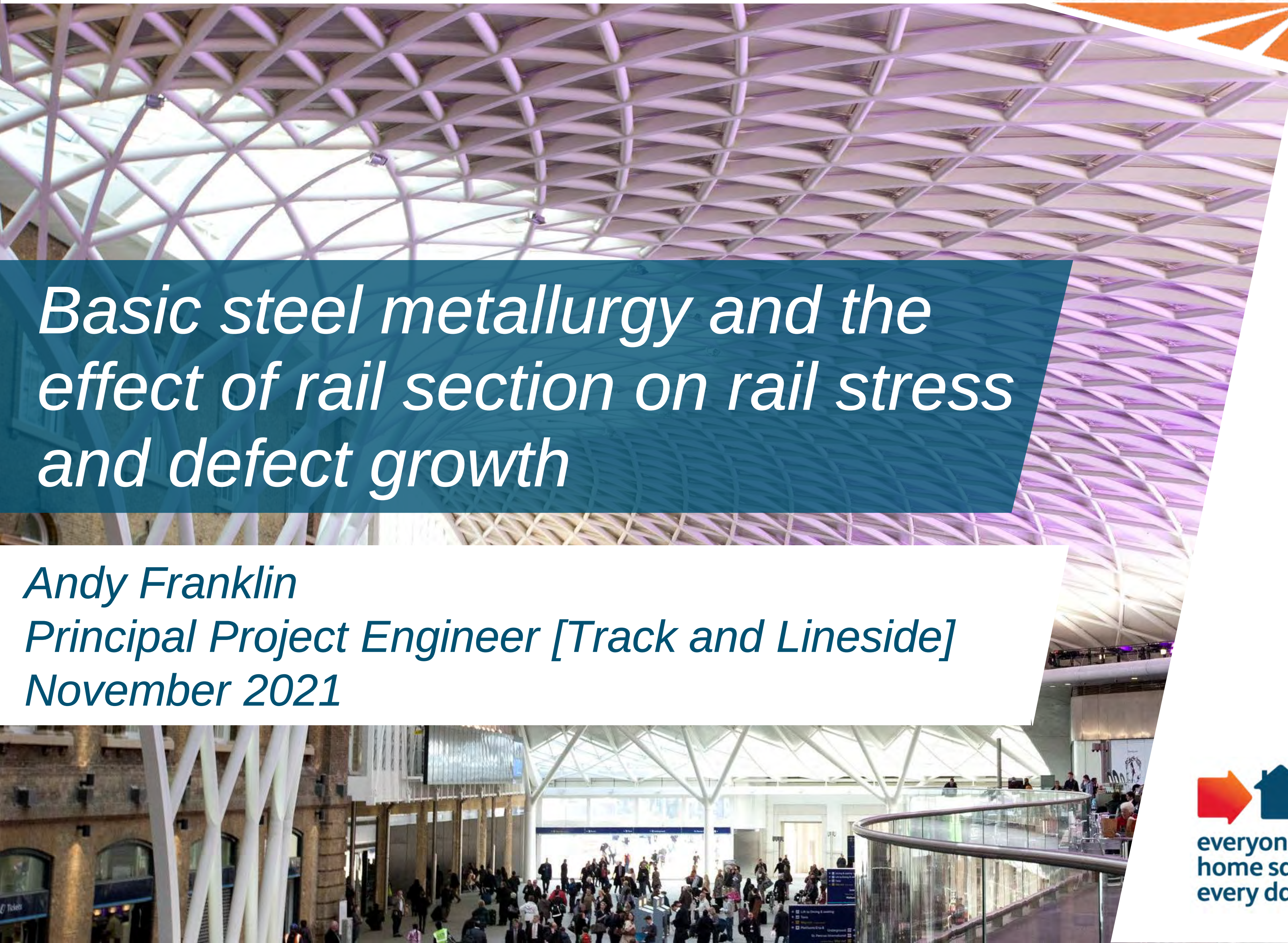
NetworkRail



Basic steel metallurgy and the effect of rail section on rail stress and defect growth

Andy Franklin
Principal Project Engineer [Track and Lineside]

November 2021

everyone home safe every day

Part 1 - Basic steel metallurgy

everyone
home safe
every day

Content

In this part of the talk we will look at:

1. Phases and crystalline structures
2. The Iron-Iron Carbide Equilibrium Diagram
3. The effect of carbon content on steel properties
4. What happens when steel is heated
5. Why it is important to control this

Phases and crystalline structures

- Cup of tea analogy

Iron-iron carbide equilibrium diagram

- The properties of steel are affected by the percentage of carbon and temperature
- As the material cools it recrystallises – this is reversible
- The speed of cooling affects the granular structure

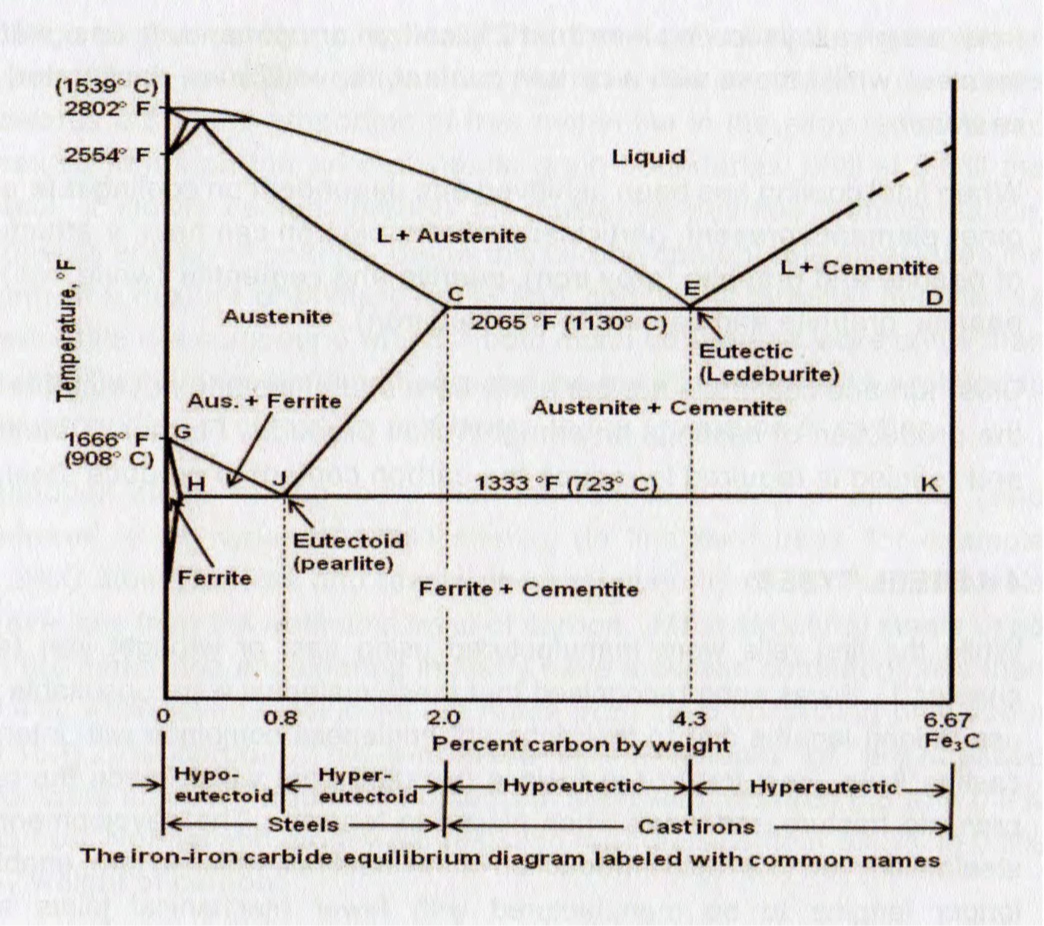


Diagram from Understanding Rail Steels & Rail Welding published by the PWI

Iron-iron carbide equilibrium diagram

- Rail steels carbon content is from content 0.4% to 1.05%

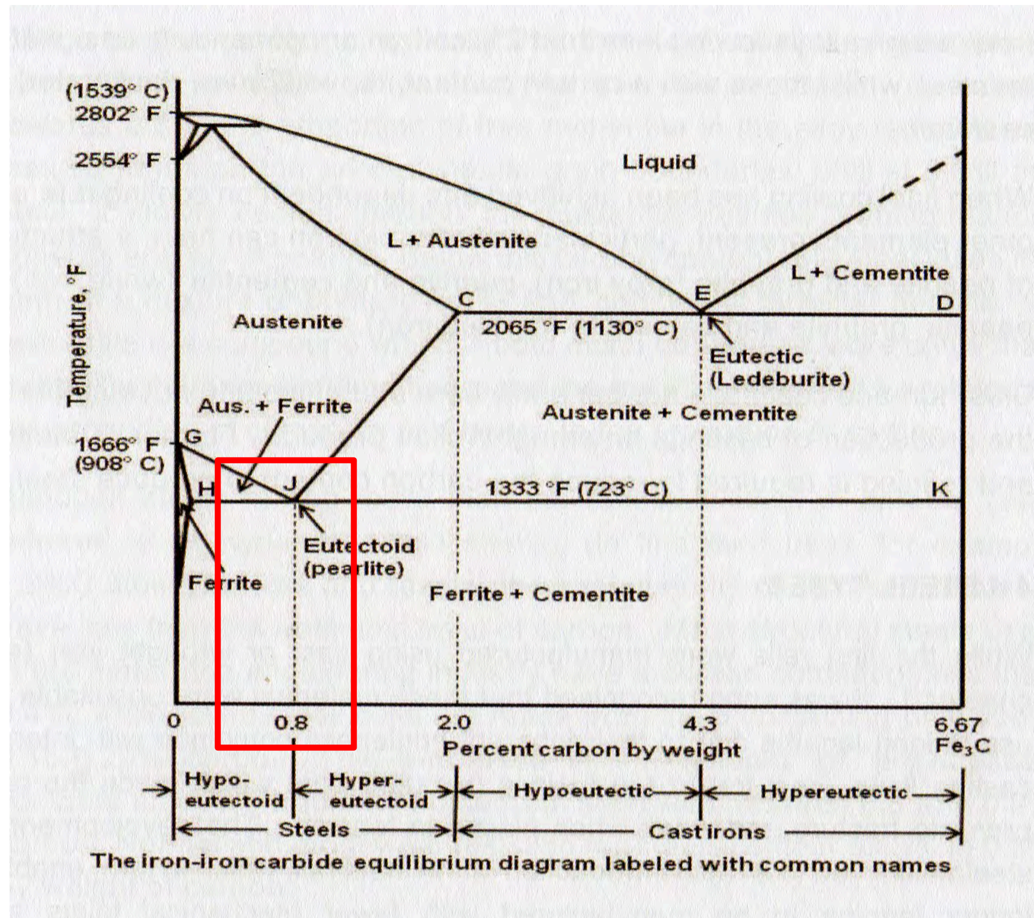


Diagram from Understanding Rail Steels & Rail Welding published by the PWI

Iron-iron carbide equilibrium diagram

- Rail steels carbon content is from content 0.4% to 1.05%
- At 0.83% carbon the steel is described as eutectoid and forms pure pearlite
- At less than 0.83% carbon Ferrite and Pearlite are formed (hypo-euctectoid)
- At more than 0.83% carbon Cementite and Pearlite (hyper-eutectoid)
- What effect do you think this has?

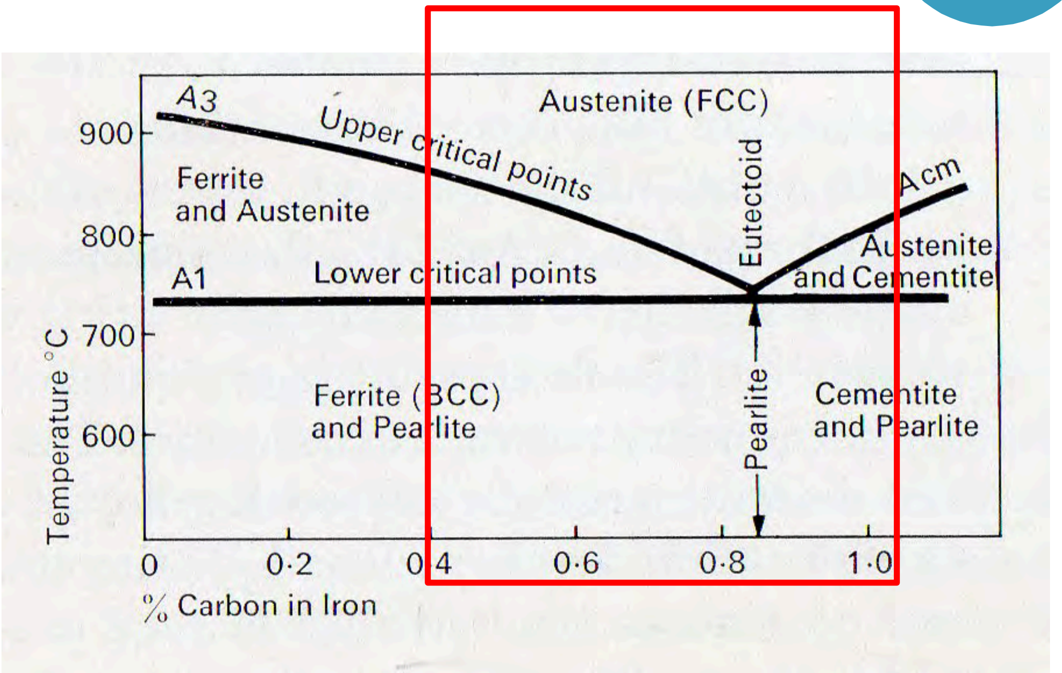


Diagram from Guide to the Structure and Properties of Steel by the British Steel Corporation

Effect of carbon on steel properties and microstructure

- Rail steels carbon content is from content 0.4% to 1.05%
- As percentage carbon increase:
  - –Tensile strength increases
  - –Hardness increases
  - –Ductility reduces

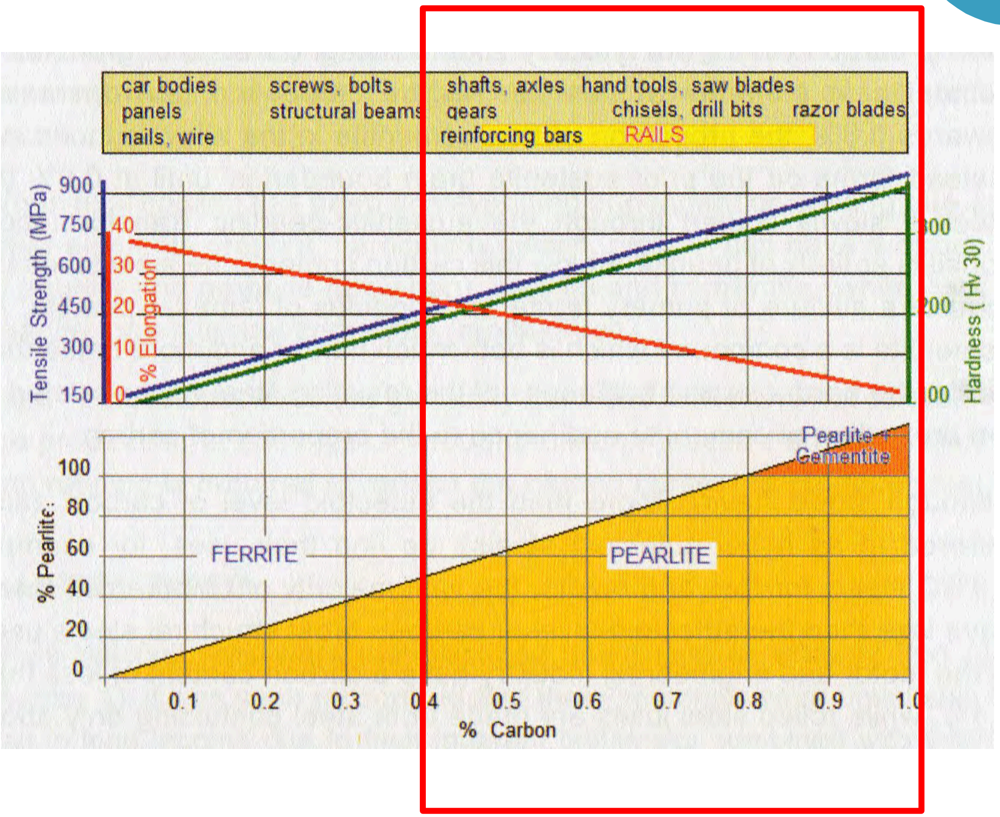


Diagram from Understanding Rail Steels & Rail Welding published by the PWI

Time Temperature Transformation (TTT) diagram for a 0.5% carbon steel

- Steel heated to 825° C for 15 minutes
- Transformation takes place at 450° C isothermally
- What would happen if the material was isothermally cooled at 680° C?
- Do we practice isothermal cooling on site?

Chemical Composition (%)

C	Si	Mn	S	P
0·53	0·35	0·70	0·01	0·020

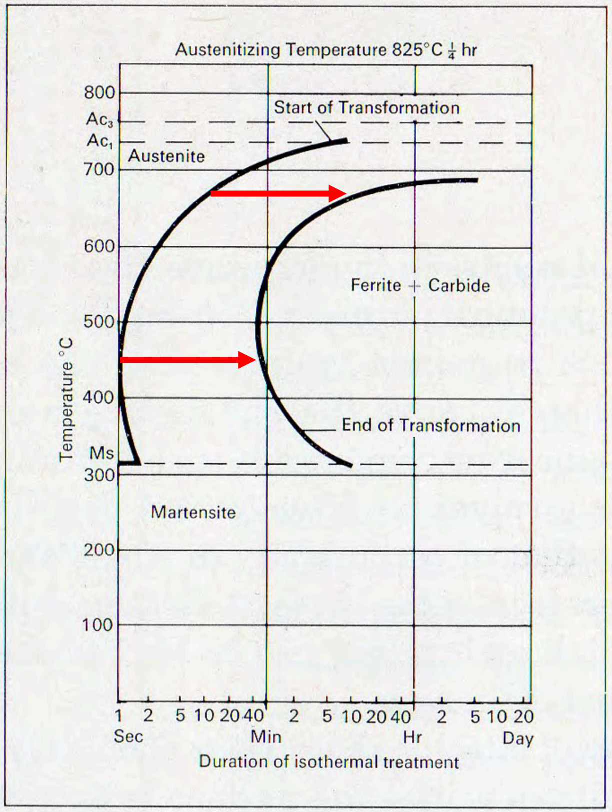


Diagram from Guide to the Structure and Properties of Steel by the British Steel Corporation

The relationship between TTT curves and curves representing continuous cooling

- This is a TTT for a plain carbon eutectoid steel
- Shows the relationship between isothermal recrystalising and cooling at a constant rate
- Demonstrates both what can be achieved in manufacturing situation but why it is important to control cooling rate
- How do we control the risk of martensite formation when we are grinding rail?

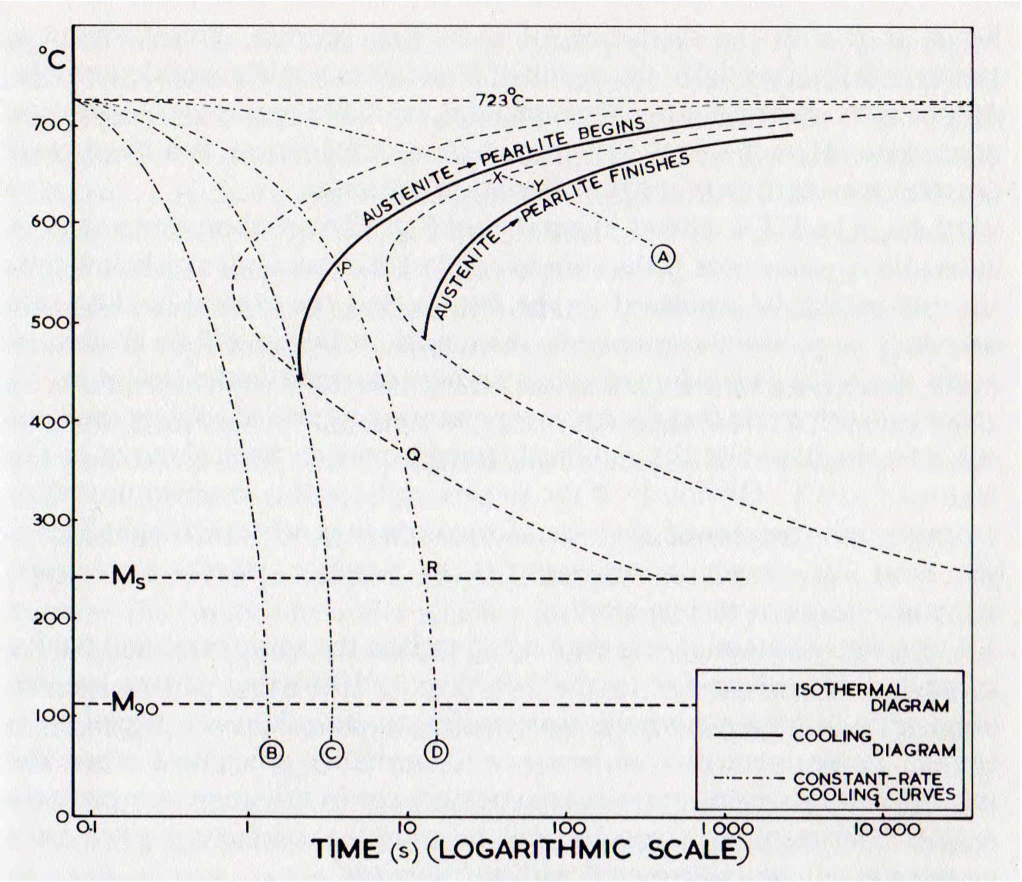


Diagram from Engineering Metallurgy - Volume 1 by R. A. Higgins

Alloy steels

- In the real world we don’t just rely on the carbon content to produce the desired properties in steel and other elements are added as alloys.
- Some go into solid solution
- Some precipitate out and form separate phases
- Common alloying elements include manganese, nickel, chromium, silicon, tungsten and vanadium.

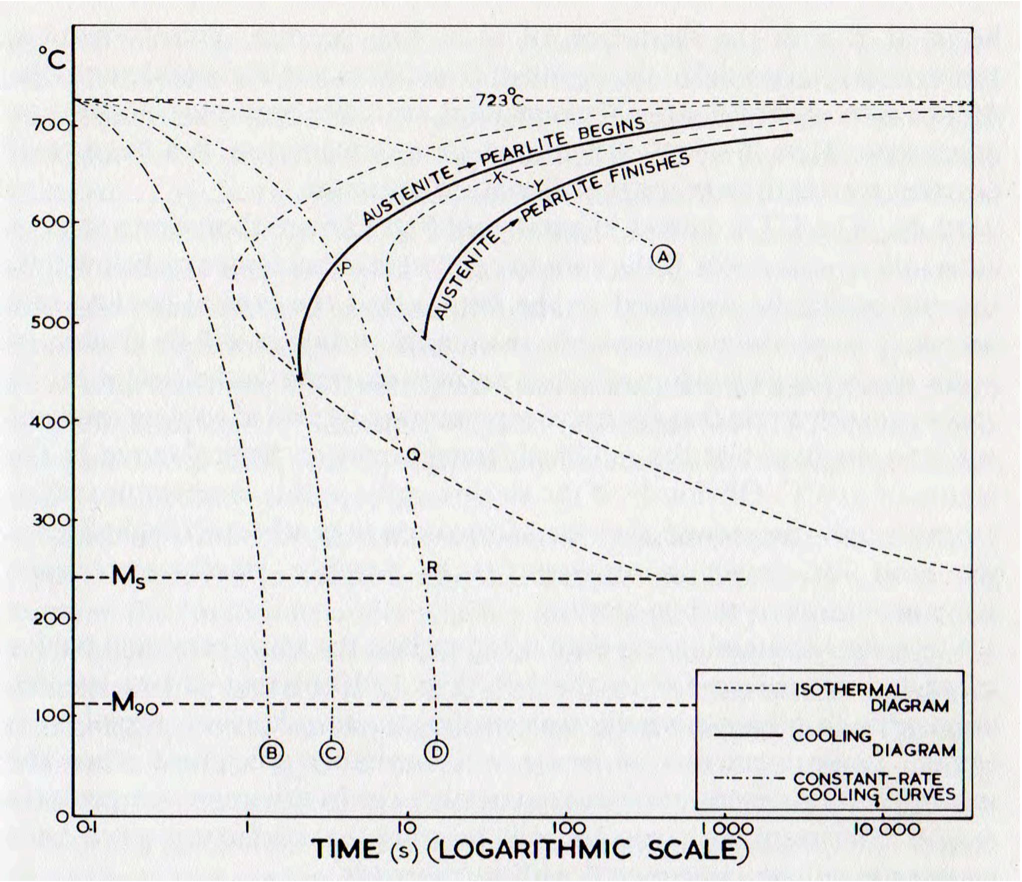


Diagram from Engineering Metallurgy - Volume 1 by R. A. Higgins

Identifying rail steels

- This table give the UK and European branding for rail steels
- In order to scope welding we need to be able to identify what steel, or steels, we are working with

UK Steels and Markings		European Steels and Markings	
Rail Steel	Brand Mark	Rail Steel	Brand Mark
N/A	N/A	R200	N/A
BS11 Normal Grade	N/A	R220	
BS11 Grade A	A	R260	
BS11 Grade B	B	R260 Mn	
UIC Grade A	A	R260	
UIC Grade B	B	R260 Mn	
BSC AREA 90	AA	N/A	N/A
90kg/mm² Cr	1 CR	N/A	N/A
110kg/mm² Cr	1 CR	R320 Cr	
HT (340-370)	HT	R350 HT	
N/A	N/A	R350 LHT	
LCAMS	Manganese-W	N/A	N/A
HCAMS	Manganese	N/A	N/A
Bainitic	BNC	N/A	N/A
Conductor Rail	N/A	N/A	N/A
Microalloyed Head Hardened	MHH	R370CrHT	
High Performance (HP335)	HP335	N/A	
Compact 1400	N/A	N/A	N/A

- This is an example of R350HT branding to EN13674-1

What happens if we don't control the heat?

- Case study 1 – Letchworth broken tri-metal weld 25-11-2020
- A Manual Metal Arc (MMA) repair had been carried out on a rail defect on the head of the TMZ.
- The weld TMZ subsequently broke and was discovered during routine track patrolling.


BRITISH STEEL

Figure 1: Views of the broken Letchworth tri-metallic welded rail, a) extracted overhead view showing surface defect, b) in-situ rail break, c) alternative view of in-situ rail break

LETCHWORTH 2359A – BROKEN TRI-METALLIC WELD

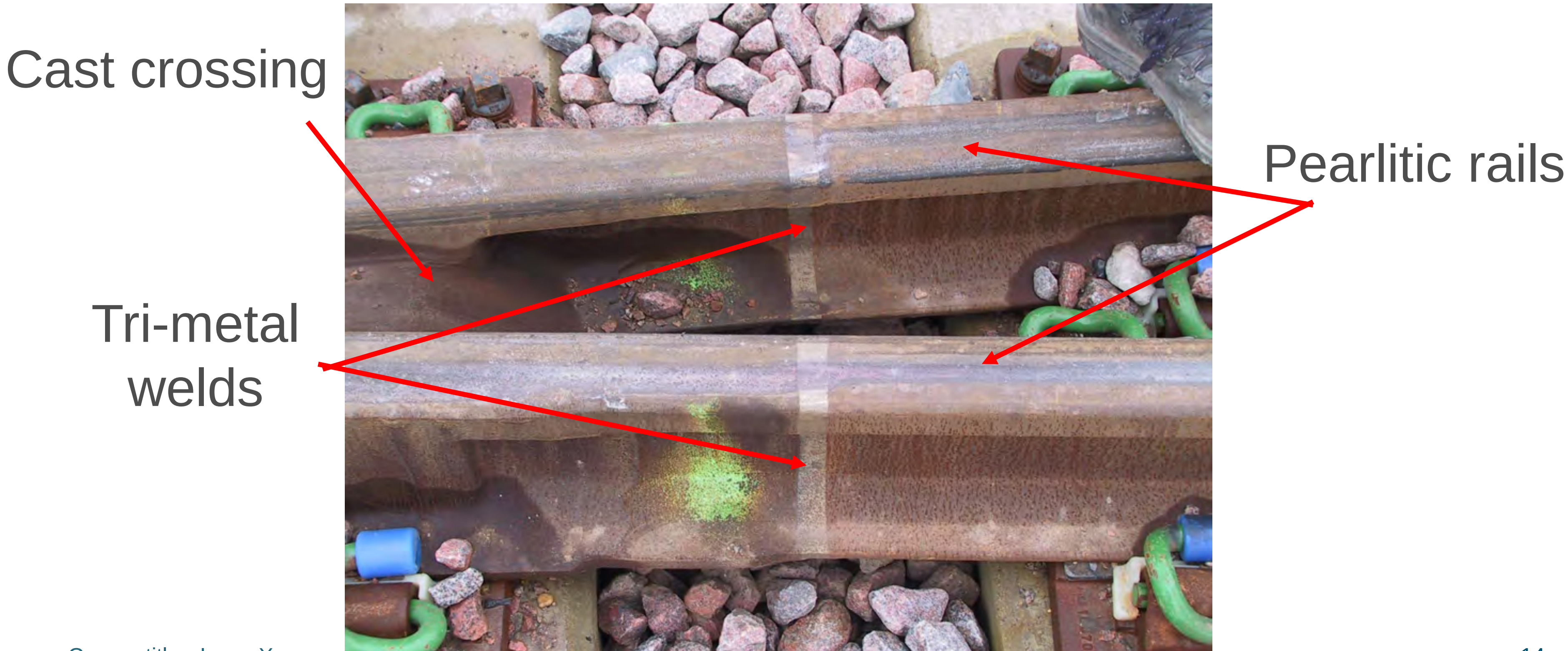
Document Number:	2020-E014
Revision Number:	R1
Status:	Final
Date:	19 April 2021

2021

BUILDING STRONGER FUTURES

Tri-Metal Weld (TMZ)

- This is a picture of a Tri-Metal Weld
- It allows pearlitic rail to be welded to a cast manganese crossing avoiding fishplated joints



Fracture faces of the broken rail

- These are the fracture faces of the broken rail

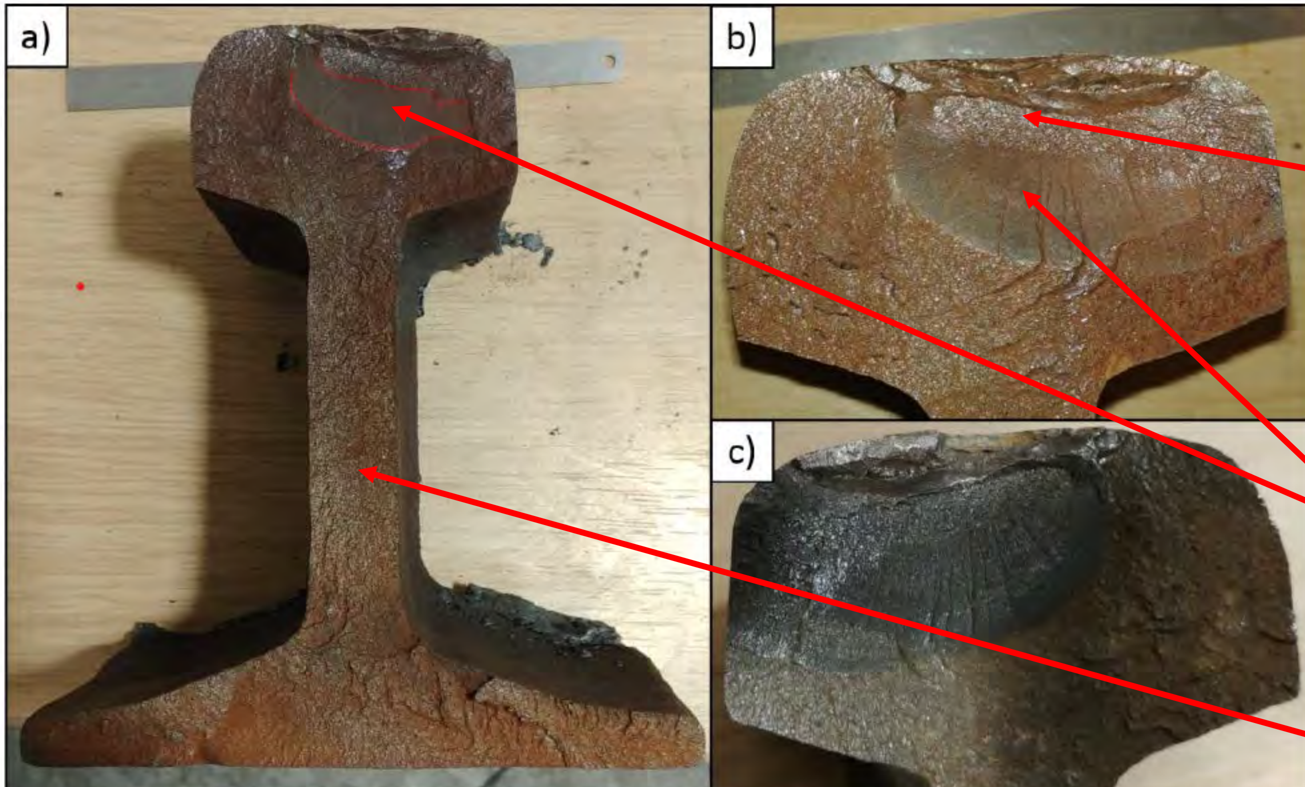


Figure 3: 20TR017 fracture face, a) whole AMS fracture face, b) AMS head view, c) R260 head view

Initiation of crack

Fatigue crack growth under cyclic loading

Brittle fracture

Pictures from the British Steel report into the Letchworth broken rai

Case study 1 – Letchworth broken tri-metal weld 25-11-2020

- Q1. What was the peak hardness of the metal in the heat affected zone and what does this indicate?

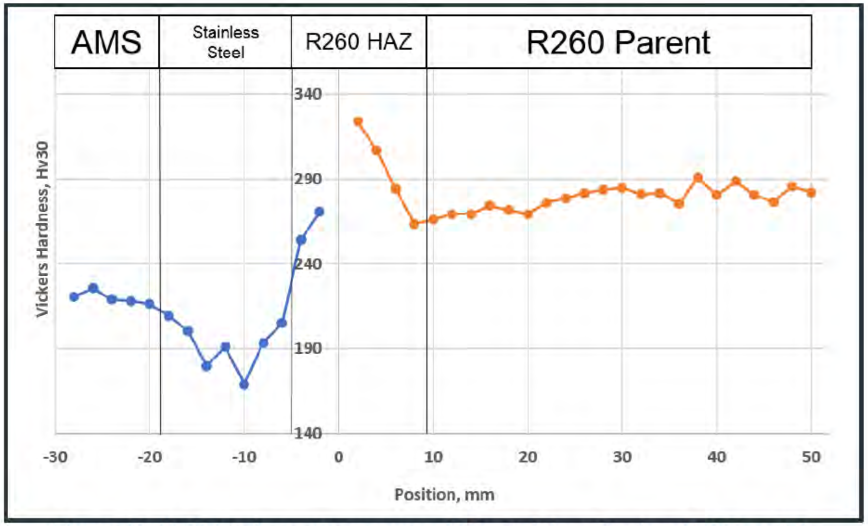


Figure 10: Hv30 hardness trace across AMS, Stainless Steel and R260 metals

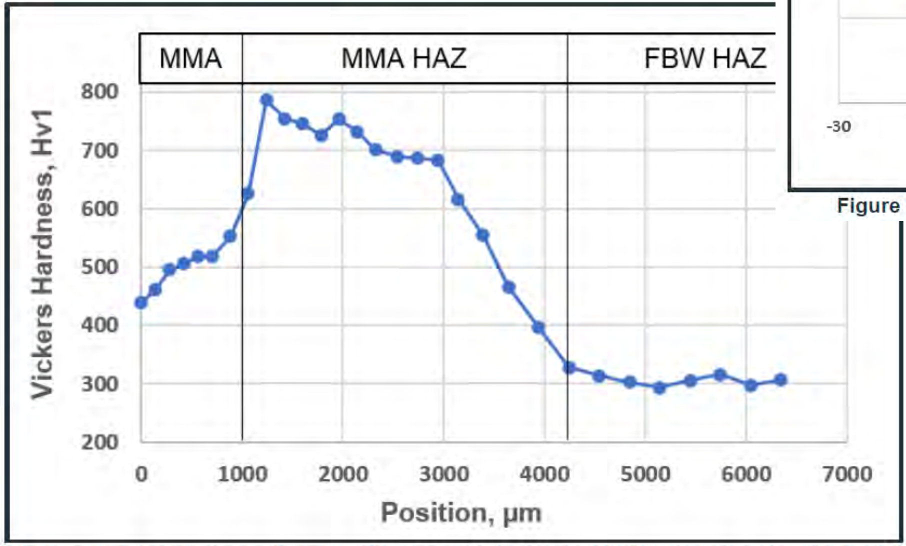


Figure 12: Micro-Vickers hardness trace from MMA deposit through MMA HAZ into the HAZ of the flash-butt weld

Pictures from the British Steel report into the Letchworth broken rai

Case study 1 – Letchworth broken tri-metal weld 25-11-2020

- Q2. What is the likely cause of the formation of martensite?

- A2. The significant proportion of martensite in the MMA HAZ of the R260 steel indicates that the TMZ will have been cold when it was welded
- The effect of the cold rail would have been to very rapidly cool the weld deposit. The quenching effect would have seen led to the formation of martensite

Case study 1 – Letchworth broken tri-metal weld 25-11-2020

- Q3. Why is welding in the tri-metal zone complex with regard to controlling temperature?
- A3. The restricted zones specified by NR/L2/TRK/0132 are due to the different heating requirements of AMS and R260 steels respectively.
- AMS cannot be heated beyond 260 – 275° C due to carbon diffusion leading to a breakdown of the steel so a maximum interpass temperature of 204° C is imposed on AMS.
- Conversely R260 steel has a minimum pre-heat requirement of 343° C. This is to provide a slow cooling rate to avoid undesirable microstructural phase transformations

Case study 1 – Letchworth broken tri-metal weld 25-11-2020

- Q4. How does Network Rail track standard NR/L2/TRK/1054 manage this complexity?
- NR/L2/TRK/1054 states:
- Rail head repairs to the TMZ of weldable AMS crossings are not normally permitted within 300 mm of the stainless steel insert on the pearlitic rail steel leg end or within 20 mm on the AMS casting.
- Repairs may be possible following assessment and agreement with the RAM [Track] and the application of careful control
- In practise this often means the SM[Welding & Grinding] or an SAE being present during the repair.

Summary - Key points from Part 1

- Steel has a granular crystalline structure that is affected by:
  - carbon content
  - temperature
  - rate of cooling
  - alloying elements

- The crystallisation process from molten metal to solid state is reversible

- Care is required with any process that imparts heat to the rail that the desired structure will be present at the end of the process

Part 2 - The effect of rail section on rail stress and defect growth

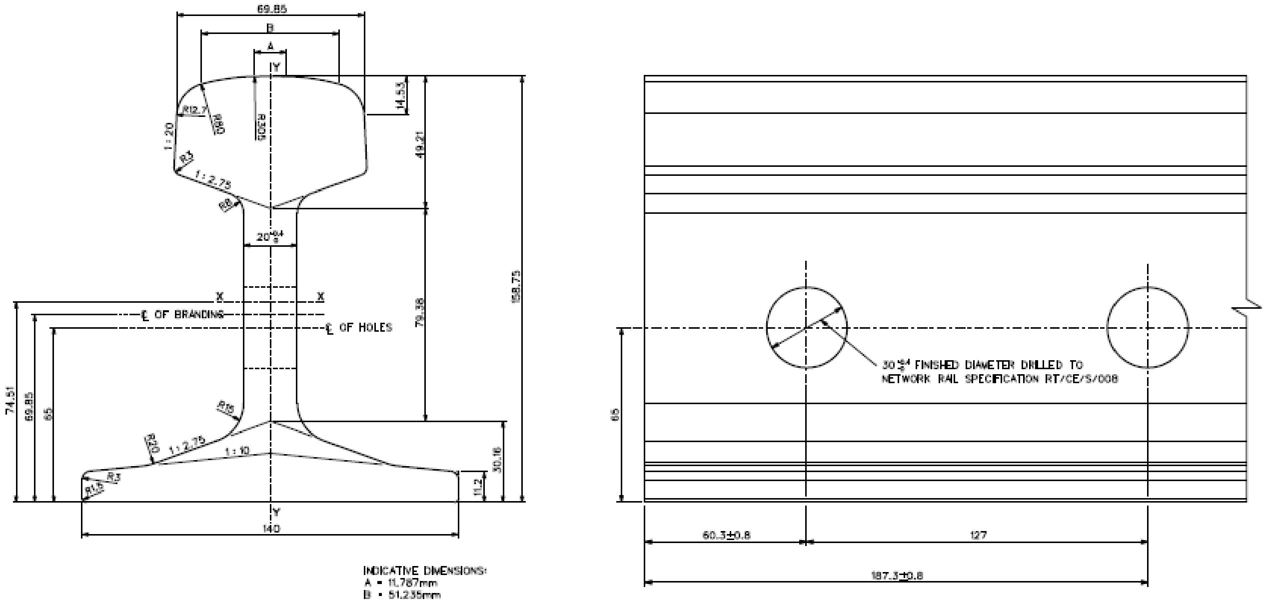
everyone home safe every day

Content

In this part of the talk we will look at:

1. Rail sections and their properties
2. The effect of shape on structural properties
3. The bending of beams
4. Residual stresses
5. Defect growth and critical defect size

Rail sections



NOTES

1. ALL DIMENSIONS IN MILLIMETRES.
2. CEN56E1 RAIL SECTION IS FULLY INTERCHANGEABLE WITH BS113A RAIL SECTION (SEE RE/PW/620).
3. RAILS TO BE MANUFACTURED IN ACCORDANCE WITH NETWORK RAIL SPECIFICATION RT/CE/S/061 AND BS EN 13674 Part 1.
4. RAILS TO BE CUT AND DRILLED IN ACCORDANCE WITH NETWORK RAIL SPECIFICATION RT/CE/S/008. (FOR BOND HOLE DRILLING SEE ALSO DRAWINGS RE/PW/563 & 596.
5. ALL FISHBOLT HOLES MUST BE COLD EXPANDED IN ACCORDANCE WITH NETWORK RAIL SPECIFICATION RT/CE/S/050.

SECTION PROPERTIES	
SECTIONAL AREA	7169 mm²
MOMENT OF INERTIA, X-X	2321 cm⁴
MOMENT OF INERTIA, Y-Y	421.6 cm⁴
SECTION MODULUS, TOP	275.5 cm³
SECTION MODULUS, BOTTOM	311.5 cm³
WEIGHT	56.3 kg/m

Amd	Date	Minute	Description of Revisions

Network Rail
40 Melton Street
London NW1 2EE
Tel: 020-7557-8000

Adopted
(Master Copy Signed by D Ventry 19 Sept 2005)
David Ventry – Head of Track Engineering

TRACK ENGINEERING STANDARD DESIGN

CEN56E1
RAIL SECTION AND
DRILLING DETAILS

Scale(s)	1 : 1	
Authorising Minute No.	Memorandum PWE/DEV/001/01	Date: 08/09/05
Drawing Number	RE/PW/792	

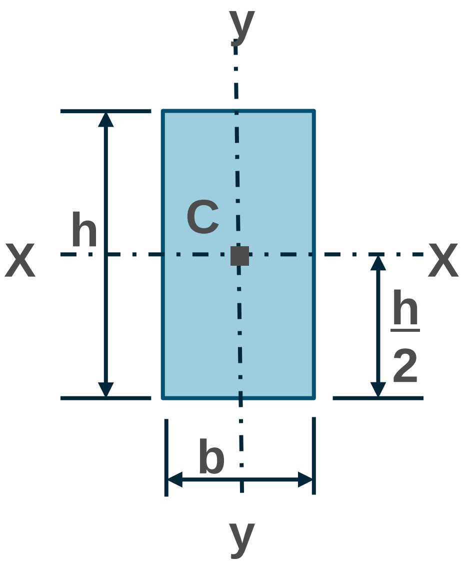
The effect of shape on stress – Exercise 1

- Your task is to find away to support your mobile phone not less than 75mm above the desk
- Once placed in position you must not touch the phone or the support
- You have 3 minutes and a single sheet of A4 paper

The effect of shape on stress – Exercise 1

- My solution is to create a tube either circular or triangular

The effect of shape on stress – Exercise 2



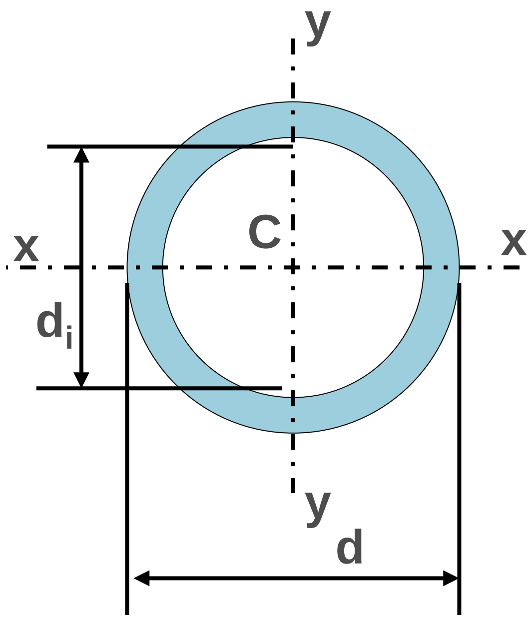
$$A = bh$$

$$I_{xx} = \frac{bh^3}{12}$$

$$I_C = \frac{bh(b^2 + h^2)}{12}$$

$$I_{yy} = \frac{b^3h}{12}$$

The effect of shape on stress – Exercise 3

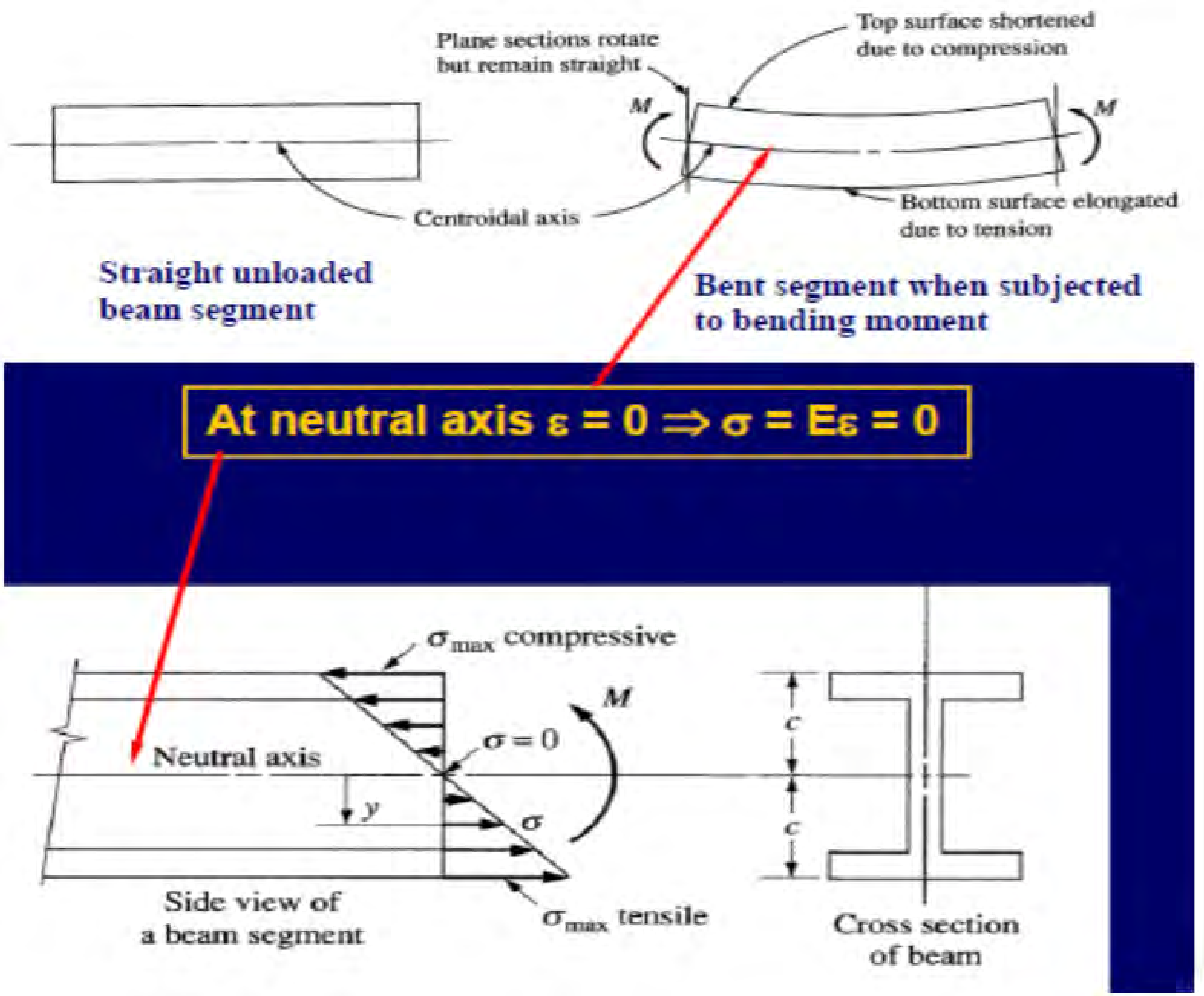


$$A = \frac{\pi}{4}(d^2 - di^2)$$

$$I_{xx} = Iyy = \frac{\pi}{64}(d^4 - di^4)$$

$$I_C = \frac{\pi}{32}(d^4 - di^4)$$

What happens when you bend a beam?



Bending stress formula

$$\sigma = \frac{My}{I_{xx}}$$

Where:

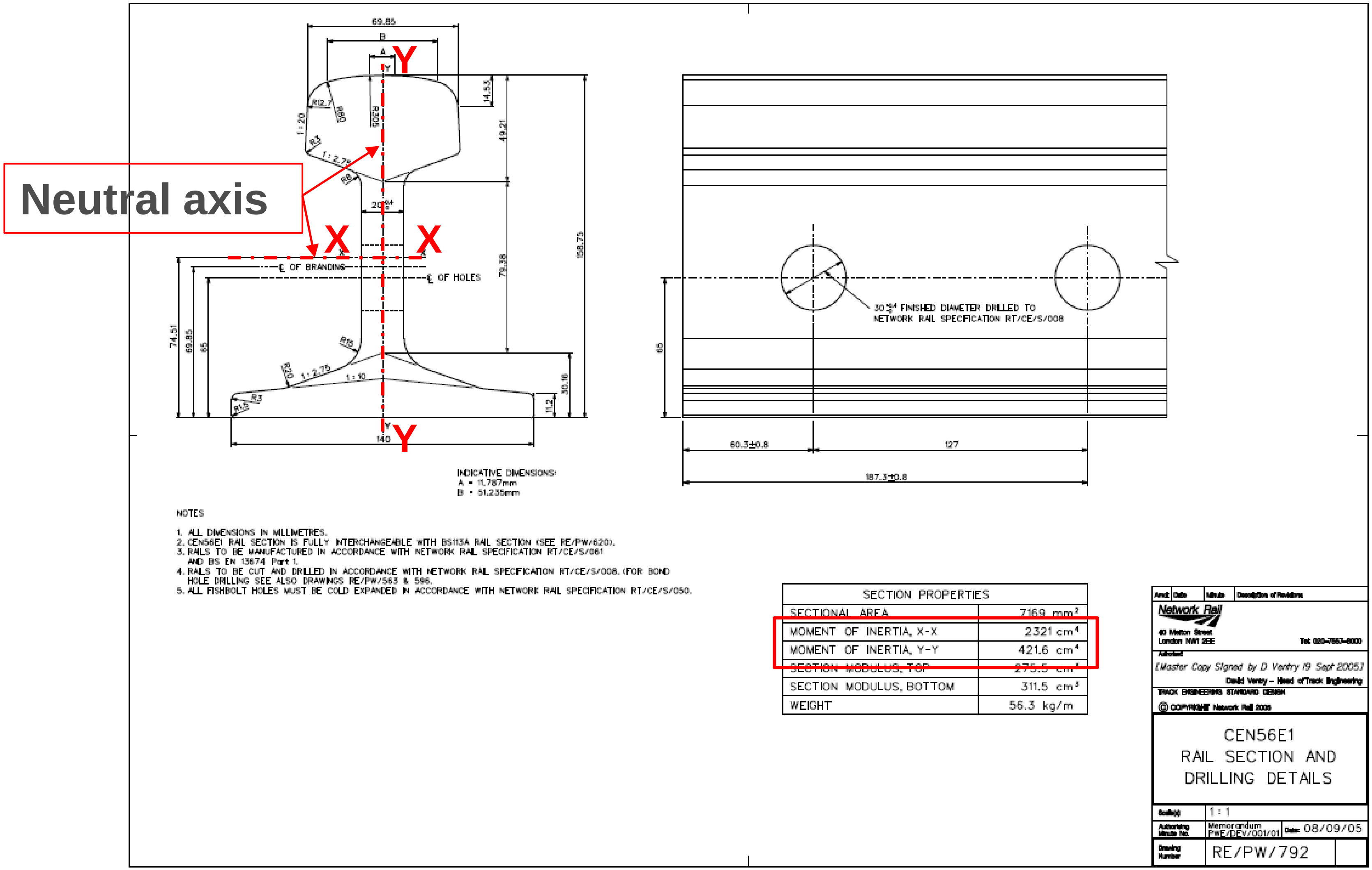
σ = Bending stress in N/m^2

M = Moment of the neutral axis in Nm

y = Perpendicular distance to the neutral axis in m

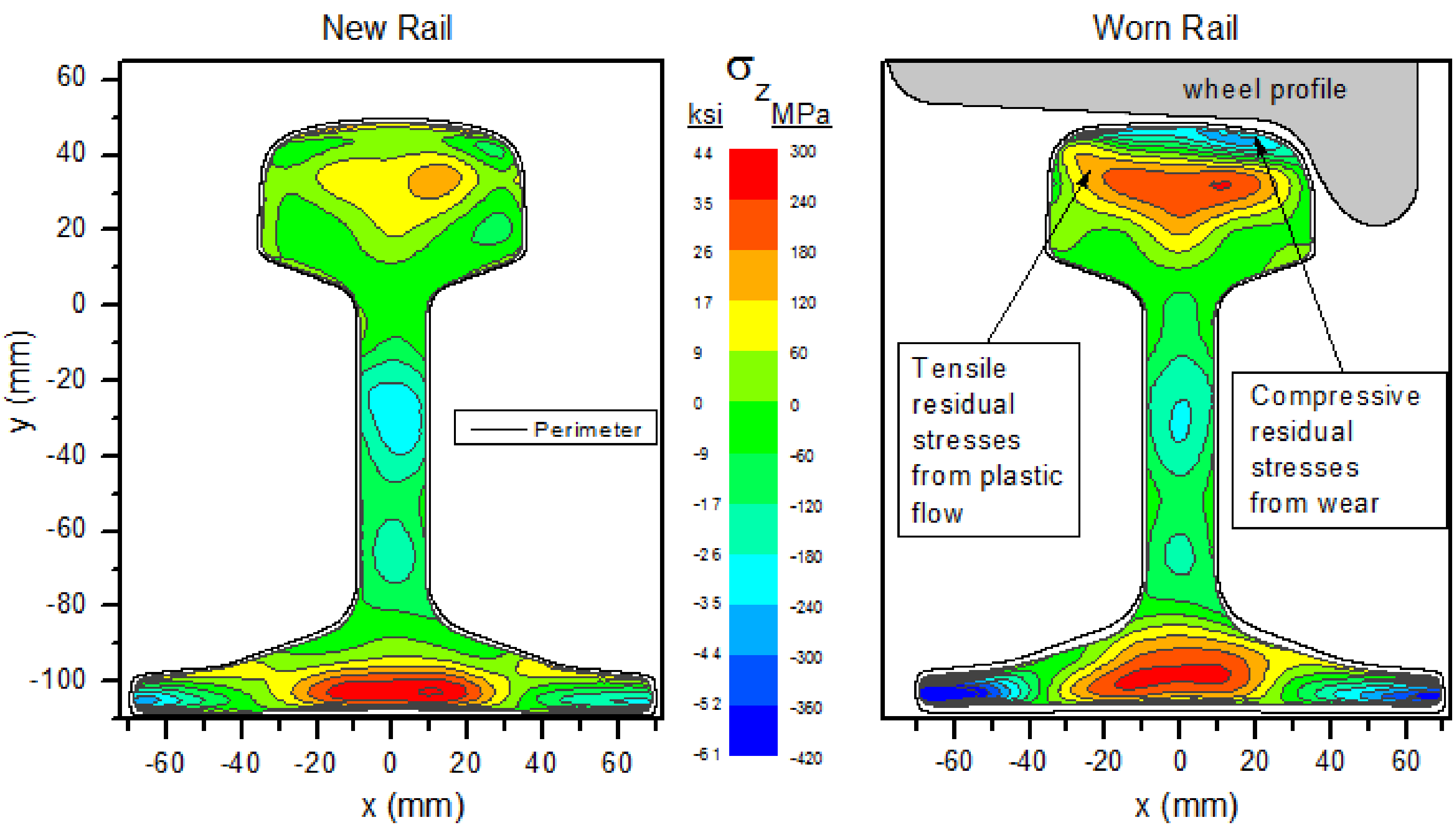
I_{xx} = Second moment of area of the section in m^4

Effect of rail section on stress



SECTION PROPERTIES	
SECTIONAL AREA	7169 mm^2
MOMENT OF INERTIA, X-X	2321 cm^4
MOMENT OF INERTIA, Y-Y	421.6 cm^4
SECTION MODULUS, TOP	275.5 cm^3
SECTION MODULUS, BOTTOM	311.5 cm^3
WEIGHT	56.3 kg/m

Stress distribution in new and worn rail



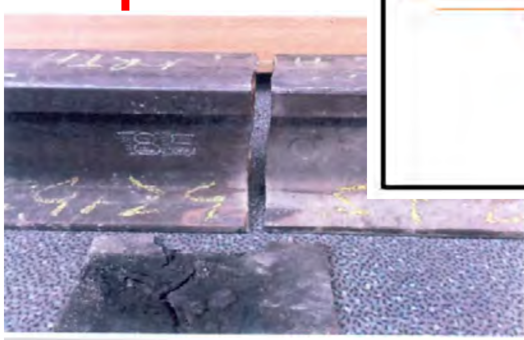
- Tensile stress is shown positive (tending to red)
- Compressive stress is shown negative (tending to blue)

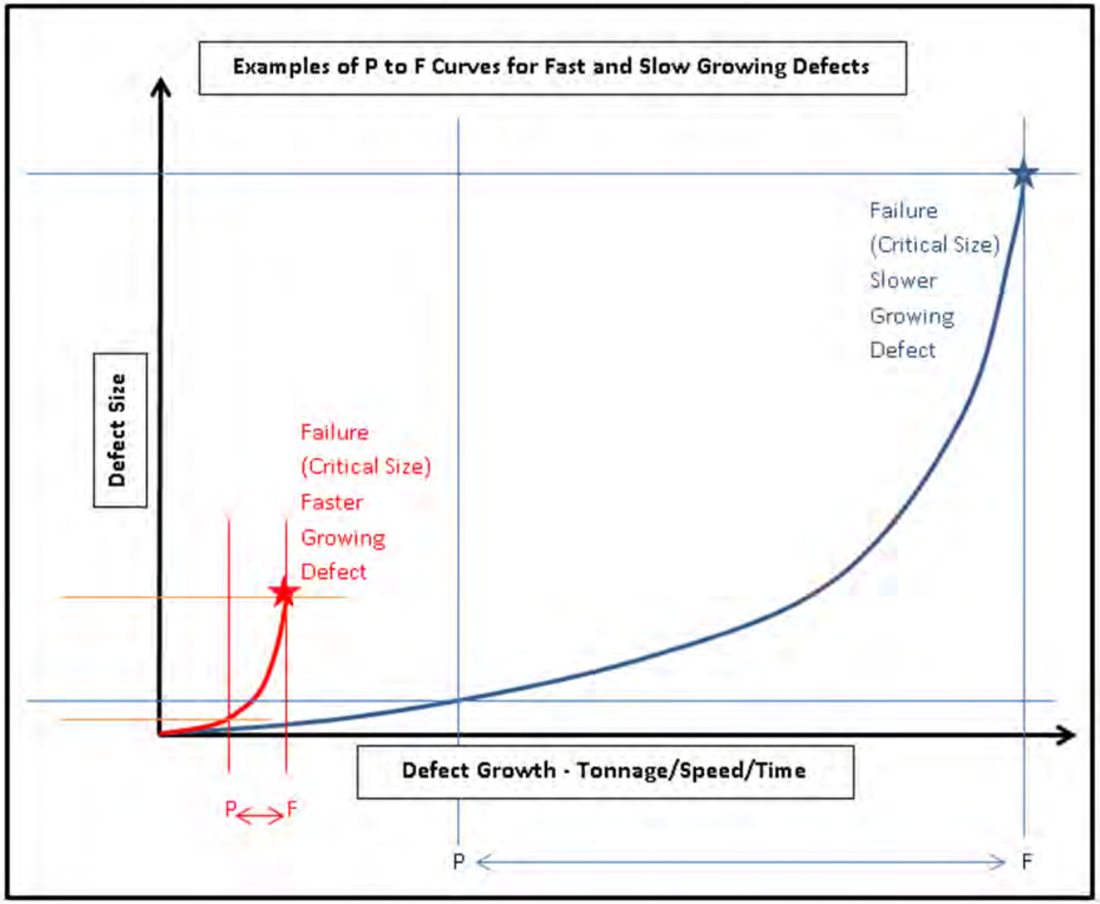
Case study 2 – Effect of rail stress on defect growth

- Let's consider two defects in a piece of 1969 BS113A flatbottom rail:
  - A small inclusion from the steel making process in the centre of the rail head
  - Corrosion of the underside of the rail foot caused by poor pad condition
- Which is the most critical defect and which is likely to grow to critical size and possibly cause a broken rail first?

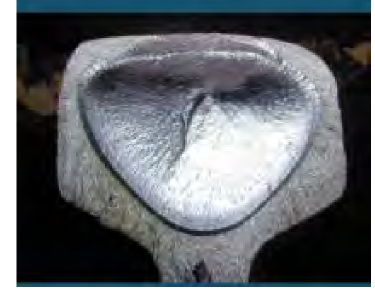
Effect of rail stress on defect growth

Corrosion Pitting





Tache Ovale



Key points – Part 2

- The cross-sectional shape of a rail section has an effect on stress distribution
- The stress under load is largest in the extreme fibres furthers from the neutral axis
- Rails are subject to stress caused by:
  - residual stresses from the manufacturing process and from wear and metal flow
  - bending and impact under traffic load
  - thermal forces dependant on Stress Free Temperature
- Tensile stress drives fatigue and crack growth in rail