Rail Steel Metallurgy: Why Different Elements are Important and Latest ‘Mixes’

PWI London Technical Seminar: Rails – On Our Mettle
Jay Jaiswal & Adam Bevan
Overview

- Brief history of rails
- Past and present rail microstructures
- Rail steel grade selection for maximum benefit
  - Rail damage mechanisms
  - Route segmentation and damage susceptibility
  - Rail selection and attributes
  - Economic impact of optimised selection
- Discussion and recommendations
Complexity of Design and Material Selection

Many Components & Many Material Challenges

*Rail* is the hub of the track infrastructure with varying duty conditions which place significant demands on correct material selection.
Brief History of Rails – Life Before Steel

- Early Railways and Wagonways (flange on wheel)
  - 600BC Ruts in Stone – Greece/Malta
  - 1540’s – Wooden rails – Central Europe
  - 1603 – Wollaton, Nottingham
  - 1767 – Cast iron plates on wood rail - Coalbrookdale

- Cast Iron “Fish bellied” Edge Rails – Late 1780’s
  - Short length (<6ft), brittle, many joints, uneven

- Tramway (flange on rail)
  - 1787 – “L” shaped Plates – Sheffield

- Trevithick’s locomotive in 1804 broke the cast iron rails

- Wrought iron rails – 1808 – Tindale Fell, Brampton, Cumberland

- Up to 30ft, soft, delaminated
1857 – The first of Mushet's steel rails was delivered to Derby Midland Station

- Heavily trafficked part of the line where the iron rails had to be renewed every six months, and occasionally every three
- "Six years later, in 1863, the rail seemed as perfect as ever, although some 700 trains had passed over it daily. Life span achieved 16 years
Past and Present Rail Microstructures

1767 Cast Iron ~ 3\%C; 200HB

1808 Wrought Iron 0.05\%C; 174HB

1857 Bessemer Steel ~ 0.25\%C; 182HB

1950 BS11 Normal (R220); ~0.55\%C, 230HB

1970 Grade A (R260) ~ 0.8\%C, 280HB

1985 MHT (R350HT) 0.8\%C, 350HB

Current HE Grades (R400HT) ~0.9\%C; >400HB
Drivers for Developments in Rail Metallurgy

• Reduce rail breaks and defects
  – Improved steel cleanness
  – Increased section and stiffness

• Reduce rail joints
  – Increased hot rolled length
  – Improved welding technologies

• Reduce wear, RCF and plastic deformation
  – Increase carbon and alloy content
  – Heat treatment to refine microstructure and increase hardness
Rail Degradation Mechanisms: Wear

- Rail Wear – remains a significant key cost driver in European Railways
  - Only 20-30% of rail section weight is available for consumption through wear – therefore need to MAXIMISE the life of the ≈20% of rail weight
  - Increase in rail life requires a reduction in rate of wear
  - Increasing traffic density makes reduction in wear rate even more desirable to increase track availability
Rail Degradation Mechanisms: RCF

• Rolling Contact Fatigue:
  – A key cost driver in most railways
    • Increased grinding costs
    • Increased inspection costs
    • Premature rail replacement well before wear limit is reached
Rail Degradation Mechanisms: Squats

- Squat Defects – growing cause of increased track maintenance
  - No universal consensus on cause
  - Can rail metallurgy contribute towards eliminating Squats?
    - Can a softer grade promote wear of initial cracks & better rail wheel contact?
Plastic Deformation – a further cause of premature rail replacement

- Highly canted track – higher forces on low rail
- Increased freight traffic resulting in high forces on low rail
Rail Degradation Mechanisms: Corrugation

- Corrugation – a further rail degradation mechanism & a cost driver
  - Increased dynamic forces leading to degradation of rail & support
  - Increased noise & vibration
  - Increased maintenance costs from remedial grinding
- Harder grades are considered to be more resistant to corrugation development & growth
Rail Damage Susceptibility

- Rate of rail degradation (and life) is not uniform throughout any railway network
  - Governed by a combination of track, traffic and operating characteristics in addition to the metallurgical attributes of the steel
- A network is made up of individual segments with varying track characteristics, degradation rates and expected life
- Selection of rail steel grade to maximise life needs to combine knowledge of the metallurgical attributes of the available rail steels with the conditions of wheel-rail and vehicle-track interfaces
Route Segmentation

• Routes segmented into sub-assets based on curve radius
• Susceptibility to the known degradation mechanisms determined for each segment
• Additional simulation cases undertaken using generic model running over a range of curve radii and cant deficiencies
Modelling Methodology

**Input data:**
- Track geometry data
- Traffic mix
- Wheel-rail profiles
- Vehicle models

**Steps:**
1. Vampire route simulations
2. Wheel-rail contact forces
3. Calculate wear and RCF damage
4. Divide route into track segments based on curvature and cant deficiency
5. Determine mean and max. for each track section

**Charts:**
- Curvature and cant variation along the route
- Wheel-rail contact forces over track distance
- Rail profile and track distance

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Damage Susceptibility Map

Rolling Contact Fatigue

Wear
Damage Susceptibility Map

Rolling Contact Fatigue

Wear
Damage Susceptibility Criteria

Rolling Contact Fatigue

Wear

- Generic - 15 PYS
- Generic - 40 PYS
- MML
- GWML
- TPE
- Wessex

Curve Radius (m)
## Damage Susceptibility Criteria

<table>
<thead>
<tr>
<th>Curve Radius (m)</th>
<th>Damage Susceptibility</th>
<th>Rail Degradation Mechanisms</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RCF</td>
<td>Wear</td>
</tr>
<tr>
<td>&lt; 600</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>600 – 1500</td>
<td>High</td>
<td>Moderate</td>
</tr>
<tr>
<td>1500 – 2500</td>
<td>Moderate</td>
<td>Low</td>
</tr>
<tr>
<td>&gt; 2500</td>
<td>Low</td>
<td>Low</td>
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</table>
## Damage Susceptibility Criteria

<table>
<thead>
<tr>
<th>Route</th>
<th>Curve Radius (m)</th>
<th>Damage Susceptibility</th>
<th>RCF</th>
<th>Wear</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt; 600</td>
<td>600 - 1500</td>
<td>1500 - 2500</td>
<td>&gt; 2500</td>
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<tr>
<td>TPE</td>
<td>No. segments</td>
<td>High</td>
<td>Moderate</td>
<td>Low</td>
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<td></td>
<td>Route miles</td>
<td>0.5</td>
<td>11.7</td>
<td>3.2</td>
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<tr>
<td>Wessex</td>
<td>No. segments</td>
<td>5</td>
<td>32</td>
<td>18</td>
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<td></td>
<td>Route miles</td>
<td>1.1</td>
<td>8.9</td>
<td>6.3</td>
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<tr>
<td>MML</td>
<td>No. segments</td>
<td>0</td>
<td>20</td>
<td>43</td>
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<tr>
<td></td>
<td>Route miles</td>
<td>0.0</td>
<td>7.5</td>
<td>19.4</td>
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<td>GWML</td>
<td>No. segments</td>
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<td>4</td>
<td>10</td>
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<tr>
<td></td>
<td>Route miles</td>
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<td>0.6</td>
<td>4.3</td>
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</table>

<table>
<thead>
<tr>
<th>Routes Total</th>
<th>No. segments</th>
<th>8</th>
<th>94</th>
<th>86</th>
<th>419</th>
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</thead>
<tbody>
<tr>
<td>Total Network</td>
<td>No. segments*</td>
<td>152</td>
<td>1031</td>
<td>862</td>
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<tr>
<td></td>
<td>Track miles</td>
<td>740</td>
<td>3376</td>
<td>2230</td>
<td></td>
</tr>
</tbody>
</table>

### Damage Susceptibility

- **TPE**
  - No. segments: 3
  - Route miles: 0.5
  - Damage: Low
  - Wear: High
  - RCF: 74%

- **Wessex**
  - No. segments: 5
  - Route miles: 1.1
  - Damage: High
  - Wear: Moderate
  - RCF: 87%

- **MML**
  - No. segments: 0
  - Route miles: 0.0
  - Damage: Moderate
  - Wear: Low
  - RCF: 69.3%

- **GWML**
  - No. segments: 0
  - Route miles: 0.0
  - Damage: Low
  - Wear: High
  - RCF: 95.8%

### Total Network

- No. segments: 152 + 1031 + 862 = 2045
- Track miles: 740 + 3376 + 2230 = 6346
# Available Rail Steels

<table>
<thead>
<tr>
<th>Steel Grade Category</th>
<th>Steel Grade</th>
<th>Composition (Liquid), % by mass</th>
<th>TS, min.</th>
<th>Elongation, min.</th>
<th>Hardness Range (HBW)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>C</td>
<td>Si</td>
<td>Mn</td>
<td>P</td>
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<tr>
<td>&quot;Soft&quot;</td>
<td>R200</td>
<td>0.40-0.80</td>
<td>0.15-0.68</td>
<td>0.70-1.20</td>
<td>0.036</td>
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<tr>
<td></td>
<td>R220</td>
<td>0.60-0.80</td>
<td>0.20-0.80</td>
<td>1.00-1.25</td>
<td>0.025</td>
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<tr>
<td>Standard</td>
<td>R260</td>
<td>0.62-0.80</td>
<td>0.15-0.58</td>
<td>0.70-1.20</td>
<td>0.025</td>
</tr>
<tr>
<td></td>
<td>R260Mn</td>
<td>0.65-0.75</td>
<td>0.15-0.60</td>
<td>1.30-1.70</td>
<td>0.025</td>
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<tr>
<td>Intermediate Non Heat Treated</td>
<td>R320Cr</td>
<td>0.60-0.80</td>
<td>0.50-1.10</td>
<td>0.80-1.20</td>
<td>0.02</td>
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<tr>
<td></td>
<td>R350HT</td>
<td>0.72-0.80</td>
<td>0.15-0.58</td>
<td>0.70-1.20</td>
<td>0.02</td>
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<tr>
<td></td>
<td>R350LHT</td>
<td>0.72-0.80</td>
<td>0.15-0.58</td>
<td>0.70-1.20</td>
<td>0.02</td>
</tr>
<tr>
<td>Hardest Heat Treated</td>
<td>R370CrHT</td>
<td>0.70-0.82</td>
<td>0.40-1.00</td>
<td>0.70-1.10</td>
<td>0.02</td>
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<tr>
<td></td>
<td>R400HT</td>
<td>0.90-1.05</td>
<td>0.20-0.60</td>
<td>1.00-1.30</td>
<td>0.02</td>
</tr>
</tbody>
</table>

New Steel Grades not yet with EN Specifications

<table>
<thead>
<tr>
<th>Tata Steel As-Rolled Hypereutectoid Steel</th>
<th>HP335</th>
<th>0.87-0.97</th>
<th>0.75-1.00</th>
<th>0.75-1.00</th>
<th>≤0.02</th>
<th>0.008-0.025</th>
<th>≤0.10</th>
<th>0.09-0.13</th>
<th>≤0.006</th>
<th>1150</th>
<th>7</th>
<th>335 minimum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tata Steel As-Rolled Carbide-Free Bainitic Steel</td>
<td>B320 Contains 0.10-0.20% Mo</td>
<td>0.15-0.25</td>
<td>1.00-1.50</td>
<td>1.40-1.70</td>
<td>-</td>
<td>-</td>
<td>0.30</td>
<td>0.10</td>
<td>-</td>
<td>1100</td>
<td>14</td>
<td>320 to 340</td>
</tr>
<tr>
<td></td>
<td>B360 Contains 0.10-0.20% Mo</td>
<td>0.25-0.35</td>
<td>1.00-1.60</td>
<td>1.40-1.70</td>
<td>-</td>
<td>-</td>
<td>0.30</td>
<td>&lt;0.03</td>
<td>-</td>
<td>1200</td>
<td>13</td>
<td>360 to 390</td>
</tr>
<tr>
<td>Voelstalpine Heat Treated Bainitic Steel</td>
<td>DOBAIN</td>
<td>0.76-0.84</td>
<td>0.20-0.35</td>
<td>0.80-0.90</td>
<td>-</td>
<td>-</td>
<td>0.40</td>
<td>0.55</td>
<td>-</td>
<td>1400</td>
<td>9</td>
<td>&gt;430</td>
</tr>
</tbody>
</table>
### Available Rail Steels – Attributes

<table>
<thead>
<tr>
<th>Steel Grade</th>
<th>Fracture Toughness [MPa m(^{1/2})]</th>
<th>Max. Fatigue crack growth rate, [m/Gc]</th>
<th>Fatigue strength</th>
<th>Residual stress</th>
<th>Hardness [HBW]</th>
<th>Tensile Strength [MPa]</th>
<th>Elongation [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>R200</td>
<td>Min. single value 30</td>
<td>Min. mean value 35</td>
<td>Delta K = 10, [MPa m(^{1/2})]</td>
<td>&lt;250</td>
<td>200-240</td>
<td>680</td>
<td>14</td>
</tr>
<tr>
<td>R220</td>
<td>Min. single value 30</td>
<td>Min. mean value 35</td>
<td>Delta K = 13, [MPa m(^{1/2})]</td>
<td>&lt;250</td>
<td>220-260</td>
<td>770</td>
<td>12</td>
</tr>
<tr>
<td>R260</td>
<td>Min. single value 26</td>
<td>Min. mean value 29</td>
<td>Delta K = 13, [MPa m(^{1/2})]</td>
<td>&lt;250</td>
<td>260-300</td>
<td>880</td>
<td>10</td>
</tr>
<tr>
<td>R260Mn</td>
<td>Min. single value 26</td>
<td>Min. mean value 29</td>
<td>Delta K = 13, [MPa m(^{1/2})]</td>
<td>&lt;250</td>
<td>260-300</td>
<td>880</td>
<td>10</td>
</tr>
<tr>
<td>R320Cr</td>
<td>Min. single value 24</td>
<td>Min. mean value 26</td>
<td>Delta K = 13, [MPa m(^{1/2})]</td>
<td>&lt;250</td>
<td>320-360</td>
<td>1080</td>
<td>9</td>
</tr>
<tr>
<td>R350HT</td>
<td>Min. single value 30</td>
<td>Min. mean value 32</td>
<td>Delta K = 13, [MPa m(^{1/2})]</td>
<td>&lt;250</td>
<td>350-390</td>
<td>1175</td>
<td>9</td>
</tr>
<tr>
<td>R350LHT</td>
<td>Min. single value 26</td>
<td>Min. mean value 29</td>
<td>Delta K = 13, [MPa m(^{1/2})]</td>
<td>&lt;250</td>
<td>350-390</td>
<td>1175</td>
<td>9</td>
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<tr>
<td>R370CrHT</td>
<td>Min. single value 26</td>
<td>Min. mean value 29</td>
<td>Delta K = 13, [MPa m(^{1/2})]</td>
<td>&lt;250</td>
<td>370-410</td>
<td>1280</td>
<td>9</td>
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<tr>
<td>R400HT</td>
<td>Min. single value 26</td>
<td>Min. mean value 29</td>
<td>Delta K = 13, [MPa m(^{1/2})]</td>
<td>&lt;250</td>
<td>400-440</td>
<td>1280</td>
<td>9</td>
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<tr>
<td>HP335</td>
<td>Min. single value 27</td>
<td>Min. mean value 31</td>
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<td>&lt;250</td>
<td>335-380</td>
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<td>7</td>
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<tr>
<td>B320</td>
<td>Min. single value 25</td>
<td>Min. mean value 30</td>
<td>Not specified</td>
<td>&lt;250</td>
<td>320-340</td>
<td>1100</td>
<td>14</td>
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<tr>
<td>B360</td>
<td>Min. single value 25</td>
<td>Min. mean value 30</td>
<td>Not specified</td>
<td>&lt;250</td>
<td>360-390</td>
<td>1200</td>
<td>13</td>
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<tr>
<td>DOBAIN380</td>
<td>Min. single value 25</td>
<td>Min. mean value 30</td>
<td>Not specified</td>
<td>&lt;250</td>
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<td>10</td>
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<tr>
<td>DOBAIN430</td>
<td>Min. single value 25</td>
<td>Min. mean value 30</td>
<td>Not specified</td>
<td>&lt;250</td>
<td>&gt;430</td>
<td>1400</td>
<td>9</td>
</tr>
</tbody>
</table>

- Key properties specified in EN13674-1: 2011
- How are they related to in-service performance
- How should they be used for the selection of rail grades
Virtually all rail steels in use today have a pearlitic microstructure comprising a lamellar of “soft ferrite” and “hard cementite”

Pearlite is a 3-dimensional entity and the wheel encounters both the ferrite & cementite laths at a wide range of orientations

How does this composite microstructure react to ratchetting?
Comparing Wear Resistance

- Hardness is a very good indication of resistance to wear for both as-rolled and heat treated grades in EN.
- Ultra high carbon steels provide very good resistance to wear - both as-rolled & heat treated conditions.
- Optimised HP335 composition has wear resistance equivalent to much harder grades – What microstructural features impart this attribute?
- Can laboratory twin disc test results represent side wear?
Resistance to RCF also increases linearly with hardness for the full range of steels in EN 13674-1:2011.

Resistance to RCF of UHC steels optimally alloyed with Si, V, N (HP335) also increases linearly with hardness but is displaced to great resistance than other pearlitic steels within EN.

Hypothesis exists for this improved performance but more systematic investigation needed for validation.
Comparing Resistance to Plastic Deformation

- 0.2% PS shows a linear dependence on hardness
- Is resistance to plastic deformation just governed by 0.2% PS?
- Samples of low rail of different grades need to be analysed to establish material flow patterns
Economic Modelling

- Aims to quantify the costs and benefits from using new rail steel grades
- Workshop held with NR to help understand and quantify costs and benefits of using premium rail steel grades
  - Additional benefits not captured in current cost models (e.g. VTISM) identified (e.g. availability, reliability, safety, environmental)
- Initial VTISM modelling undertaken (on 4 selected routes) to identify potential costs savings from deployment of premium rail on entire routes
  - Further benefits may be obtained from optimum deployment of steel in correct locations
- Further work on-going to improve the cost benefit analysis in collaboration with NR
RCF and Wear Costs

- RCF and wear damage rates reduced based on observations from previous HP335 trial sites
- Grinding interval for all track sections = 45MGT
  - Lower damage depth ≈ less metal removal required during grinding

Total costs per route mile

% cost savings from premium rail
Discussion and Recommendations

• A number of GB routes segmented based on track characteristics

• Susceptibility of these segments to RCF and wear damage quantified to support selection of optimum rail steel grade to maximise life

• Experimental data for a range of steel grades have been compared to quantify resistance to key damage mechanisms
  – Further controlled testing and microstructural assessment of the full matrix of rail steels is on-going – a singularly unique database for the industry

• Research has helped to quantify the benefits of current NR strategy for rail steel grade selection
To reduce whole life costs, **premium rail steels** should be considered for use in critical curves where RCF or wear causes the premature replacement of the rail.

- **Low** RCF and **Low** wear are used in moderate curves to preserve the ground rail profile and increase the resistance to RCF.
- **High** RCF and **Low** wear are used in tight radius curves with a high wear rate.

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**RCF Damage Index/Vehicle**

- **Low** RCF
- **High** RCF
- **Moderate** RCF

**Wear Rate (mm³/Vehicle)**

- **Low** wear
- **High** wear
- **Moderate** wear

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Institute of Railway Research
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  - University of Cambridge
  - University of Leeds
  - Cranfield University