to forge out large craters created by flashing
  - Specifications require recording of flat spots
  - However, clear lack of correlation between bend test loads & flat spot area. Observations suggest that surface breaking flat spots could lower bend test loads & could potentially increase probability of fatigue but no available evidence

Weld Degradation & Required Improvements (8)

In-service Degradation – "Cupping" & Dips





- **Factory FB welds supplied to very tight specifications on vertical & lateral alignment but passage of wheels can lead to:**
  - **Weld "Cupping": caused by DIFFERENTIAL WEAR across the HAZ that can lead to increased track forces beyond the weld.**
    - **Required improvement: Reduced gradient of hardness/wear resistance across HAZ**
  - **Weld "Dip": The loss of vertical alignment is lost over a much greater span than "cupping" – causes of dipping – many beliefs but little supporting data.**
    - **How do you address a degradation mechanism if causes remain unknown?**

Countering FB Weld Degradation - Summary

- **Running Band Deviation at & following FB Welds**
  - Better profile could be achieved through milling rather than grinding but can the increased cost be justified?
  - Reliable in-service degradation data needs to be obtained
- **Weld Breakage Risk**
  - Rail manufacturing flaws: No longer an issue with modern practices
  - Welding flaws: Better machine maintenance & operator awareness
  - Potential of fatigue failures: Fatigue strength much higher than in-service loading conditions, therefore, not an improvement target
- **In-service Degradation**
  - Weld “Cupping”: Improved resistance to wear across HAZ required
  - Weld Dips: Cause needs to be established through monitoring of in-service performance

Drivers for Narrow HAZ Development

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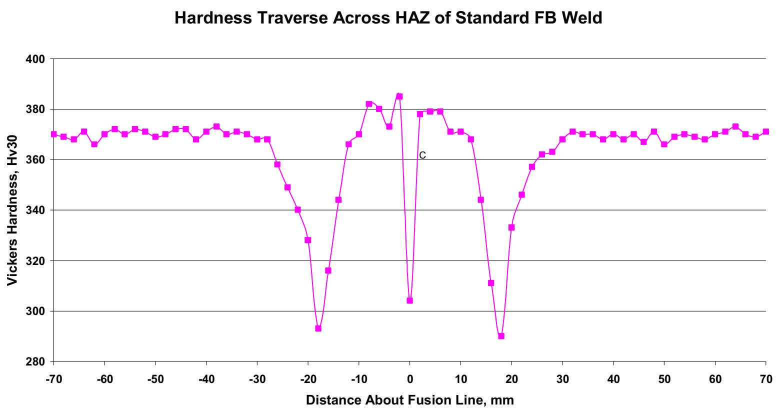
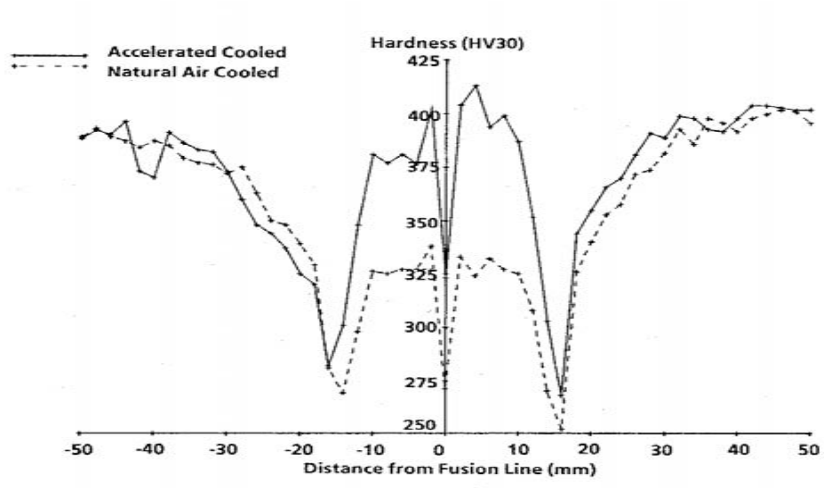


Hardness Traverse Std. FB Welds

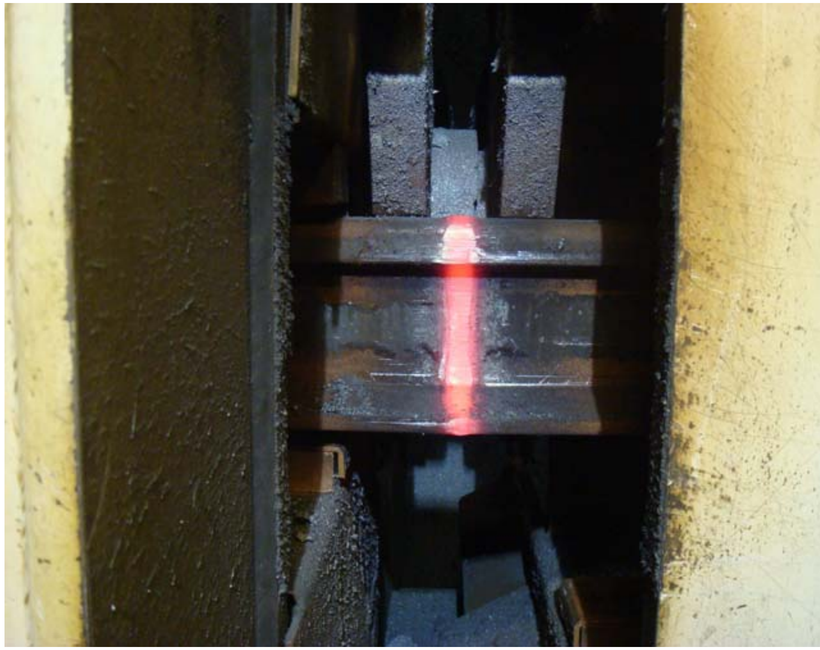


Grade R350HT

- **Width of HAZ and the inherent hardness variation across is more visible to the wheel & leads to differential wear causing "cupping"**
- **Degraded vertical weld geometry has consequences for track forces, corrugation development, track settlement, noise etc**
- **Minimising hardness variation across HAZ for Premium Rail Steels is particularly important because of the higher parent rail hardness**

Key Features of Narrow HAZ FB Welding

- **Two key aims:**
  - **Reduce heat input**
  - **Reduce time available for conduction**
  - **Balanced heat input with conduction cooling to achieve uniformity**
- **Aims achieved through**
  - **Slightly longer initial flash duration**
  - **Lower number of preheats**
  - **Reduced Preheat "On" and "Off" durations**
  - **Shorter final flash duration**



Narrow HAZ – Key Properties (1)

Grade Corus 400 MHH 56E1 Welded at NR Eastleigh LWRP
Bend Test Loads

Bend Test No.	Weld Type	Bend Test Load, KN	Deflection, mm	Comments
S1	Standard	1872*	10.54	Running surface HAZ width of 36 mm, Hardness - 363HB
N-HAZ 1	Narrow	2275*	28	Running surface HAZ width of 28 mm, Hardness - 388HB
N-HAZ 2		2270	27	
N-HAZ 3		2097	17	
N-HAZ 4		2033*	17	
N-HAZ 5		2072*	18	
N-HAZ 6		2513*	47	
Average		**2210**	**26**	


Mowlem Railways
Eastleigh Rail Welding Plant

Customer: networkrail welded 11/11/08
Test: 1178
Specimen: trial
Date: 11/11/2008

Max. Deflection: 4.697 cm.
Max. Load: 2513.09 kN.

Bend Test Chart: Load vs. Displacement

(9)

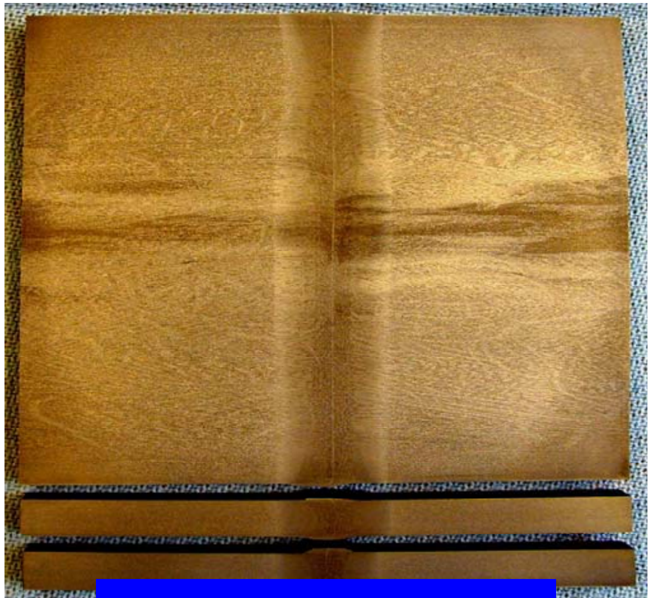
Machine
Operator: Lee
Date Serviced: 26/02/08

Rail
Rail Grade: 400mhh
Rail Type: 60 E2
Orientation: BASE DOWN
Temperature: 12degrees

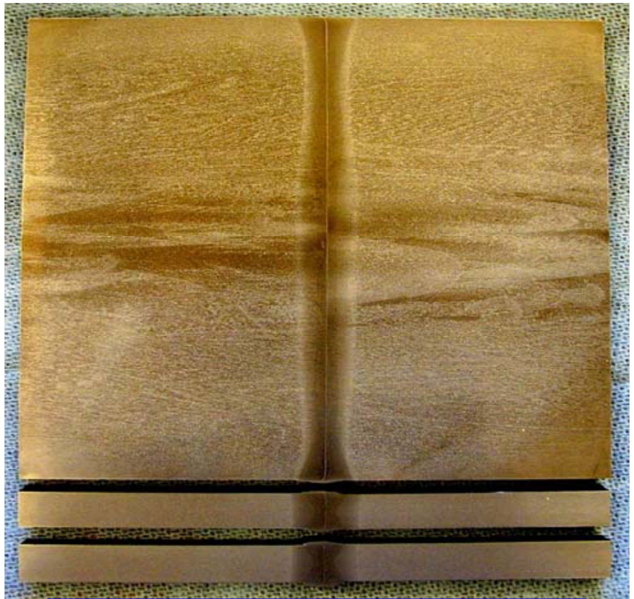
Comments:

Narrow HAZ – Key Properties (2)

Macro Examination



R350HT Std FB Weld



R350HT Narrow FB Weld

400MHH Narrow FB Weld

- HAZ width in standard FB welds is ~36mm but can be as high as 45mm
- Narrow HAZ welds have widths in the range 25-33 mm depending on composition being welded and HAZ hardness required

Narrow HAZ – Key Properties (3)

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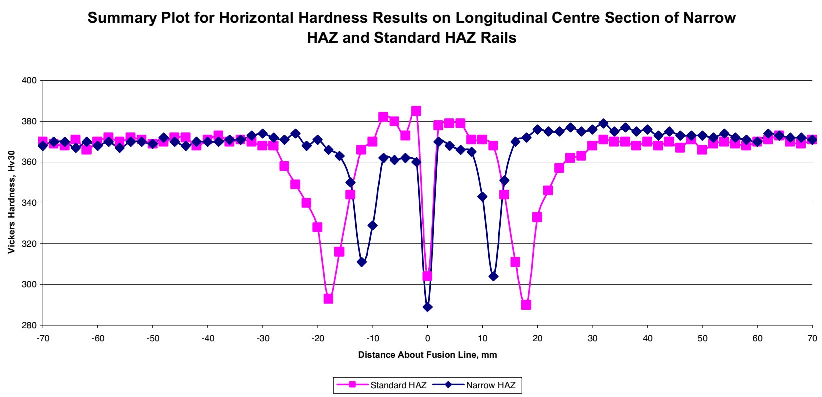
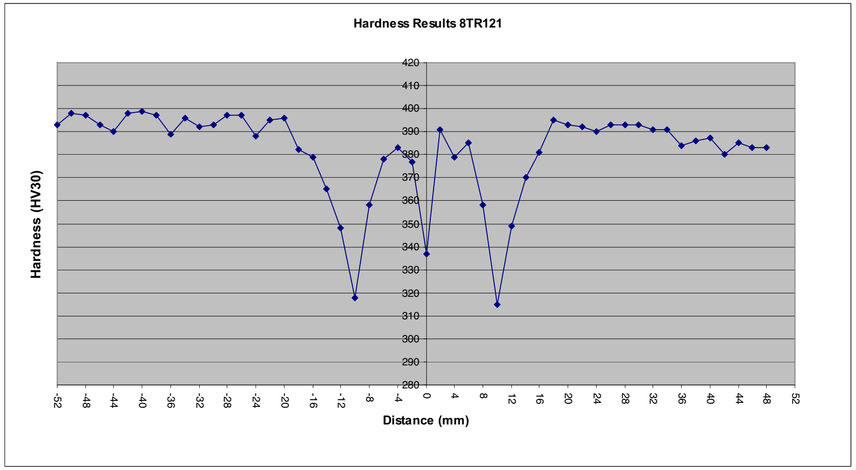
Hardness Traverse



Std. & Narrow HAZ R350HT

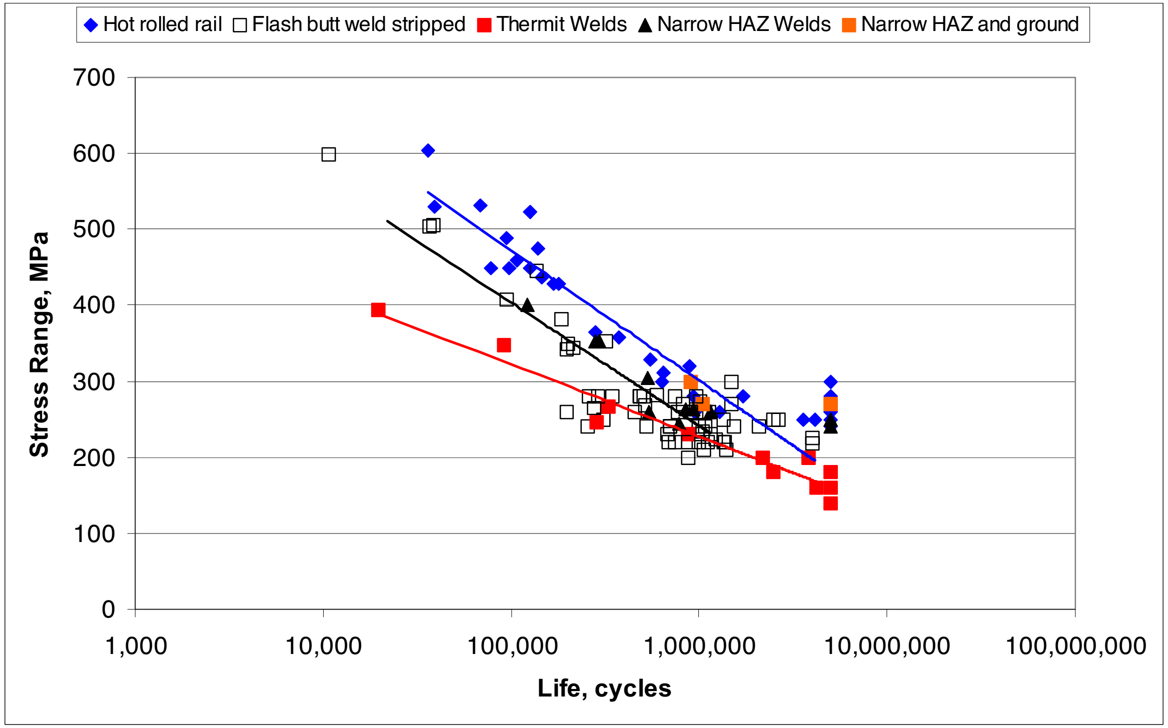


Narrow HAZ Corus 400MHH

- **Process offers opportunities for tailoring hardness gradient by balancing heat input and the resulting post weld cooling rate for the composition of the steel**

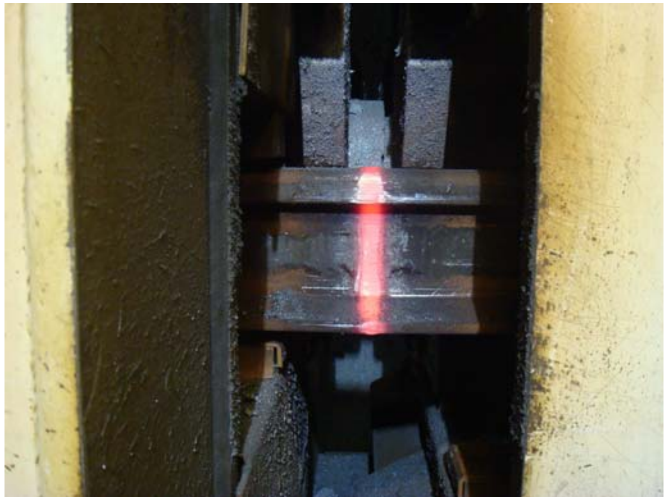
Narrow HAZ – Key Properties (4)

Fatigue performance



- Fatigue strength of Narrow HAZ slightly better than standard FB welds demonstrating that this property is more influenced by external factors such as strip quality

Narrow HAZ – Key Properties (5)



- Economic advantages of Narrow HAZ
  - Shorter welding process cycles – greater plant productivity
  - Lower energy consumption
  - Less wear & tear on equipment
- Narrow HAZ process is covered by a Corus Patent: GB2403174; EP patent published

Future Developments

- Future developments
  - Study of weld degradation in service but this needs to be done in a coordinated manner with the other rail welding techniques – particular focus on weld dips as this is a costly maintenance activity
  - Material property variation across HAZ – currently it is just hardness
- These initiatives would improve in-service performance
  - Consequences of weld degradation on RCF in follow on track, vertical settlement etc need to be established objectively
  - Weld suppliers can react with process developments to achieve target properties but cost benefit analysis is essential
  - Therefore, wider railway Industry funding

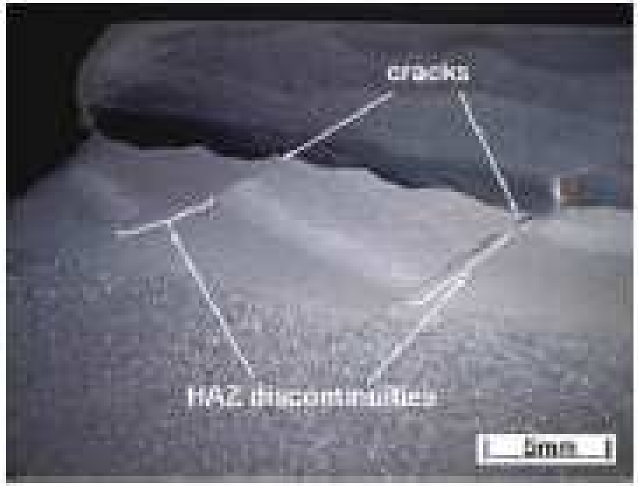
Discrete Defect Repair – A Novel Process

- The Drivers for Innovation
- The Challenges
- The developed Process
  - **The Metallurgical Foundations**
  - **A Pictorial Walkthrough**
  - **Metallographic Assessments**
  - **Structural Integrity Tests**
- Summary & Way Forward

The Drivers for Innovation (1)

- **Complex Contact Conditions: even the best maintained railway networks develop discrete defects –**
  - **wheel burns, squats, Belgrospies …**
- **Network Rail Assessment: ~10,000 squats/wheelburns removed annually - ~6000 weld repairable**
  - **Average cost of replacement estimated at ~£2.5k per defect or ~£15 million annual expenditure**
- **Application into the wider Railway World provides a very strong case for innovation of a repair procedure**

The Drivers for Innovation (2)



Pictures from Welding Lines

- **Current remedial measures:**
  - **"5m Closure Rail":**
    - **Introduces two aluminothermic welds, geometry changes, re-stressing,**
  - **Wide gap aluminothermic welds:**
    - **Limited to shorter length, differential wear, increases the number of AT welds in network**
  - **MMA repair:**
    - **high preheat, inconsistent results and high perceived failure rate, availability of skills**
  - **Thermit Rail Head Repair:**
    - **Recent implementation, cast material on running surface?, cast –wrought steel interface?**

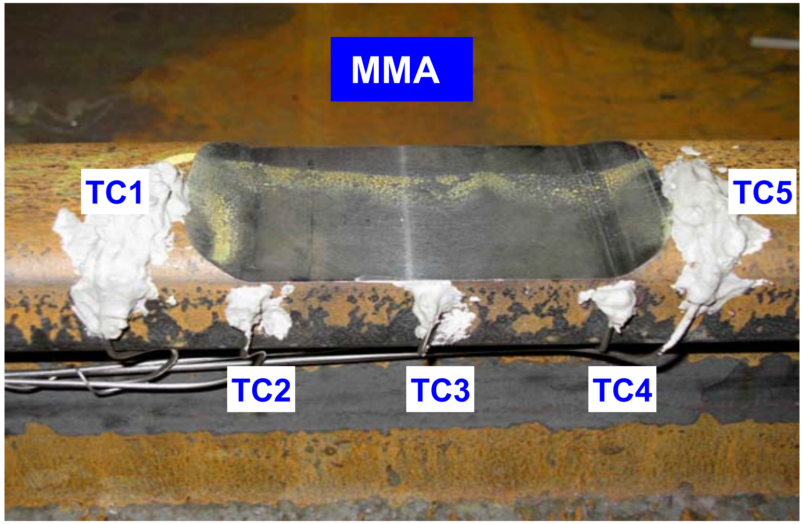
The Challenges

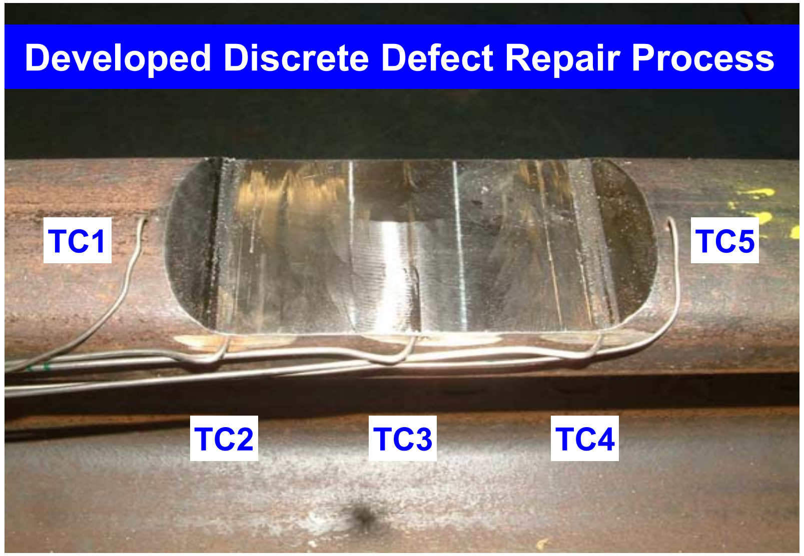
- **AVOID**
  - high temperature preheat
  - need for re-stressing
  - introduction of new AT welds
- **Reduce**
  - Cost of repair
  - Time to complete repair
  - Complexity of equipment & skills
- **Increase**
  - Integrity of repair under cyclic loading
  - Consistency of hardness across repair
  - Consistency through automation & standardisation

The Metallurgical Foundations

- The key factor influencing HAZ microstructure & integrity is the thermal history it undergoes.
- Comparative instrumented thermocouple trials have been undertaken for:
  - MMA repair
  - Developed Discrete Defect Repair (DDR) process
  - Thermocouples in five locations surrounding the excavated cavity at ~2-3mm from edge

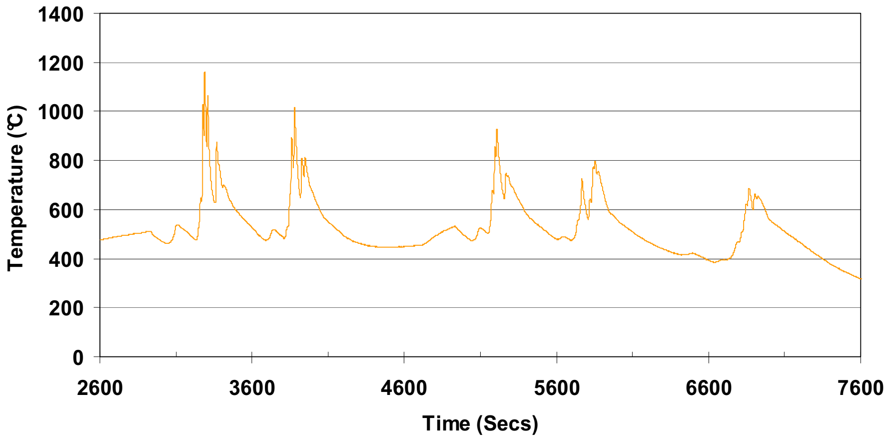
Instrumented Trial Samples



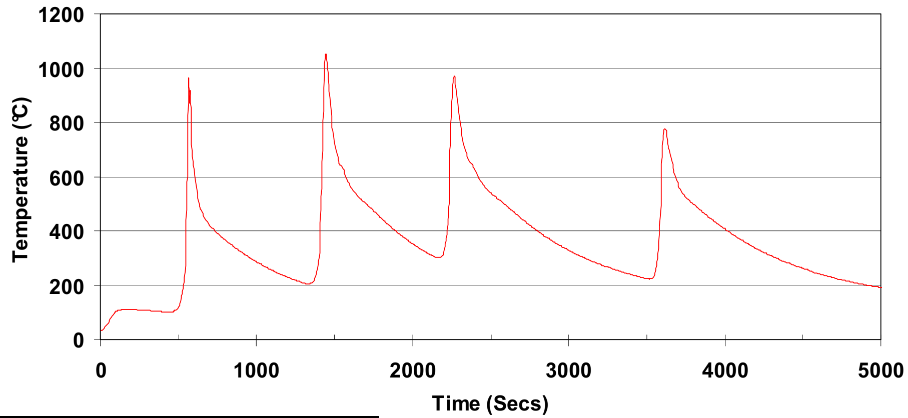


The Thermal History

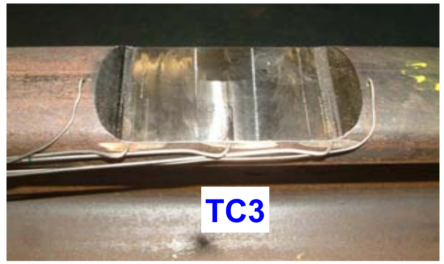
R260 MMA Rail Welding Trial - 30.3.2009, TC3



R260 Flux-Cored Rail Welding Trial - 8.5.2008; TC3



Parameter	MMA	Developed Process
No of passes	5	4
Preheat Temperature, ^{0}C	350	80
Cooling Rates, ^{0}C/s (800^{0}C - 500^{0}C)		
Pass 1	1.1	5.2
Pass 2	1.3	1.3
Pass 3	0.9	1.0
Pass 4	1.1	1.5



- **Despite the very significant preheat temperature differences, the cooling rates for all but the first are almost identical.**
- **Note the consistency of the thermal history in the developed process**

Comparative Thermal History – Passes 1-4

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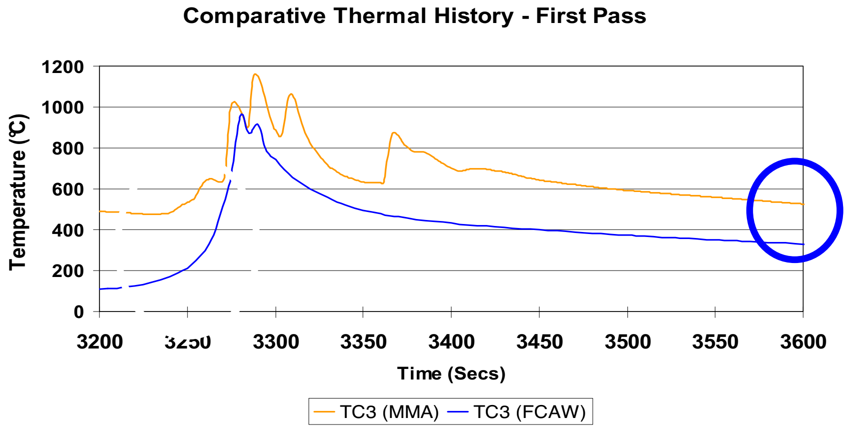

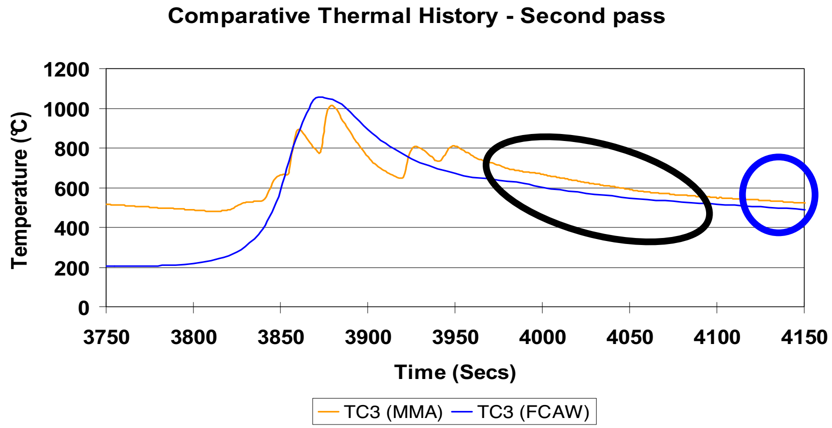

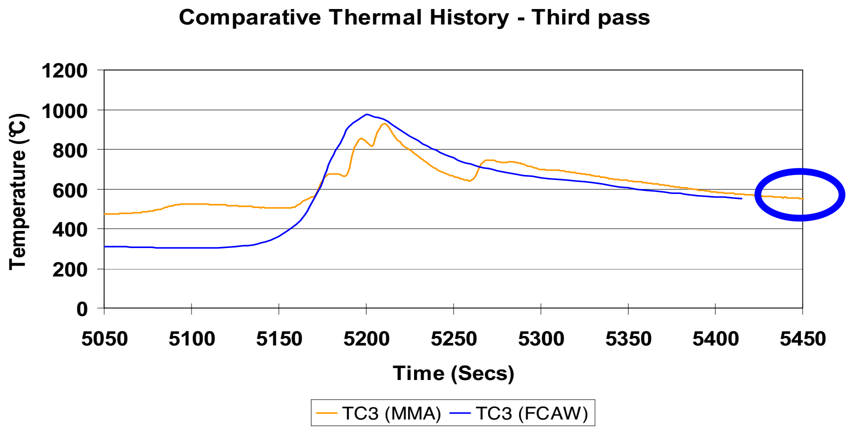

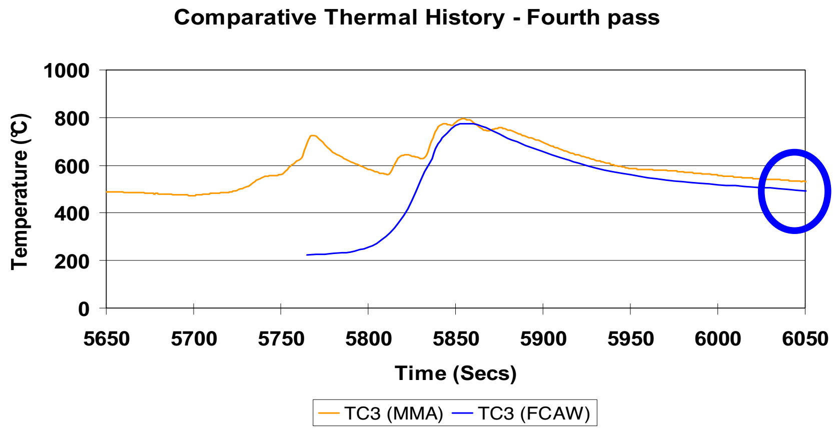

Comparative Thermal History

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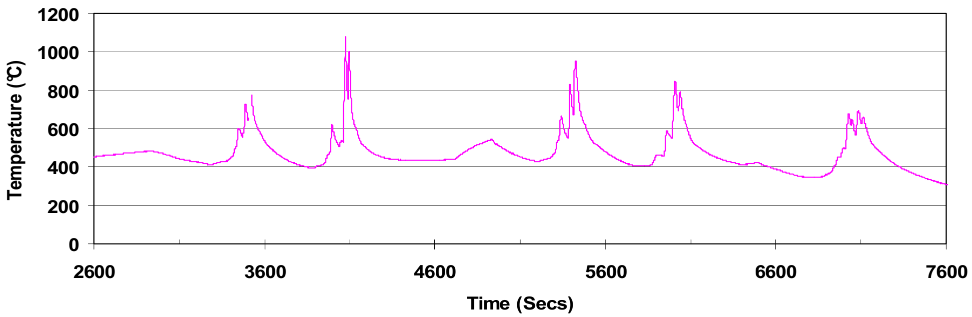
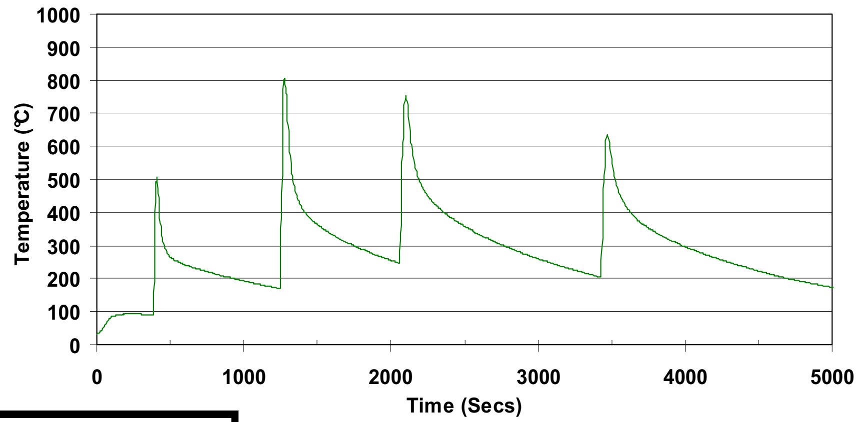
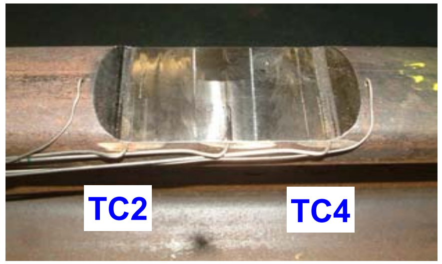
R260 MMA Rail Welding Trial - 30.3.2009; TC4



R260 Flux-Cored Rail Welding Trial - 8.5.2008; TC2



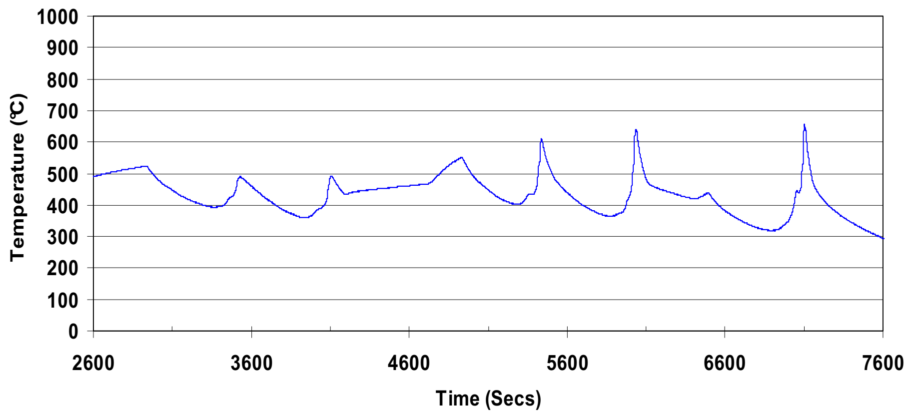
Parameter	MMA	Developed Process
No of passes	5	4
Preheat Temperature, ^{0}C	350	80
Cooling Rates, ^{0}C/s (800^{0}C - 500^{0}C)		
Pass 1	2.6	Not Austenitised
Pass 2	3.4	5.6
Pass 3	2.3	2.8
Pass 4	2.6	Not Austenitised



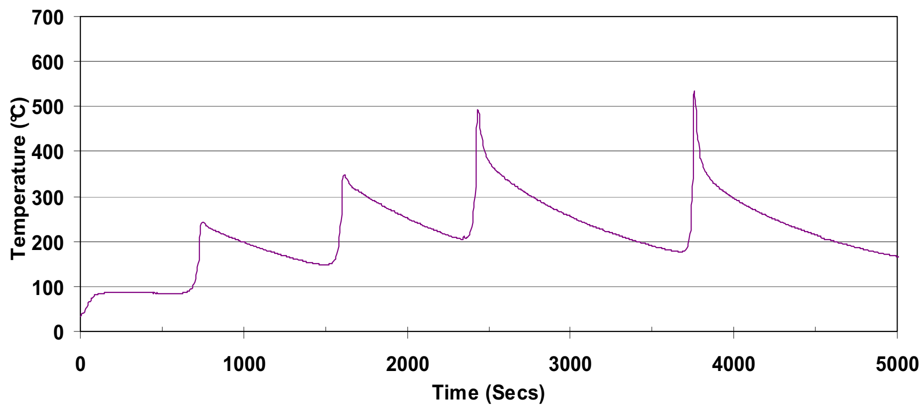
- Note that in Passes 1 & 4 of the developed process, the HAZ is not reaustenitised.
- Note the consistency of the thermal history in the developed process

Comparative Thermal History

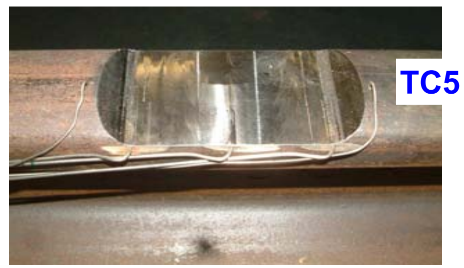
R260 MMA Rail Welding Trial - 30.3.2009; TC5



R260 Flux-Cored Rail Welding Trial - 8.5.2008; TC5



Parameter (TC5)	MMA	Developed Process
No of passes	5	4
Preheat Temperature, ^{0}C	350	80
Cooling Rates, ^{0}C/s (800^0C - 500^0C)		
Pass 1	Not Austenitised	
Pass 2	Not Austenitised	
Pass 3	Not Austenitised	
Pass 4	Not Austenitised	

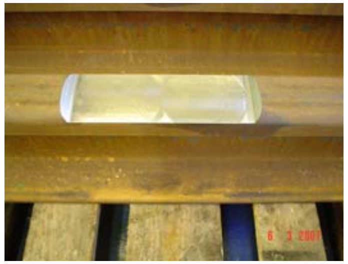
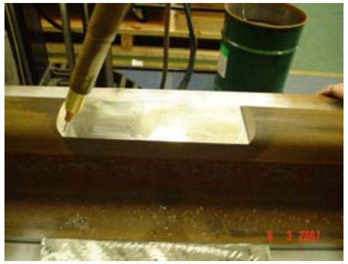
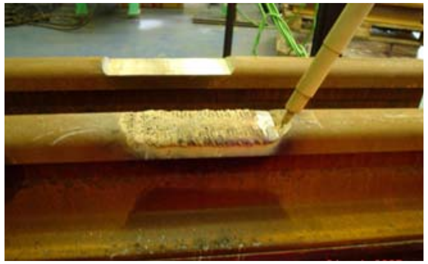


- Note that HAZ has not been austenitised at this location for both processes but maximum temperature reached increases with the number of passes
- Note the consistency of the thermal history in the developed process

Metallurgical Foundations for Weld Repair of High Carbon Rail Steels

- **The fastest cooling rate of 5.6^{0}C/s is well below the critical rate for non-pearlitic transformation – Previous BR Research has concluded rates of >10^{0}C/s result in martensite in the microstructure**
- **The lowest temperature achieved for each weld deposit is above 200^{0}C/s – i.e. above M_s temperature of ~160 ^{0}C – Consequently there is no possibility of forming martensite even if the cooling rate was much faster**
- **The maximum temperatures & cooling rates closer to the fusion line are not expected to affect the overall integrity of the repair.**

A Pictorial Walk Through the Developed Process


The Developed Process – Stage 1

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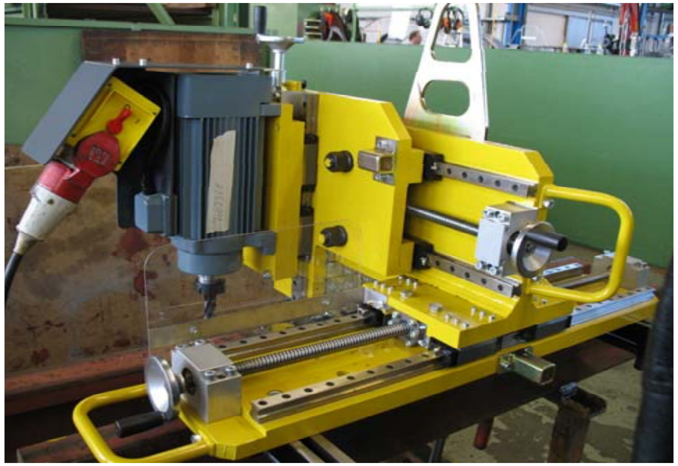
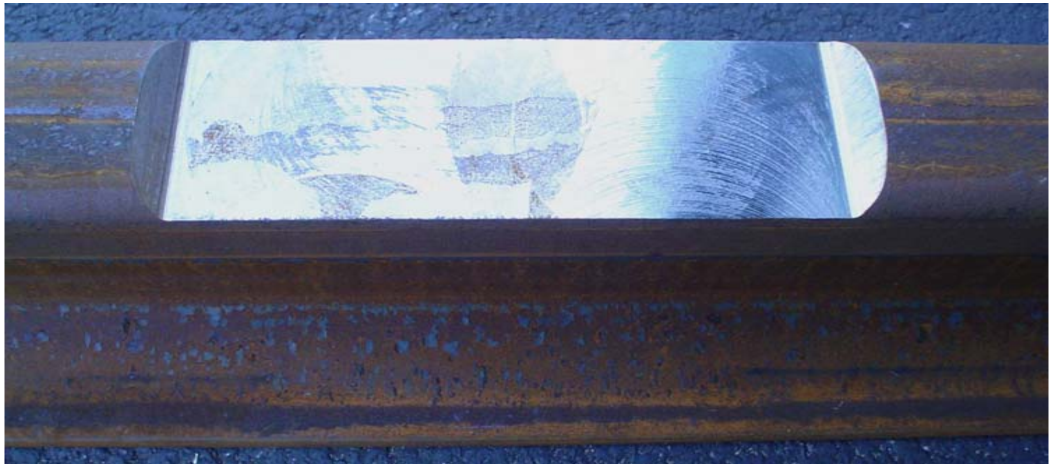


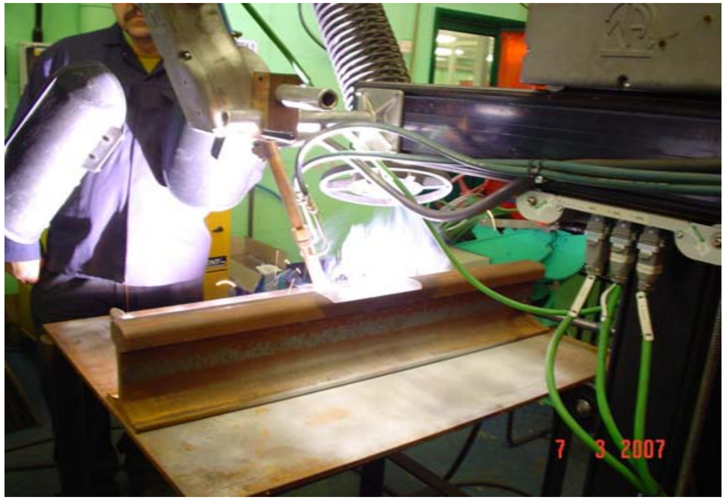
- **Rail Milling:**
  - **Choice of milling was based on the need for consistency, speed & automation**
  - **Can be undertaken with a currently available portable milling unit:**
    - **a manually operated 3-axis milling machine that clamps onto the sides of the rail head.**
    - **2kW motor and standard milling cutters between 16mm and 20mm diameter.**
    - **Fully portable - consists of two parts that easily clamp together (41kg + 62kg)**
  - **Time to excavate defect (200mm x ~72mm x 10mm) = 15min**
  - **Some modifications planned to make it compatible with subsequent welding**

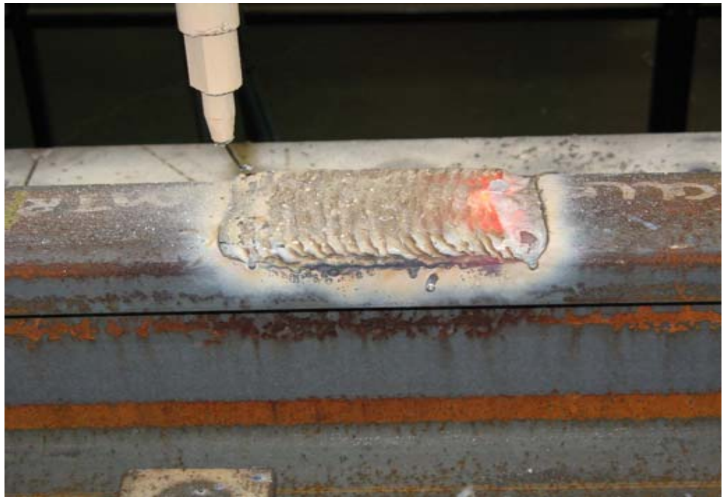
The Developed Process – Stage 2



- **Rail Temperature Conditioning:**
  - **For practical purposes, this stage is akin to preheating as in MMA repair**
  - **Choice of temperature is based on the need to prevent reaching M_S (Martensite Start) temperature and hence avoid martensite formation.**
  - **Development of the process to date has employed propane heating but other heating techniques under consideration to reduce time on track**

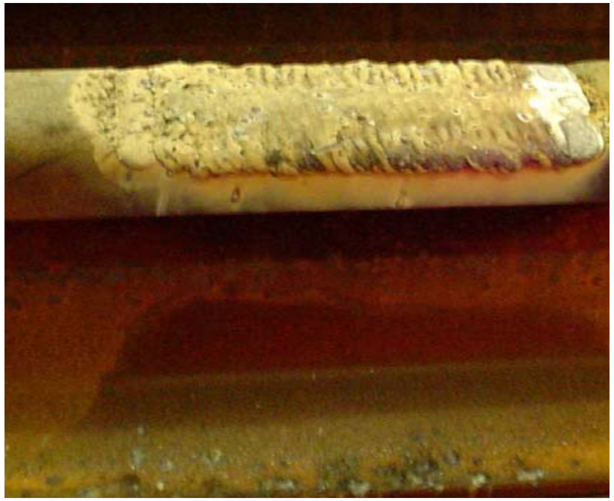
The Developed Process – Stage 3

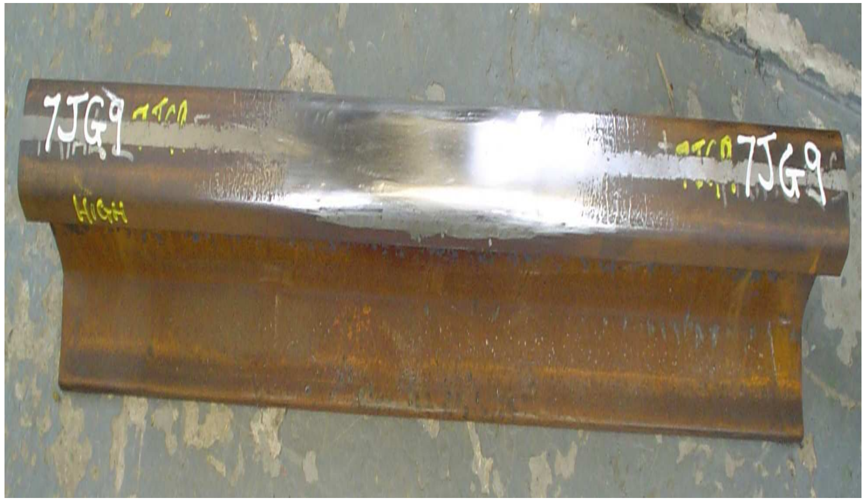




- **Weld Repair:**
  - **Semi- automatic Open Arc Welding employing Flux Cored Arc Wire**
  - **Controlled patterned weave and energy input to minimise HAZ width**
  - **Precise positioning of top layer to temper any hard microstructure at boundaries**

The Developed Process – Stage 4





- **Finish Profile Grinding:**
  - **Currently undertaken using grinders in common use on railways**
  - **Consideration being given to developing a milling tool**

Microstructures Developed

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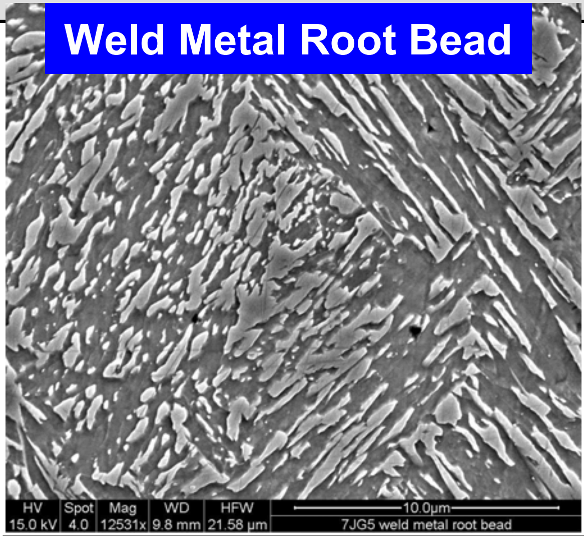
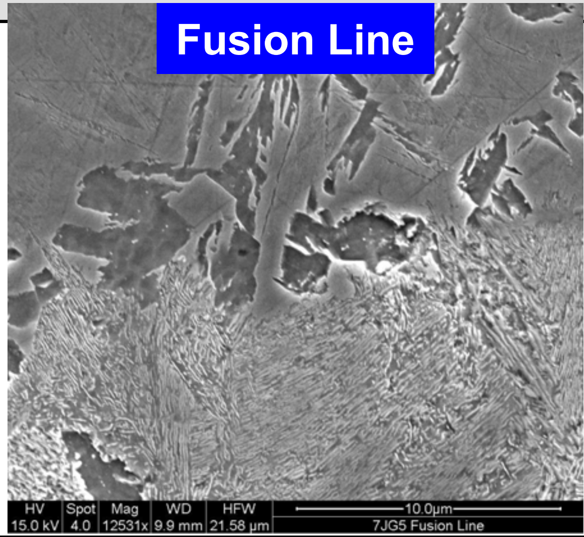
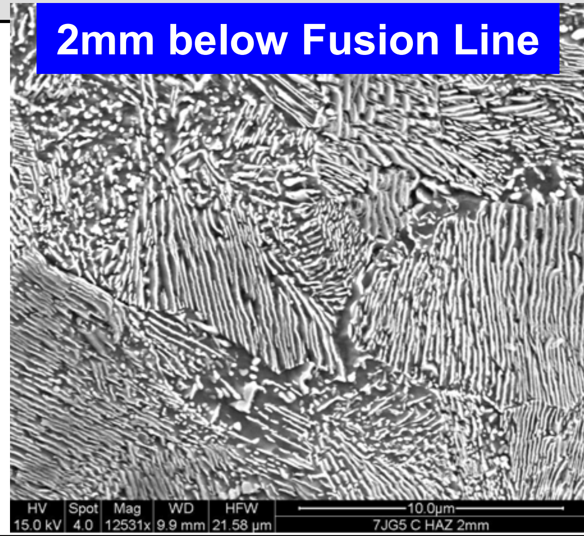
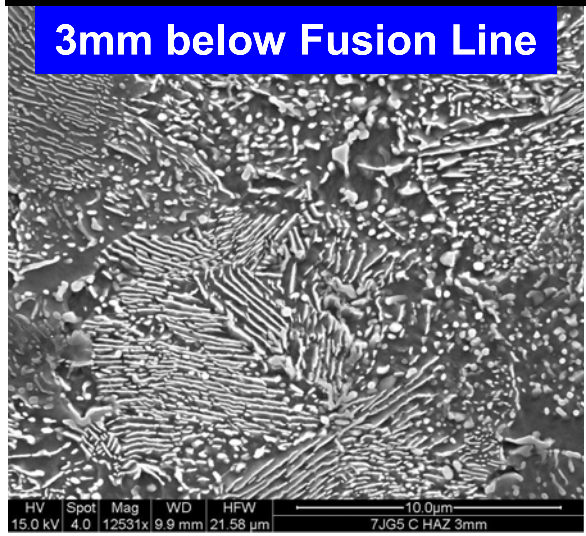
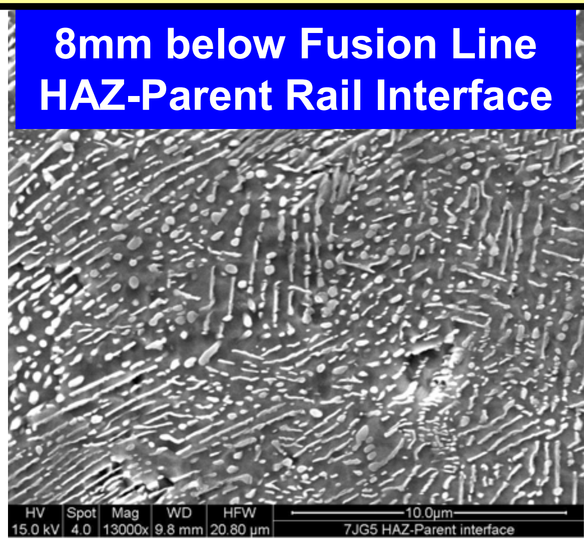


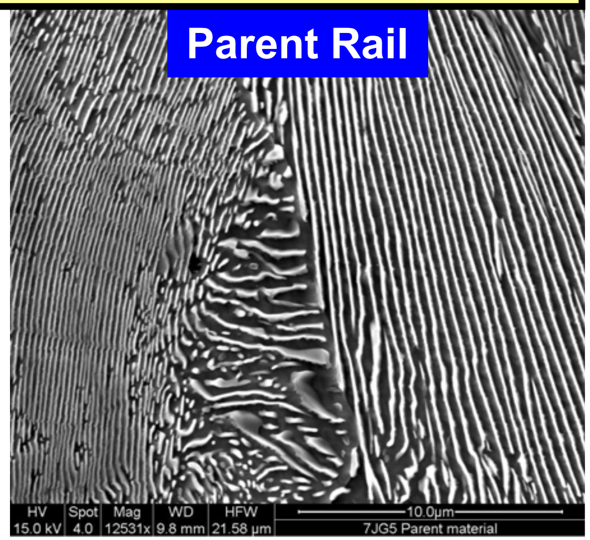




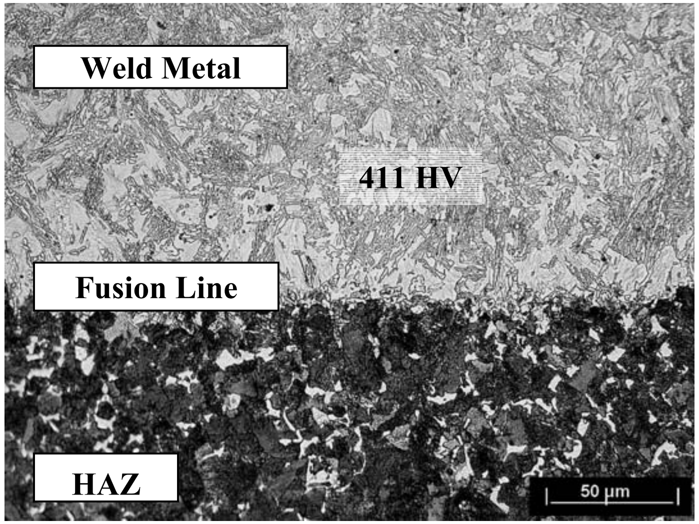
Scanning Electron Micrographs at Various Depths – Weld Metal to Parent Rail

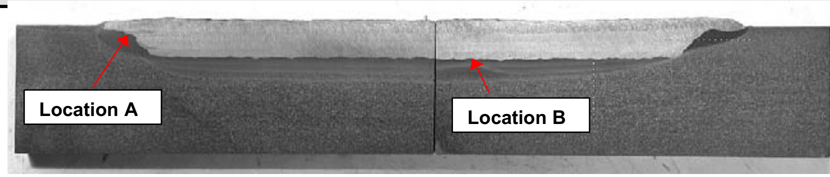


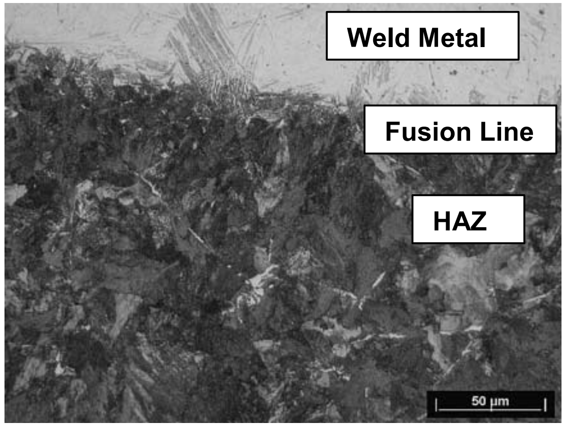


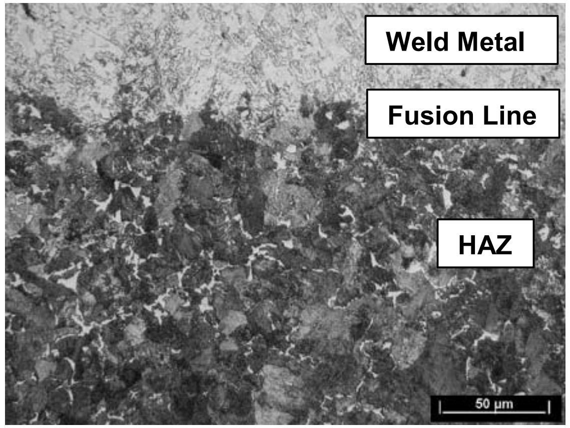


Microstructural Integrity of Deposit



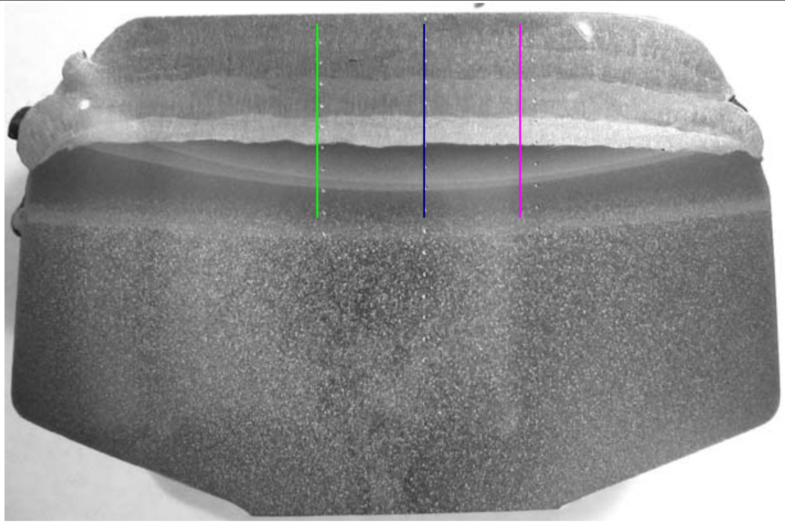


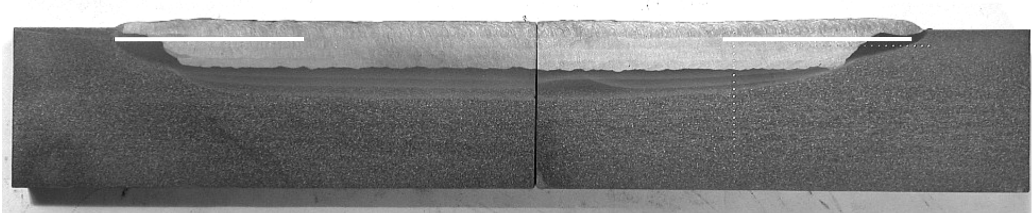


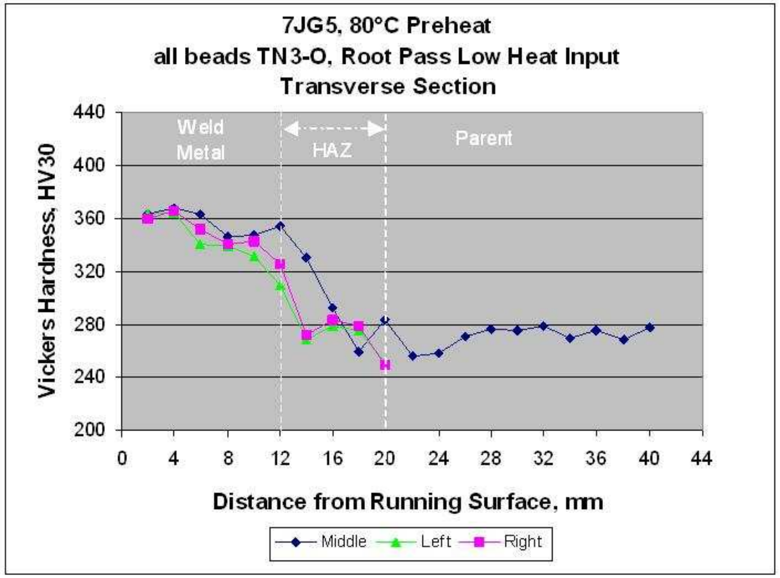


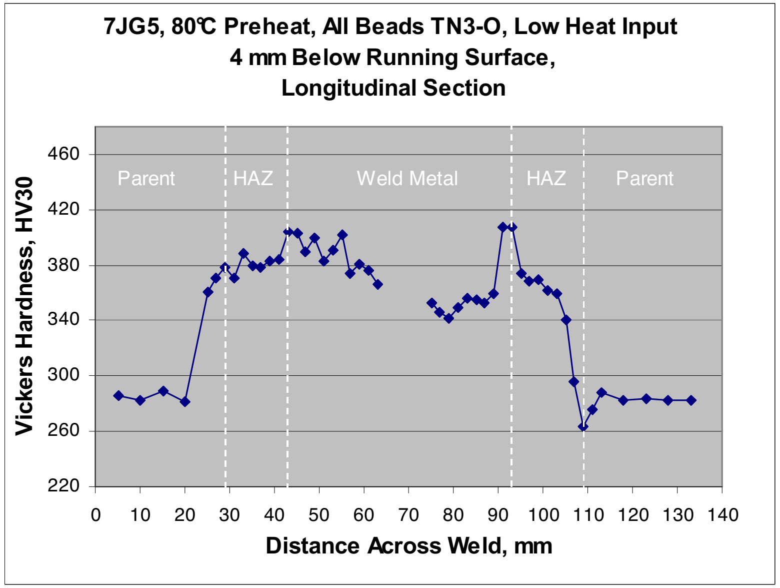
- **Crack Free Interface is apparent in all transverse and longitudinal slices**
- **HAZ microstructures are free from any martensite or bainite. Some ferrite at grain boundaries is a reflection of the carbon diffusion into the weld metal**
- **The weld metal microstructure is, as expected, bainitic with a high hardness in the root bead from the carbon pick up.**

Hardness Integrity



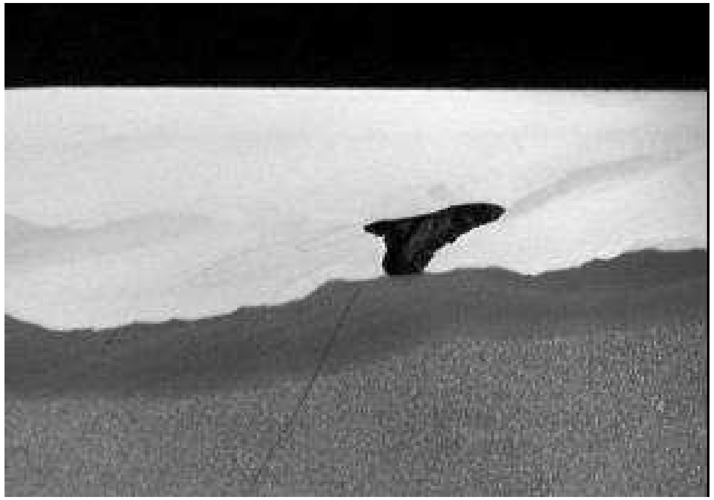






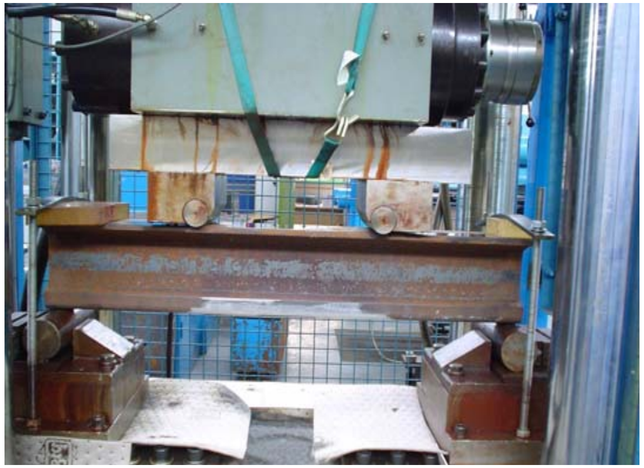
- Weld deposit hardness of ~360HV at the surface = good wear resistance
- Relatively uniform hardness across longitudinal section

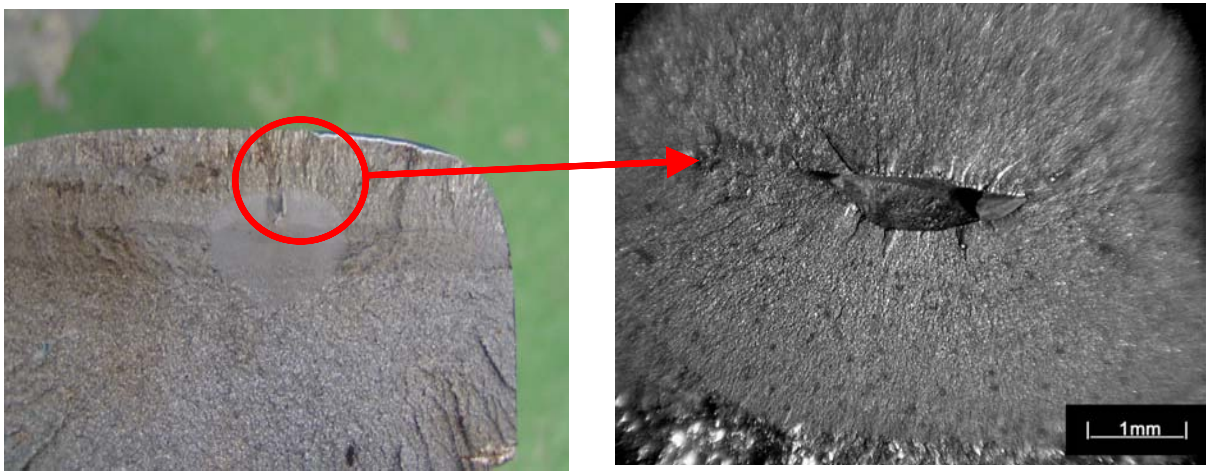
Fatigue Failure Resistance – MMA Repair



- Failure mode often encountered with MMA repairs is fatigue initiated from flaws at the weld-parent metal interface.
- Such defects, like the classical Tache Ovale defects are not detected till they are sufficiently large leading to rail replacement.
- Statistical data for such failures is often inaccurate - mistaken for Tache Ovale or Vertical-Transverse breaks.

Fatigue Failure Resistance – DDR Process





- Fatigue Resistance: 4-point Bending Fatigue test with Rail Head in tension
- Stress range = 3 times expected service load – passed 5 million cycles
- Further 4.3 million cycles at a stress range = ~8 times service load on same sample
- Failure in service extremely unlikely

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Summary – Have we met the Challenges?

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The Challenges	Response from Developed Process
AVOID	
High temperature preheat	Challenge met - Heati
Need for re-stressing	Challenge met; a stressing
Introduction of new AT welds	Challe
Reduce	
Cost of repair	lished but expected to mpetitive
Time to complete repair	cted to be ~1 hour for repair of 100 x 72 x 10mm section
Complexity of equi	Automation of milling and welding processes with data logging planned
Increase	
Inte oading	Challenge met, fatigue failure unlikely
s across repair	Challenge met, uniform hardness and microstructures
rough automation & standardisation	Being designed into dedicated unit

Next Steps:

A dedicated welding unit being designed to gain process approval from various Railways

Summary & Conclusions

- Role of metallurgy in reducing the Life Cycle Costs of track is increasingly becoming apparent and acknowledged
- Full realisation of the benefits of Premium grade steels can only be achieved if weld degradation is minimised & effective weld repair techniques are developed
- Failure statistics confirm the robust quality of FB welds but the key issues that need to be addressed are:
  - "Cupping" because of differential wear across HAZ, this is particularly important in the case of premium grade steels
  - Causes of weld dips needs to established objectively
  - Consequences of running band deviation needs to established objectively
- Development of Narrow HAZ FB welding process has significantly reduced hardness (wear) variation across HAZ. It also offers significant economic advantages
- A novel semi-automatic weld repair process developed


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Thank You