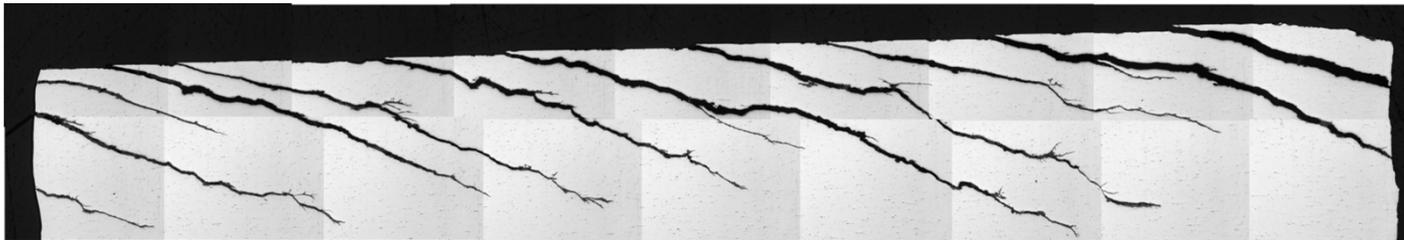


Modeling of RCF

Metallurgy, Microstructure, Mechanical
Properties & Crack Modeling



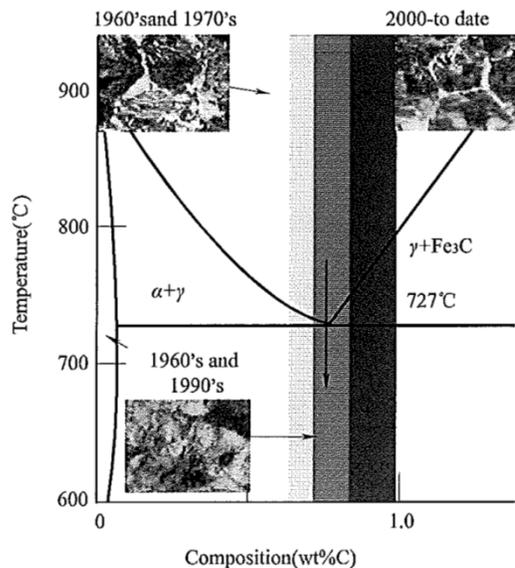
RCF Modeling – Objectives

- **Acquire RCF data from in-service rails through ‘RCF Quantitative Assessment’ project**
 - Variety of rail types, curves, MGT life-cycles, etc.
 - Library of crack path morphologies
 - Crack: location, angle, length, depth, branching, density
 - Crack path: trans vs. intergranular
 - Grain: size, morphology
 - Mechanical assessment of rail steel properties
 - Uniaxial tensile test (YS, UTS, El.)
 - Fracture toughness test (K_{Ic})
 - Nano-hardness testing: mech. prop. of ‘small volumes’ (i.e. phases)
- **Mathematical modeling of RCF**
 - Element & mesh selection to reflect rail steel microstructure
 - Accurate phase morphologies and phase micro-mechanical properties
 - Adaptive meshing techniques
 - Appropriate grain boundary selection
 - Modeled crack path(s) to propagate as in-service RCF cracks

RCF Modeling – Metallurgical Considerations

Fe-C phase diagram

- Increasing the carbon content in rail increases rail hardness and improves wear resistance
 - Microstructure needs to be fully-pearlitic to achieve best mechanical and wear performance
 - Variable steel microstructures
 - **Hypo**euctectoid (**below** eutectoid composition)
 - Eutectoid (at eutectoid composition)
 - **Hyper**euctectoid (**above** eutectoid composition)



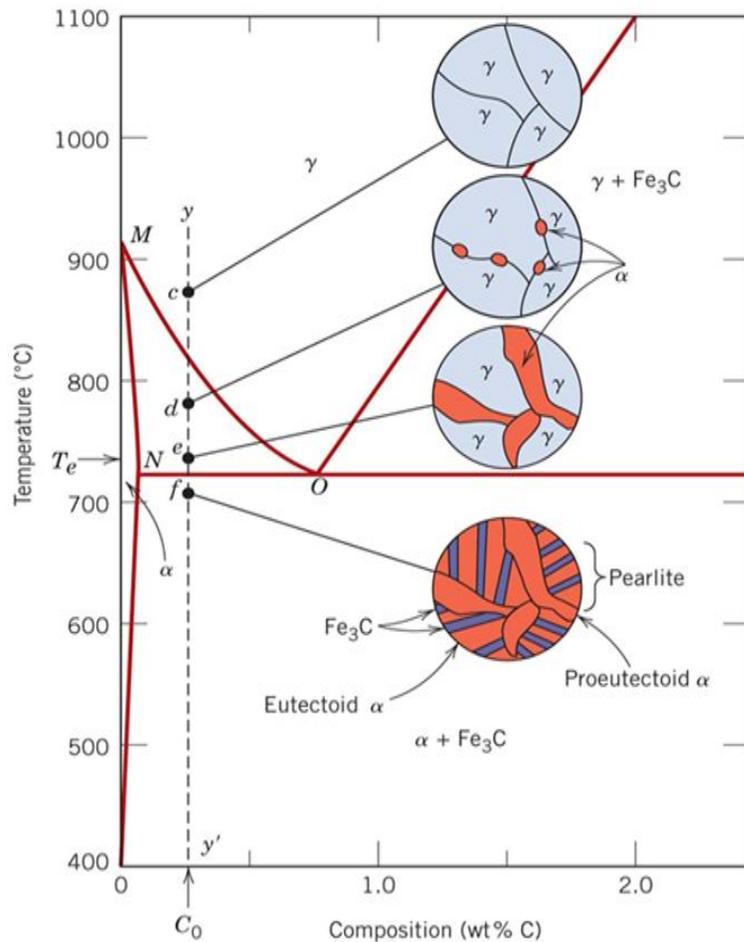
Composition (wt% C)			
Decad (generation)	C Content (wt%)	Average Hardness (HB)	Failure Mode
1960's	0.7	248	RCF and Wear Present
19800's	0.8	360	Mostly Wear Present
2000's	1.0	400	Mostly RCF Present

Figure 1 Evolution of the rail steel metallurgies, hardness levels, and failure modes in the past 50 years

Robles Hernandez F.C., Ordonez Olivares R., Szablewski D., Garcia C.I., DeArdo A., Kalay S.

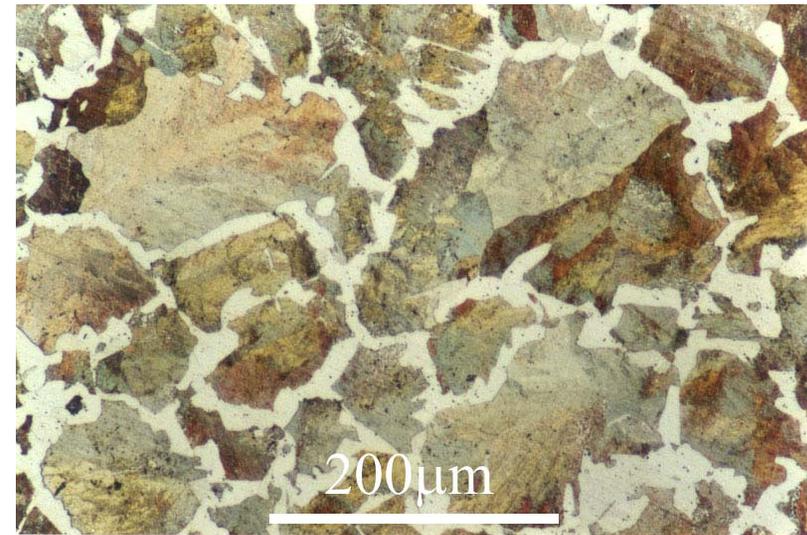
'Development of the Next Generation Rail Steels for Heavy Axle Loads'

RCF Modeling – Metallurgical Considerations



W.D. Callister Jr., D.G. Rethwisch
'Material Science and Engineering an Introduction'

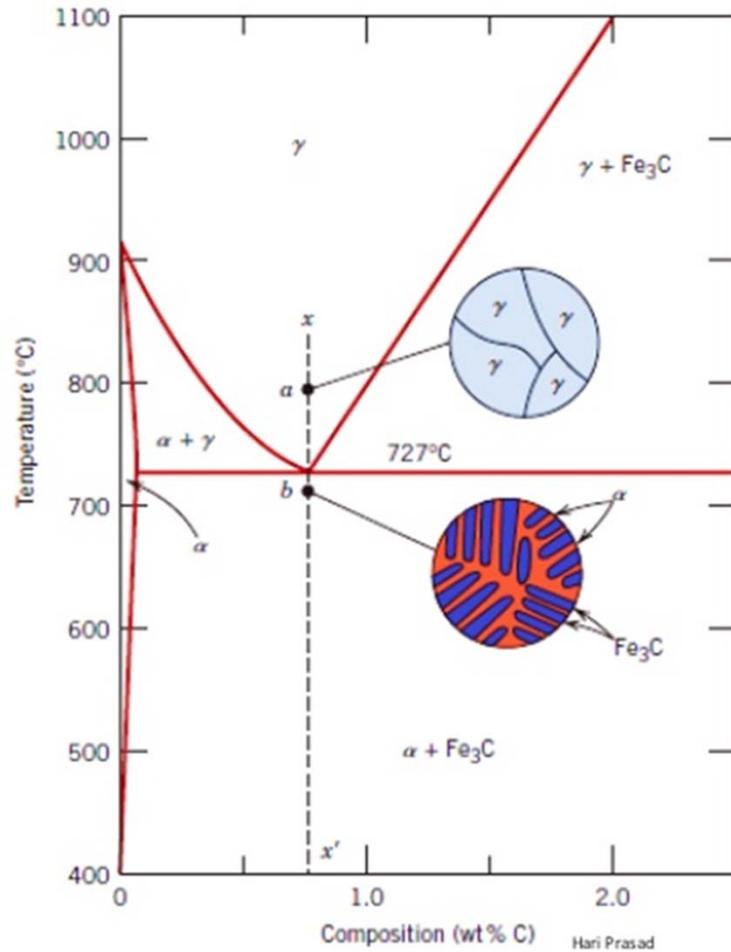
Hypoeutectoid Carbon steel
($<0.77\text{C}$), normalized, nital etched



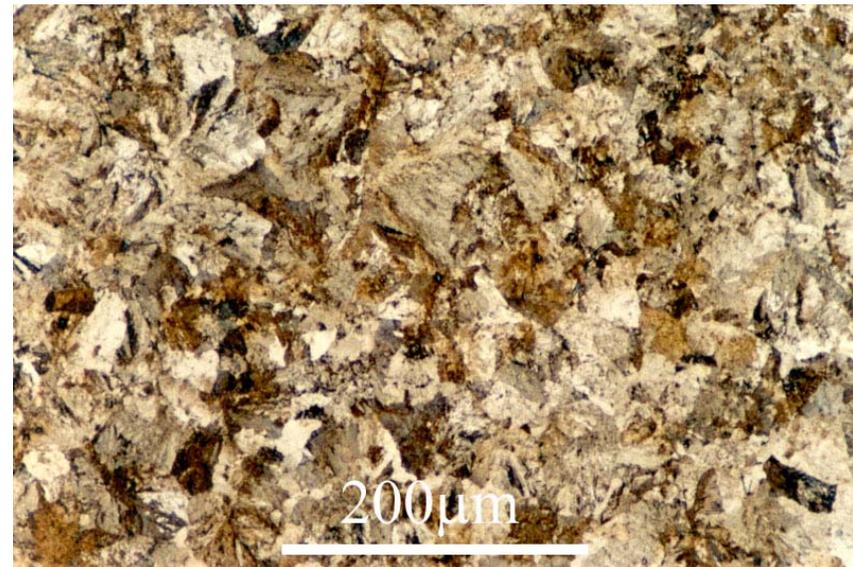
Microstructure:
Pearlite + Pro-eutectoid Ferrite (α)
 $\alpha + Fe_3C$

Micrograph courtesy of
https://www.doitpoms.ac.uk/miclib/micrograph_record.php?id=230

RCF Modeling – Metallurgical Considerations



Eutectoid Carbon steel
(~0.77C), normalized, nital etched

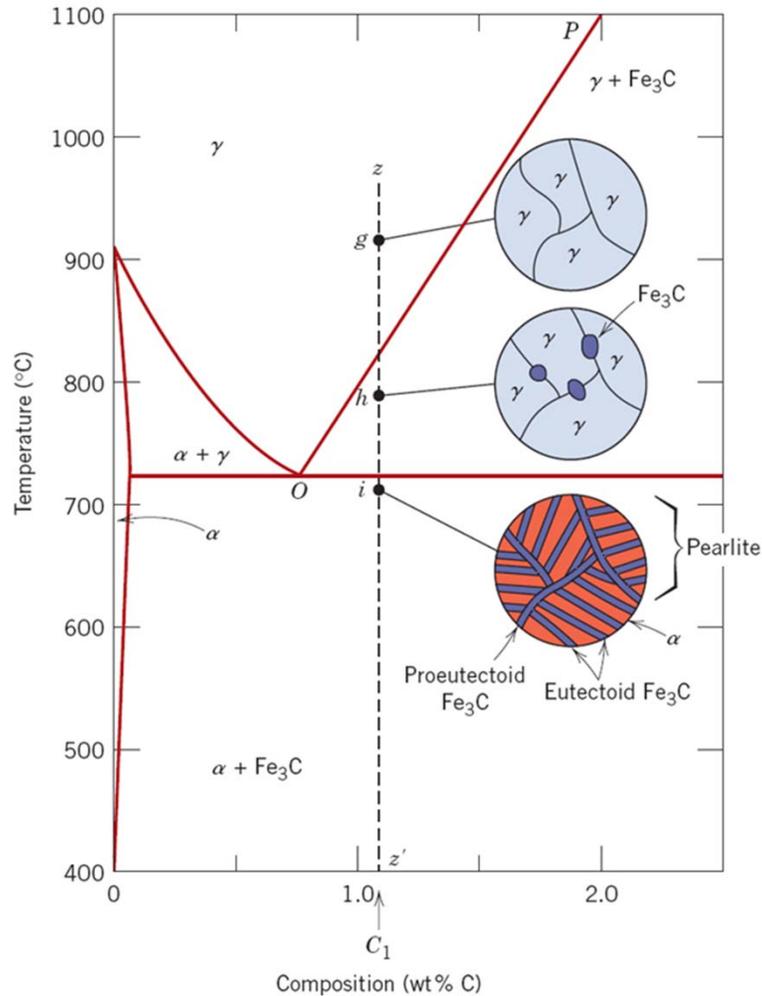


Microstructure:
100% Pearlite
α + Fe₃C

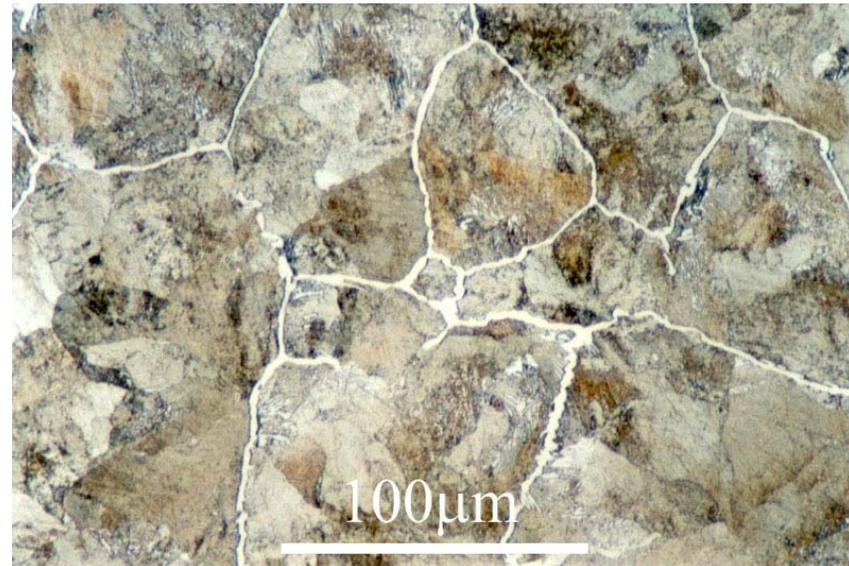
W.D. Callister Jr., D.G. Rethwisch
'Material Science and Engineering an Introduction'

Micrograph courtesy of
<https://www.doitpoms.ac.uk/miclib/micrograph.php?id=264>

RCF Modeling – Metallurgical Considerations



Hypereutectoid Carbon steel
($>0.77\text{C}$), normalized, nital etched

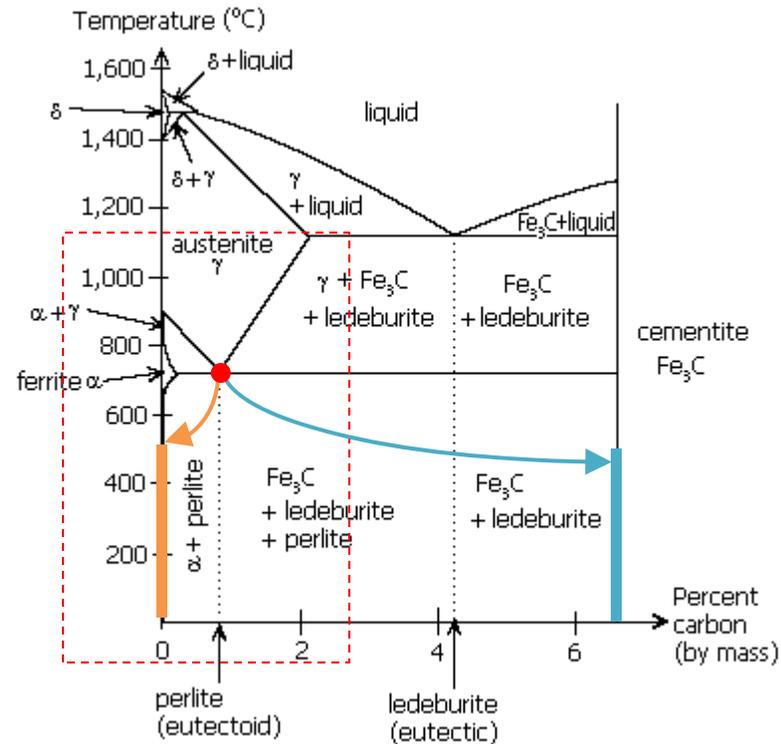


Microstructure:
 Pearlite + Pro-eutectoid Cementite (Fe_3C)
 $\alpha + \text{Fe}_3\text{C}$

W.D. Callister Jr., D.G. Rethwisch
'Material Science and Engineering an Introduction'

Micrograph courtesy of
<https://www.doitpoms.ac.uk/miclib/micrograph.php?id=250>

RCF Modeling – Metallurgical Considerations



0.022% C solubility in α

Ex. Ferritic Stainless Steels

YS: 25-64 ksi (at T_{RM})

UTS: 55-80 ksi (at T_{RM})

El. up to 30% (at T_{RM})

(exceptional formability)

ASM International, Metals Handbook
J.R. Davis, Editor

6.67% C solubility in Fe_3C

A study of bulk cementite

YS: approx. 1700 ksi (at T_{RM})

UTS: approx. 1700 ksi (at T_{RM})

El. <1% (at T_{RM}), El. $\uparrow\uparrow$ as $T\uparrow$

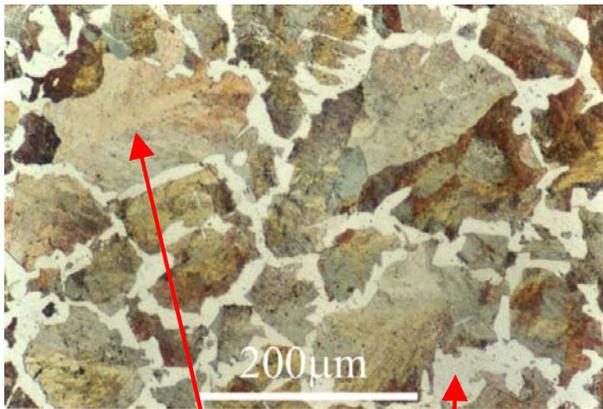
(extremely brittle at T_{RM})

Umemoto M., Todaka Y., Tsuchiya K.,
Mechanical Properties of Cementite and Fabrication of Artificial Pearlite

RCF Modeling – Metallurgical Considerations

Hardness of Microstructural Features

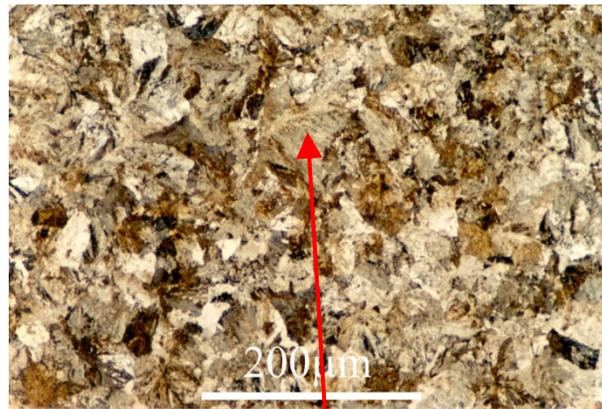
Hypoeutectoid Steel



Pearlitic Grain
(300-400 HB)

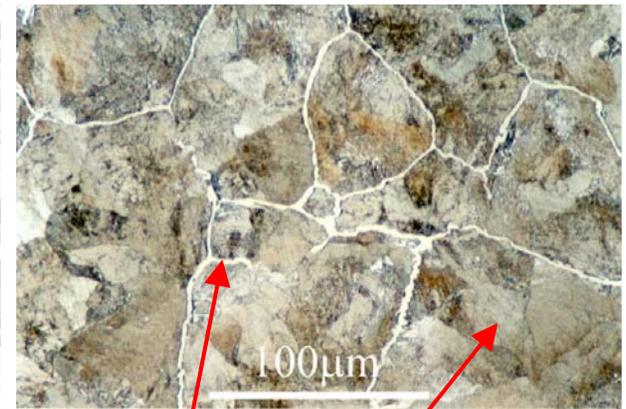
Ferrite
Approx. 80 HB

Eutectoid Steel



Pearlitic Grain
(300-400 HB)

Hypereutectoid Steel



Pearlitic Grain
(300-400 HB)

Cementite
Approx. 800 HB

Pearlite (eutectoid composition)

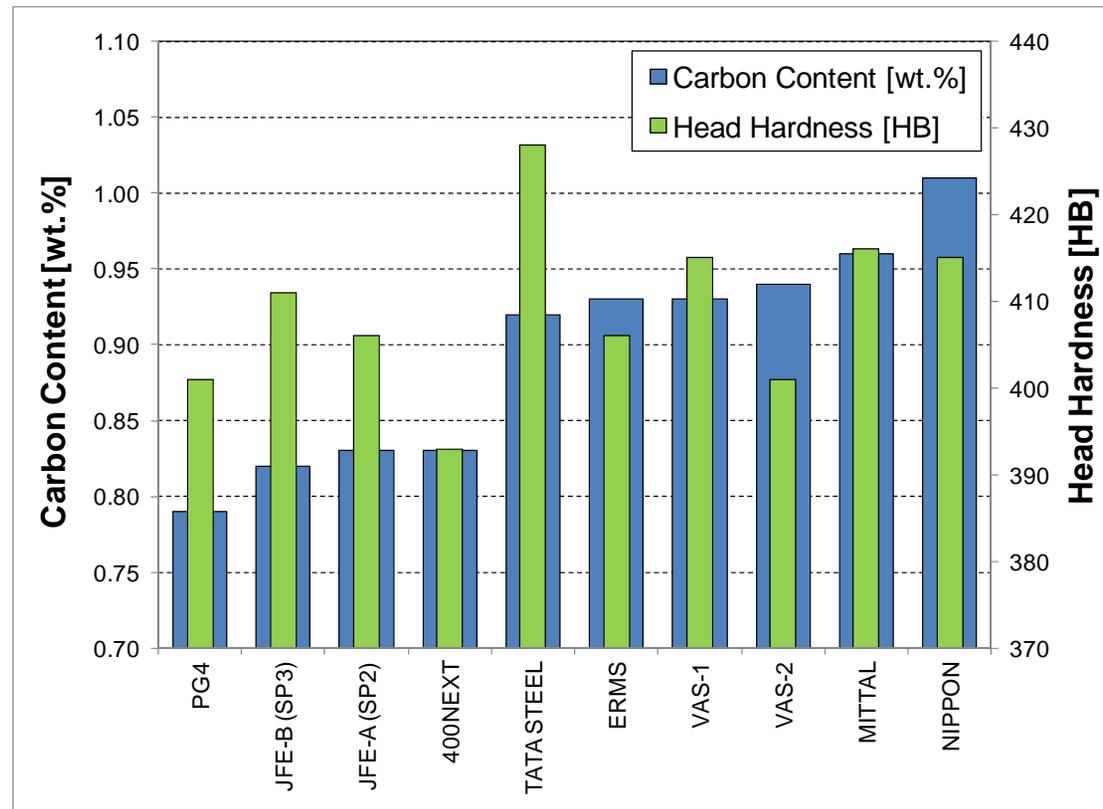
Lamellar spacing ↓ HB ↑

Lamellar spacing ↑ HB ↓

RCF Modeling – Metallurgical Considerations

Influence of rail processing during production

- Poor relationship between carbon content and hardness
- Rail mechanical properties are a combination of chemistry and thermomechanical processing



Szablewski D., Gutscher D., LoPresti J., Kalay S.,
Effect of Heavy Axle Load on Super Premium Rail Steels and Rail Joining Methods
10th IHHA Conf., 2013

RCF Modeling – Metallurgical Considerations

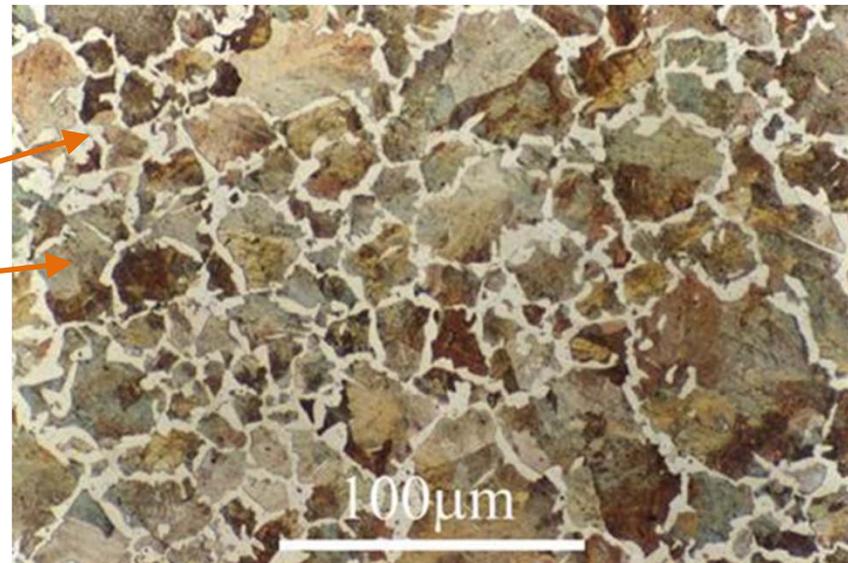
Solid State Diffusion (SSD) of Carbon

- Decarburization is only an issue with new rails
 - Fick's First Law (i.e. Carbon migration down a concentration gradient)
 - Takes place at rail rolling surface
 - Temperature activated process (during rail production)
- Results in Carbon-poor (i.e. decarburized) phase (ferrite) at the grain boundaries

Decarburized Layer (ferrite)

Pearlitic Grain

**Typical Decarburized Pearlitic
Rail Microstructure**

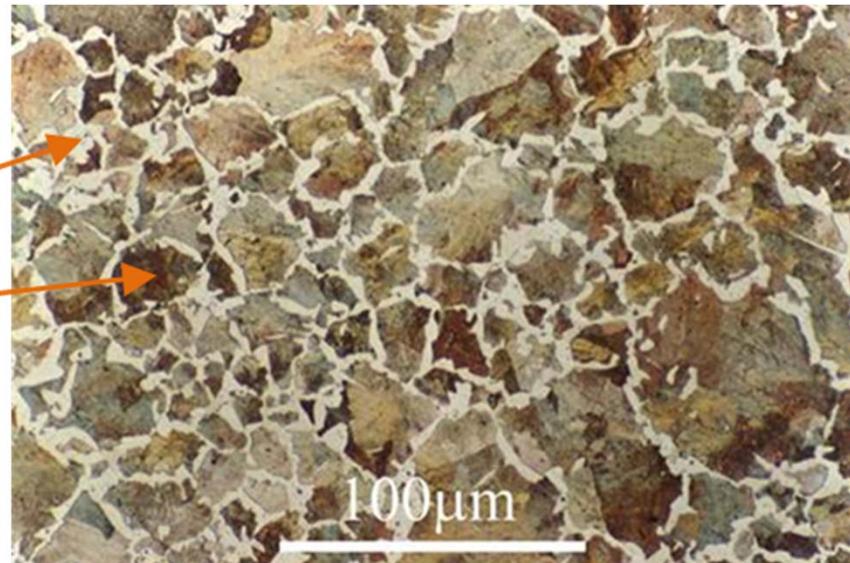


RCF Modeling – Metallurgical Considerations

- Decarburized rail microstructure is less uniform (less homogenous) below W/R contact zone
- It is softer than surrounding pearlite matrix structure:
 - Easier to plastically deform the decarburized layer
 - RCF cracks form more easily in the decarburized zone

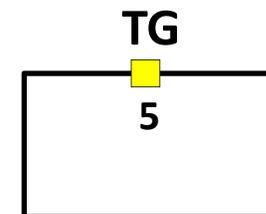
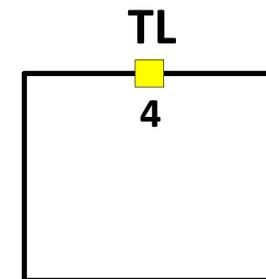
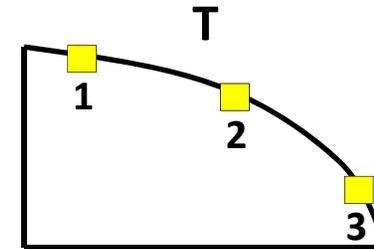
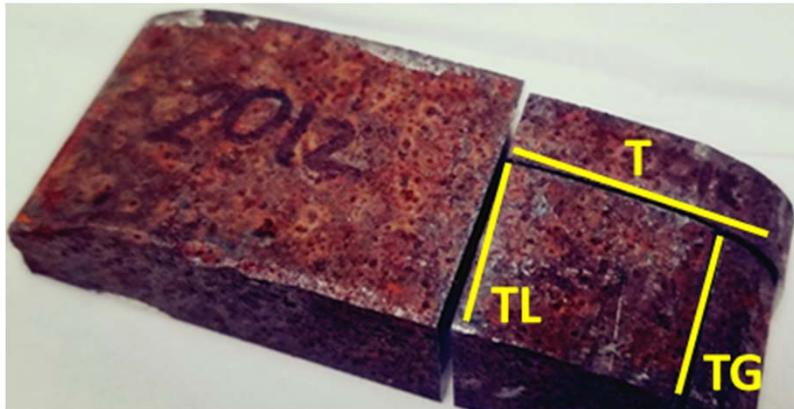
Decarburized Layer (ferrite)
Approx. 80HB

Pearlitic Grain (**300-400HB**)



RCF Modeling – Metallurgical Considerations

Railhead of a typical intermediate rail type



T – Transverse section

TL – Transverse Longitudinal section

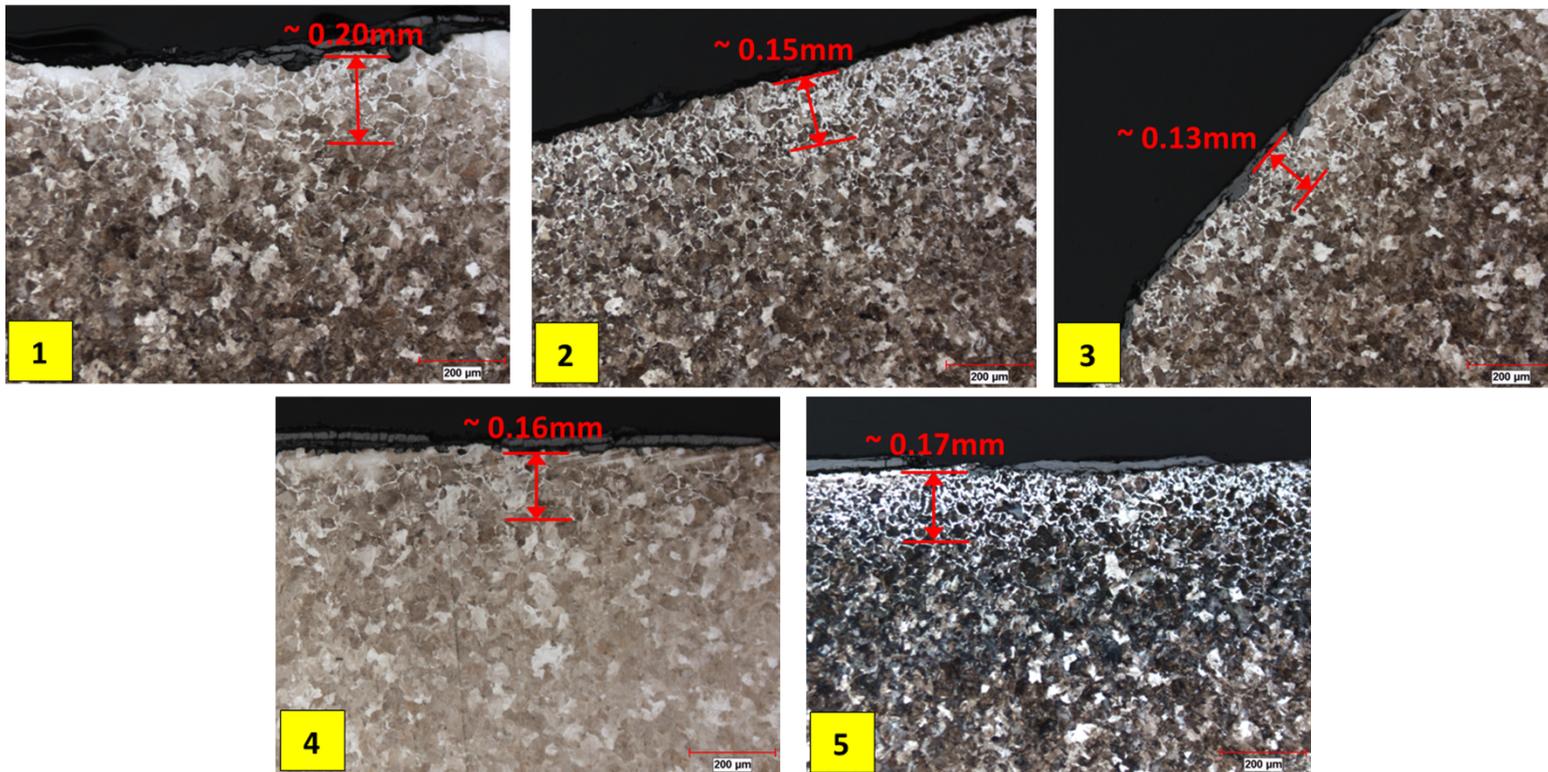
TG – Transverse Gage section

RCF Modeling – Metallurgical Considerations

5 microstructure locations:

Decarburized layer present in all 3 cross-sections

Average decarburized layer thickness: **0.16 ± 0.03 mm** (~0.006 in)

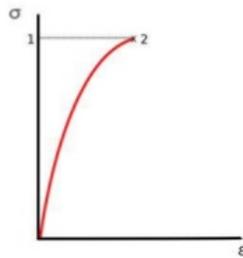


RCF Modeling – Mechanical Considerations

- Brittle vs. Ductile failure mode

Brittle Fracture

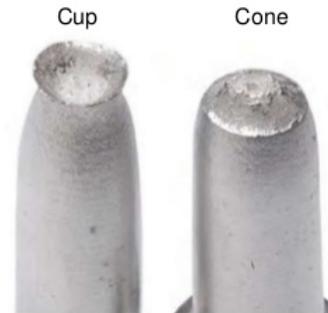
- Brittle fracture takes place without any appreciable deformation, & by rapid crack propagation. The direction of crack motion is very nearly perpendicular to the direction of the applied tensile stress & yields a relatively flat fracture surface
- When gradual tensile load is applied on material in tensile test, at the end of elastic limit, without any prior indication material breaks. This type of fracture is called as Brittle Fracture



(b) Brittle fracture in a mild steel.

Cup & Cone Fracture

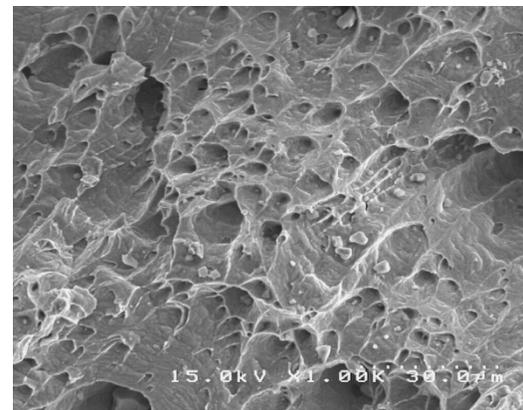
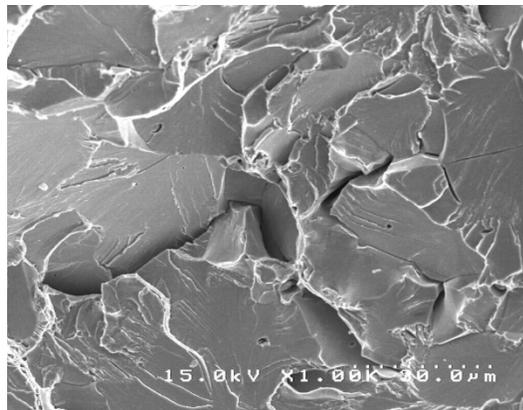
- Finally, fracture ensues by the rapid propagation of a crack around the outer perimeter of the neck by shear deformation at an angle of about 45 degree with the tensile axis this is the angle at which the shear stress is a maximum.
- Sometimes a fracture having this characteristic surface contour is termed a **cup-and-cone fracture** because one of the mating surfaces is in the form of a cup, the other like a cone.
- In this type of fractured specimen the central interior region of the surface has an irregular & fibrous appearance, which is indicative of plastic deformation.



(a) cup-and-cone fracture

Cleavage Failure

- No warning sign
- Fast crack
- No deformation
- Flat fracture surface



Ductile Failure

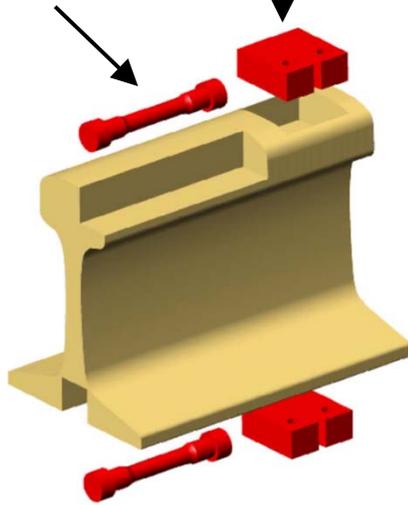
- Warning signs
- Slow crack
- Deformation
- Dimple (cup & cone) surface

Figure courtesy of <https://www.slideshare.net/shaikhsaif/failure-mechanism-in-ductile-brittle-material>

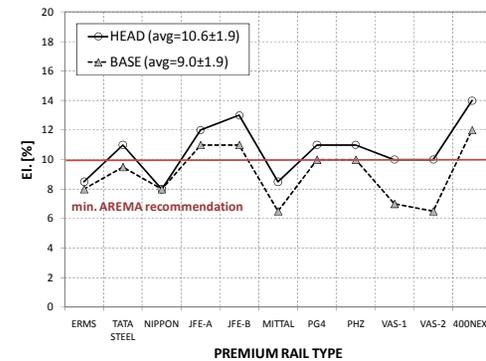
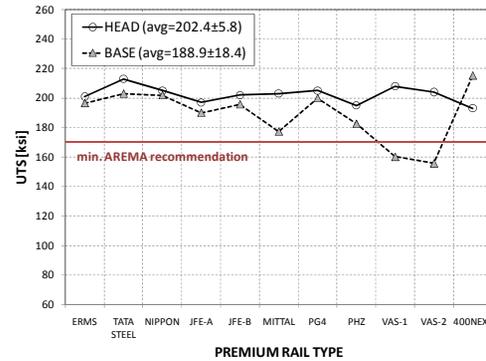
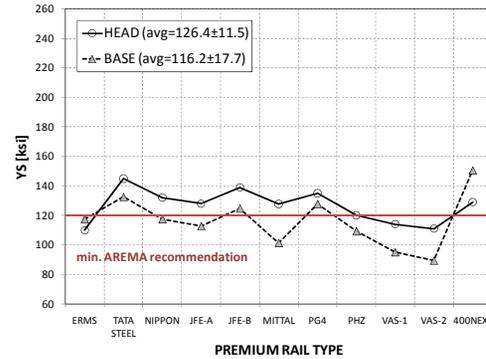
RCF Modeling – Mechanical Considerations

Tensile
(YS, UTS, El.)

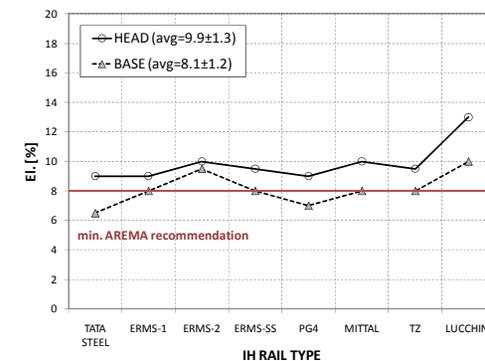
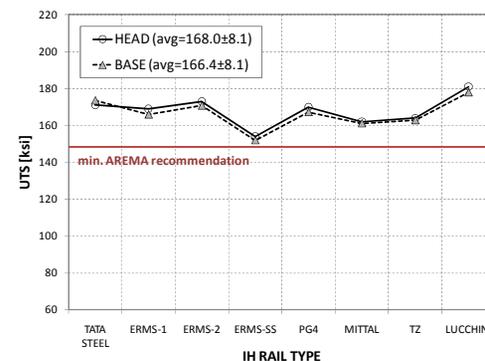
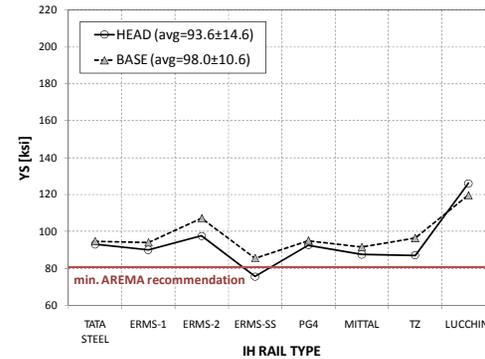
K_{IC}



Premium Rails



IH Rails



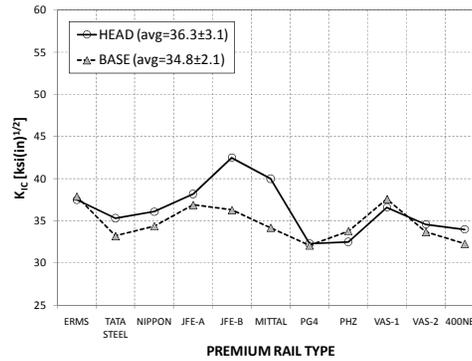
Szablewski D., Kalay S., LoPresti J.

'Development and Evaluation of High Performance Rail Steels for Heavy Haul Operations'

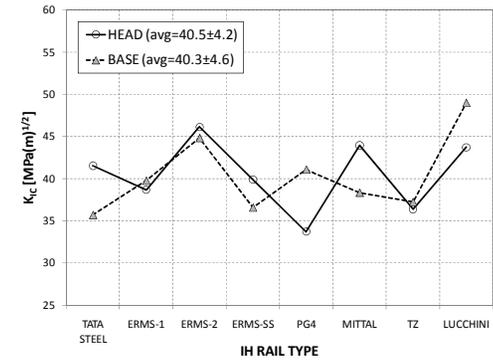
RCF Modeling – Mechanical Considerations



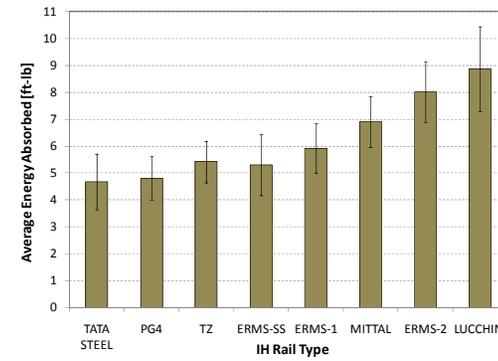
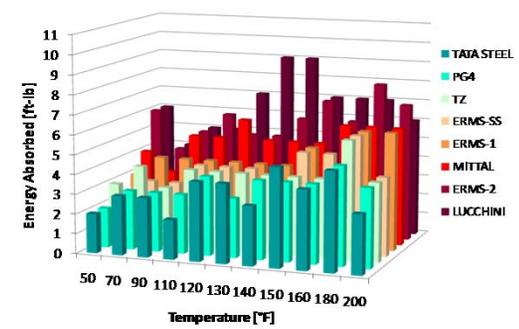
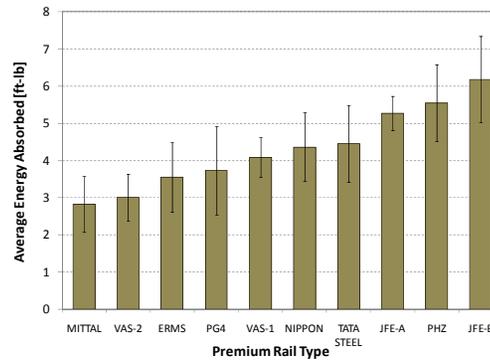
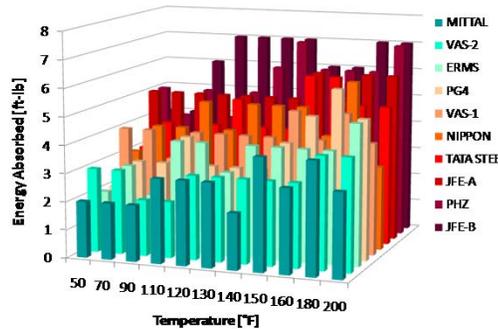
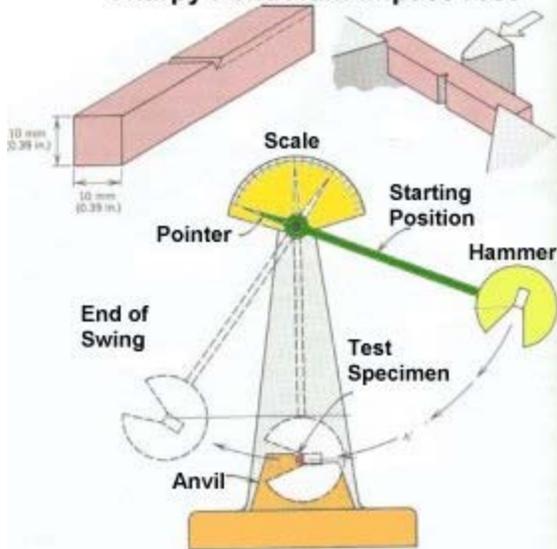
Premium Rails



IH Rails



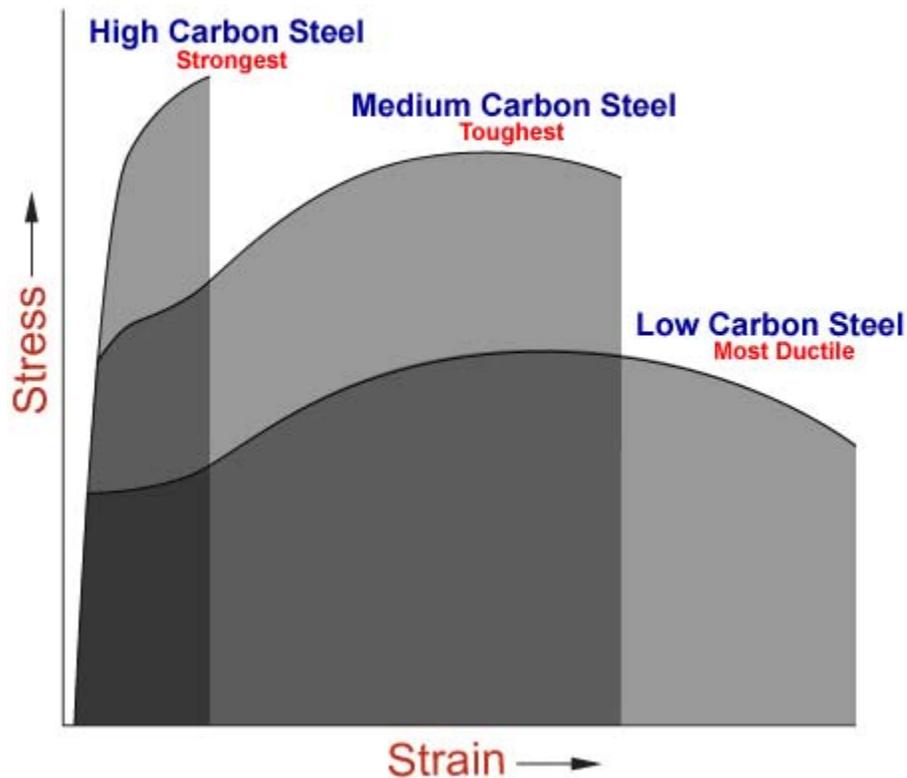
Charpy Pendulum Impact Test



Szablewski D., Kalay S., LoPresti J.
 'Development and Evaluation of High Performance Rail Steels for Heavy Haul Operations'

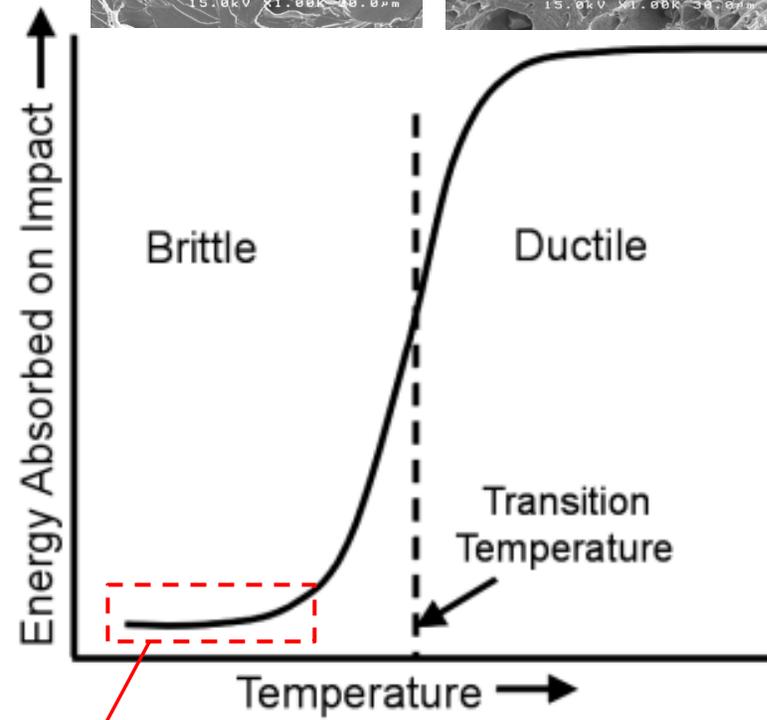
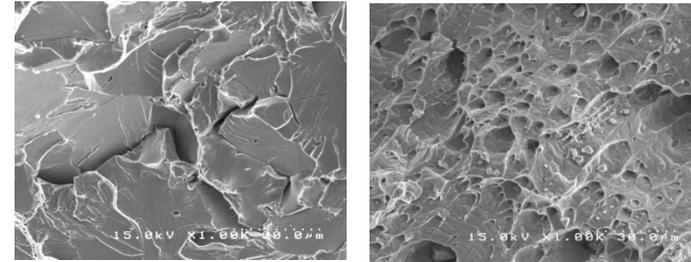
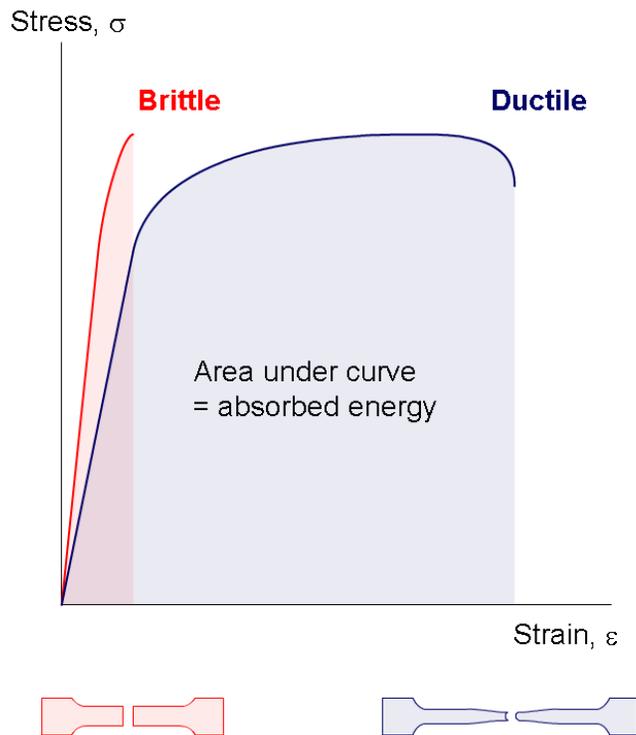
RCF Modeling – Mechanical Considerations

- Toughness: ability of the metal to deform plastically to absorb energy before critical failure
- Toughness = area under the stress/strain curve
 - Good ductility does not necessarily mean good toughness
 - Key is a good combination of strength (YS, UTS) and ductility (El.)



RCF Modeling – Mechanical Considerations

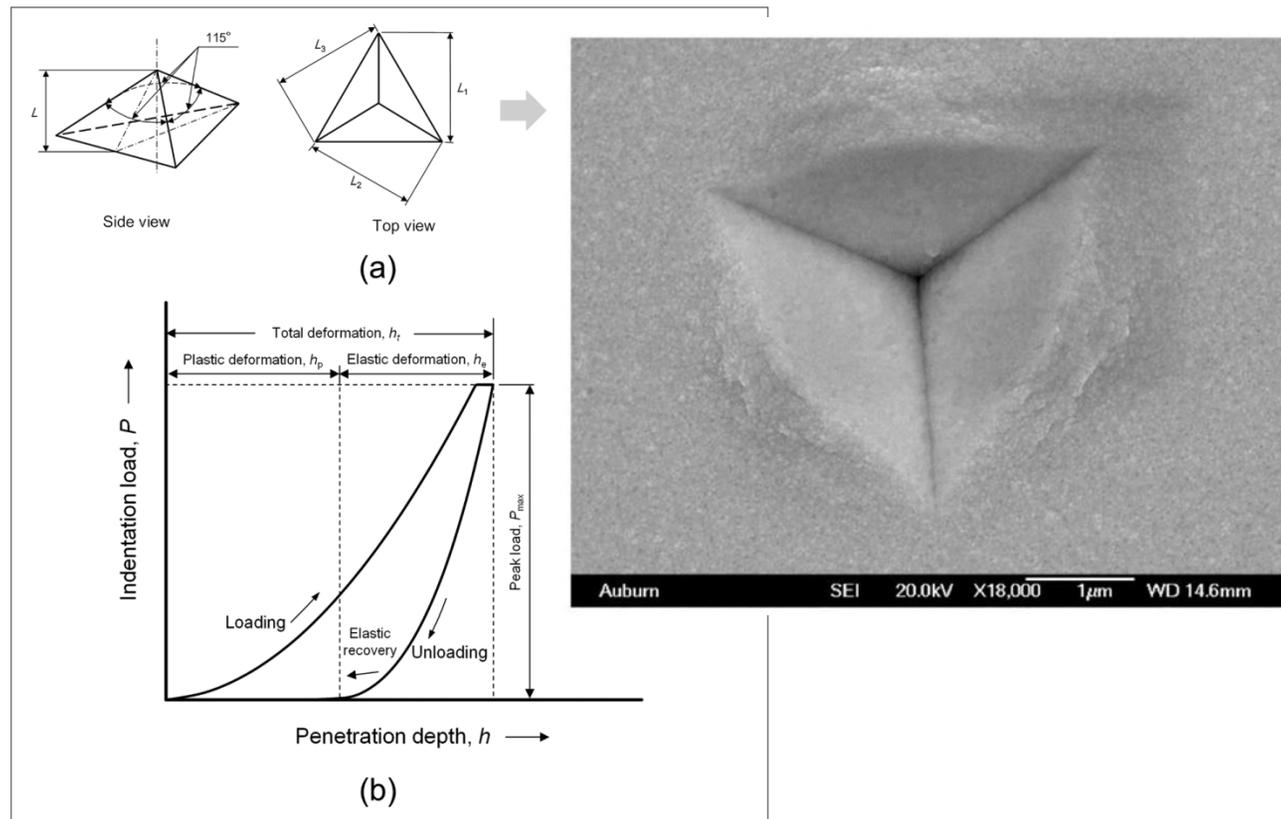
- Brittle to Ductile transition



Most Rails Today

RCF Modeling – Mechanical Considerations

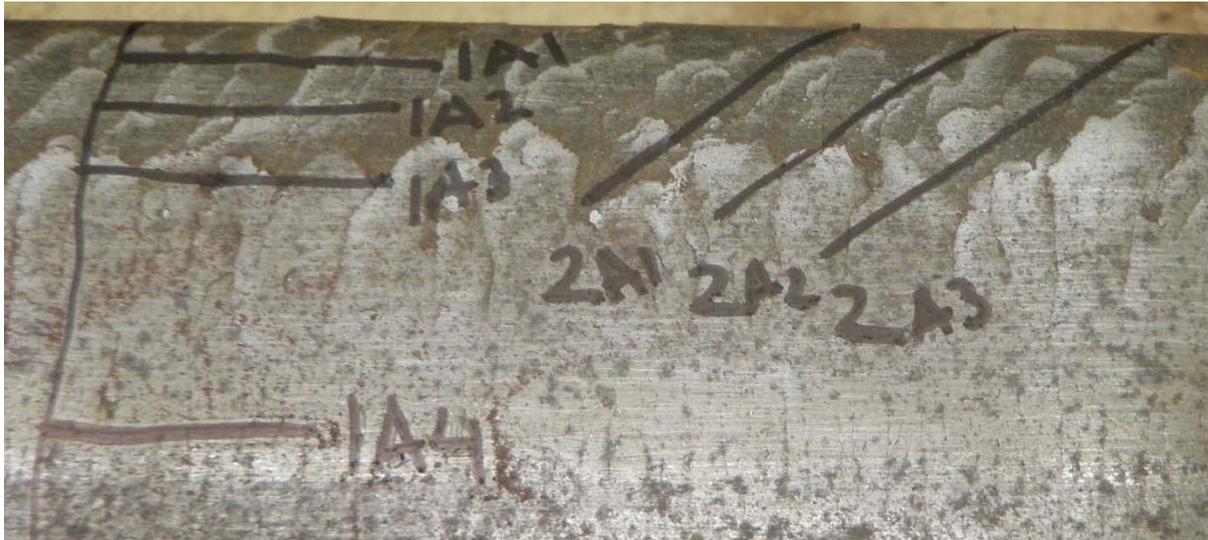
- We need similar type of comprehensive characterization of phases in the microstructure
 - Dynamic micro-indentation: investigate mechanical properties of small volumes of materials



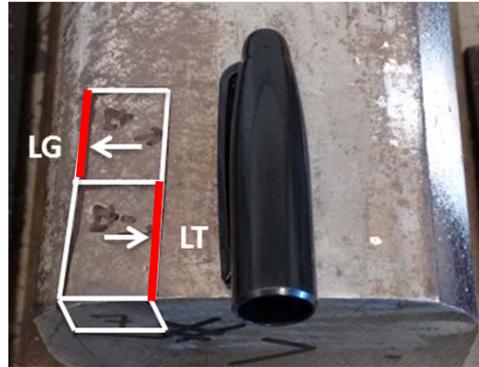
Hirayama S., Iwai H., Tanimoto Y.,

'Mechanical evaluation of five flowable resin composites by the dynamic micro-indentation method'

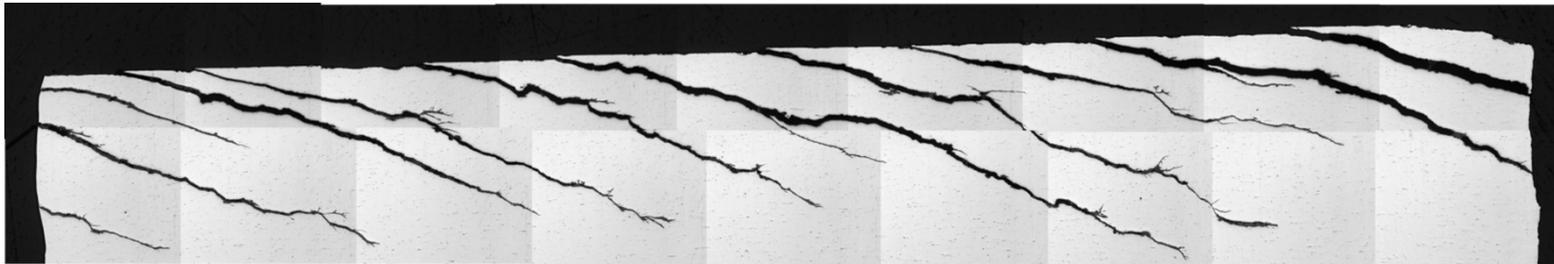
RCF Modeling – Crack Metallography



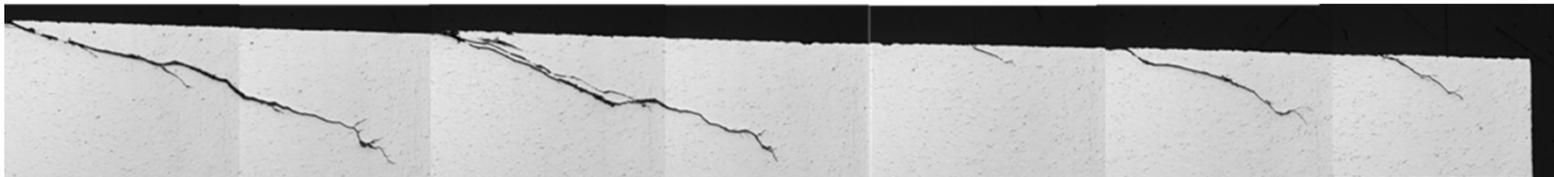
RCF Modeling – Crack Metallography



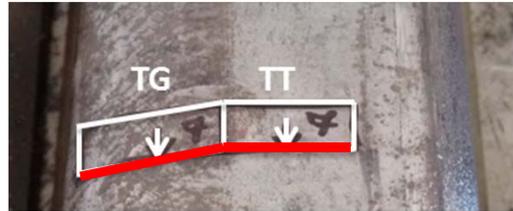
LT



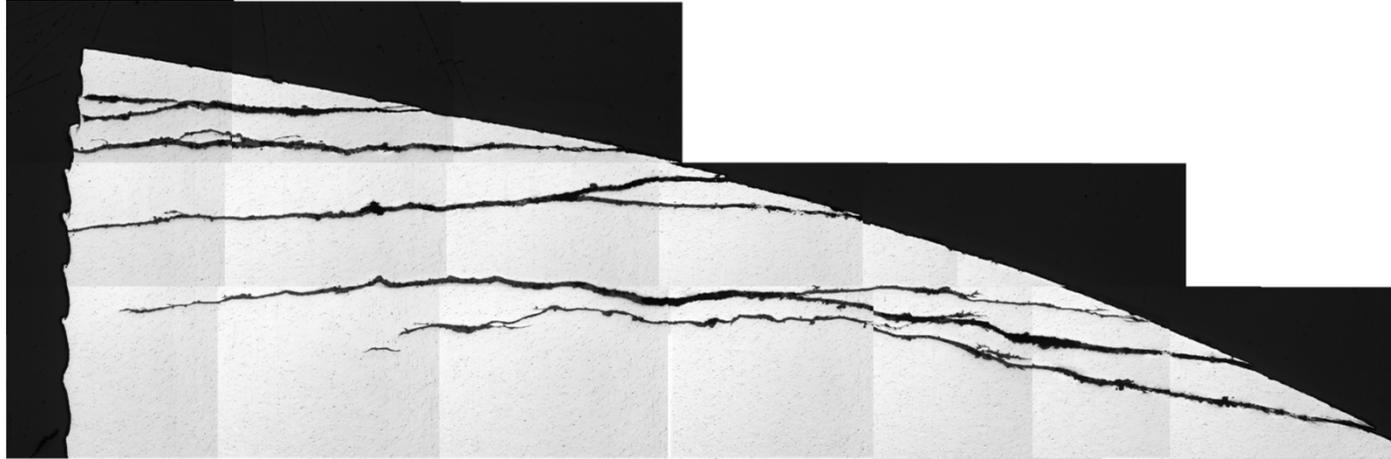
LG



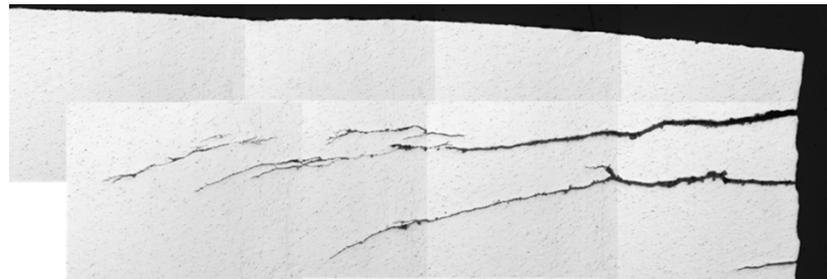
RCF Modeling – Crack Metallography



TG

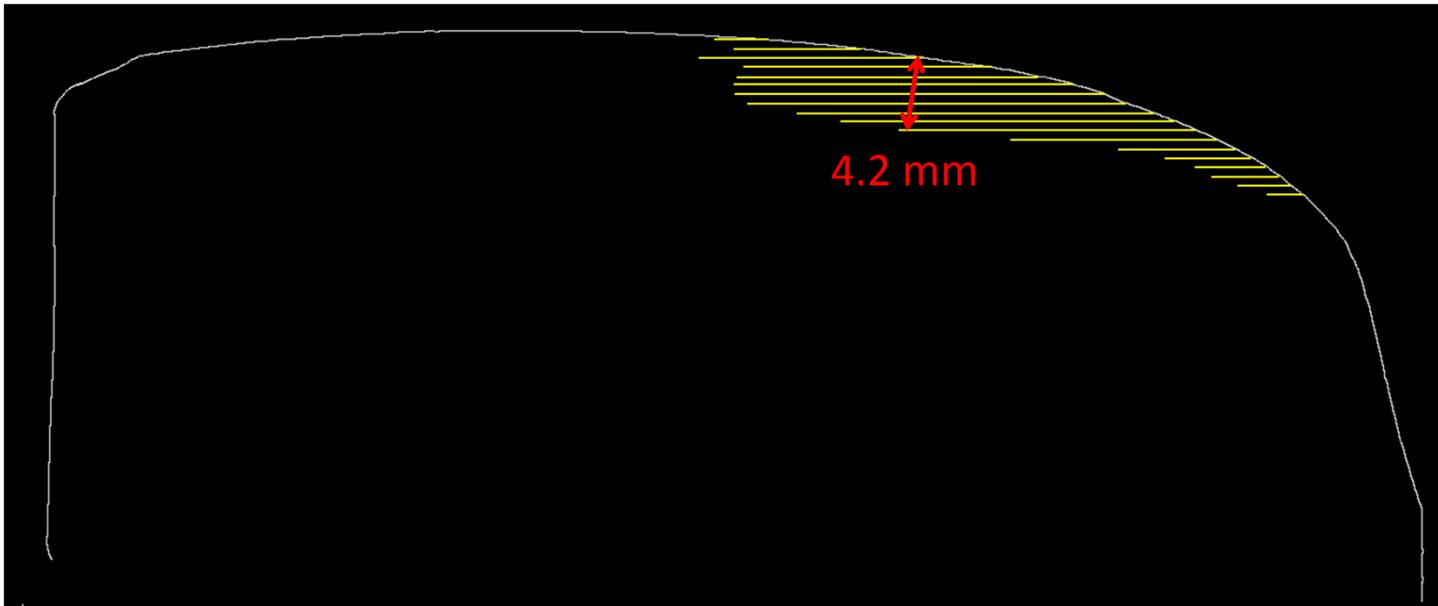


TT



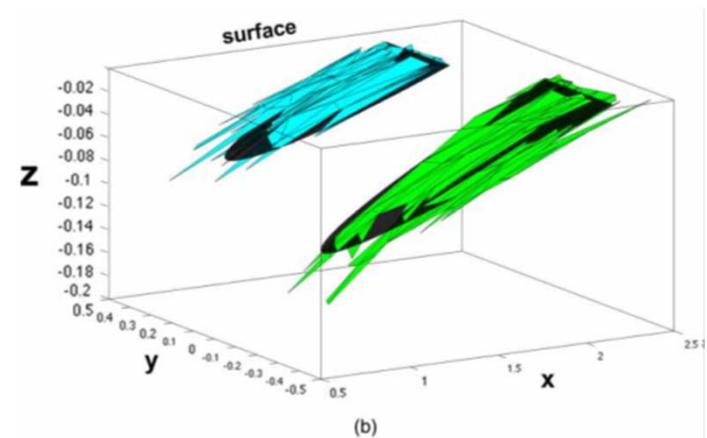
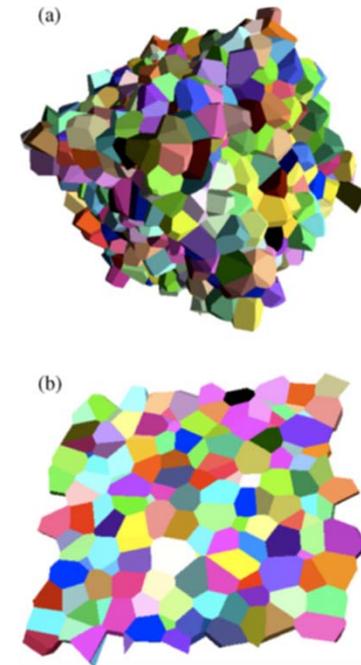
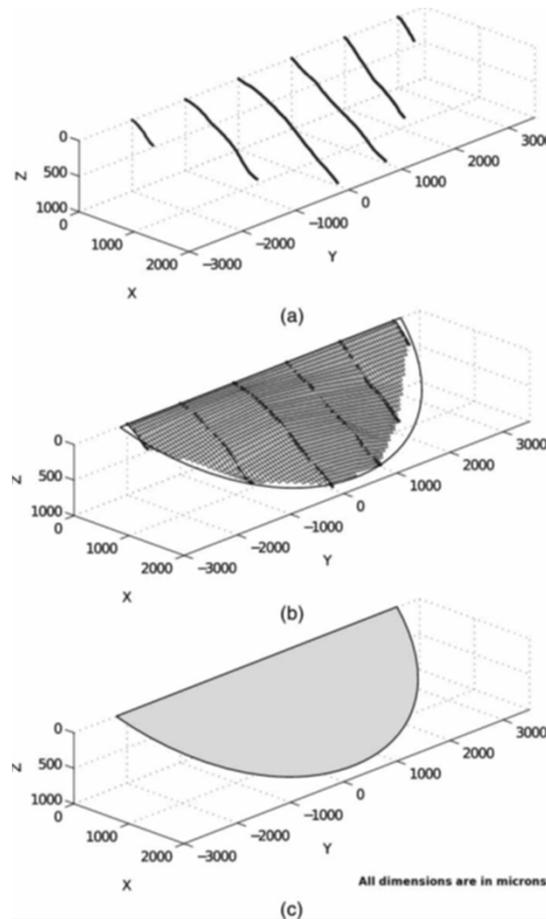
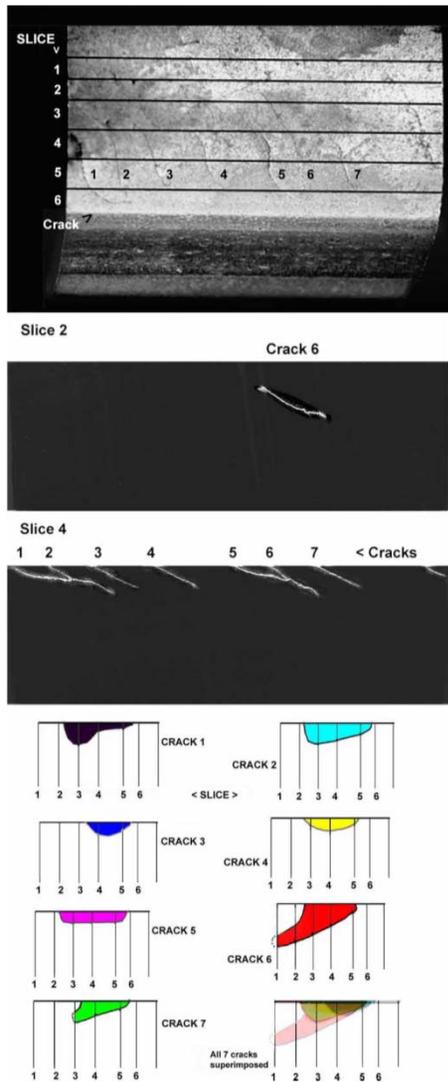
RCF Modeling – Crack Metallography

End view of a crack plane



Rail from BNSF line

RCF Modeling – Crack Metallography / 3D Representation



J.E. Garnham et al., 'Visualization and modelling to understand rail rolling contact fatigue cracks in three dimensions', Proc. IMechE Vol. 225 Part F: J. Rail and Rapid Transit

RCF Modeling – Crack Metallography

- Morphology of the crack path
 - Transgranular vs. Intergranular fracture

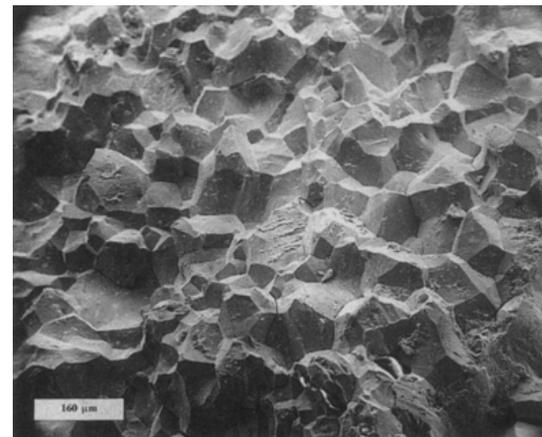
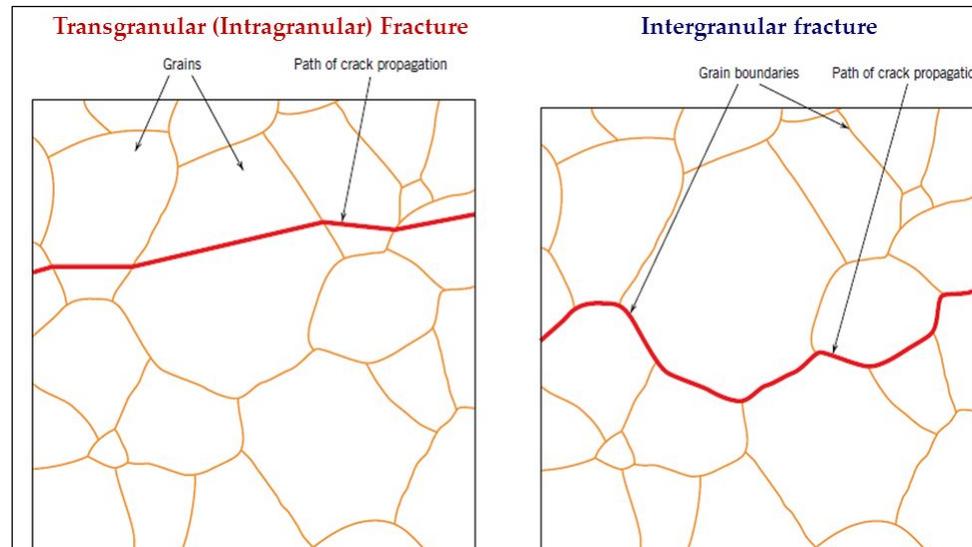


Figure courtesy of
<https://www.slideshare.net/HarshalPatil7/introduction-to-fracture-mechanics>

RCF Modeling – FE model

- Crack propagation in a cohesive material
- **Adaptive meshing**
 - Mesh refinement at crack tip
 - Microstructural considerations: grain size, grain boundary phase, inclusions

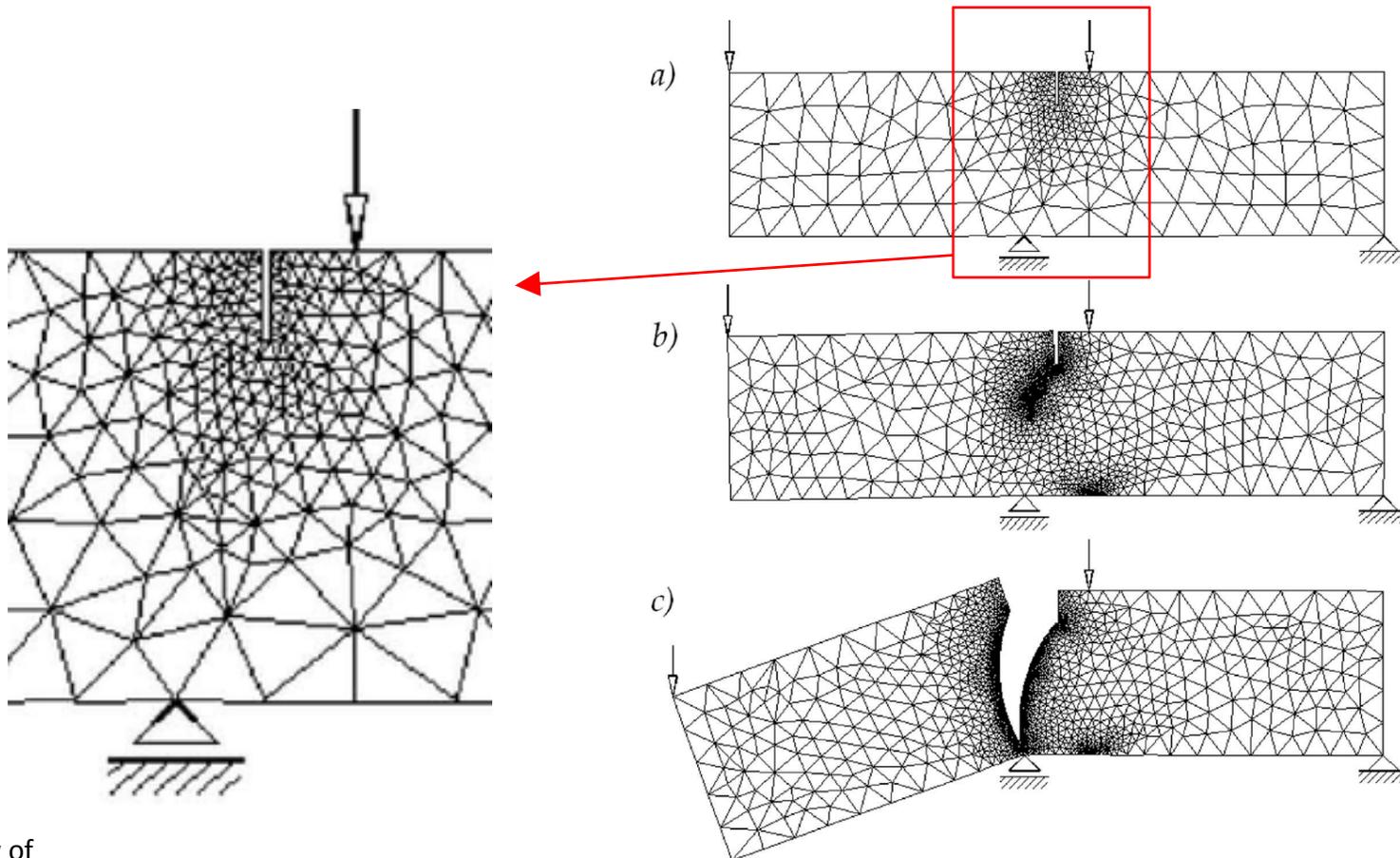


Figure courtesy of
https://www.researchgate.net/figure/222298402_fig7_Fig-15

RCF Modeling – Long Term Goals

- **Build database of microstructures & RCF cracks**
 - Microstructural analysis of different rail types
 - Variable RCF crack morphologies
- **Conduct Nano-hardness testing on microstructural features**
 - Collect micro-mechanical properties of phases
- **RCF predictive modeling**
 - Build elements to reflect phases
 - Assign boundary conditions to reflect micro-mechanical properties
 - Assign load conditions to reflect in-service conditions
 - Initiate cracks → run model → compare results to RCF crack data → modify inputs → repeat modeling
- **Help needed**
 - Rail types with early onset of RCF (<30MGT into lifecycle)
 - Modeling expertise (so far 1 M.A.Sc. student is completing his degree on the topic at UoA) more help is needed

Work continues...

Participation welcome

My contact info:

Daniel Szablewski, Metallurgist

Daniel.Szablewski@nrc-cnrc.gc.ca

Cell: (613) 462-9396

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