European Structural Integrity Society

TC24 – Structural Integrity of railway components

Seminar: 3-4 March 2011

Predicting real world axle failure and reliability

Introduction:

Axle fatigue overview

Roderick A Smith

Co-Chair TC24
Future Rail Research Centre, Imperial College London

The Versailles accident of 8 May 1842.

Broken axle - derailment of engine – fire in wooden carriages – doors locked – approx. 70 killed

An internationally reported sensation.

First railway accident to cause major loss of life

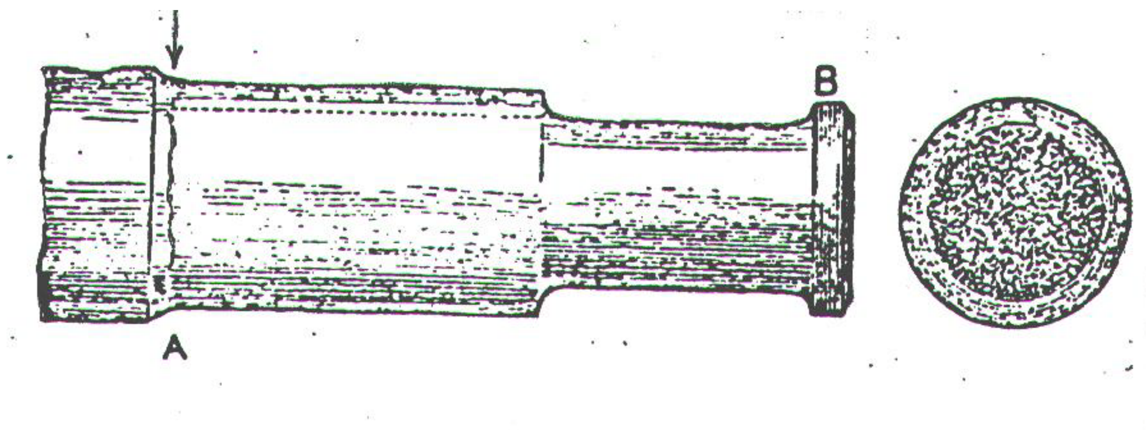
The origins of study of the fatigue problem generally and axles in particular

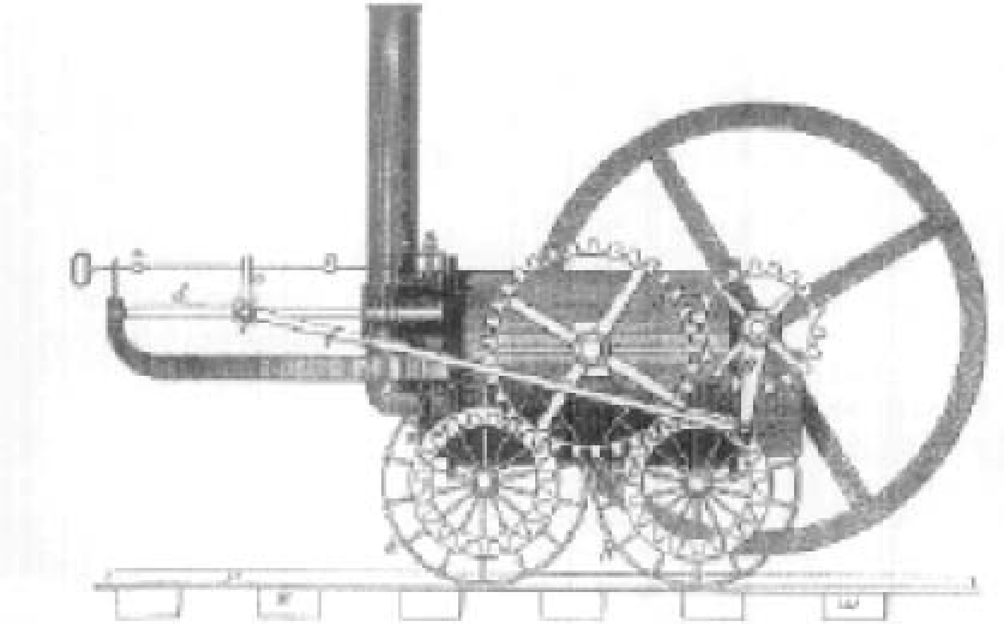
Versailles, Sunday 8 May 1842

Catalyst of much early work on what became known as “fatigue”

Interesting reports of discussions in Proceedings

I Mech E, I C E.

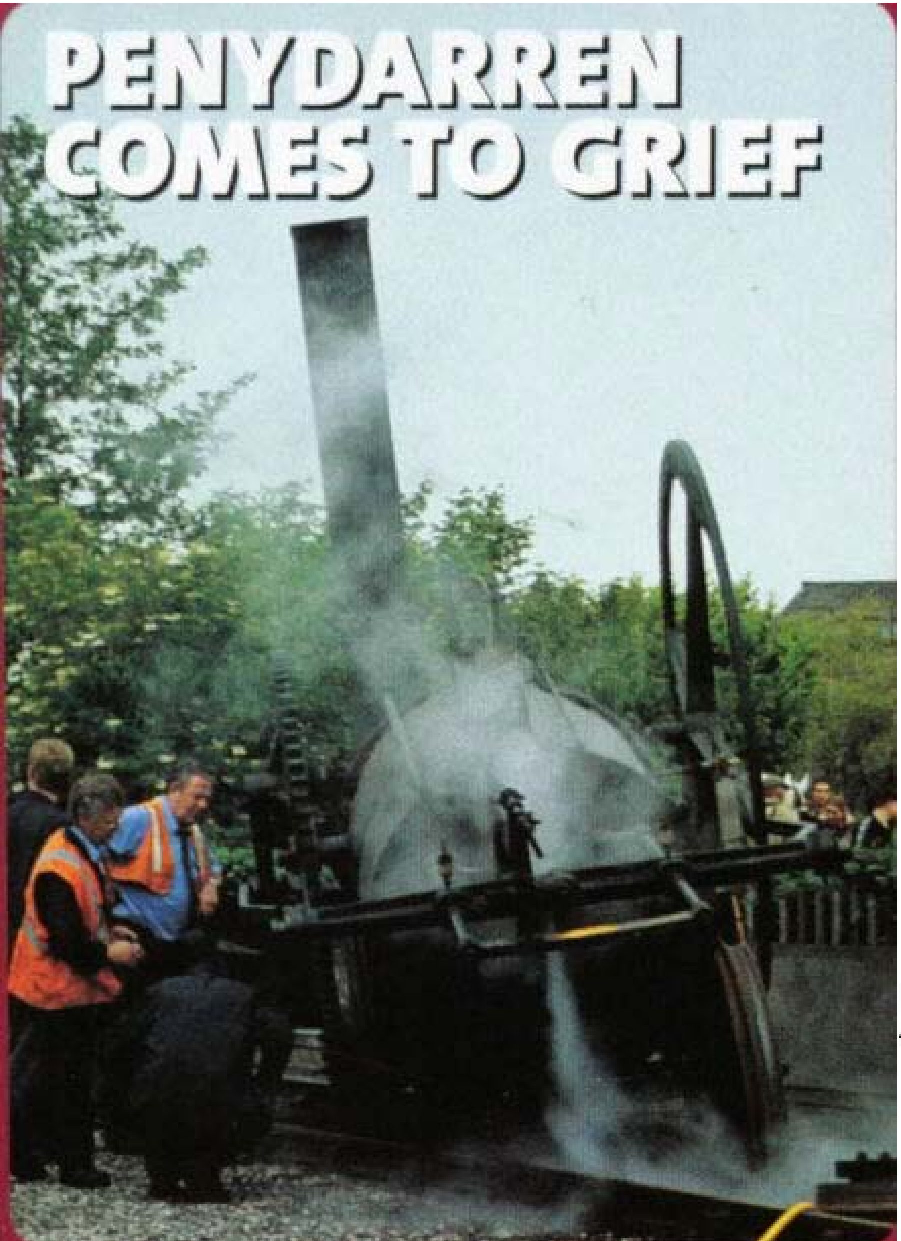


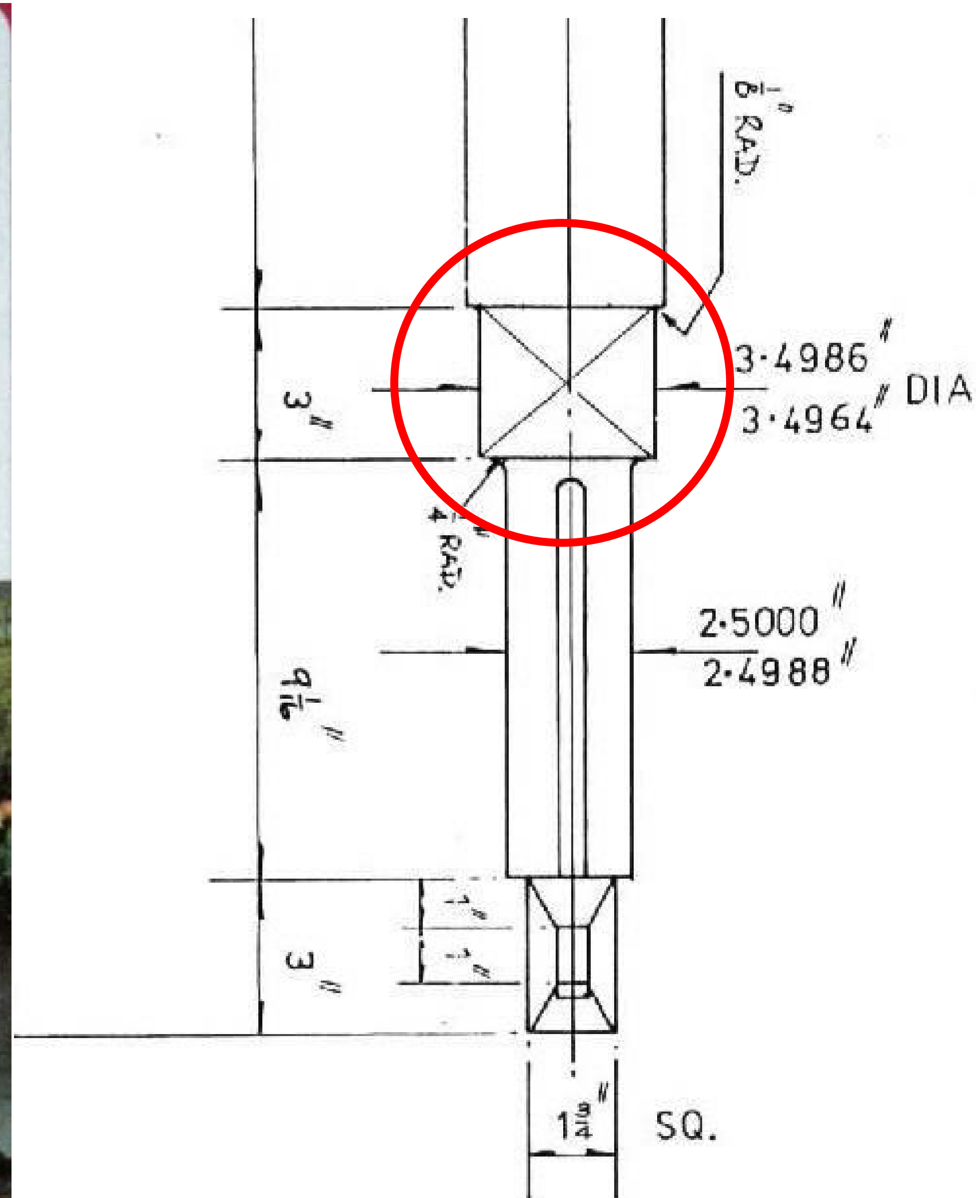


In 1804 Richard Trevithick demonstrated the first working rail locomotive.

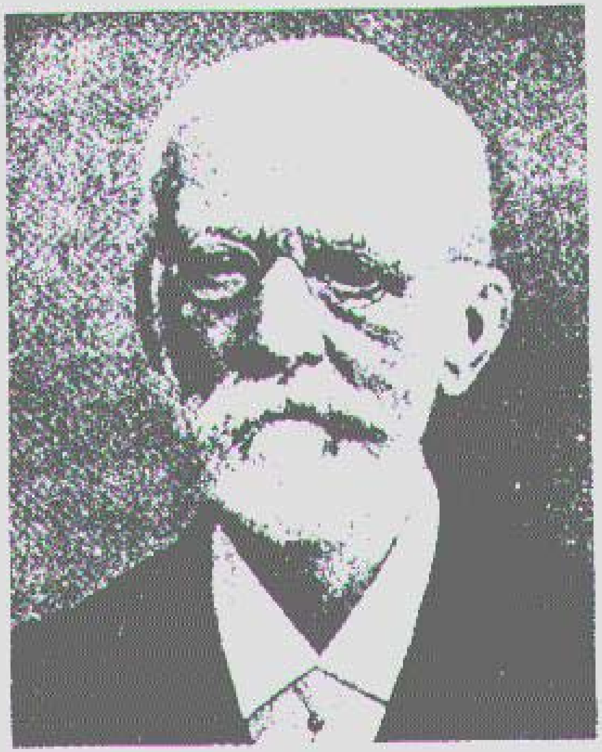
In May 2004, Railfest in York celebrated this notable bicentenary.


Saturday 29 May 2004

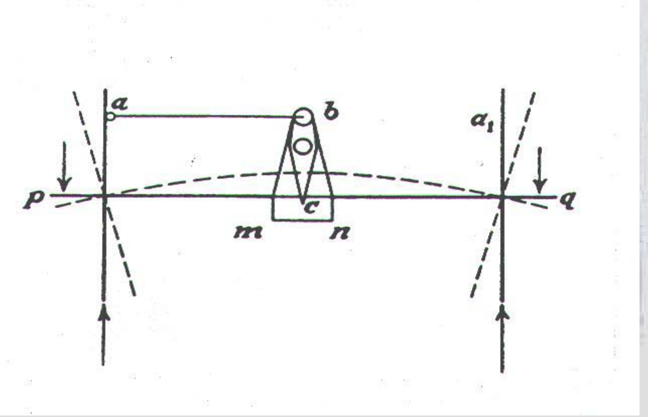

PENYDARREN
COMES TO GRIEF


1/8" RAD.
3·4986"
3·4964" DIA
3"
1/4" RAD.
2·5000"
2·4988"
9 1/16"
3"
1 3/4" SQ.

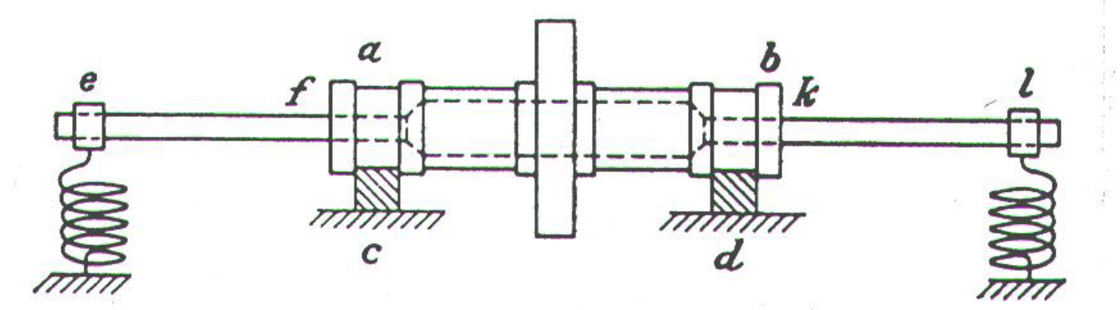
The classic work of Wohler (c.1855 to 1870)



Strain measurements



Experiments replicate real loading



Established the concept of a fatigue limiting stress range

Franz Reuleaux, 1829-1904

German entrepreneur, design engineer and scientist

Method of calculation of bending stress in axles given in the “Constructer”

(Chapter viii, Axles)

First edition 1861.

Longstanding problem:

Fatigue

- The science is (rather) well known
- The longer the crack, the easier it is to predict its growth
- Initiation is very difficult to quantify and is controlled by local factors (defect, corrosion, fretting, notch etc.)
- Material properties are generally well known and quality has improved
- Quantification of laboratory tests is generally easy because the loads (stresses) are well defined and controlled
- **Similitude** between laboratory and real world often difficult because in the real world loads are often ill defined and generally of variable amplitude

Inspection

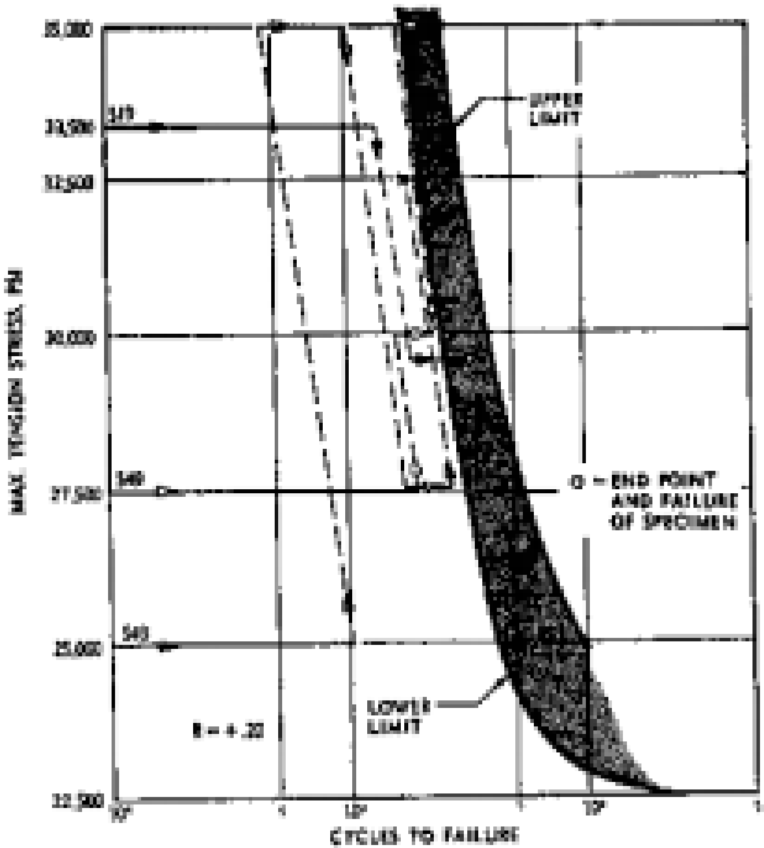
- NDT to reliably identify and size cracks has long been an Achilles Heel

Problems for railway axles:

- Load measurements need to be converted to stresses in the **critical location**
- Not many axles fail!
- Light weighting is becoming increasingly important to save energy (minor role) and to reduce dynamic loads (major role)
- Inspections need to be managed to minimise possible damage
- Crack initiation dominated by relatively few high stresses, the full spectrum playing an increasing part as the crack length increases
- Life between a reliably detectable crack size and final failure is likely to be short!

Circa 1910 Data Acquisition

Miner

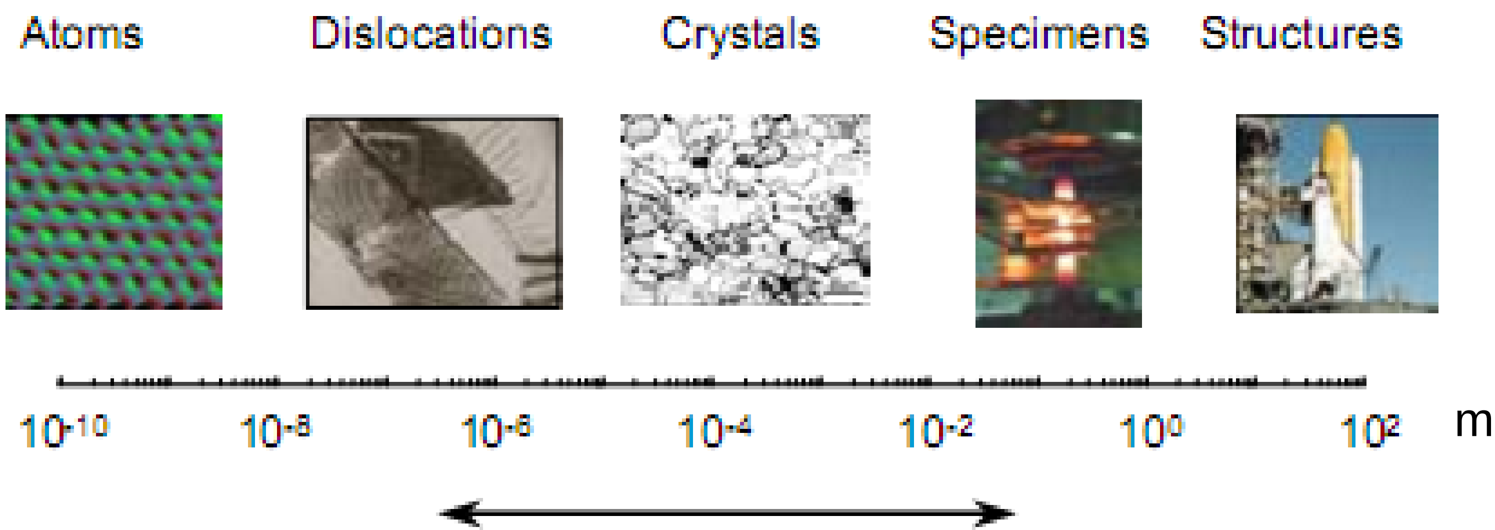


The phenomenon of cumulative damage under repeated loads was assumed to be related to the net work absorbed by a specimen

"proved" linear damage rule

Miner (1945) Cumulative Damage in Fatigue, *Journal of Applied Mechanics*, Vol. 12, 1945, A159-A164

Size Scale for Studying Fatigue



Method	Physics	Size
Stress-Life	Crack Nucleation	0.01 mm
Strain-Life	Microcrack Growth	0.1 - 1 mm
Crack Growth	Macrocrack Growth	> 1mm

Things Worth Remembering

- The physics of fatigue has been well known for over 100 years
- Application of this knowledge still poses challenges

Most “design” is based on some form of empiricism which works over a limited range of conditions: trouble occurs when extrapolation takes us out of the “comfort zone”

Wheelsets - the GB perspective

ESIS TC24 Workshop
3/4 March 2011

Ken Timmis

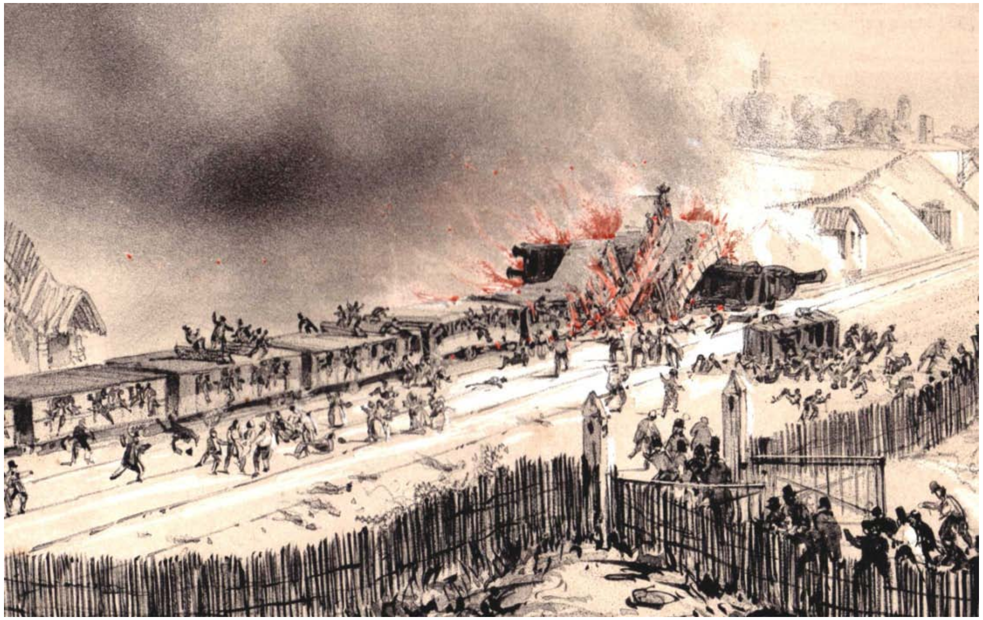
Railway Wheelsets

- Risk
- Axle failures
- Responsibilities for wheelsets
- Wheelset research programme

Railway Wheelsets

Axle risk

- Single point failure
- Failure invariably result in catastrophic consequences
  - Significant damage to vehicle / infrastructure
  - Fatalities



Safety Risk Model

- Models all risk on the railway - including all causes of rolling stock derailments
- Uses Fatalities and Weighted Injuries (FWI) per year as the measure of risk.

Safety Risk Model

- Total risk from train accidents (collisions, collisions at level crossings, derailments and fires) is 7.4 FWI/year
- Frequency of freight train derailments is 16 per year
- Total risk from freight train derailments is 0.38 FWI/year
- Predicted frequency of axle failure approx.1 in 5 years
- Total risk from axle failures is 0.005 FWI/year
  - **1.4% of the freight train derailment risk**

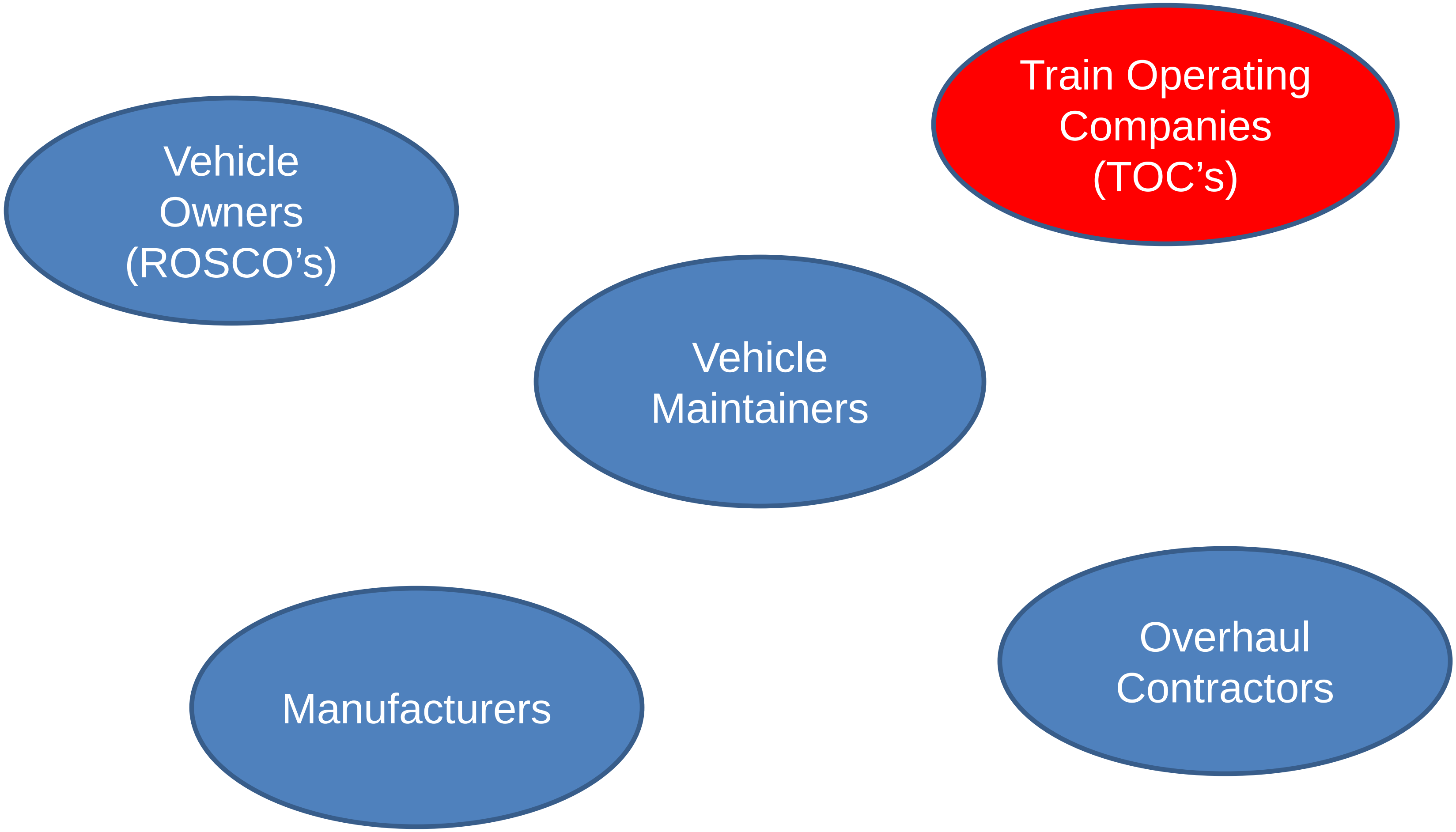
Railway Wheelsets

Testing regime

- All axles tested by Magnetic Particle Inspection (MPI) or equivalent process during workshop overhaul
- In-service inspection by Ultrasonic Testing at defined periodicity or mileage
- Wheelsets Non-Destructive Testing (NDT) inspection no greater than 8 years

Post Privatisation

Wheelset responsibilities



Post Privatisation

Regulation and Management of Wheelsets

Standards

Workshop Overhaul Specifications

Drawings and Specifications

In-service Maintenance Procedures

Guidance and Good Practice

Wheelset Management Group

•Representation from parties with interests in Wheelsets from across the industry

•Aim – to share best practise amongst participants, support development of appropriate documentation and provide guidance on wheelset research projects

•Develop a Wheelset Research Programme

- Wheelset Safety
- Wheelset Whole Life Cost
- Wheelset Knowledge Retention and Application

Wheelset Research Programme

Wheelset Safety

- In-service NDT
  - Axle environment and strain histories – T356
  - Effects of human factors in axle inspection – T774
  - Model the NDT inspection requirements for axles - T728
- Effects of corrosion damage
  - Understanding the risk of fatigue initiating from corrosion – T728

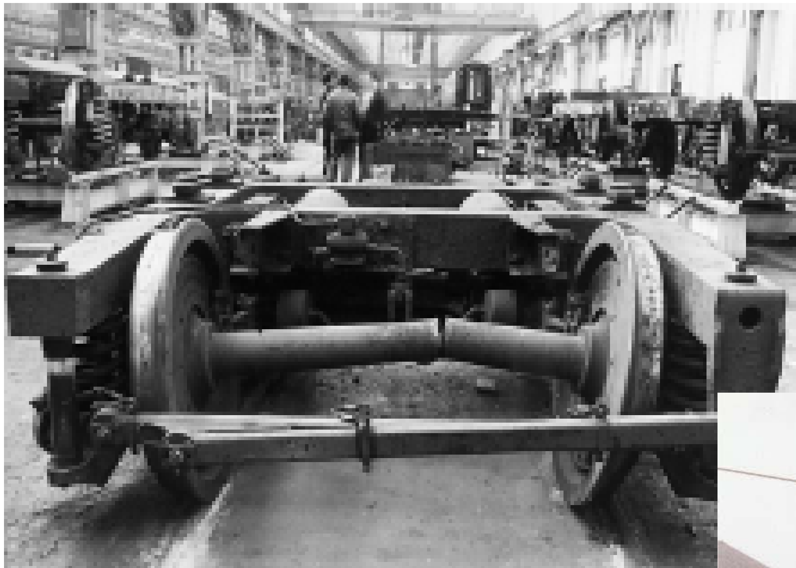
Wheelset whole life Cost Reduction

- Develop model to analyse cost drivers and indirect costs
  - – Wheelset management model – T792
- Provision of tool to drive down wheelset operational costs
  - – Automatic wheel lathe data collection – T577
- Optimisation of the wheel-rail interface
  - – Modelling of the wheel/rail system using VTISM including the wheel management model element

Wheelset Knowledge Retention and Application

- Identification of data, valuable material, knowledge, etc
  - – Collate data, information, etc that resides with representatives of the industry
  - – Historic information to support current practices
- Provide platform for industry to access
  - – Identify most appropriate repository for the information and means of making available to industry



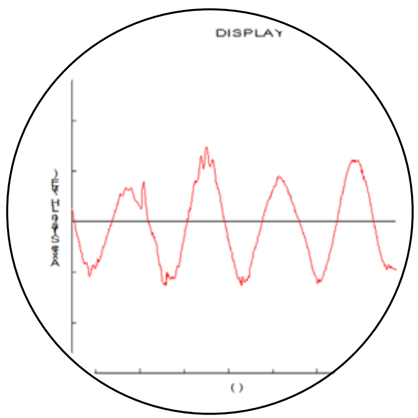



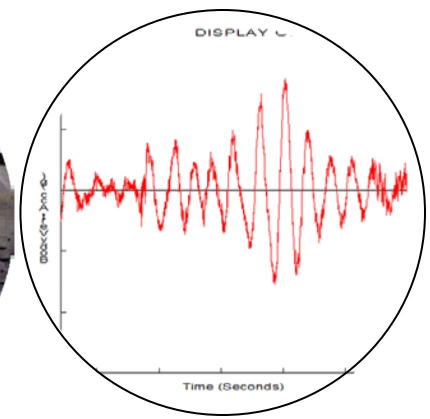
The UKAxle Project

RSSB T356: Optimising Wheelset Design and Maintenance

Presentation to ESIS

Milan, 13 – 14 October 2008





Project Partners

- **RSSB**
  - Management and funding of overall T356 programme
  - Link to stakeholders
  - Liaison with wider research programme (WIDEM, Deufrako)
- **DeltaRail**
  - Manage and carry out T356 work packages WP1 and WP3
  - Apply technical expertise and railway experience

Rail Safety & Standards Board

DeltaRail

Why do we need new Axle Design Standards?

- **Existing standards only address fatigue crack initiation**
  - Only valid for axles fully protected against corrosion and impact damage
  - Other axles will need regular NDT throughout their service lives
  - Existing standards do not provide a methodology to set the NDT periodicity
- **Existing standards do not take account of actual stress spectrum applied to axle**
  - Do not account for route geometry – likely to be non-conservative for LRT (Metro) type axles
  - Do not account for actual passenger load spectrum
- **Existing standards are not consistent for different axle layouts**
  - Tend to be over-conservative for outboard-journal powered axles
  - Can be non-conservative for inboard-journal powered axles
- **Has led to unexpectedly short NDT intervals for axles that actually comply with design standards**

Possible New Basis for Axle Design Standard

- **Use fracture mechanics to calculate probability of failure during service life, with or without NDT**
  - “Allowable” failure probability based on currently acceptable axle design?
  - Relative approach of this type has considerable operational advantages
- **Principal inputs to fracture mechanics based methodology**
  - Fracture mechanics model – to be considered in detail in RSSB Project T728 (currently underway) and recent WIDEM work
  - Axle material crack growth behaviour – RSSB Project T728 and WIDEM
  - Flaw size distribution – RSSB Project T728
  - Effectiveness of NDT procedures – considered in recent WIDEM work
  - **Axle stress spectrum – considered in RSSB Project T356. First stages of this work now complete**.

Rail Safety & Standards Board

DeltaRail

Background to RSSB Project T356

- **Aims**
  - Optimise the design and maintenance of wheelsets
  - Provide input to new European axle design standards
  - Reduce whole life costs
- **Work Package 1 (complete)**
  - Data acquisition for one UK vehicle type (Class 319 EMU)
  - Data validation and processing
- **Work Package 3 (complete)**
  - Use of WP1 data to develop predictive model
  - Validation for Class 319 EMU
  - Limited validation for a few other vehicle types (high speed locomotive and passenger coach)
- **Work needs to be extended to other vehicle types**

T356 Work Package 1 – Data Acquisition

- **Trial Vehicle: Southern Class 319 EMU**

- **Route: Bedford to Brighton & Sutton Loop**

Curvature (m)	% running	Linespeed (mph)	% running
< 500	3.5	< 25	1.4
500 - 1000	7.1	25 - 40	6.1
1000 - 1500	12.1	45 - 60	12.2
1500 - 2500	14.7	65 - 80	11.1
2500 - 5000	16.2	85 - 100	59.0
> 5000	46.4	> 100	10.2

T356 WP1 - Data acquisition process

- **Parameters measured:**
  - Bending strains at both ends and centre of axle: 2000 samples/sec
  - Torsional axle strains : 2000 samples/sec
  - Vertical axlebox accelerations: 2000 samples/sec
  - Lateral axlebox accelerations, and body accelerations in three directions: 500 samples/sec
  - Yaw damper displacement (curve radius): 500 samples/sec
  - Brake pressure and AWS detector (location on route): 500 samples/sec
  - Airspring pressure (passenger loading) and digital line: 1 sample/sec
  - GPS recorded to establish geographic location.
- **Test started March 2006 and finished January 2008**
  - Data downloaded approximately monthly
  - About 3 Terabytes of time history data recorded, covering 160,000 miles
- **Also strain histograms from data loggers, covering 240,000 miles**

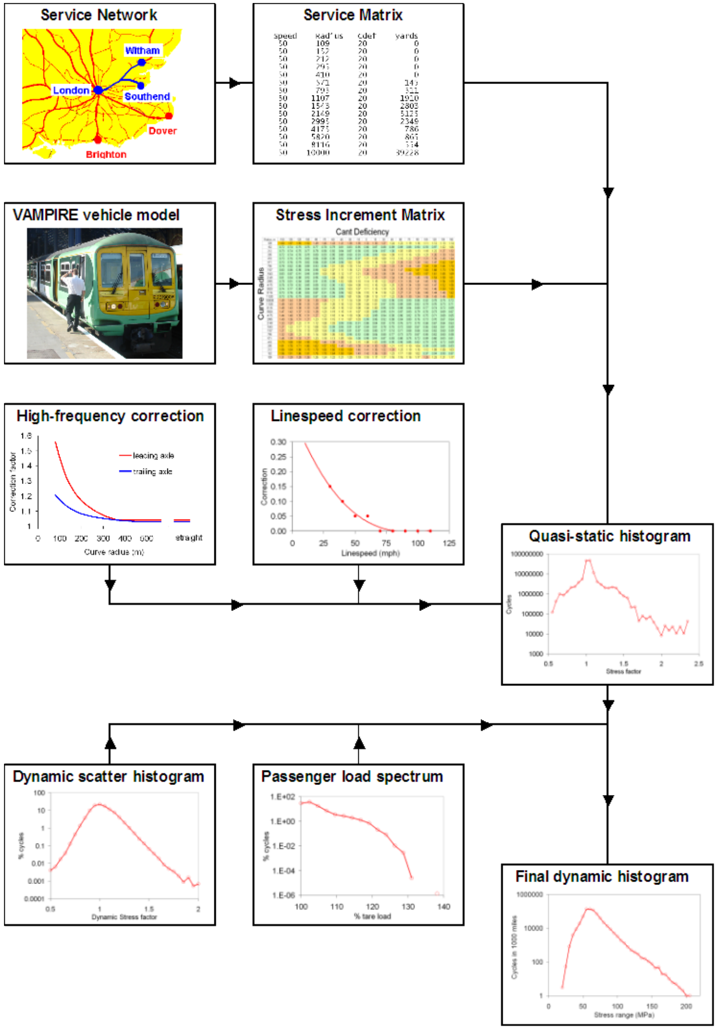
T356 Work Package 3 – Predictive Model

- **Use data measured in Work Package 1 to understand the influence of a range of inputs, for example:**
  - Route geometry and overall track quality
  - Effect of discrete irregularities such as S&C
  - Wheelset and suspension characteristics
  - Effect of braking and position of axle within train
- **Develop methodology to predict axle stress spectrum**
- **Validate for Class 319 EMU over test route**
- **Limited validation for other UK vehicles and routes**
- **Define directions for any further work**
  - Output intended to form a key input to new European standards

Axle stress prediction methodology - overview

- **Firstly calculate quasi-static stresses based on**
  - Axle load
  - Curvature of route
- **Then correct for influence of additional relevant parameters**
  - High frequency dynamic forces
  - Discrete irregularities (e.g. S&C or wheelflats)
  - Braking loads
  - Changes in wheel profile
- **But which effects are important?**
  - Class 319 measurements used to find out
- **Leads into proposed methodology**

Axle stress prediction methodology - overview



Axle stress prediction methodology - stage 1

- **Service route expressed as a matrix ("Service Matrix") of geometry and track quality**
  - Geometry expressed by curve radius and cant deficiency
  - Track quality best expressed by line speed**.** Currently no routinely measured track quality parameter that can be directly related to axle stress

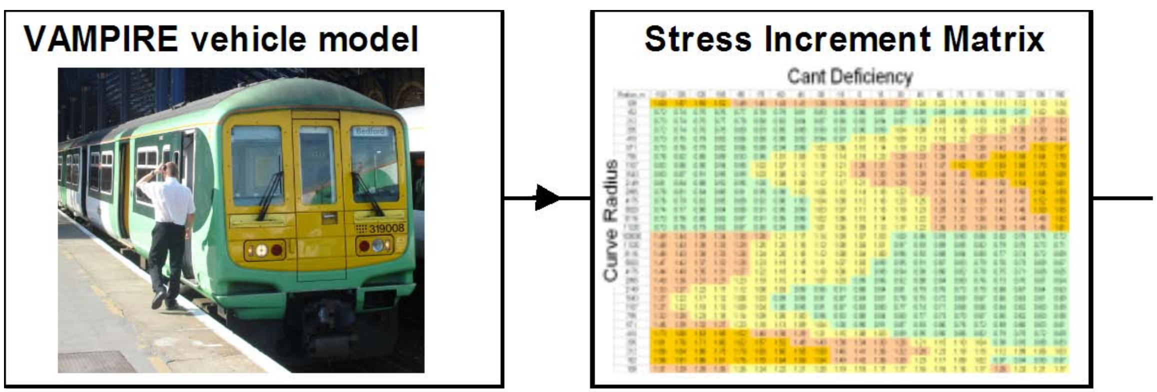
Service Network

Service Matrix

Speed	Radius	Cdef	yards
50	109	20	0
50	152	20	0
50	212	20	0
50	295	20	0
50	410	20	0
50	571	20	145
50	795	20	511
50	1107	20	1910
50	1543	20	2803
50	2149	20	5125
50	2995	20	2349
50	4175	20	786
50	5820	20	865
50	8116	20	554
50	10000	20	39228

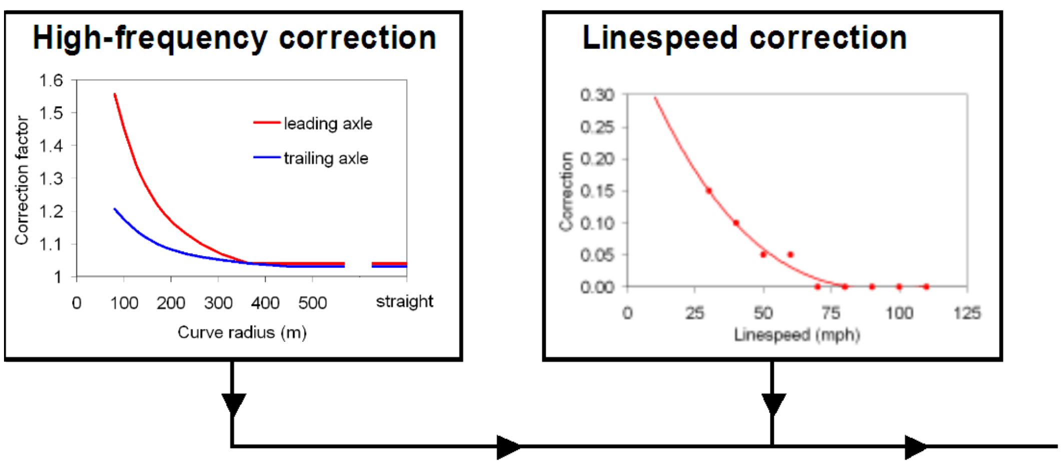
Axle stress prediction methodology – stage 2

- **A railway vehicle track interaction package, such as VAMPIRE®, is used to predict wheel/rail forces generated in quasi-static curving**
  - Calculate for the same combination of curvature and cant deficiency as in the Service Matrix
  - Derive the increment in axle stress for these geometry cases (“Stress Increment Matrix”)



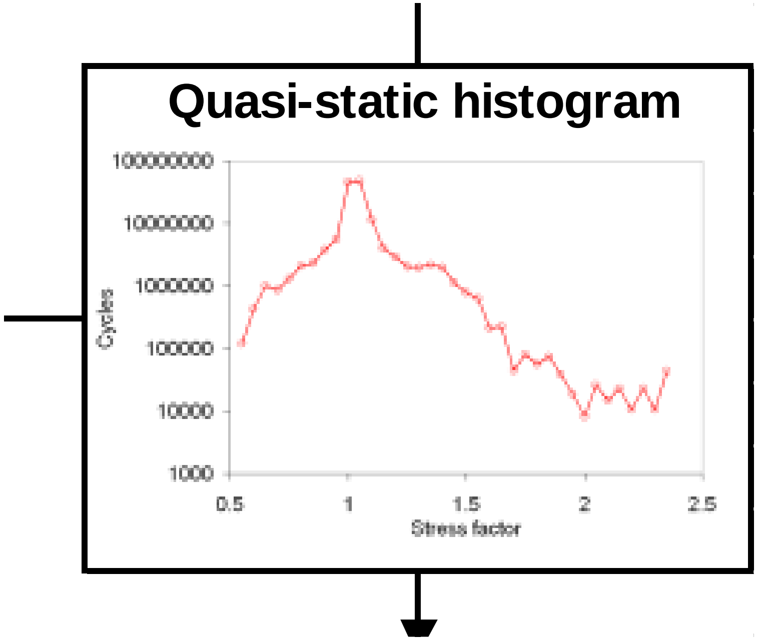
Axle stress prediction methodology – stage 3

- **Corrections are applied to the quasi-static Stress Increment Matrix to allow for the effects of high frequency behaviour and track roughness as a function of line speed.**
  - Both these corrections are currently derived from Class 319 measurements, but in principle they should apply to the particular vehicle and perhaps route under consideration**.**



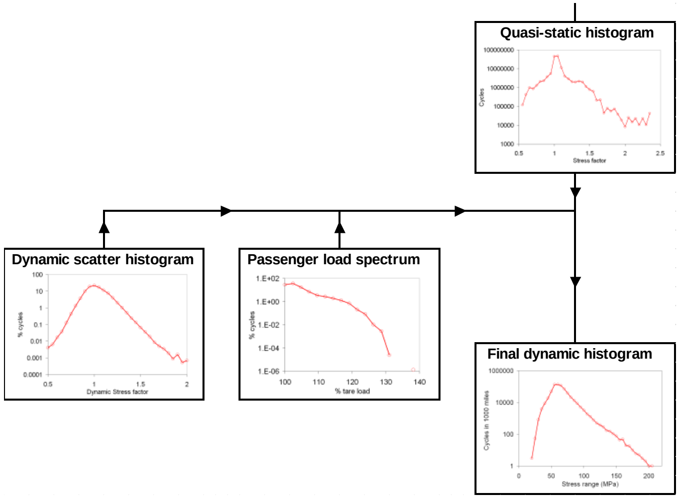
Axle stress prediction methodology – stage 4

- **The Service Matrix and corrected Stress Increment Matrix are combined to derive a “Quasi-static histogram” of stress increment against percentage of cycles.**



Axle stress prediction methodology – stage 5

- **The final dynamic axle stress histogram is derived by combining:**
  - static stress
  - quasi-static histogram
  - dynamic scatter histogram, which characterises the effect of track roughness,
  - passenger load spectrum (if appropriate)



Rail Safety & Standards Board

DeltaRail

Sensitivity analysis methodology

- **List input parameters that might influence axle strain**
- **Define reasonable range of inputs that might occur on UK railways**
- **Determine effect on axle stress**
  - use measured Class 319 data and/or VAMPIRE® simulations
- **Determine effect on failure probability using a probabilistic fracture mechanics model developed by DeltaRail**
  - standard axle NDT assessment methodology
  - assume far end scan at periodicities between 125,000 and 1 million miles
- **Parameters divided into three final categories**
  - must be included in model to predict stress histograms
  - should be included as correction factors on failure probability
  - not significant and can be discounted

Results of sensitivity analysis (1 of 7)

- **Route, covering track curvature, cant deficiency, and track quality (expressed in terms of linespeed)**
  - Increase in failure probability between least severe (Kings Cross – Peterborough) and most severe (North London Line) UK routes: **11.7**
  - Increase in failure probability from including track roughness: **2.3**
  - Reduction in failure probability from using an approximation of Class 319 service network: **1.3**
  - Conclusion: track geometry and quality must be included in predictive model
  - 1.3 factor taken as threshold of sensitivity. Any change that gives a larger factor should be included in predictive model

Results of sensitivity analysis (2 of 7)

- **Discrete track irregularities, such as dipped joints, lateral misalignment, and S&C**
  - Cannot easily be included in model (track data not available)
  - Effect investigated by removing small groups of large cycles from measured strain data – reduced calculated failure probability by a factor of **1.2**
  - Discrete irregularities not regarded as significant for axles according to proposed criterion
  - Included implicitly anyway in proposed model as part of track roughness

Rail Safety & Standards Board

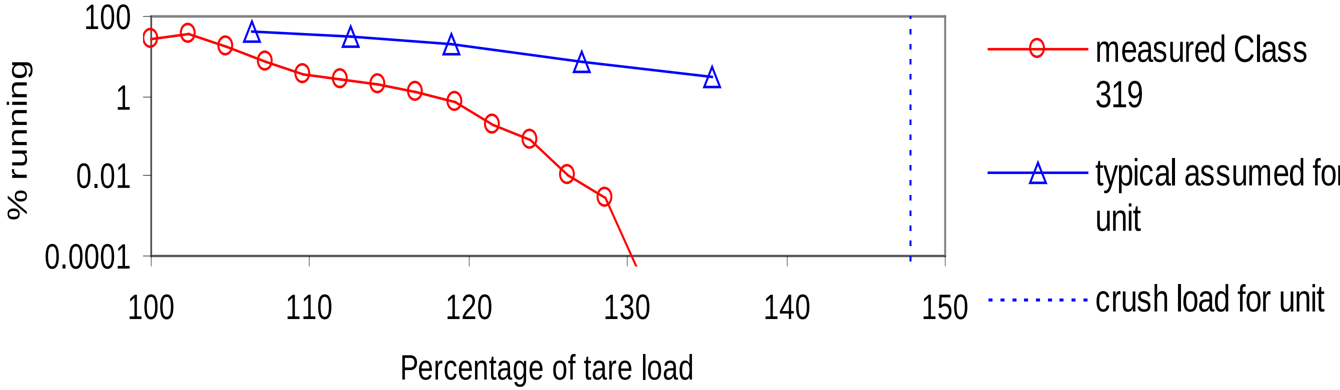
DeltaRail

Results of sensitivity analysis (3 of 7)

- **Vehicle type, covering wheelset and suspension parameters**
  - Class 319, Mk4 coach and Class 91 locomotive compared over a range of routes
  - Maximum difference in failure probability between vehicles: **2.4.** This is significant and means that vehicle type must be included in predictive model.
- **Static Axle Load**
  - Increase in calculated failure probability from 5% overestimate in calculation of tare static stress: **1.75**
  - Increase in failure probability if Class 319 axle load was increased to maximum allowable according to BASS design standards (currently 80% of allowable): **14**
  - Conclusion: static stress must be calculated accurately

Results of sensitivity analysis (4 of 7)

- **Passenger Load Spectrum**
  - Measured for Class 319 from airspring pressure. Shows that previous estimates for multiple unit trains and current standards requirements are grossly conservative



  - Increase in calculated failure probability if estimated spectrum used instead of measured: **3.3**
  - Conclusion: Passenger load spectrum must be included

Results of sensitivity analysis (5 of 7)

- **Weather, influencing wheel/rail friction**
  - No observable effect from considering similar runs under different weather conditions
  - Does not need to be considered in model.
- **Braking**
  - Effect depends on brake configuration. Including realistic Class 319 braking conditions could increase failure probability by up to **1.3**
  - Conclusion: as braking is relatively easy to incorporate into predictive model, it should be included

Rail Safety & Standards Board

DeltaRail

Results of sensitivity analysis (6 of 7)

- **High Frequency Behaviour**
  - defined as any cycles of a frequency greater than that corresponding to maximum wheel rotation frequency (~20 Hz). More marked on tight curves - stick-slip behaviour?
  - Included by an empirical correction in predictive model. Resulting increase in calculated failure probability: **2.4**
  - Conclusion: Should be included in predictive model
- **Position of Axle in Train**
  - Proposed European axle design standards assume a more severe environment for leading axle of train
  - Confirmed by Class 319 test. Failure probability **1.3** times higher for leading axle compared to centre of train
  - Conclusion: may be appropriate to apply correction to calculated failure probabilities

Results of sensitivity analysis (7 of 7)

- **Long term changes, including wheel wear and suspension degradation**
  - Axle stress environment became less damaging as test progressed
  - Reason not clear, but could be linked with changes in wheel profiles – more work needed
  - If such changes are to be included, best as correction to calculated failure probabilities
- **Wheel Defects, covering wheelflats and out-of-round wheels**
  - can have significant effect on axle stress, but severe cases will not remain in service for long, particularly if WHEELCHEX on route
  - Probable maximum increase on failure probability: **1.2**
  - Conclusion: can be ignored for purposes of model

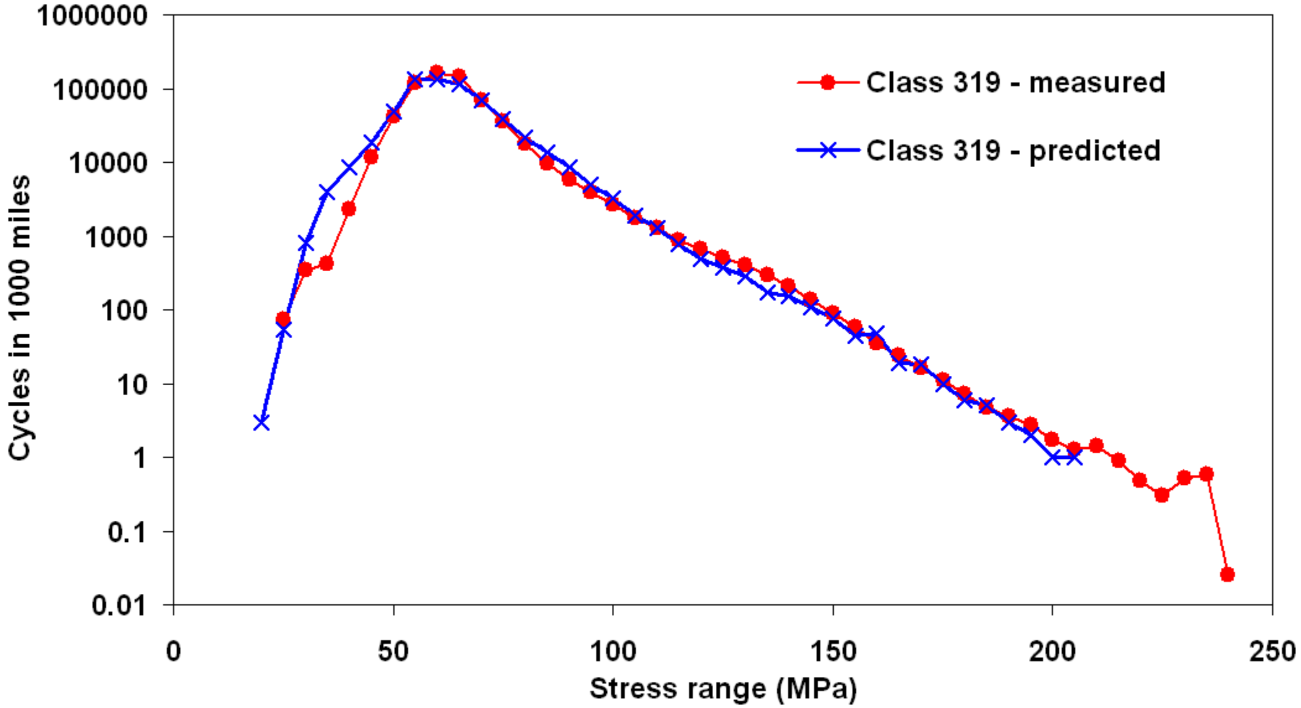
Summary of sensitivity analysis

- **Parameters that need to be included in synthesising axle stress histograms:**
  - Route geometry and quality, vehicle type, static axle load, passenger load spectrum, braking (for some brake configurations), high frequency behaviour
- **Parameters that may need to be included by applying corrections to calculated axle failure probabilities.**
  - Leading axle in train effects, long term changes in wheelset
- **Parameters that do not need to be included because their effect is not significant:**
  - Discrete track irregularities, weather, wheelflats and out-of-round-wheels (for routes fitted with WHEELCHEX)

Validation

- **Stage 1 – Replicate Class 319 measured strain data over extended period of running (2 months)**
- **Stage 2 – Extend to further vehicles and routes, by replicating readily available measured axle stress histograms**
  - Mk4 coach measured from Kings Cross to Glasgow
  - Mk4 coach measured from Kings Cross to Peterborough (particularly straight route)
  - Class 91 locomotive measured over 105 miles covering various portions of the ECML
  - Some approximation necessary (track roughness and high frequency behaviour assumed identical to Class 319 as measured)

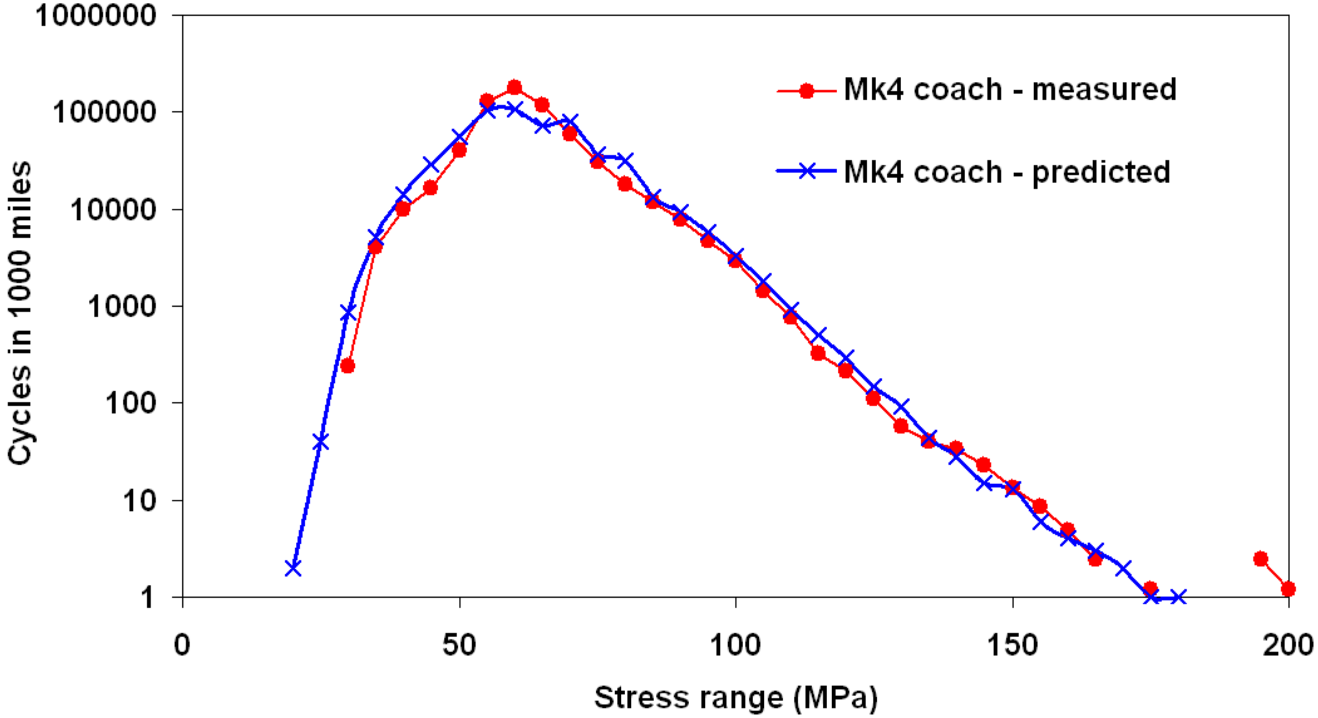
Validation: Class 319 histogram



Calculated Failure Probabilities at 125,000 mile UAT interval:

- Based on measured histogram: 0.000451%
- Based on predicted histogram: 0.000415%
- Measured / Predicted: 1.09 (within 1.3 threshold)

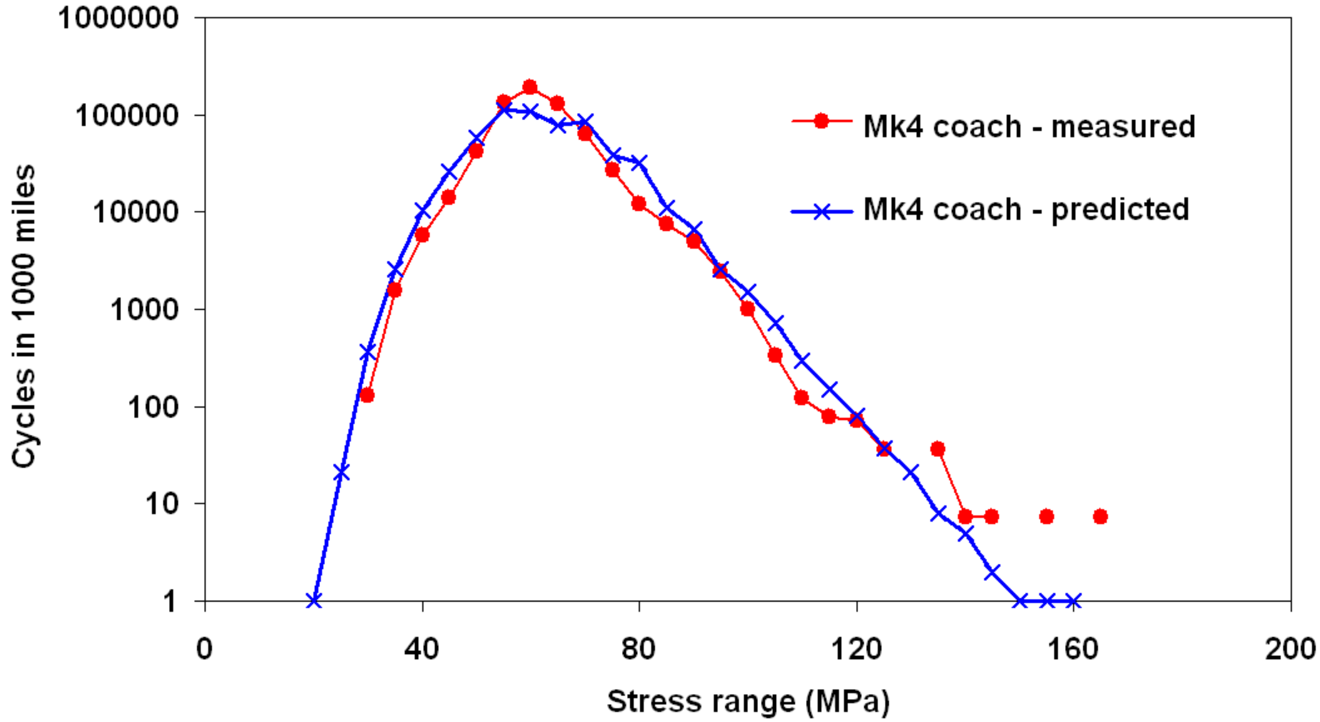
Validation: Mk4 coach, Kings Cross - Glasgow



Calculated Failure Probabilities at 125,000 mile UAT interval:

- Based on measured histogram: 0.000223%
- Based on predicted histogram: 0.000328%
- Predicted / Measured: 1.47

Validation: Mk4, Kings Cross - Peterborough



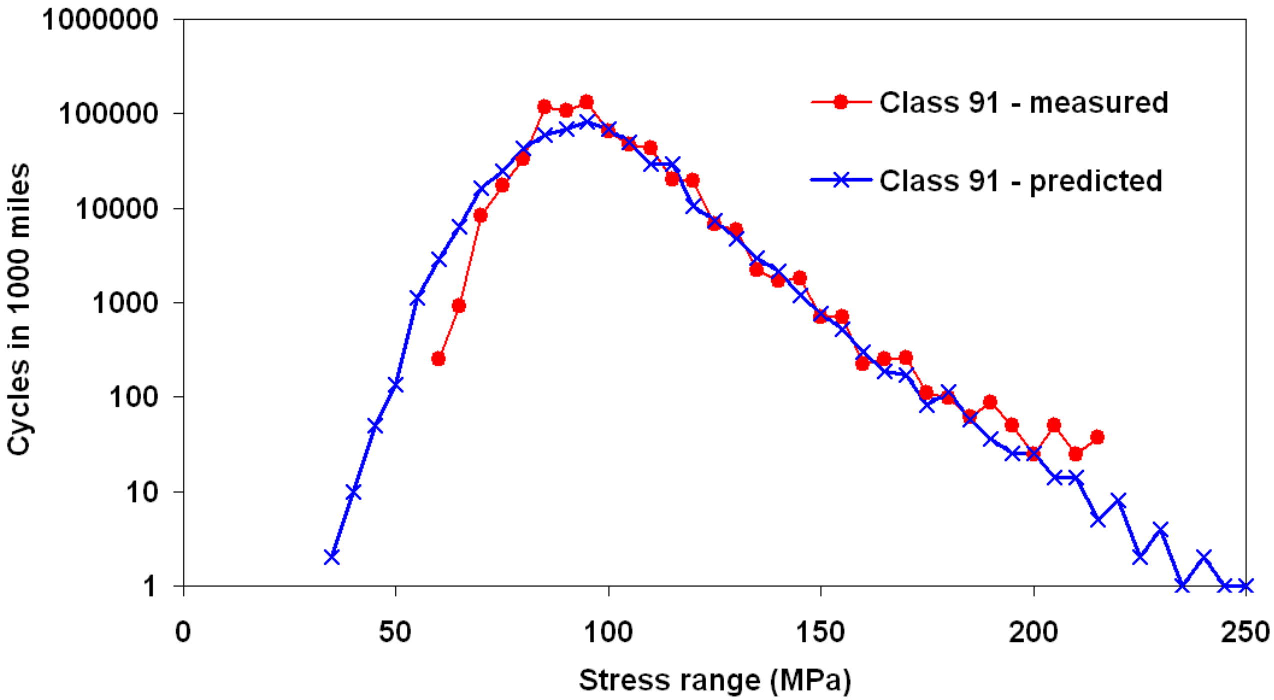
Calculated Failure Probabilities at 125,000 mile UAT interval:

- Based on measured histogram: 0.000071%
- Based on predicted histogram: 0.000107%
- Predicted / Measured: 1.51

Rail Safety & Standards Board

DeltaRail

Validation: Class 91, 105 miles of ECML



Calculated Failure Probabilities at 125,000 mile UAT interval:

- Based on measured histogram: 0.0153%
- Based on predicted histogram: 0.0125%
- Measured / predicted: 1.22

Additional Findings from T356 WP3

- **Class 319 unpowered axle is significantly overdesigned**
  - However very little opportunity to reduce the diameter whilst maintaining safety levels
  - NDT periodicity could be safely extended
- **Class 319 unpowered axle subject to static torsion and torsional oscillation, but the stress amplitudes are not large enough to affect the structural integrity of the axle.**
- **Running within depots and sidings can be very damaging per mile run (tight curves), but the actual mileages involved are not large enough to be significant**
- **For relatively long service routes, axle tests should cover at least 500 miles of representative track**

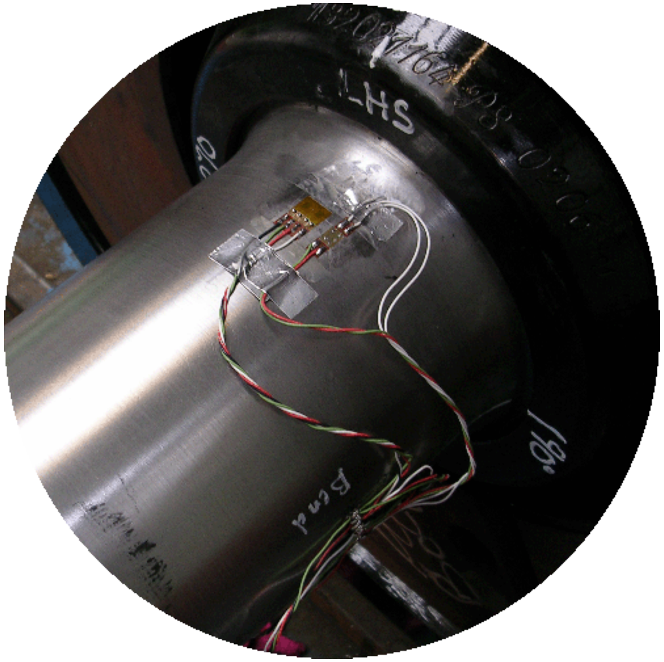
Future work for RSSB T356

- **For use in a European design standard, the proposed methodology would need to cover all UK and European vehicles and routes**
  - Needs to include vehicles with inboard journals
  - Needs to include LRT routes with tighter curves than mainline routes
- **Measured axle strain histograms are needed to determine the effect of track roughness and high frequency for other vehicles**
  - Some suitable data already available from previous tests
  - Little or no axle strain data for freight wagons
- **Possible work programme**
  - Review existing axle data in UK and Europe
  - Additional testing if necessary
  - Further development and validation of proposed predictive model to include all required vehicles and routes

Rail Safety & Standards Board

DeltaRail

Questions and discussion…



How good are axle non-destructive testing techniques?

John Rudlin TWI

TWI
Technology
Engineering

ESIS TC 24 3/4 March 2011

Copyright © TWI Ltd 2011

Content

- Methods of NDT for Fatigue cracks
- Capabilities
- Inspection for Corrosion?

Copyright © TWI Ltd 2011

Methods of Axle NDT

- Visual
- Surface Accessible
  - MPI
  - Eddy Current
  - ACFM
  - Ultrasonics
- Sub-Surface or Non-accessible
  - Ultrasonics
- Latest Developments

Copyright © TWI Ltd 2011

MPI

Copyright © TWI Ltd 2011

MPI

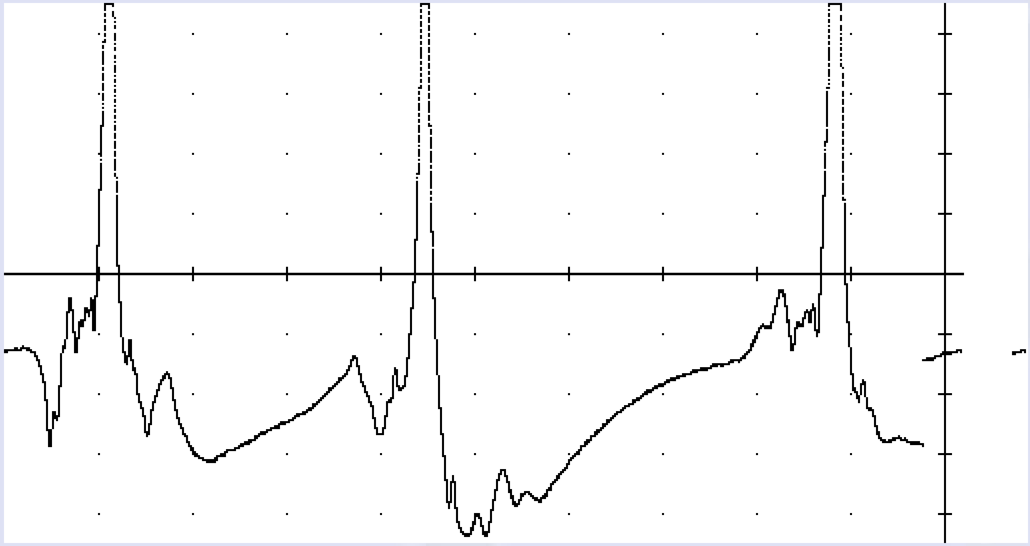
- Carried out at overhaul with wheels removed (so inspects normally inaccessible areas)
- Clean (grit blasted) surface ideal
- Bench Unit
- Visual indication of crack
- Operator Dependent (equipment set up/interpretation/alertness)

Copyright © TWI Ltd 2011

Eddy Current Probes

Copyright © TWI Ltd 2011

Eddy Current Signal (2mm deep crack)



Copyright © TWI Ltd 2011

Eddy Current/ACFM

- Can be carried out on exposed surfaces with axles in-situ
- Requires “small” probe to scan surface
- Can scan though non-conductive coatings/with minimum cleaning
- Visual/audible indication from instrument
- Requires operator to have manual dexterity as well as interpretation skills and alertness

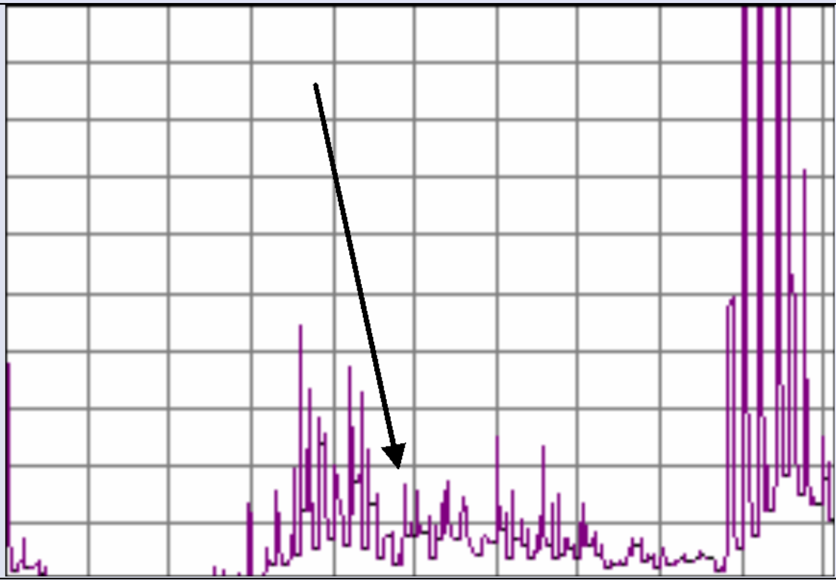
Copyright © TWI Ltd 2011

Far end UT in progress

TWI
Technology
Engineering

Copyright © TWI Ltd 2011

Examples of Signals

Complex Geometry	Simple Geometry
	
MASTER 0 DEG (DOUBLE CRYSTAL) CLASS 455 G.E. SAMPLE E	MASTER 0 DEG (DOUBLE CRYSTAL) CLASS 455 N.G.E. SAMPLE E
17% F.S.H. @ 4.8 DIVISIONS	F.S.H 24% @4.2 DIVISIONS

Copyright © TWI Ltd 2011

Ultrasonics (exposed and non-exposed surfaces)

- Scans from axle end (far end test, near end test)
- From axle body (high angle scan, internal bore scan)
- Requires clean surfaces and applied couplant

Copyright © TWI Ltd 2011

Ultrasonics (exposed and non-exposed surfaces)

- **Detection of cracks subject to skew and tilt relative to ultrasonic beam (probe and frequency), gape of crack and axle geometry**
- **Generally poorer detection capability than surface methods**
- **Manual operation highly skilled – automation introduced for some cases**

Copyright © TWI Ltd 2011

Performance Assessment

- Usually needed as probability of detection (POD) curves
- False Calls also important
- Can be assessed by:
  - Anecdotal evidence
  - Expert opinion
  - Measurement of Indications
  - Inspection Reliability Trials

Copyright © TWI Ltd 2011

MPI

- Difficult to measure (frequently used as reference)
- Expectation of crack detection less than 1mm deep on good surfaces
- Sometimes false calls from scratches/machining marks

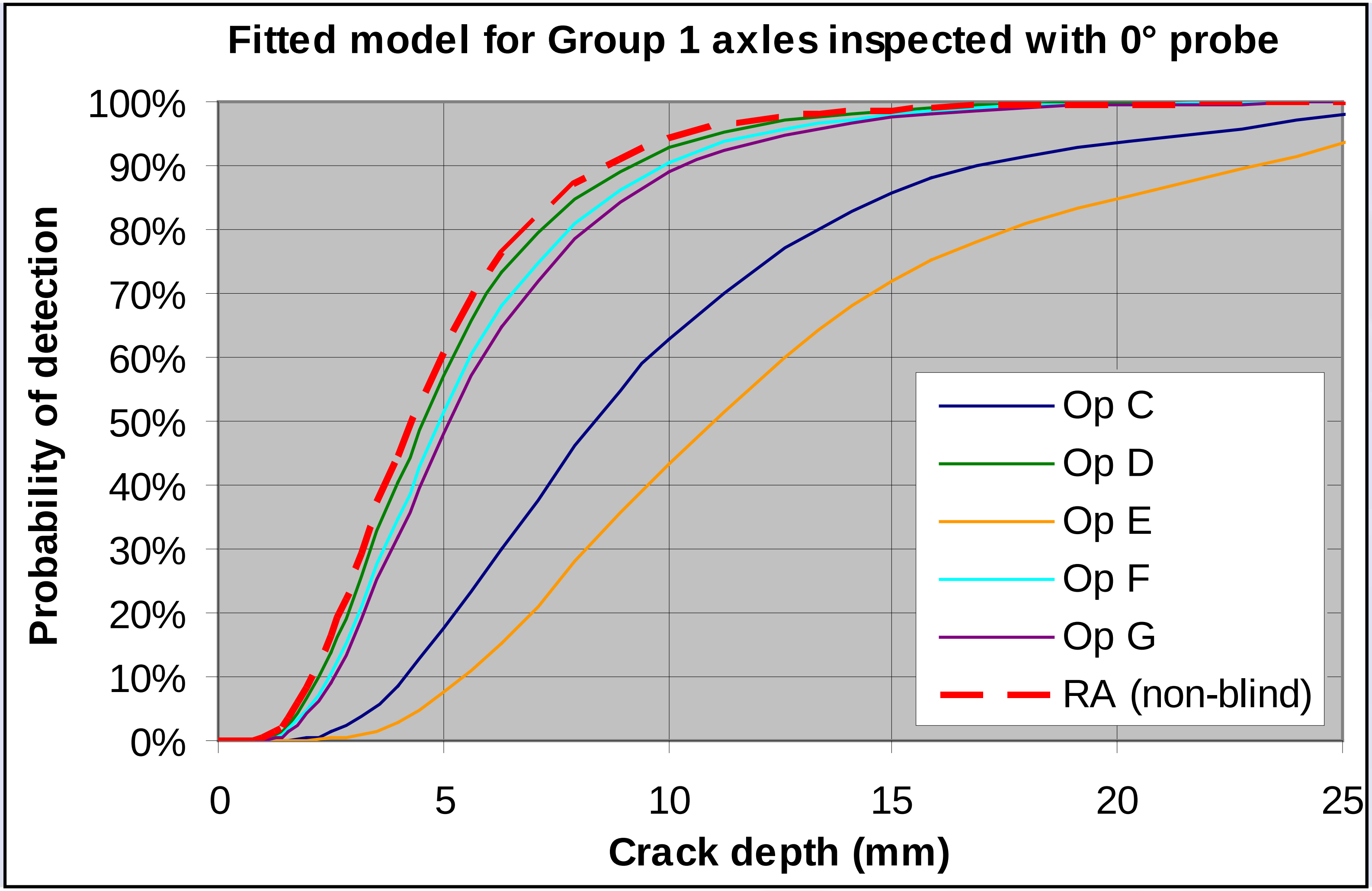
Copyright © TWI Ltd 2011

Eddy Current

- Sensitivity approaches MPI
- Cracks of 1mm deep can be expected to give 100% screen height signal with around 20% noise from surface
- (Unable to produce POD in WIDEM because 90% POD was less than 1mm crack depth)

Copyright © TWI Ltd 2011

Far End PODs – Simple Geometry, 0° probe

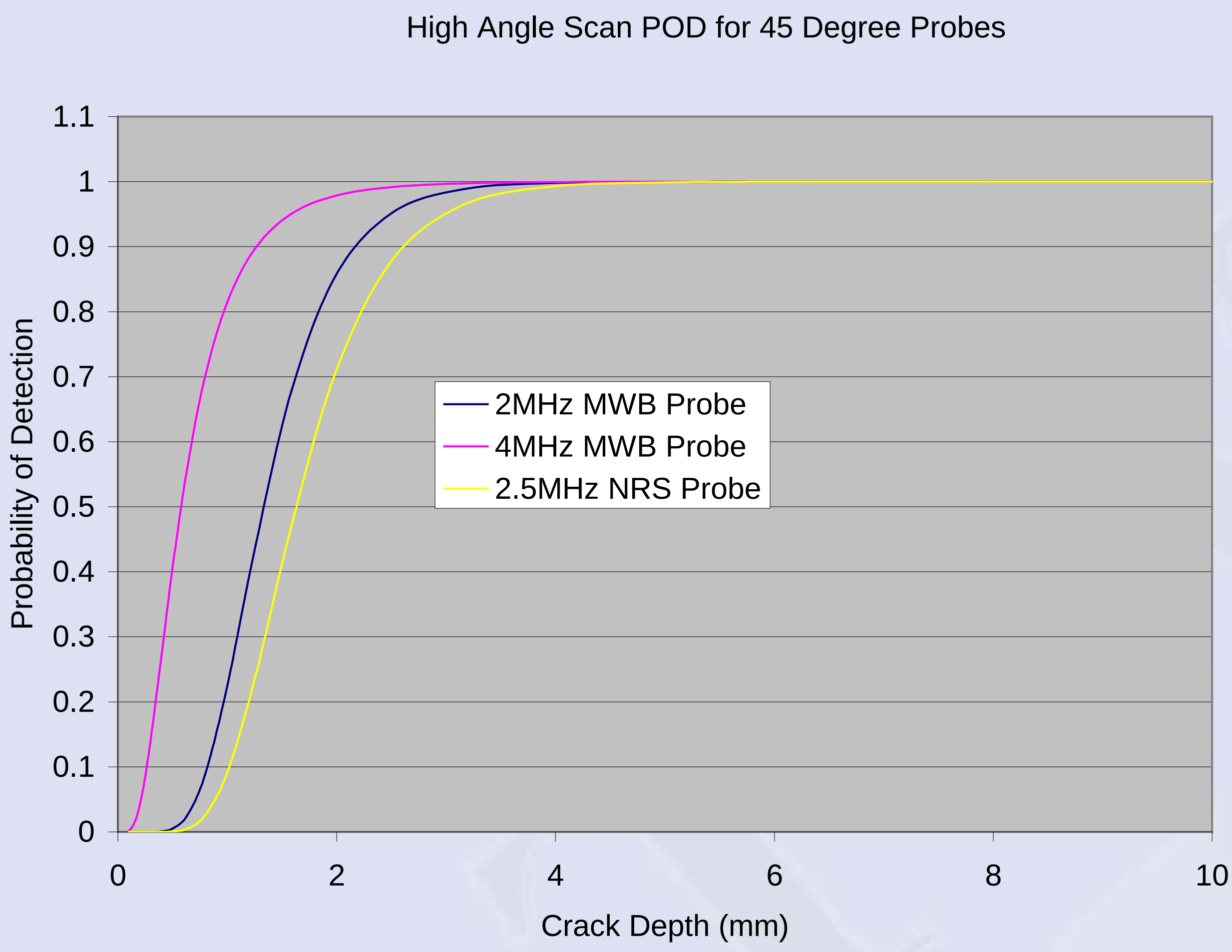


TWI Technology Engineering

ESIS TC 24 3/4 March 2011

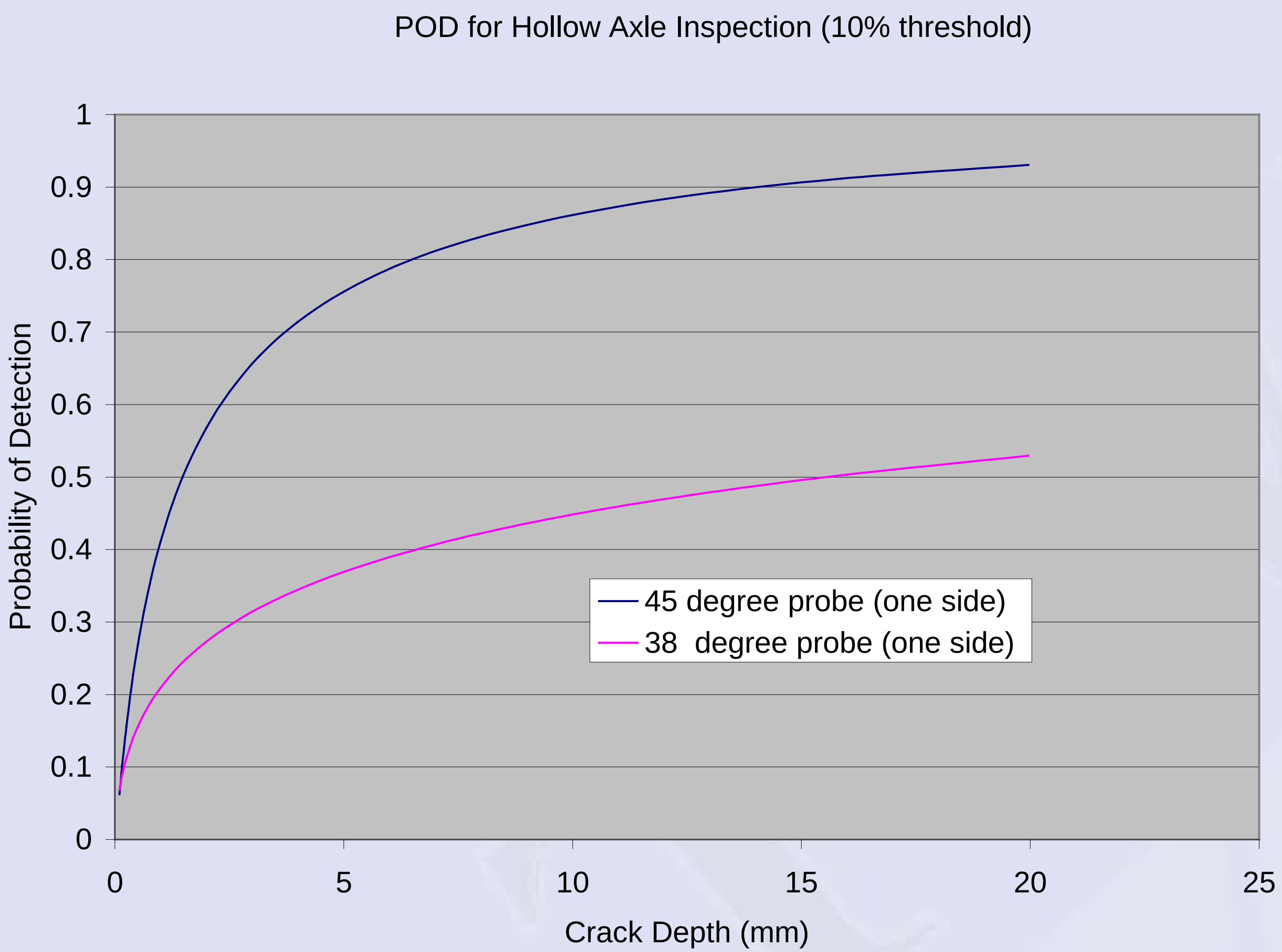
Copyright © TWI Ltd 2011

High Angle Scan



Copyright © TWI Ltd 2011

Hollow axle Bore Inspection

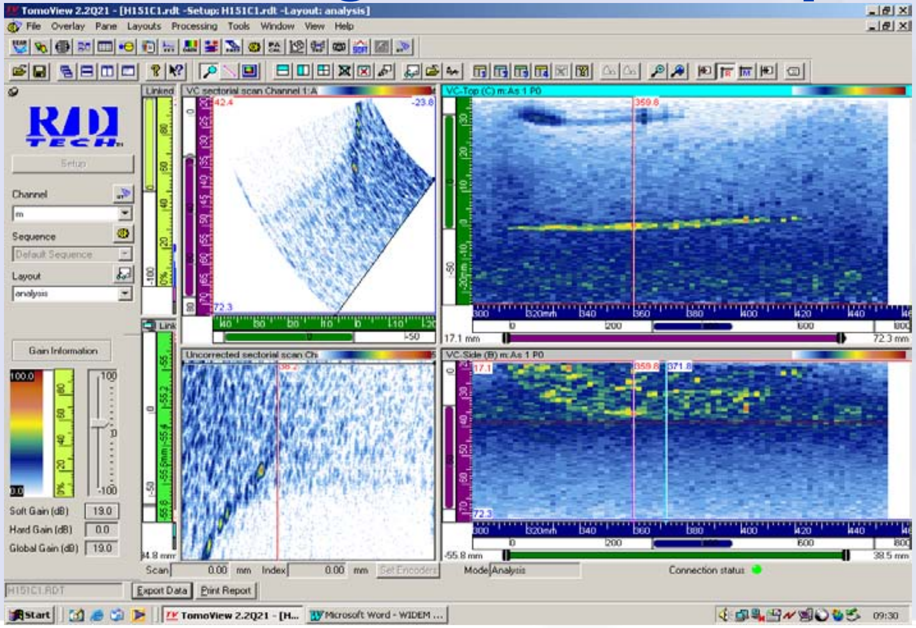


Copyright © TWI Ltd 2011

New UT: Phased Array

- **Produces electronically scanned beam and image of any flaws**
- **Easier for operator interpretation?**

Automatic scanning to reduce operator error



Copyright © TWI Ltd 2011

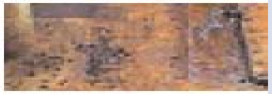
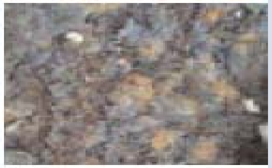
Conclusions for fatigue cracks

- For surface flaws surface methods give best results
- For UT inspection best results from high angle type inspections if possible
- Always bear in mind the effect of crack and component geometry and interaction with UT beams
- Human factors affect all techniques (even automated techniques have to be set up and checked to establish reliability)

Copyright © TWI Ltd 2011

Assessment of Corrosion

- **Currently visual inspection only – highly qualitative**
- **Reference standards? Pit gauge?**

Category	Description	Pit metal loss measurement (mm)	Pictorial exampl
C1	Light surface corrosion relative to substrate thickness, little (<2mm) or no scale.	=<0.5mm	
C2	Moderate surface corrosion with scale (>2mm, =<5mm) and pitting, slight substrate loss profile.	=<2.5 mm	
C3	Heavy corrosion and scale (> 5mm), clearly visible substrate loss profile and/or deep frequent pitting after scale removal.	> 2.5mm, =<5mm	
C4	Severe corrosion highly visible substrate loss profile, evidence of detachment of heavy (> 5mm) scale, further scale formation and metal loss. Dependent upon section thickness, may exhibit structural deformation and/or penetration of substrate.	> 5mm	

TWI
Technology
Engineering

Copyright © TWI Ltd 2011

Useful for axles?

Pit Depth

<0.5mm

<2.5mm

<5mm

>5mm

Copyright © TWI Ltd 2011

Corrosion fatigue

- Corrosion fatigue more subtle than this!

- What to measure?
  - Remaining thickness?
  - Surface roughness/shape parameters → early crack initiation at low loads or ?
  - Changes over time?
- How to measure?
  - Optical/electromagnetic/other

Copyright © TWI Ltd 2011

WOLAXIM Project

- **EU funded R4SME project developing 3 new NDT techniques-one of which is a to develop an instrument for corrosion assessment related to risk of crack growth**
- **www.wolaxim.eu**
- **Also EURAXLES project**

Copyright © TWI Ltd 2011

Presentation prepared for xxx by TWI
under Project No. yyy

Copyright

TWI holds copyright on this presentation.

All rights reserved. No part of this presentation may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopy, recording, or any information storage and retrieval system, without the express permission of TWI.

Copyright © TWI Ltd 2011

POLITECNICO DI MILANO

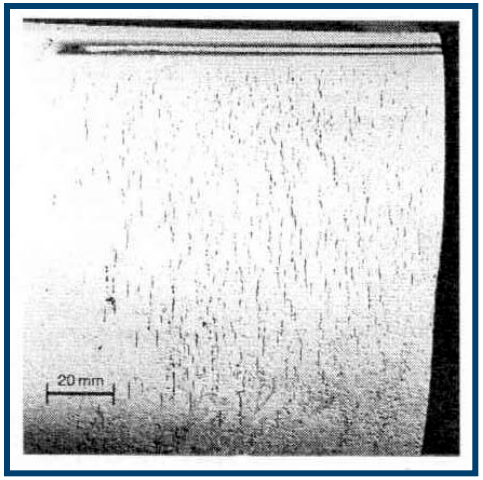
Environmental Effects on Fatigue and Fracture Propagation of A1N Grade Railway Steel

S. BERETTA, M. CARBONI, A. LOCONTE

Politecnico di Milano, Department of Mechanical Engineering

Funded by a MIUR 2004 project – *Maintenance of Freigth Trains*

- **Rickerscote**, Stafford (UK) – 8 March 1996
  - On an axle (1970): crack 50 μm deep; others by mean 30 μm
- **Shields Junction**, Scotland (UK) – 29 January 1998
  - Many cracks: the deepest 12 mm
  - Ductile fracture 15% of section
- **Bennerley Junction**, Nottingham (UK) – 21 June 2002 – MGR
  - On an axle (1968) slow propagation of the crack (~120 mm)
  - Ductile fracture 25% of section
- **Trudel**, Quebec (Canada) – 15 February 2001
  - *Corrosion fatigue* break near a journal on the external fillet (5 other failures related to corrosion)



Hoddinott, 2004

Relevant for Heavy Haul & Freight

(Lonsdale & Stone)

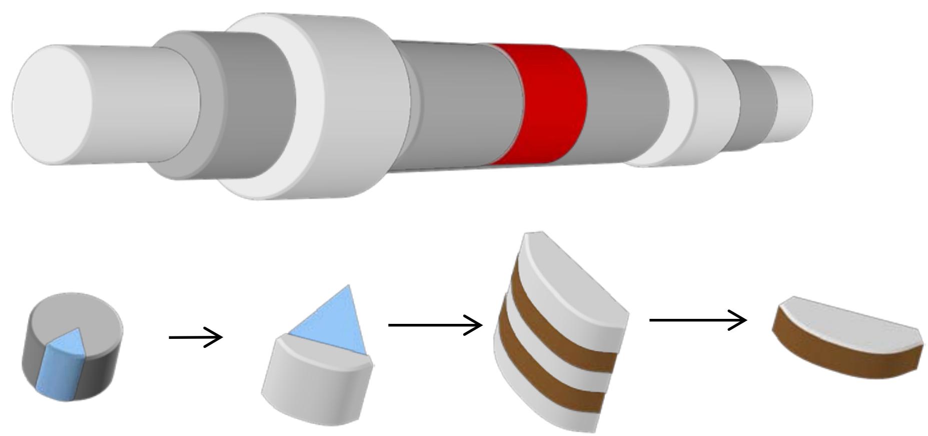
CORROSION PITS ANALYSIS
Analysis of corrosion in retired axles

three A1N steel railway axles retired from service

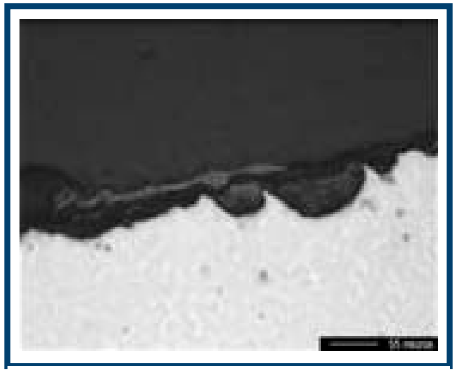
05-046A
(1978)

05-046B
(1991)

05-046C (1984)



CORROSION PITS ANALYSIS
Analysis of corrosion in retired axles

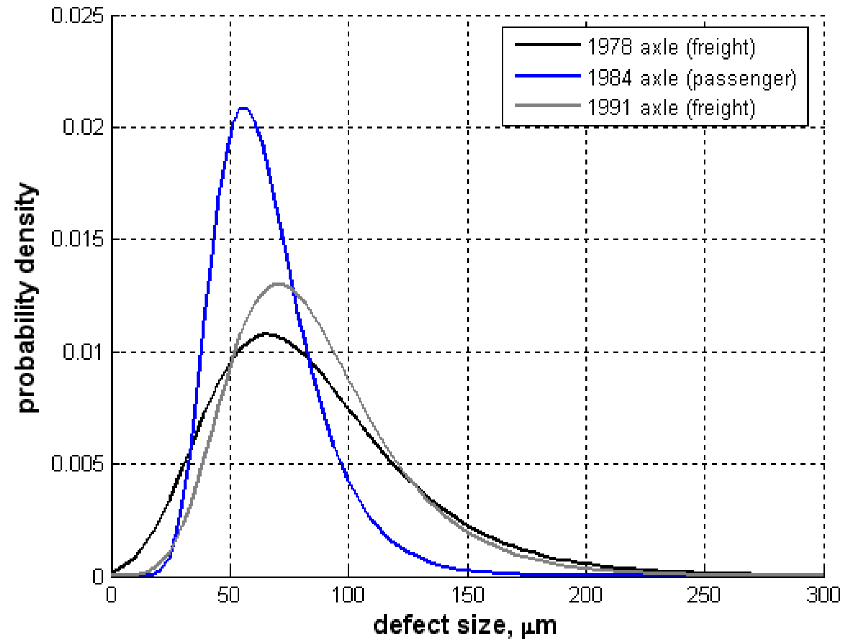


Typical pit (200x)

Sharp pit (500x)

Size measured as √area

Analysis with ‘statistics of extremes’



Estimated maximum defects in an axle:

350 – 550 µm

No indications for design in 13103 !

Is corrosion relevant for fatigue properties of A1N ?

Ideas for assessment of crack growth ?

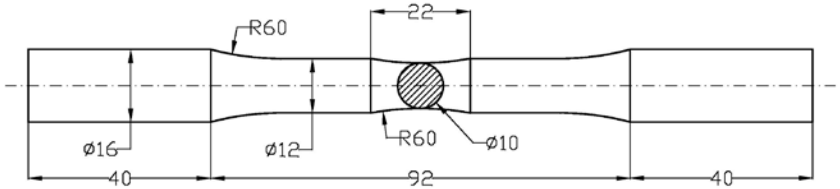
- **Fatigue tests in air**
  1. Kitagawa diagram (fatigue strength vs. defect size)
- **Bending corrosion fatigue tests**
  1. Dropping system and test plan
  2. S-N diagrams
  3. Fractographies and Microscopical analysis
- **Conclusions**

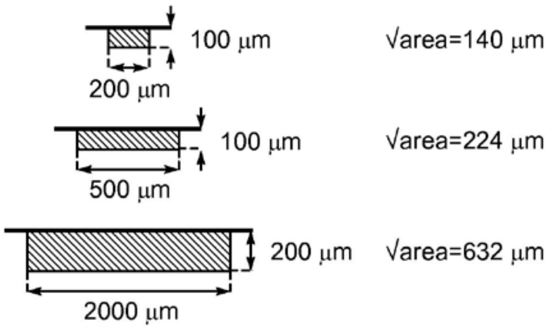
  Prospective S-N diagram for design

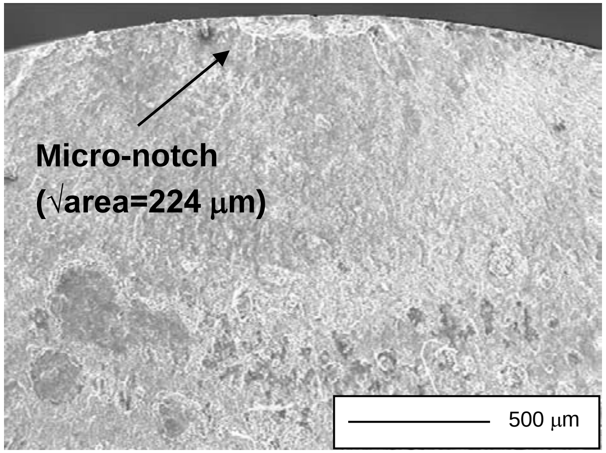
  Propagation ?

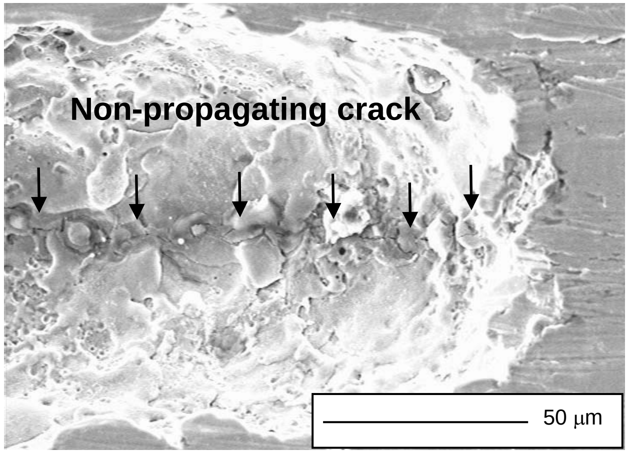
FATIGUE TESTS in AIR
Test description

Smooth and micronotched specimens subjected to fatigue limit tests (stair-case sequences, interruption at 10^7 cycles)







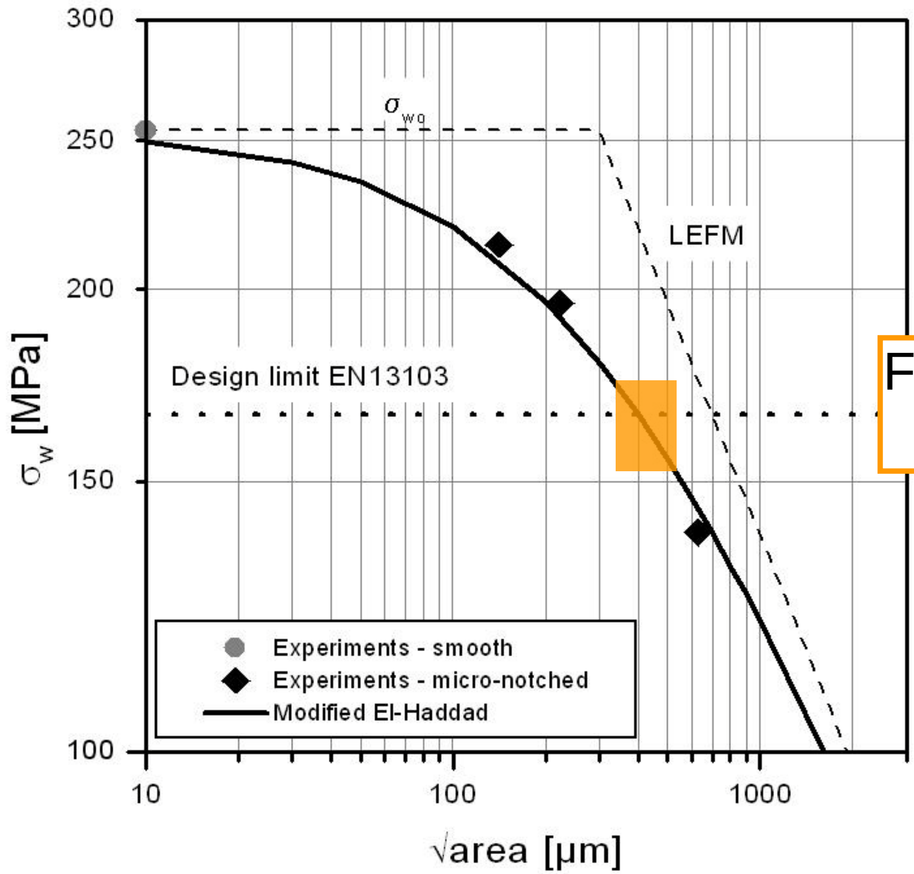


non-propagation of cracks (ΔK_{th}) ↔ Non-propagating cracks on specimens survived 10^7 cycles

AXIAL FATIGUE TEST
Kitagawa diagram

Relationship between fatigue limit and defect (crack) size

Safety factor

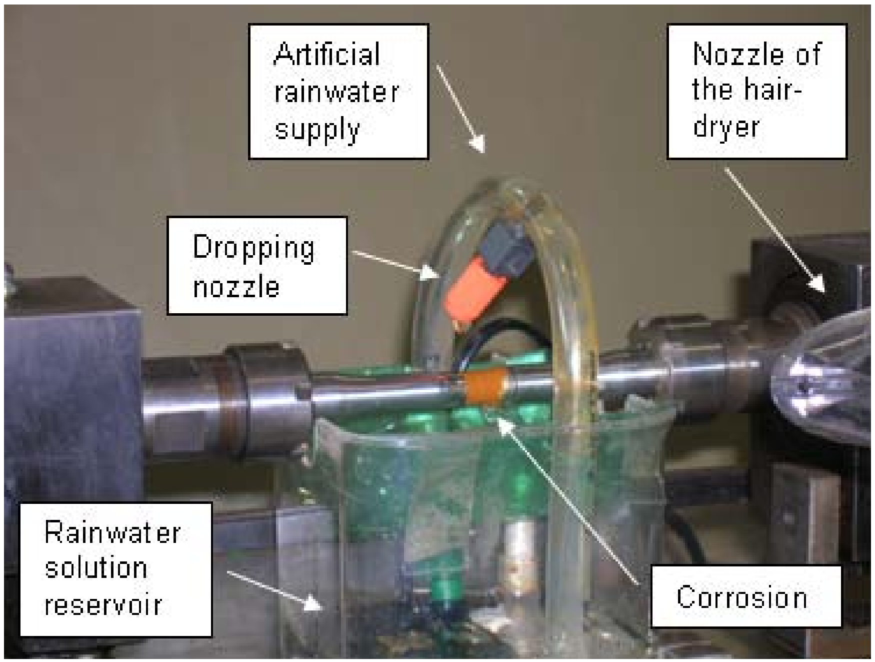


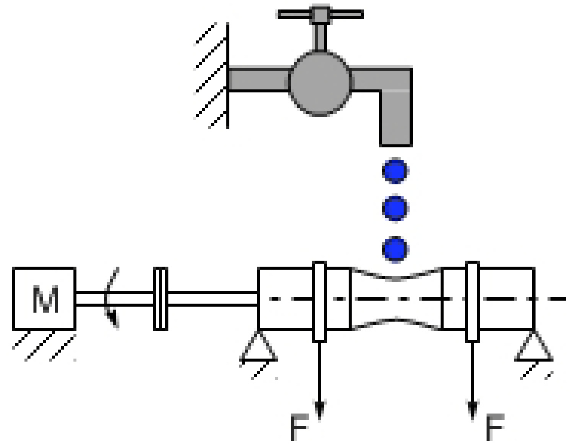
Fatigue limit for detected corrosion defects

Safety factor

If we treat corrosion damage as defects (mechanical effect) design limit drops to approx. 100 MPa (BASS indications for allowance of corrosion)

Investigation of rotating bending fatigue limit onto specimens corroded by dropping synthetic rain (pH5)





- frequency 8 Hz;
- wet-dry tests (1h wet + 2h dry);
- 1% NaCl solution (10 min per day);

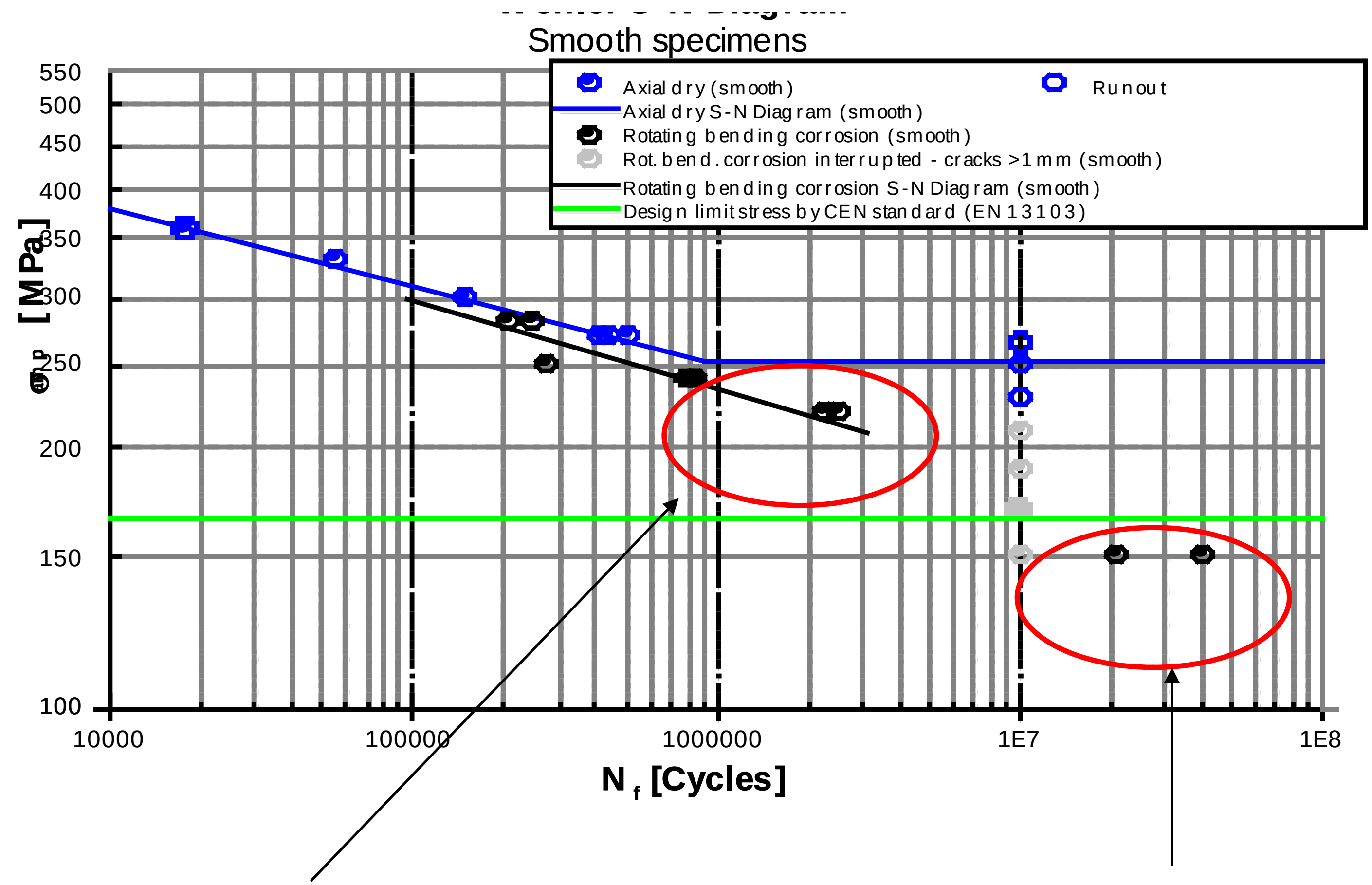
<u>Smooth specimens</u>

<u>Specimens with defects</u>

($\sqrt{area}$ = 224 μm)

- precracked specimens (tested at R=-1 for 10^7 cycles);
- micronotched specimens.

BENDING CORROSION FATIGUE TEST
S-N Diagrams – Smooth axial and bending

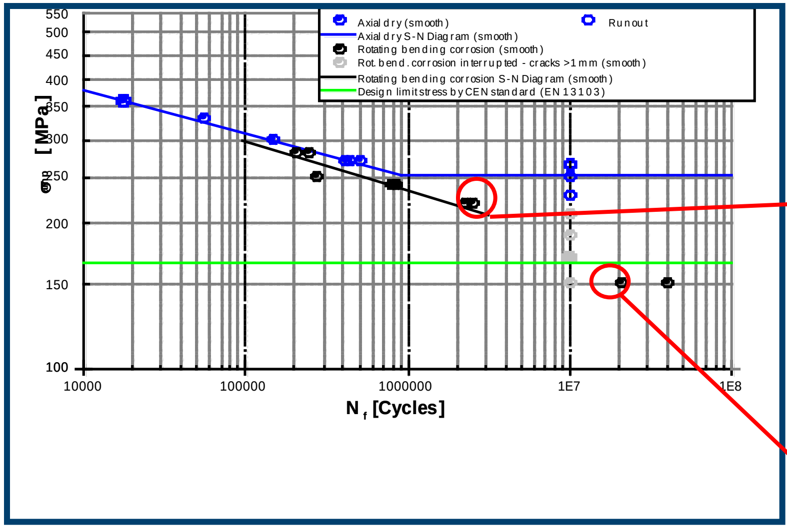


‘knee’ disappears

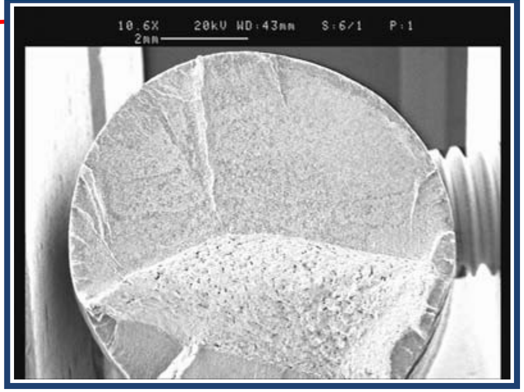
very long failures

(below En13103 design limits)

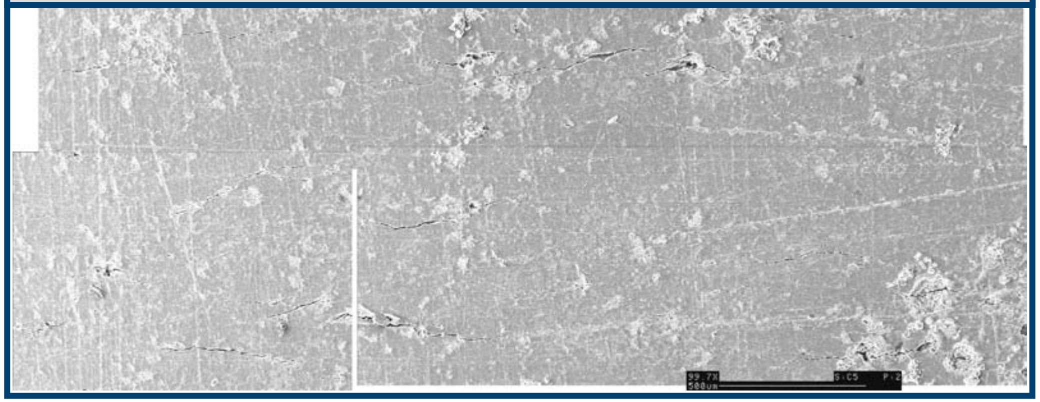
BENDING CORROSION FATIGUE TEST
SEM analysis – Smooth



Specimen 6/1
broken at 220MPa
at 2.3MLNcycles

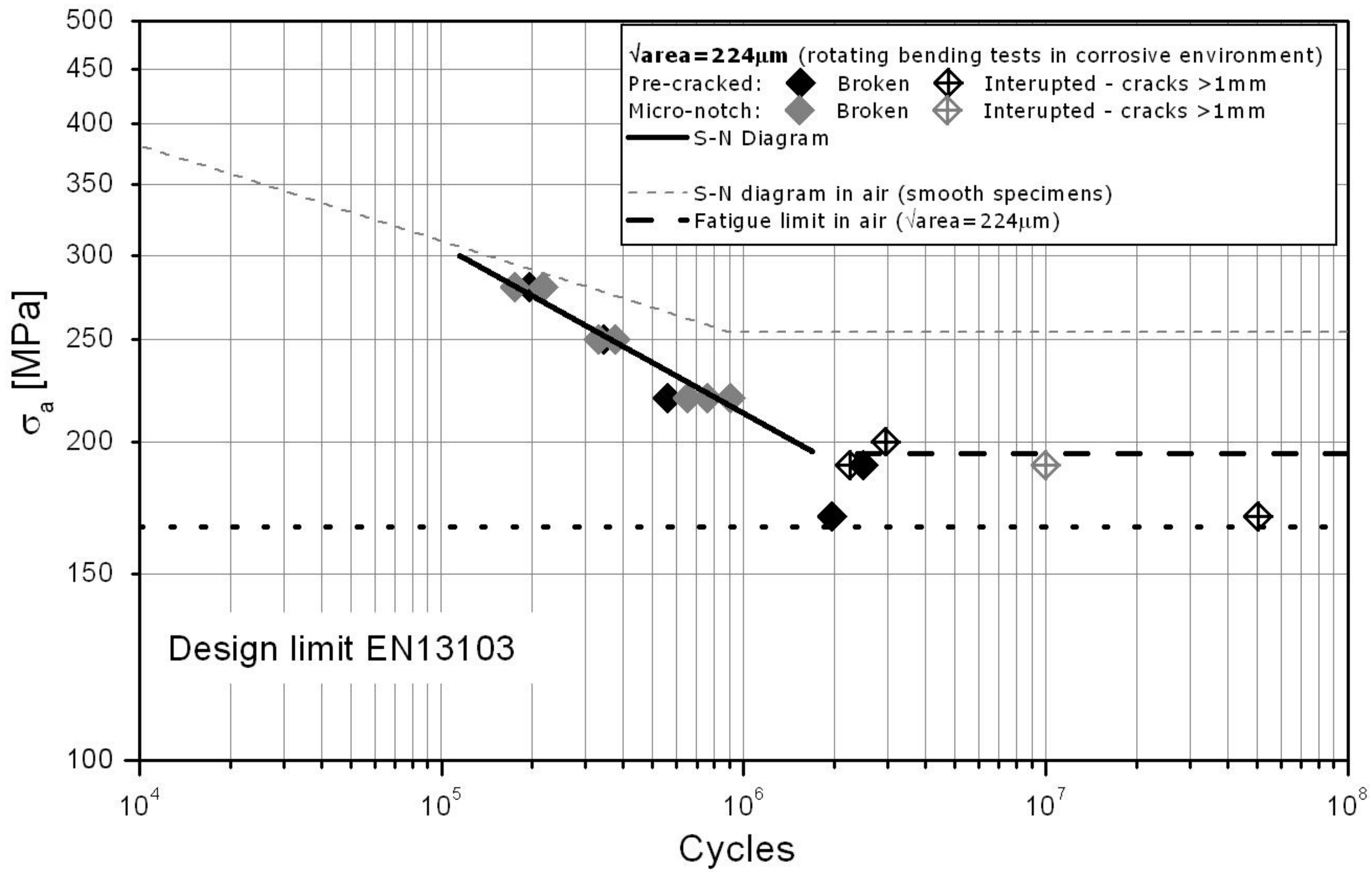


Specimen C5 - cracks >1mm
Interrupted at 170MPa at 10MLNcycles



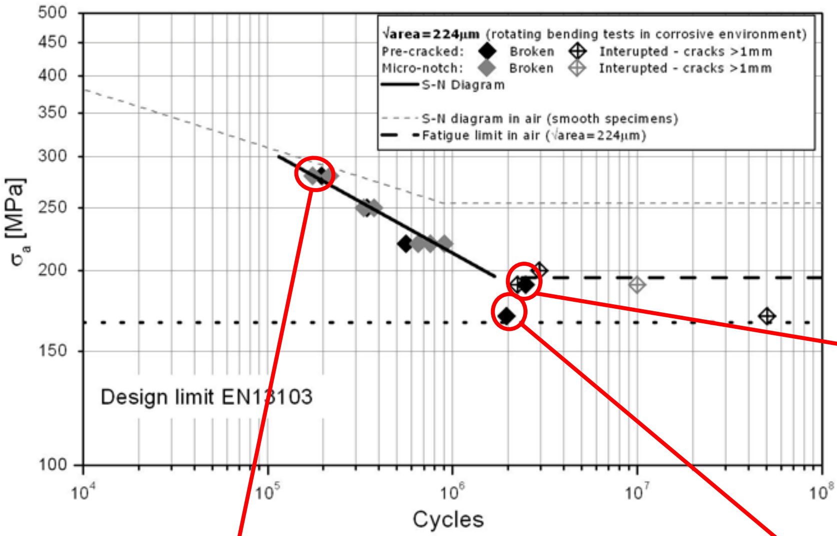
Surface cracking similar to Hoddinott's pictures

BENDING CORROSION FATIGUE TEST
S-N Diagrams – defect $\sqrt{area}$ = 224 µm comparison

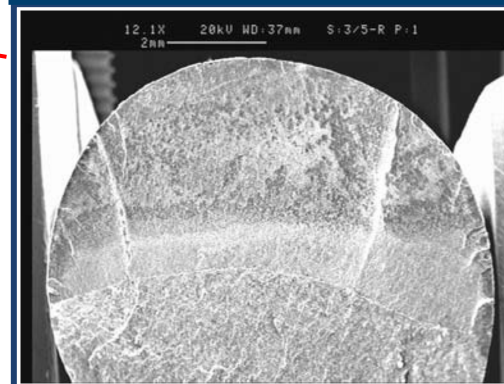


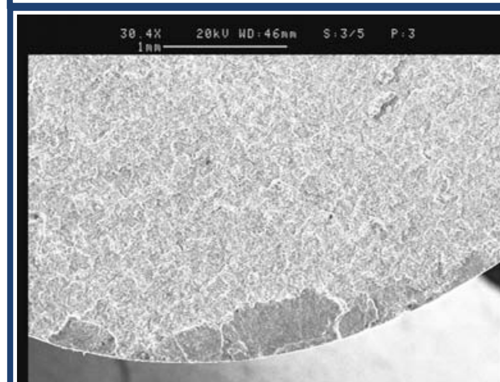
No difference between micronotches and pre-cracks

BENDING CORROSION FATIGUE TEST
SEM analysis – Micronotch $\sqrt{area}$ = 224 µm

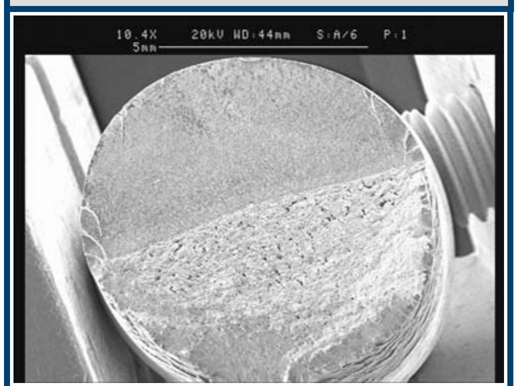


Specimen 3 / 5
broken at 190MPa
at 2.4MLNcycles

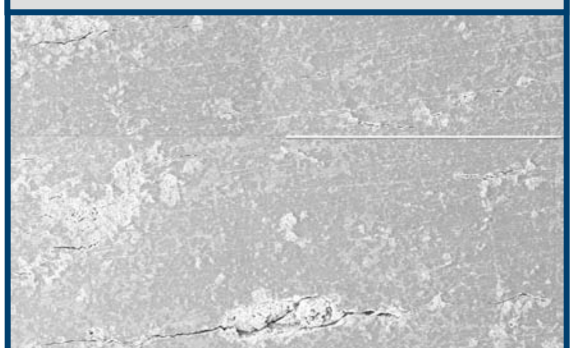




Specimen A6
broken 196kcycles
at 280MPa

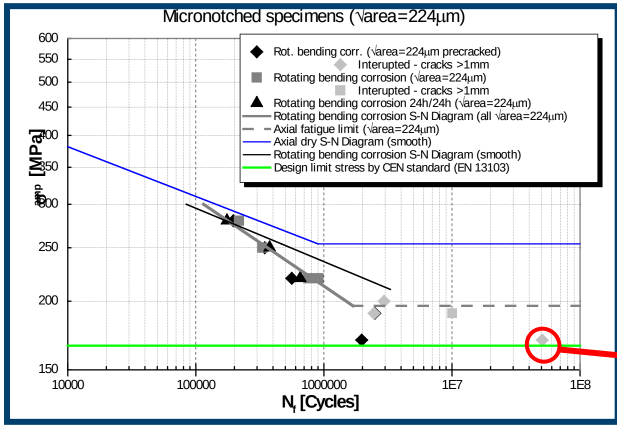


Specimen A15
broken 1.97MLNcycles
at 170MPa

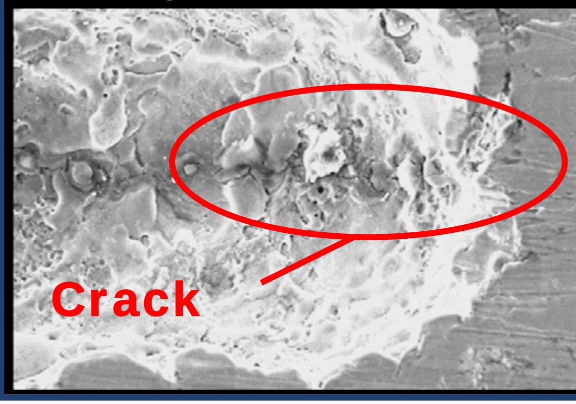


BENDING CORROSION FATIGUE TEST

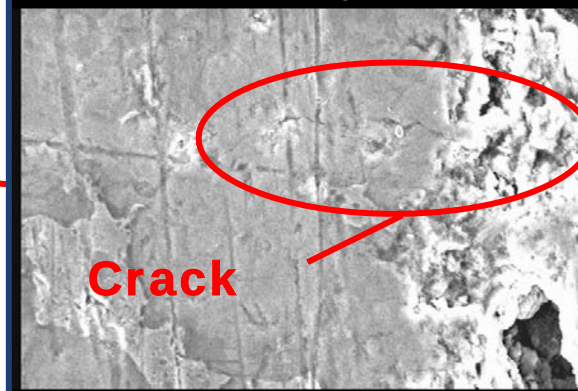
SEM analysis – Micronotch $\sqrt{area}$ = 224 µm



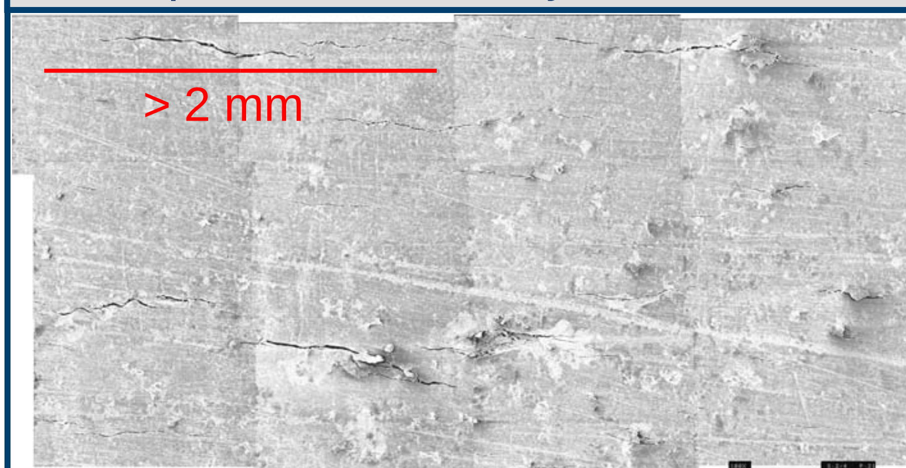
Specimen 2/4 precracked



Specimen 2/4 10Mln Cycles

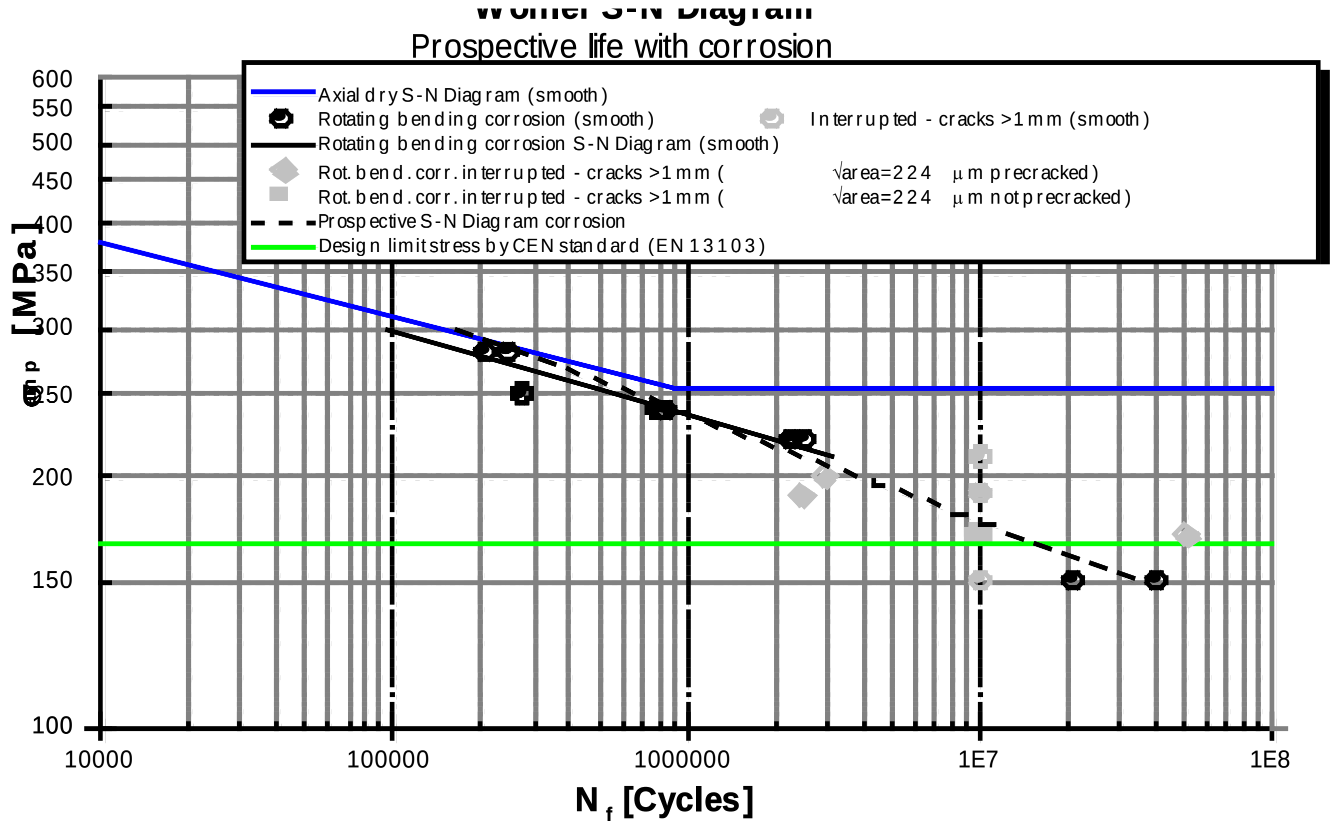


Specimen 2/4
nterrupted at 50MLNcycles at 170MPa



- Competition between crack growth and surface thinning;
- Specimens show a typical micro-cracking produced by corrosion-fatigue.

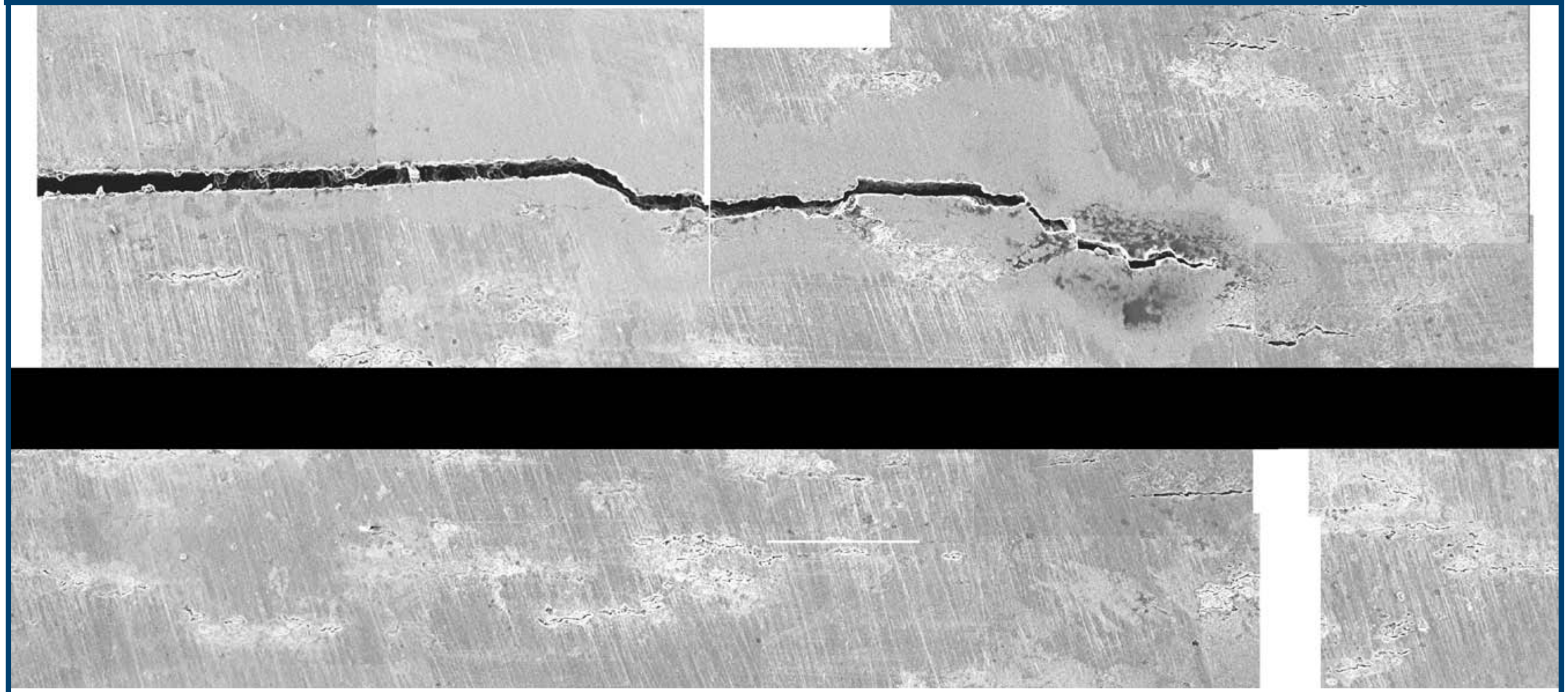
BENDING CORROSION FATIGUE TEST
S-N Diagrams – smooth/micronotch with cracks >1mm



- ‘nucleation life’ at 160 MPa is approx. $2{\cdot}10^7$ cycles equivalent to 60000 km;
- at 100 MPa (BASS limits) is approx. 600,000 km.

BENDING CORROSION FATIGUE TEST
SEM Analysis – Cracks and corrosion

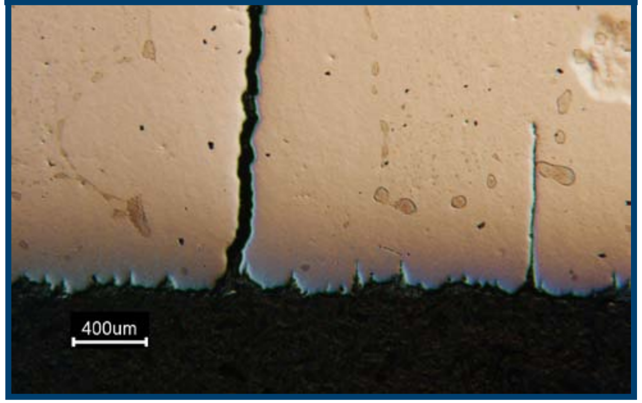
Specimen 2/1 – Test stress 250 MPa



Crack adavance is accompanied by ‘microcracking’ near the crack tip.

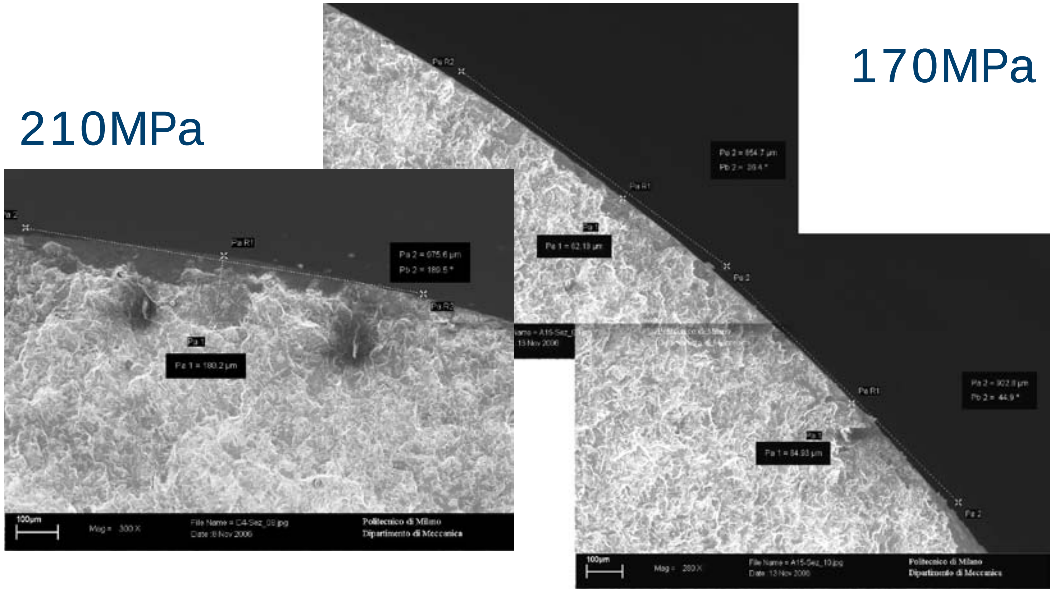
BENDING CORROSION FATIGUE TEST
SEM Analysis - Aspect ratio

Specimen D2 – 150MPa
BROKEN at 20MLNcycles



210MPa

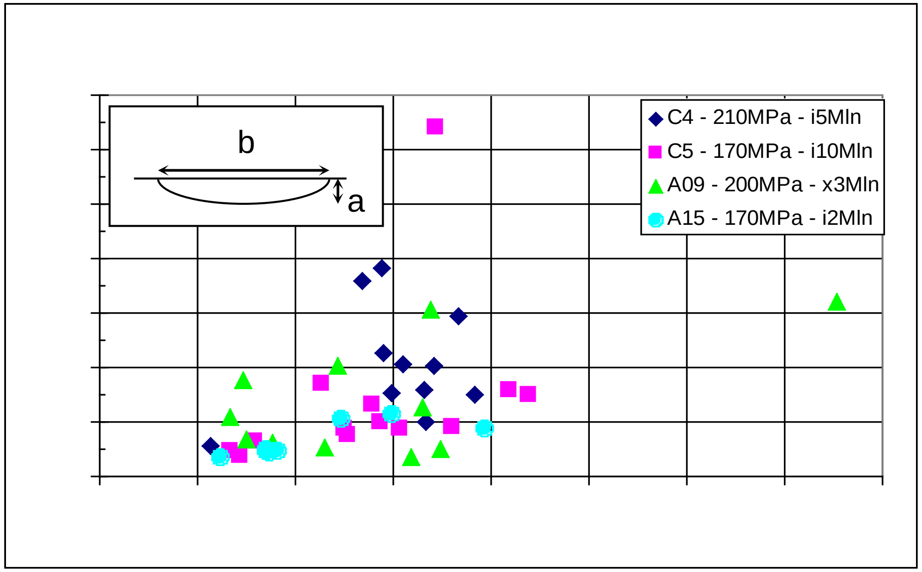
170MPa



Cracking ?

Run-out specimens have been broken under liquid nitrogen

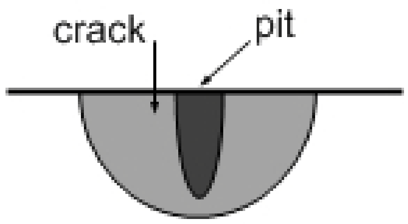
The crack propagation is characterized by an aspect ratio much lower than the typical range of 0.85-1 for air fatigue (**evidence of corrosion-fatigue**)



Fatigue thresholds in presence of corrosion

Corrosion effect in fatigue:

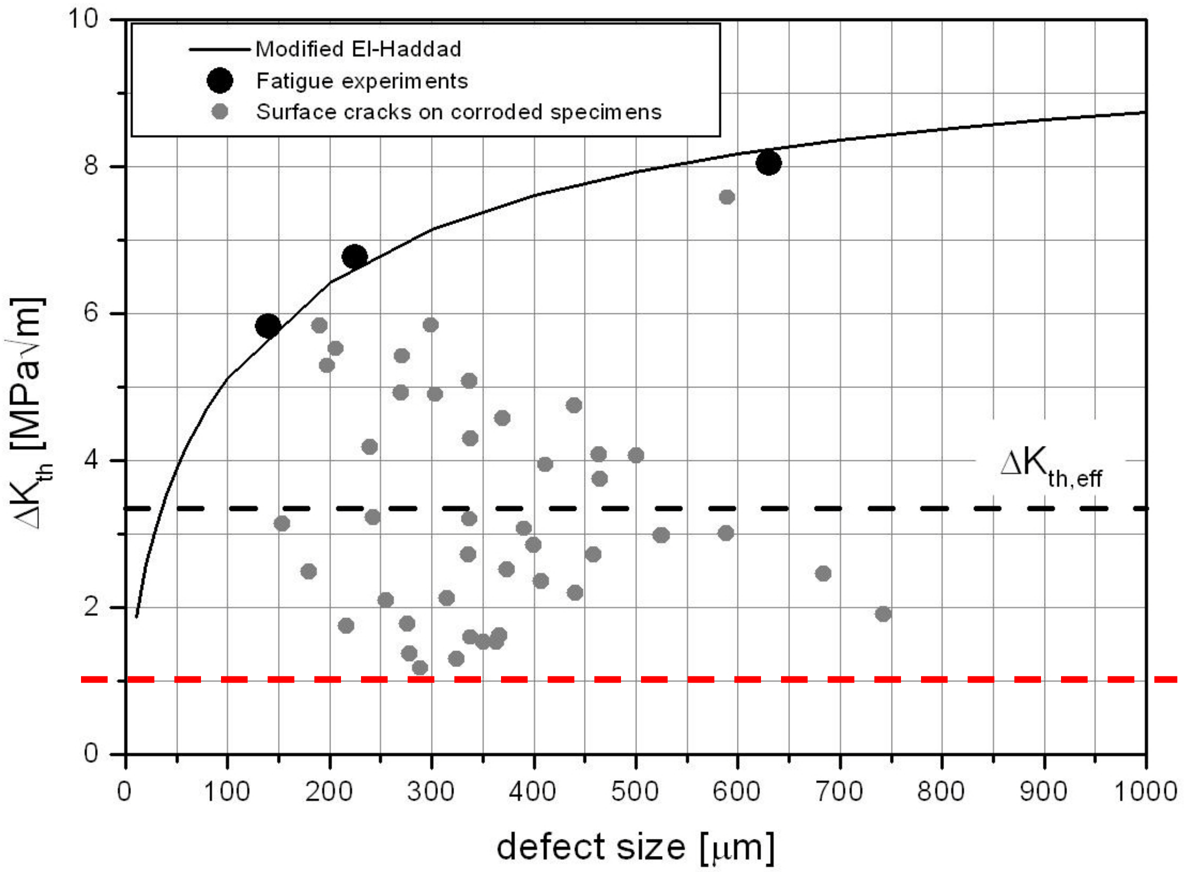
pit → crack



$\Delta K_{I,p\text{-}t\text{-}c}$

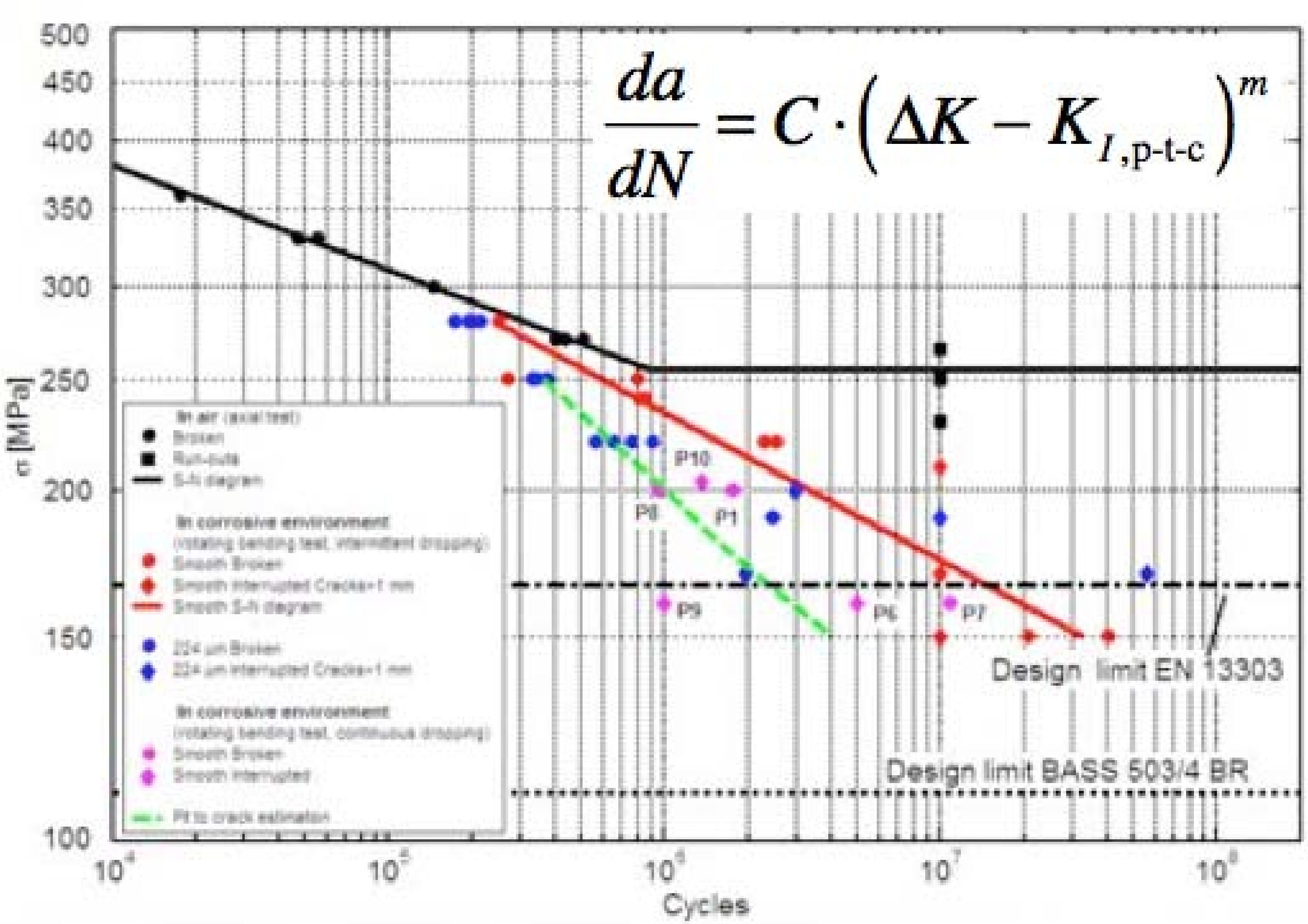
SIF for pit-to-crack transition

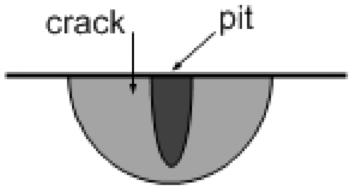
SIF was calculated for the cracks found on run-out specimens (they were growing)



$$\Delta K_{I,p\text{-}t\text{-}c} \leq 1 \quad MPa\sqrt{m}$$

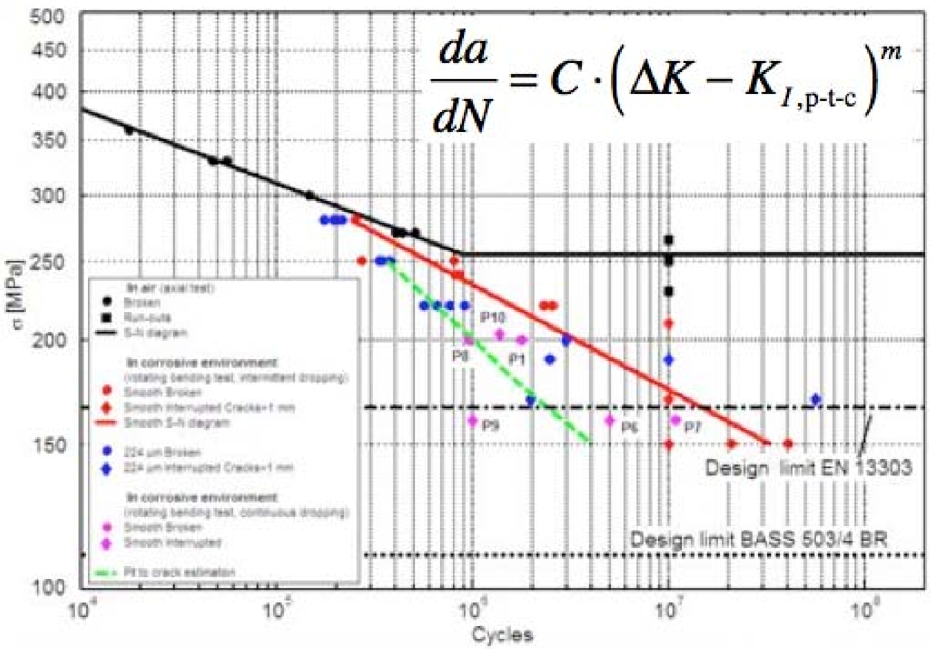
Life prediction under corrosion fatigue

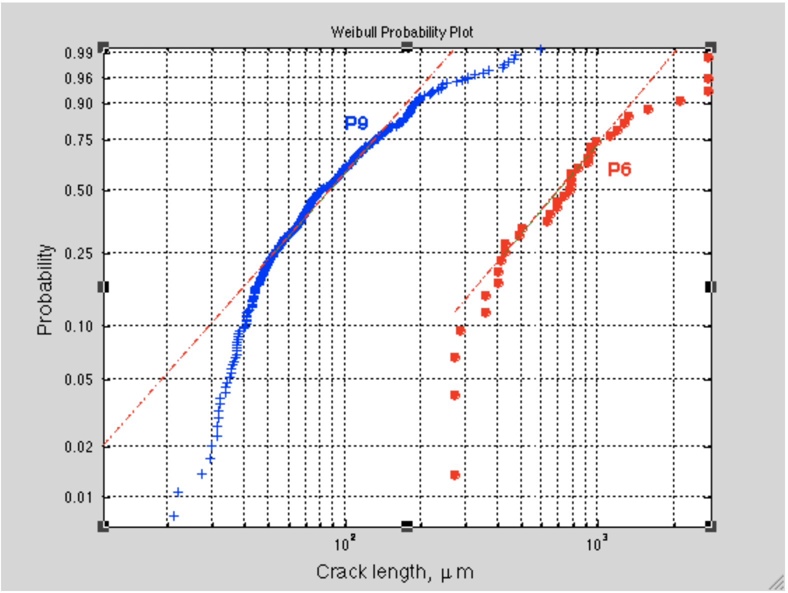


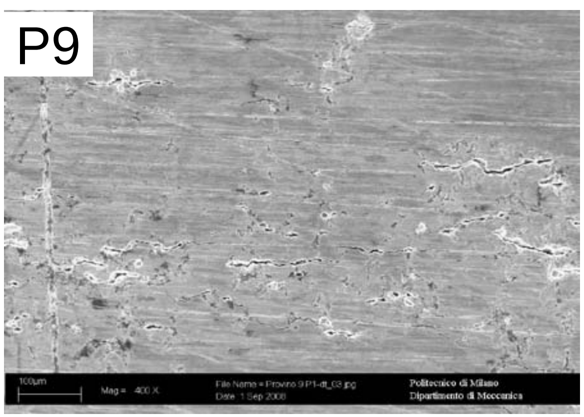


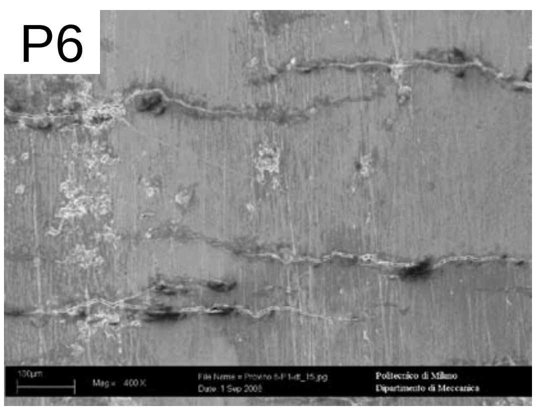
Conservative predictions with a simple model which includes $K_{I,\text{p-t-c}}$

Evolution of corrosion fatigue damage









Analysis of the populations of small cracks show that there is a significant coalescence of cracks

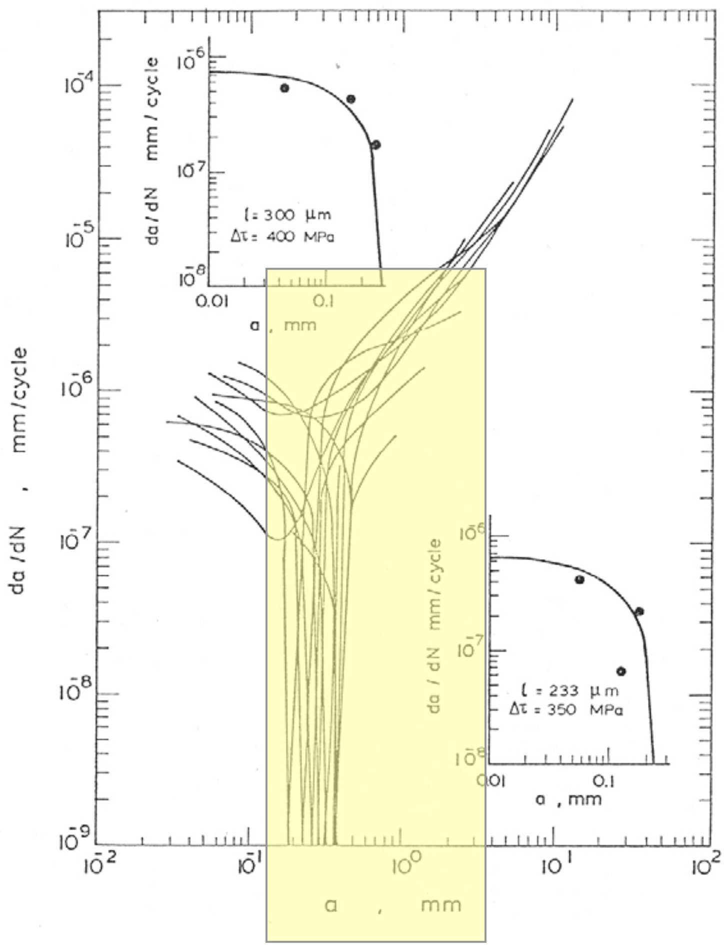
CONCLUSIONS

Corrosion is often claimed to be a cause of failure for axles: in this paper we wanted to analyze the effect of corrosion fatigue (acid rain) onto the fatigue properties of A1N steel

- A simple ‘mechanical assessment’ of corrosion defects can be obtained with the Kitagawa diagram;
- Exposure to acid rain can cause corrosion fatigue onto A1N steel;
- Effects of corrosion-fatigue are a disappearance of fatigue limits (BASS recommendations are close to experimental results);
- there is an increase in crack growth rates due to environmental effects and **$\Delta K_{I,p\text{-}t\text{-}c}$ is lower than 1 MPa$\sqrt{m}$;**
- **over**conservative predictions can be obtained with a growth model of the type:

$$\frac{da}{dN} = C \cdot \left(\Delta K - K_{I,\text{p-t-c}}\right)^m$$

CONCLUSIONS - Crack growth rates



Fatigue in air

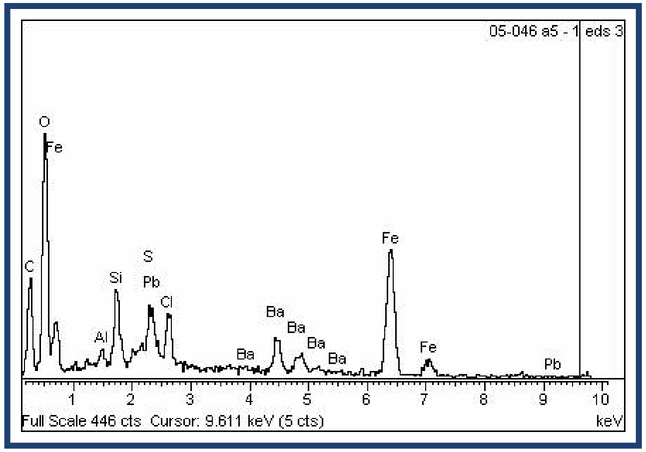
$$\frac{da}{dN} = C \cdot \left(\Delta K^{m} - \Delta K_{th}^{m} \right)$$

Corrosion fatigue

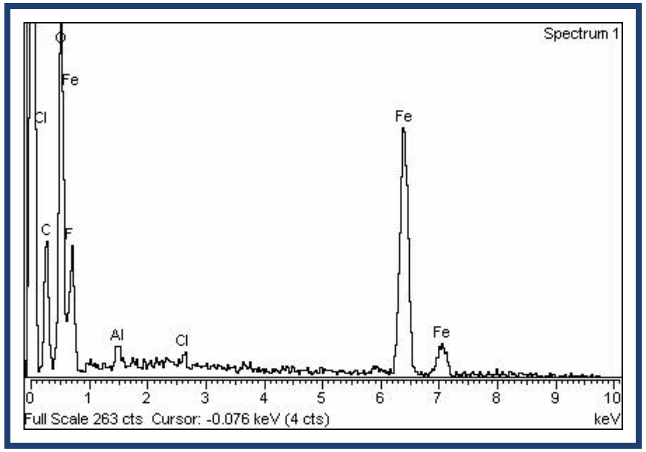
$$\frac{da}{dN} = C \cdot \left(\Delta K_{eff}{}^{m} - \Delta K_{I,\text{p-t-c}}^{m} \right)$$

Oxide composition

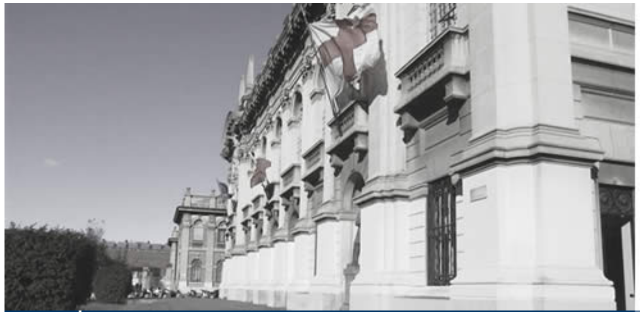
- Oxide of axles were analyzed on SEM with EDS in order to compare the composition with one of tested specimens
- The composition in two cases is enough similar



Axles oxides



Tested specimens oxides



POLITECNICO DI MILANO





Corrosion-fatigue and european axles steels

S. BERETTA, M. CARBONI, A. LOCONTE

Politecnico di Milano, Department of Mechanical Engineering

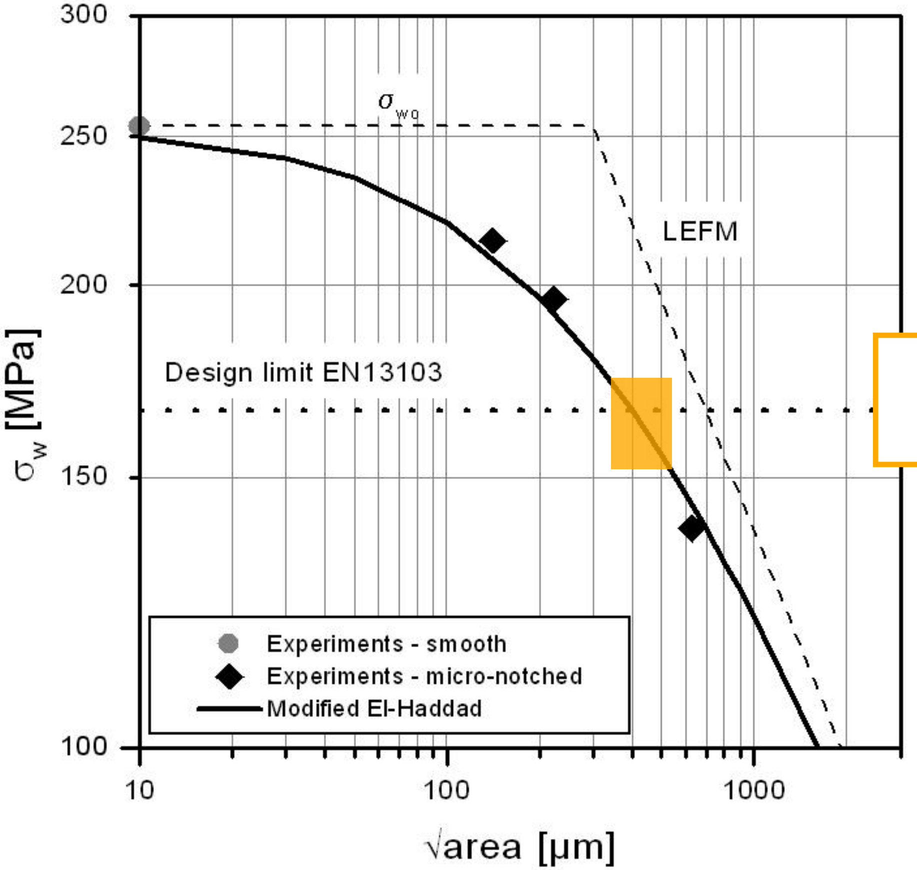
funded by:

•a MIUR 2004 project – *Maintenance of Freigth Trains;*
•RSSB – *T728 – UK Axle Safety Model*

Assessment of A1N axles retired from service
Kitagawa diagram

Relationship between fatigue limit and defect (crack) size

Safety factor



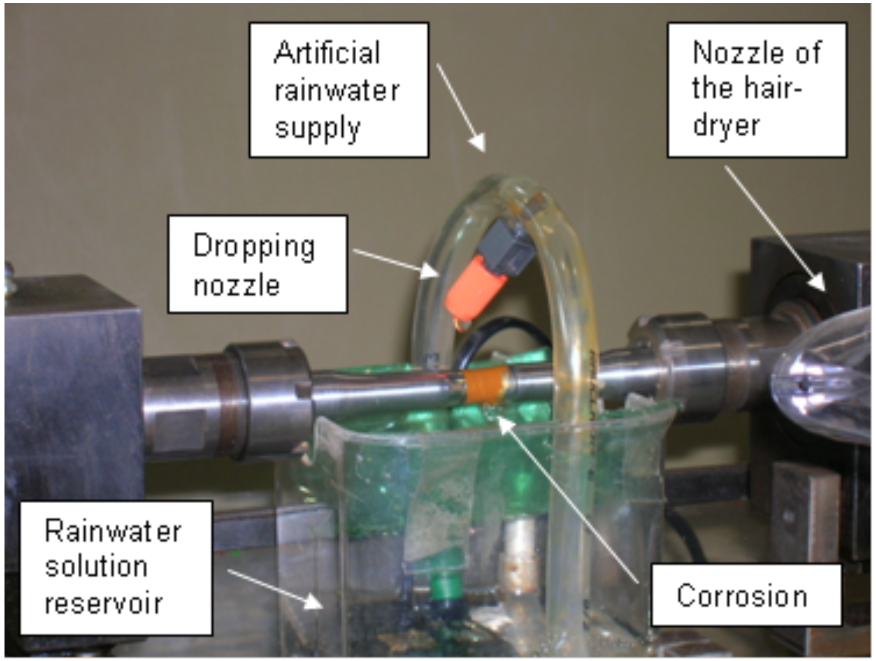
Fatigue limit for corrosion defects

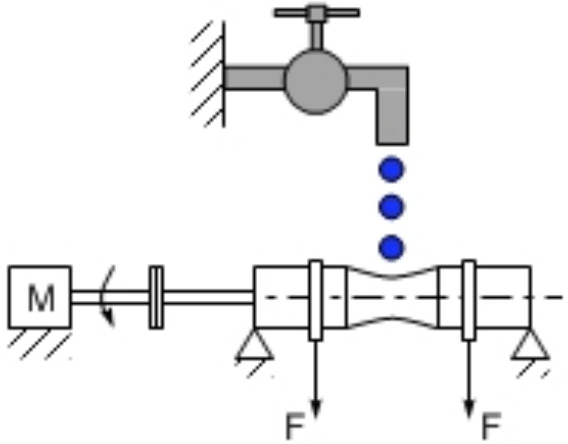
Safety factor

If we treat corrosion damage as defects (<u>mechanical effect</u>) design limit drops to 110 MPa (BASS indications for allowance of corrosion)

BENDING CORROSION FATIGUE TEST
Dropping system and test plan

Investigation of rotating bending fatigue limit onto specimens corroded by dropping synthetic rain (pH6)



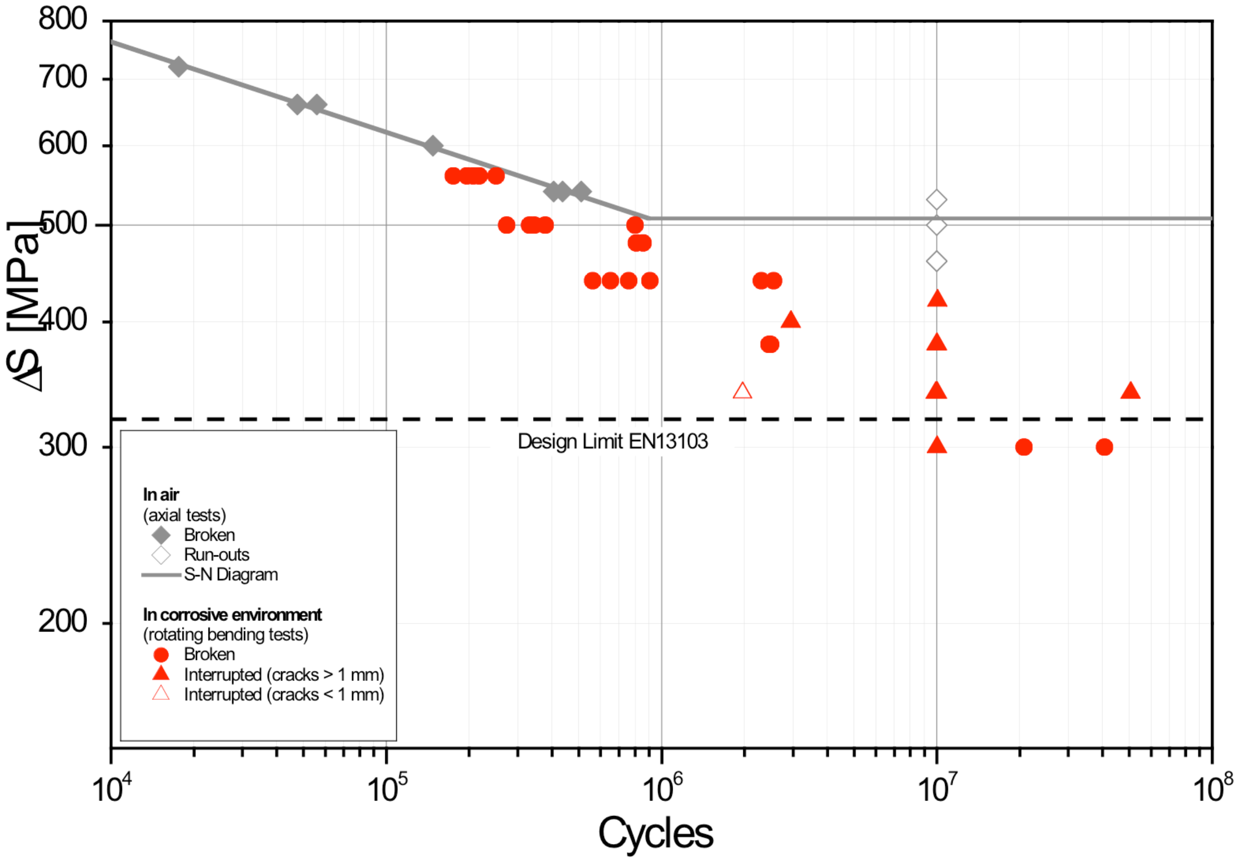


- frequency 8 Hz;
- wet-dry tests (1h wet + 2h dry);
- 1% NaCl solution (10 min per day);

Smooth specimens

Specimens with defects
($\sqrt{area}$ = 224 mm)
- precracked specimens (tested at R=-1 for 10^7 cycles);
- micronotched specimens.

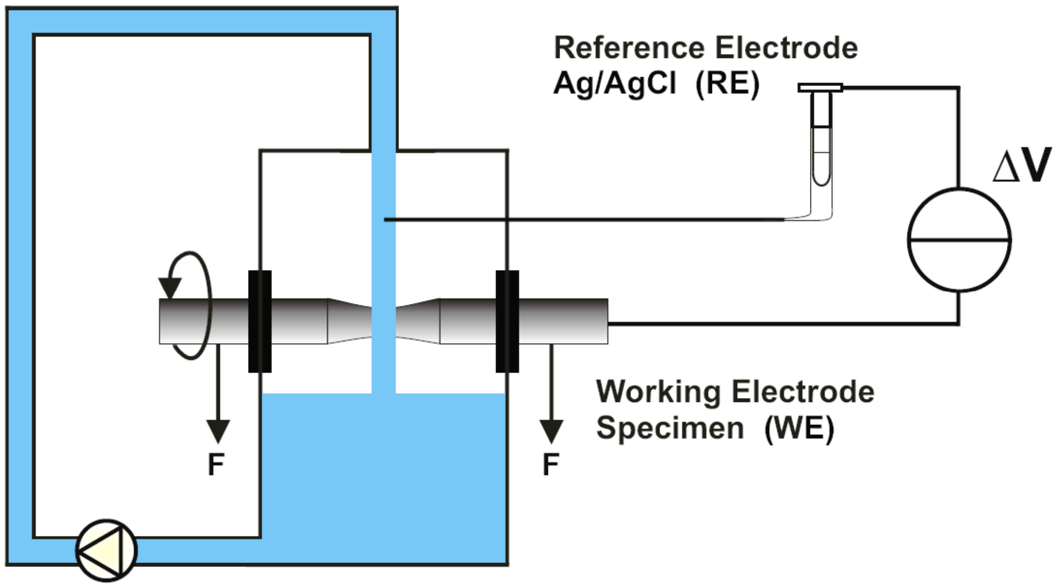
S-N diagram under corrosion
intermittent dropping



- Results show a continuous decrease of fatigue life;
- No difference if we introduce pre-cracks;
- Corrosion potential ? Growth rate ?

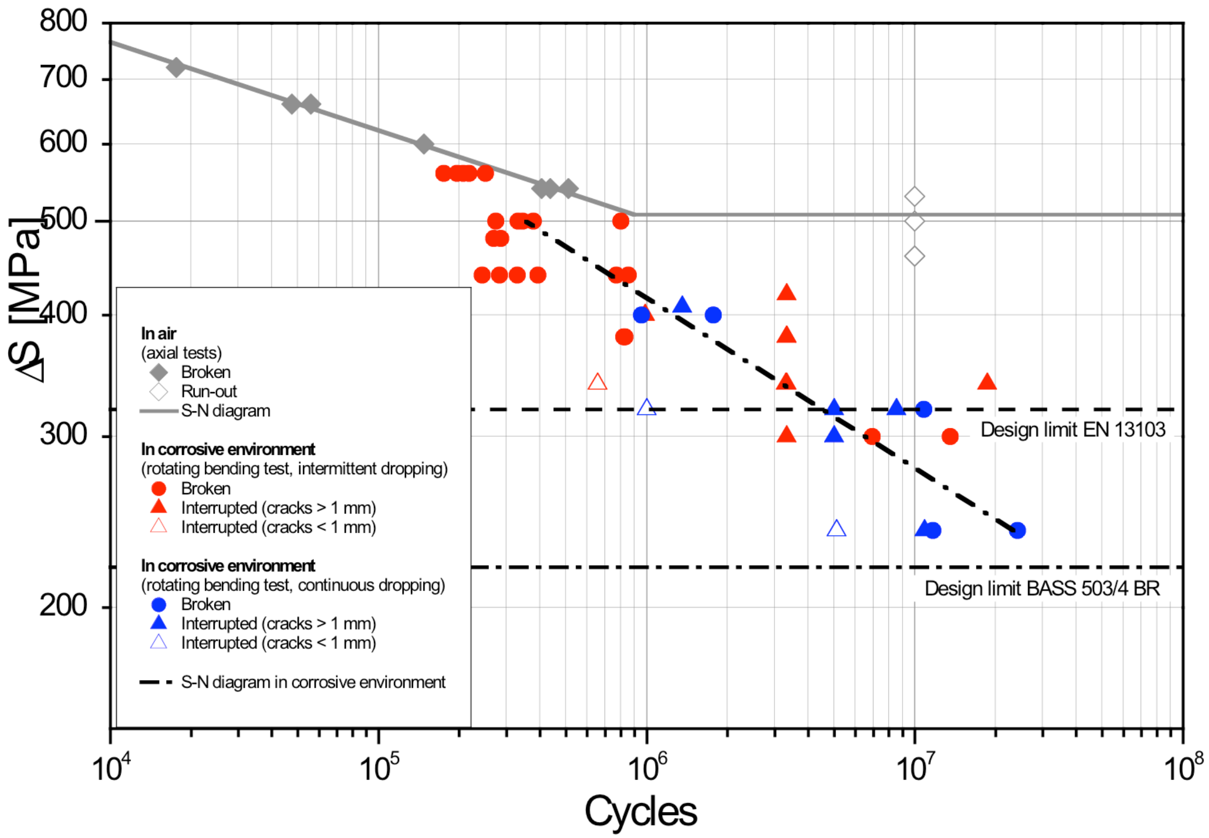
New results for A1N (Sep. 2008 - Feb. 09)

New test arrangement



- New tests with continuous dropping in order to measure corrosion potential;
- crack growth rate with plastic replicas;
- Confirmation of $\Delta K_{p\text{-}t\text{-}c}$ estimate;
- crack growth model under corrosive environment.

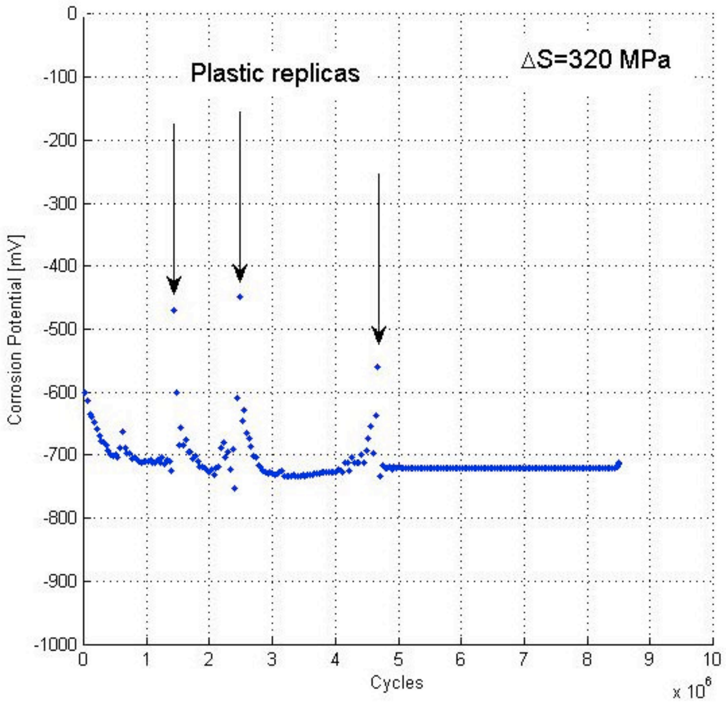
S-N diagram under corrosion

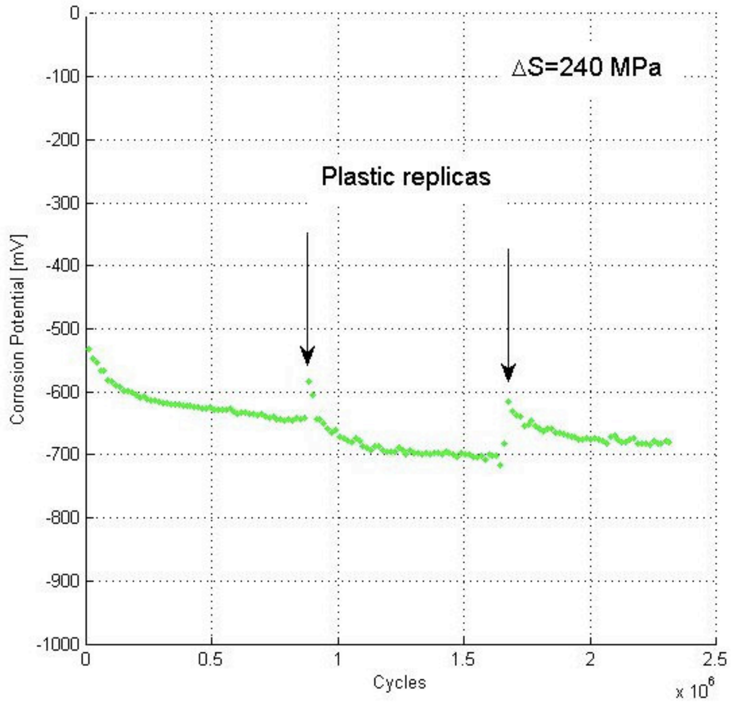


•Intermittent (wet periods) and continuous dropping tests follow the same trend;

•BASS limits correspond to a life of 600,000 km.

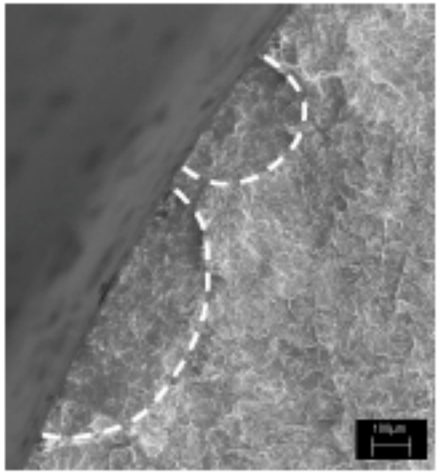
Corrosion potential

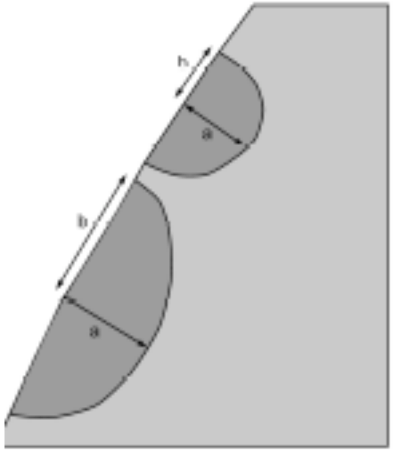


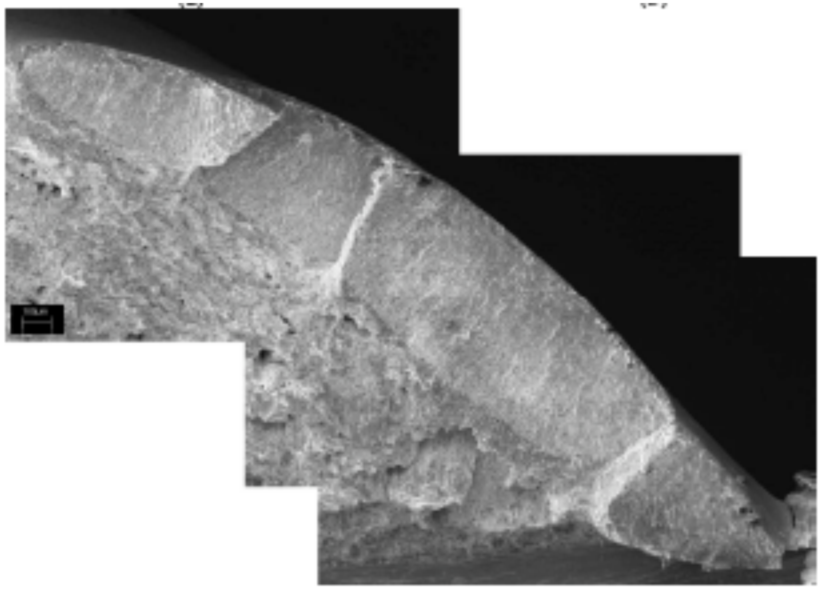


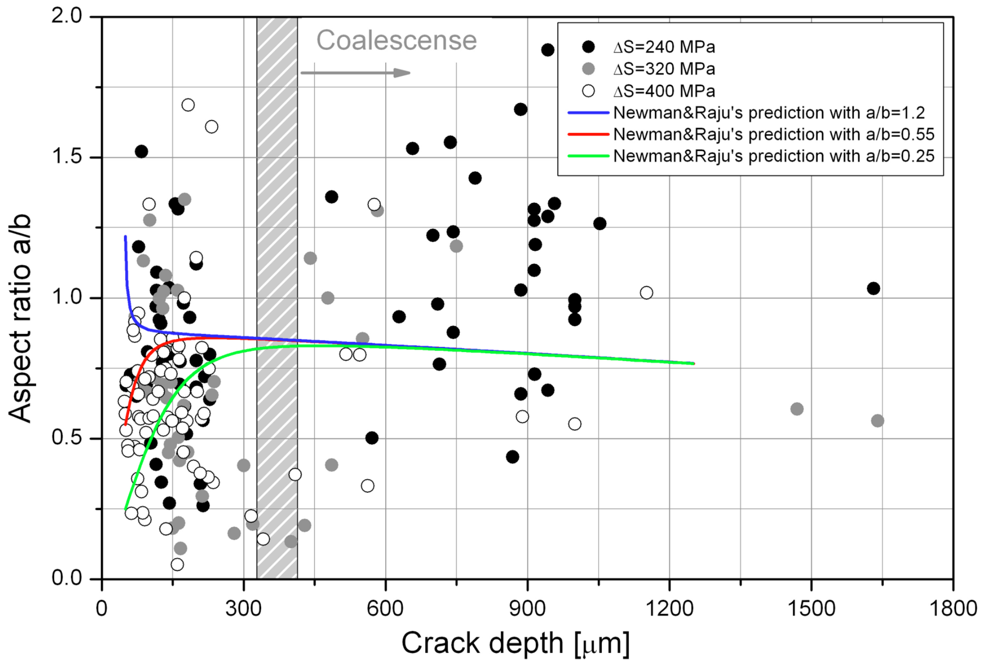
- Stable potential at -700 mV;
- ‘free-corrosion’ condition.

Crack shape – interrupted tests



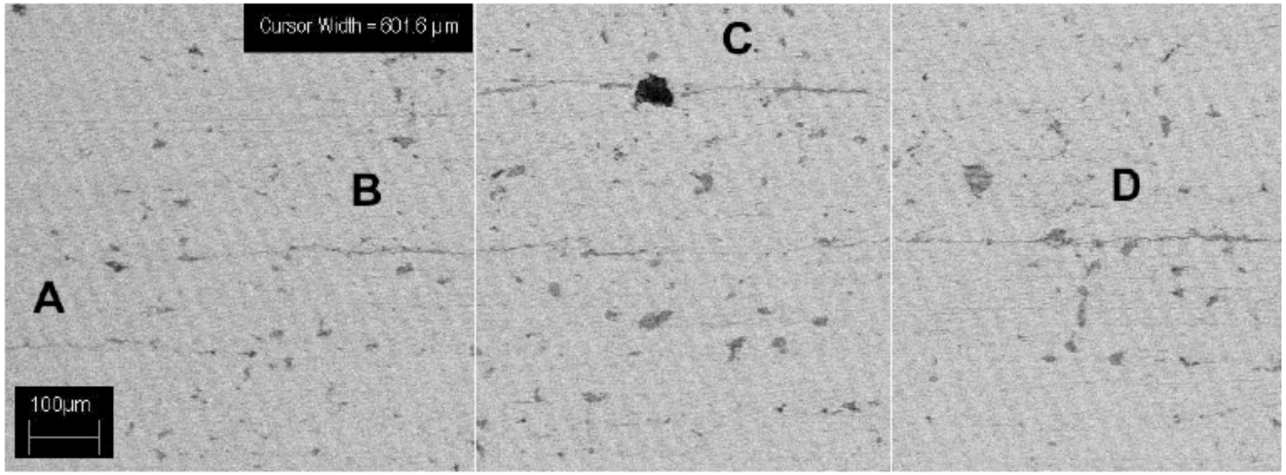




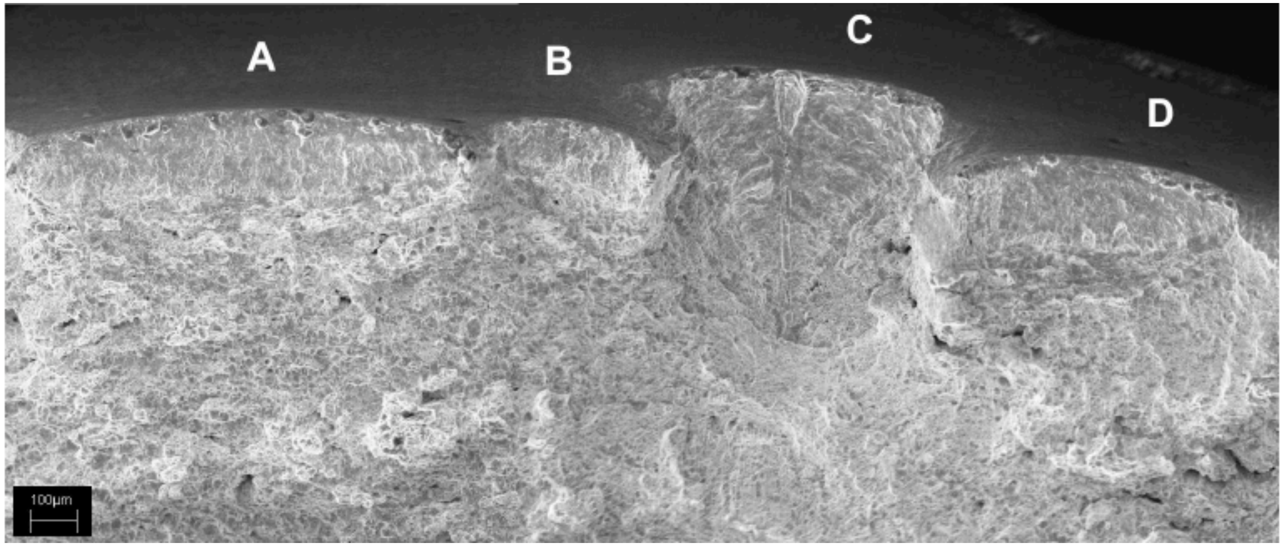


- great dispersion for a< 300 μm;
- coalescence for a> 300 μm.

Crack growth rate measurements

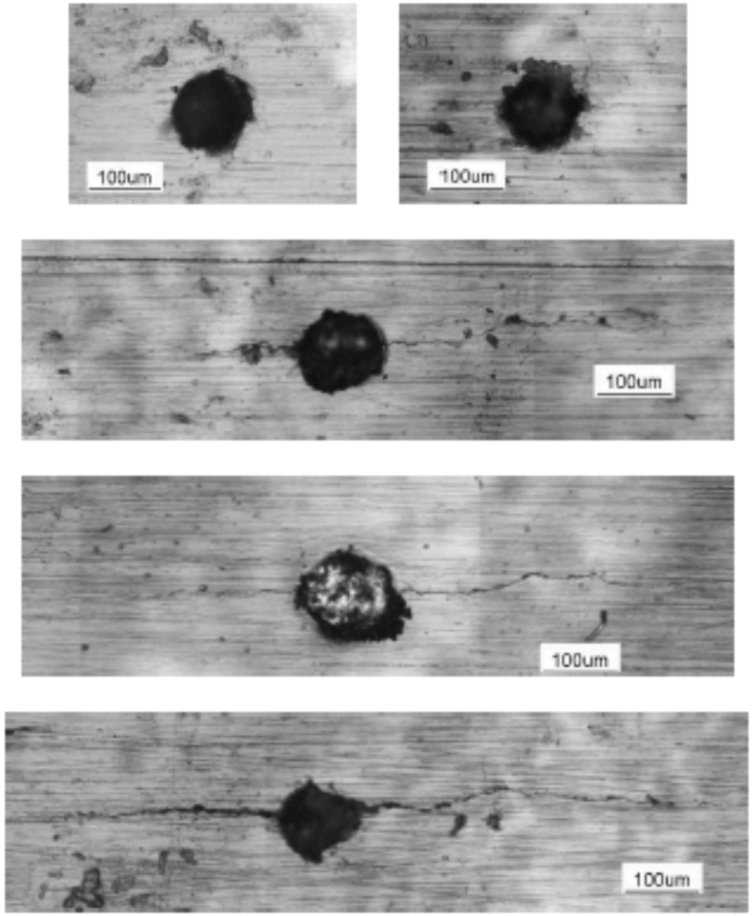


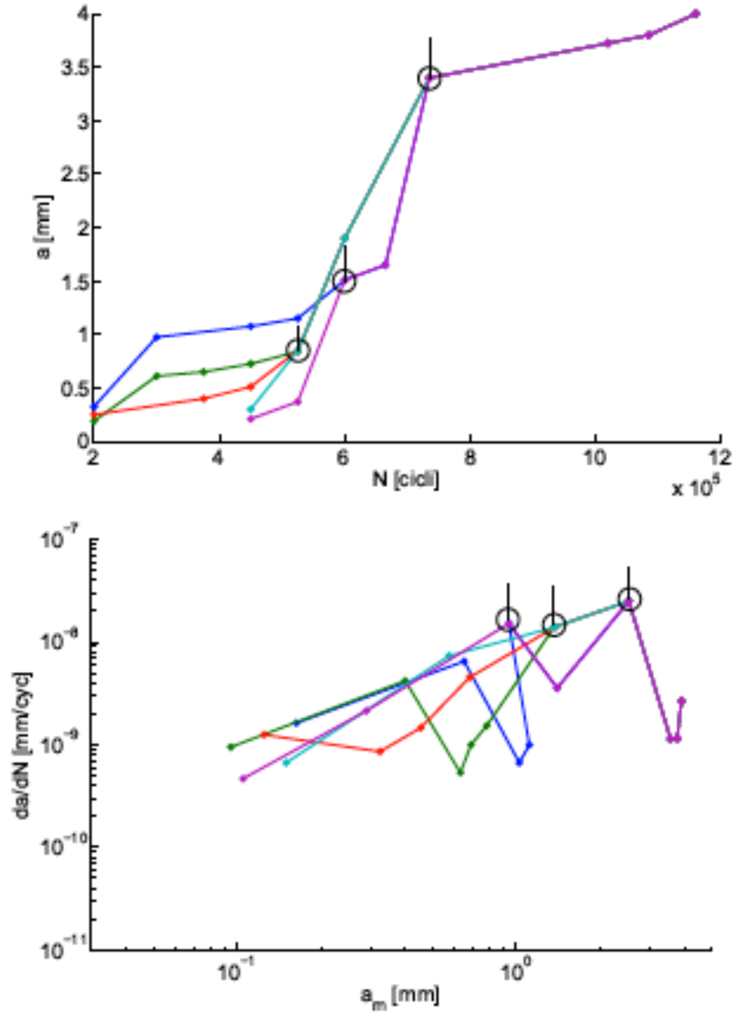
- micro-holes onto the specimens;
- plastic replicas.



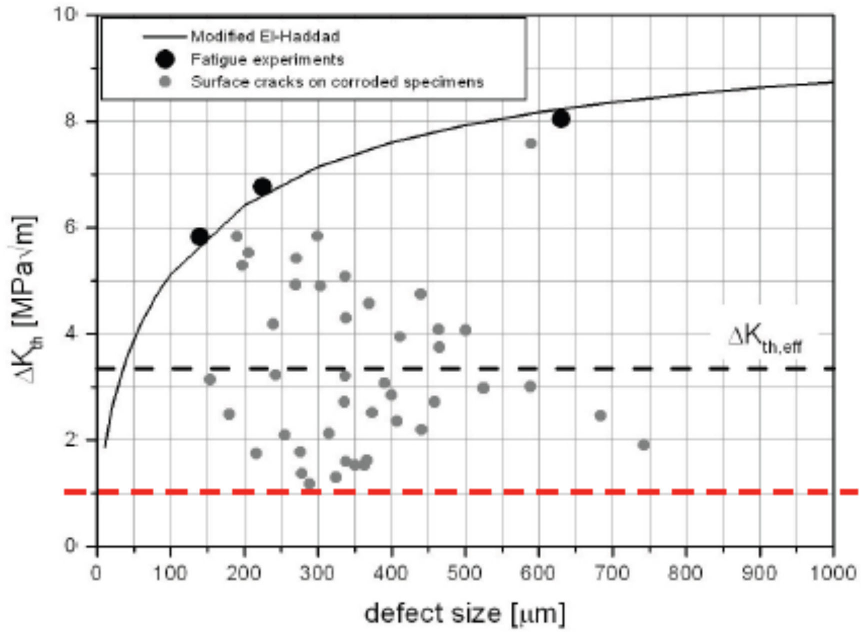
- crack coalescence

Crack growth rate measurements





Crack growth rate

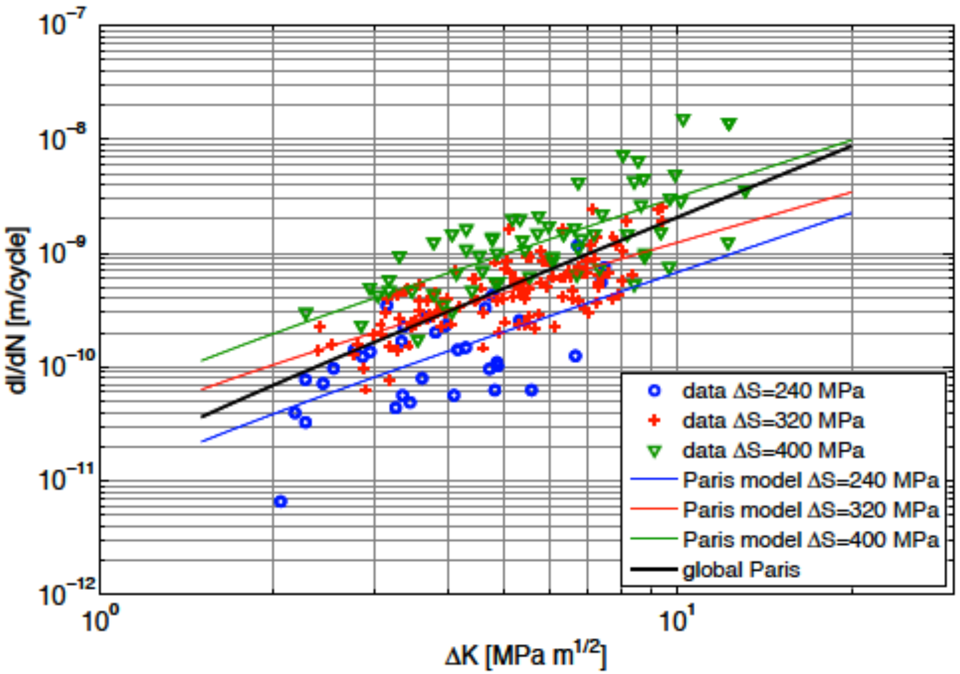


Cracks are able to propagate below the ‘mechanical threshold’

The data do not collapse onto a single curve of the type:

$$\frac{da}{dN} = C \cdot \left(\Delta K - K_{I,\text{p-t-c}}\right)^m$$

(no ΔK control)



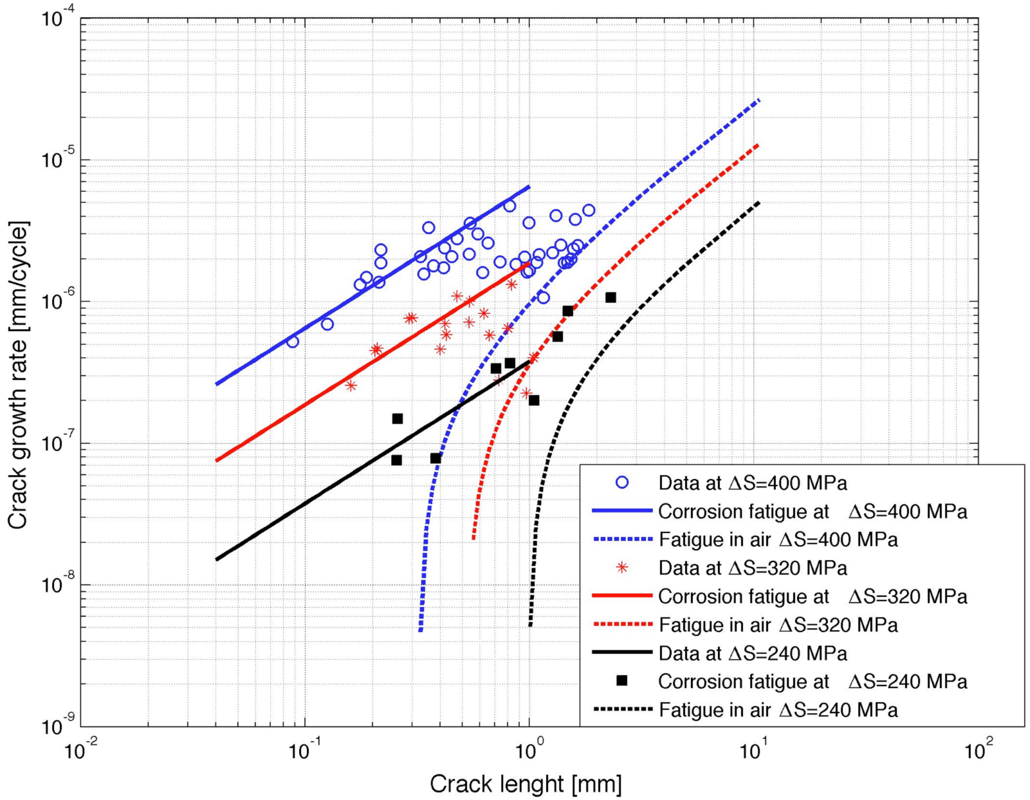
Growth rate model

Modified Murtaza&Akid model

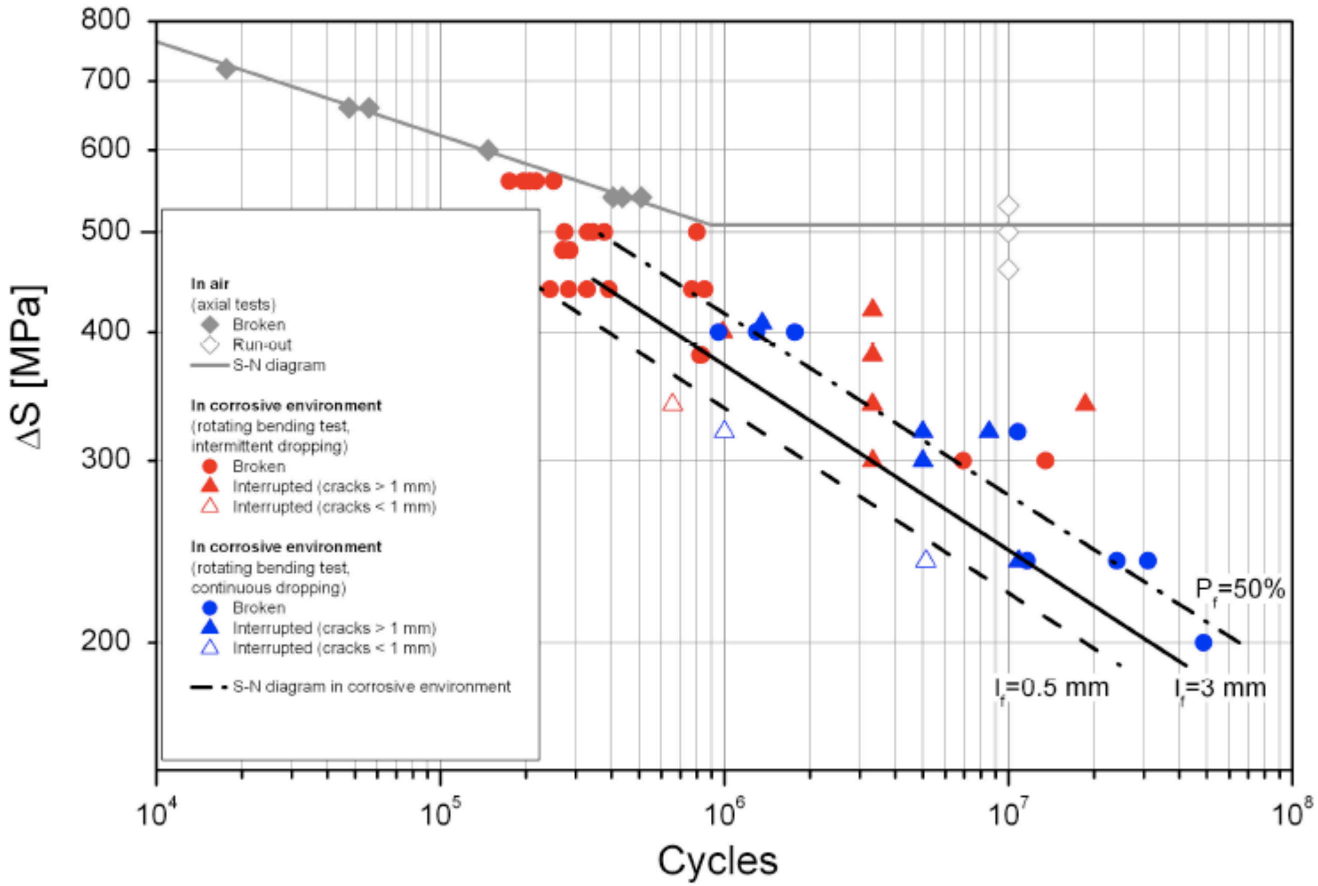
$$\frac{dl}{dN} = B \cdot (\Delta S)^{\beta} \cdot l - B \cdot \left(\Delta \sigma_{fl}\right)^{\beta} \cdot d_m$$

'mechanical' threshold under aggressive environment

$$\Delta \sigma_{fl} = \frac{\Delta K_{p-t-c}}{0.67 \cdot \sqrt{\pi \cdot d_m}}$$



Life prediction



The model describes very well the corrosion fatigue process.

S. Beretta *, M. Carboni, G. Fiore, A. Lo Conte (2010)
Corrosion–fatigue of A1N railway axle steel exposed to rainwater. *Int. J. Fatigue*, 32 (2010) 952–961

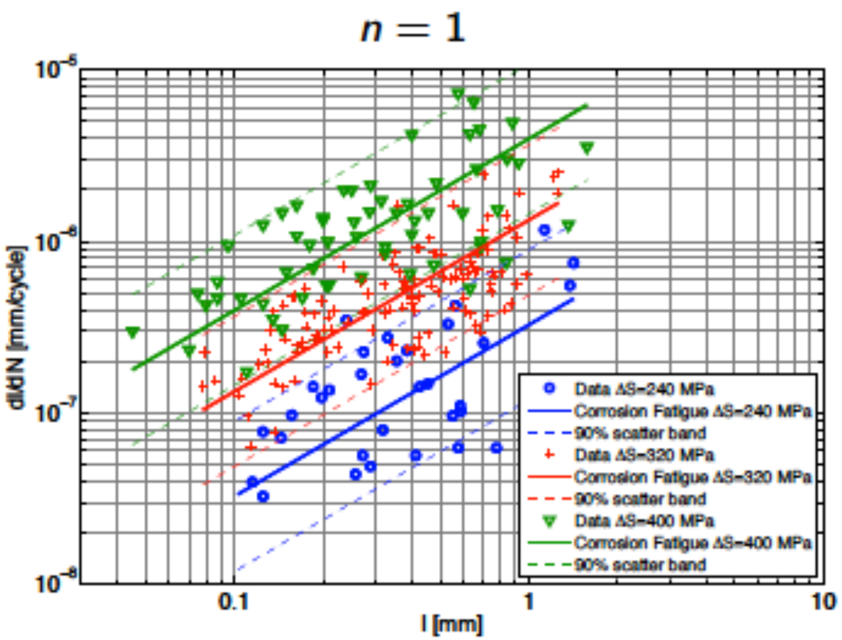
New results within T728 – Axle Safety Model (june 2009-April 2010)

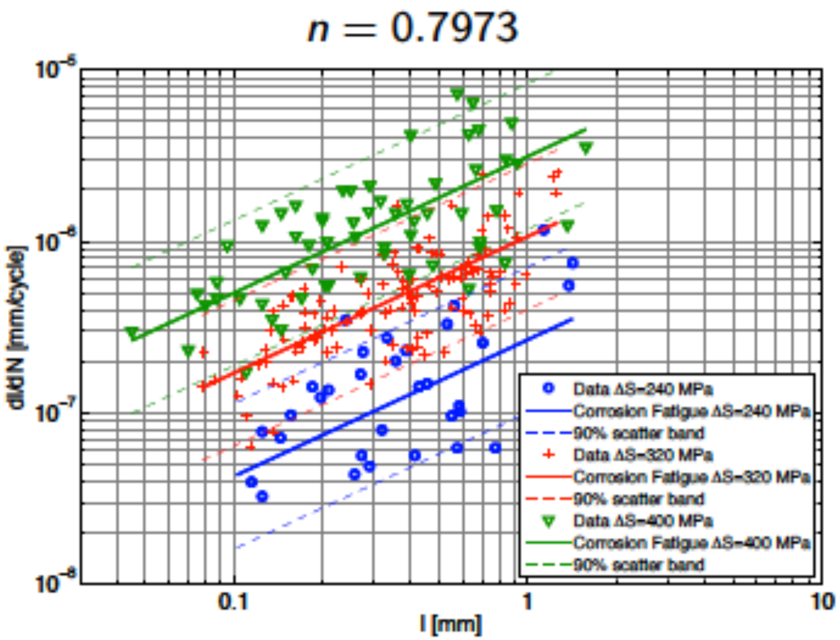
Simplification of the model

Further simplification of the Akid model into:

$$\frac{dl}{dN} = B \cdot (\Delta S)^{\beta} \cdot l - D$$

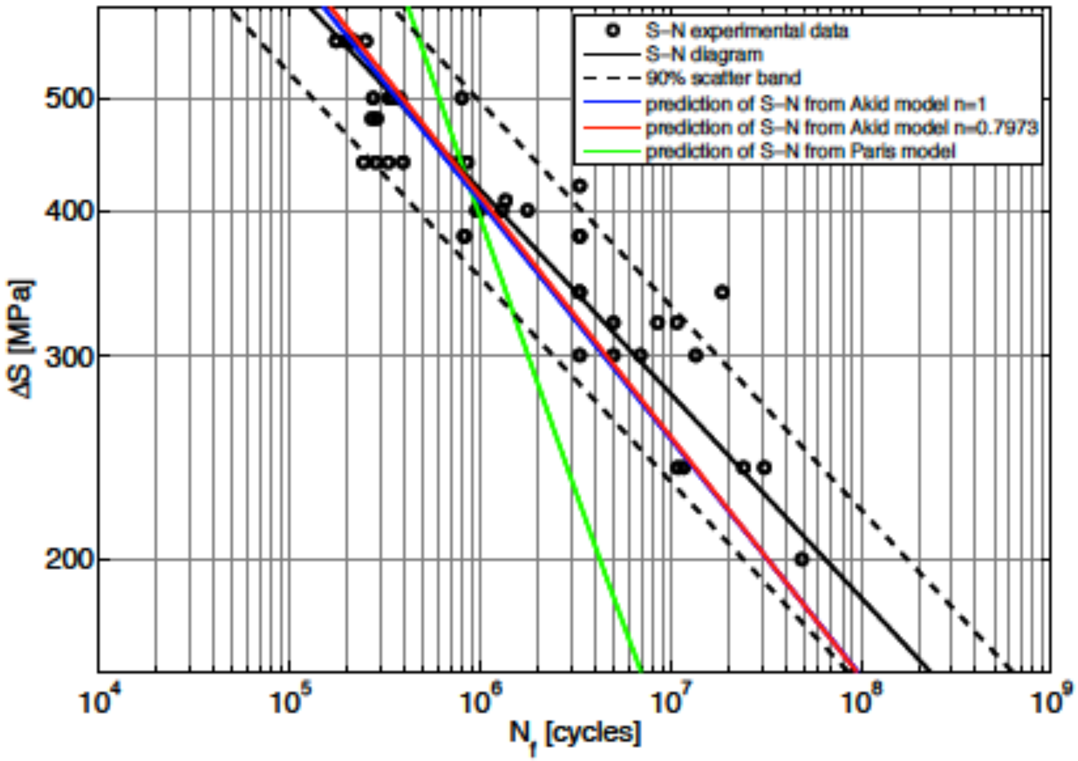
$$\frac{dl}{dN} = B \cdot (\Delta S)^{\beta} \cdot l$$





Simplified model

$$N_f = \int_0^{N_f} dN = \frac{1}{B \cdot (\Delta S)^{\beta}} \int_{l_0}^{l_f} \frac{dl}{l^n} = C \cdot (\Delta S)^m \rightarrow \begin{cases} C = \frac{1}{B} \int_{l_0}^{l_f} \frac{dl}{l^n} \\ m = -\beta \end{cases}$$

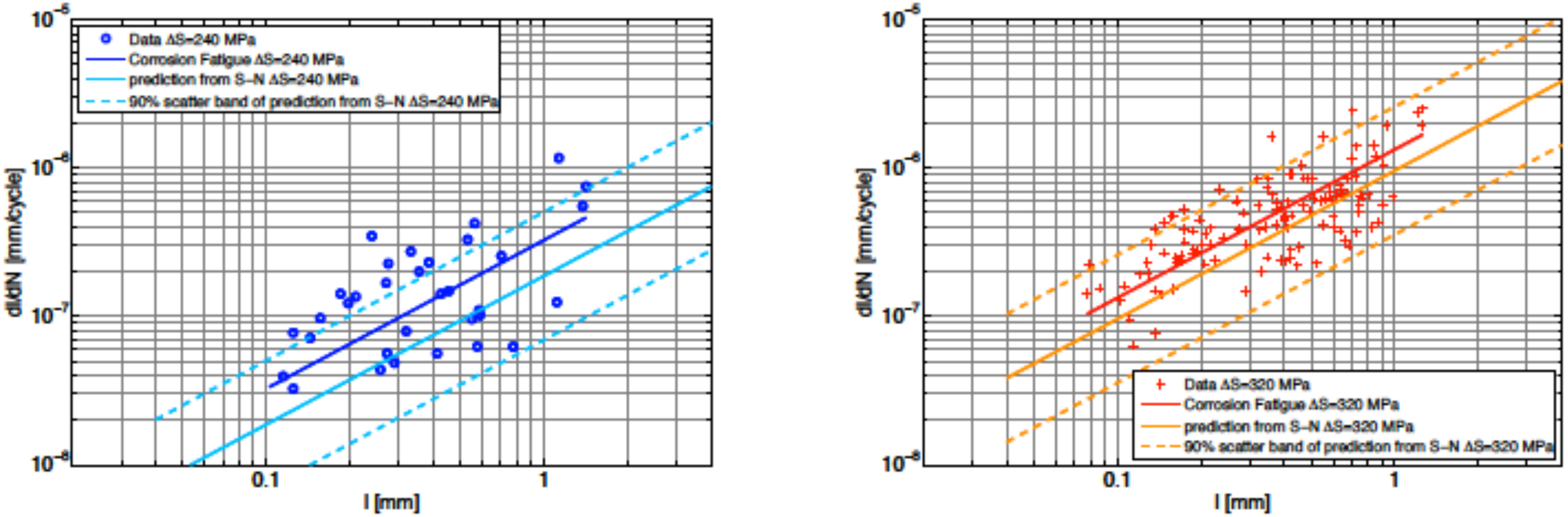


if we include the scatter of the da/dN diagram we have a good prediction of the S-N scatter band

Extra features of the simplified model

$$N_f = \int_0^{N_f} dN = \frac{1}{B \cdot (\Delta S)^\beta} \int_{l_0}^{l_f} \frac{dl}{l^n} = C \cdot (\Delta S)^m \rightarrow \begin{cases} C = \frac{1}{B} \int_{l_0}^{l_f} \frac{dl}{l^n} \\ m = -\beta \end{cases}$$

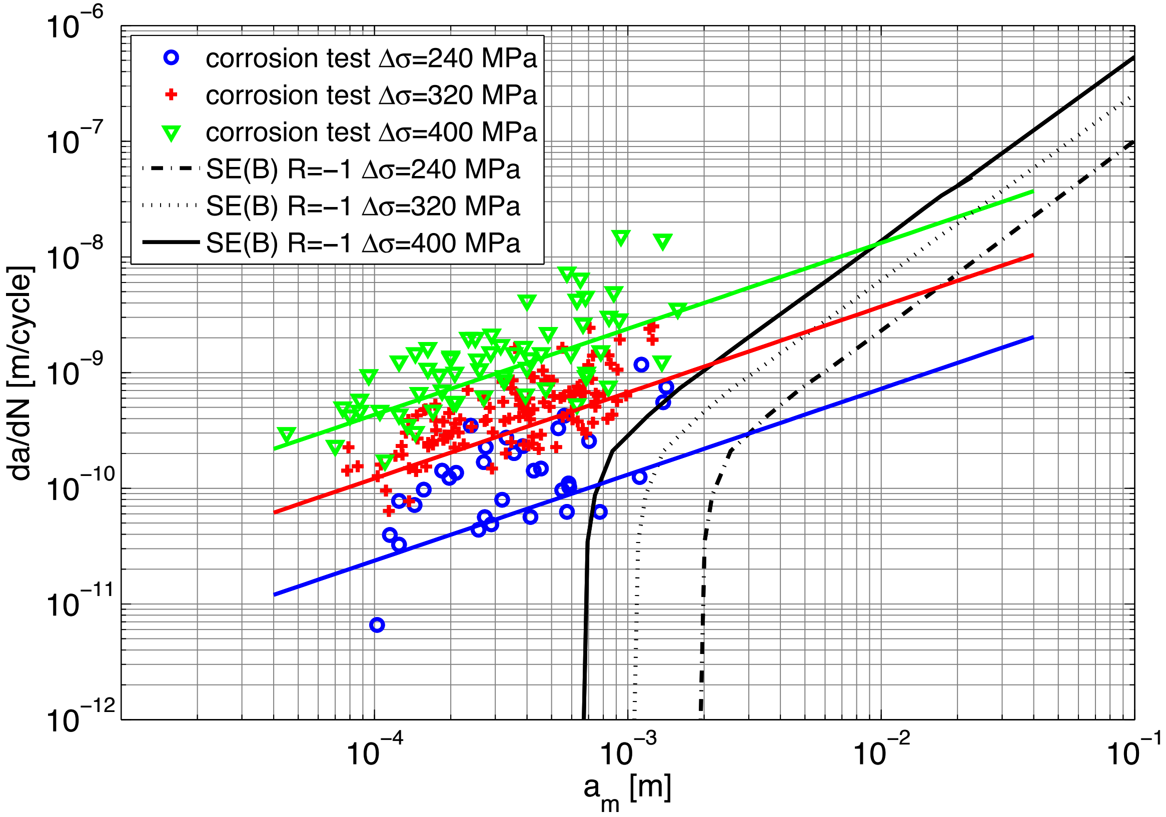
we can estimate the parameters directly from the S-N diagram



estimates are quite good !

Competition with crack growth in air

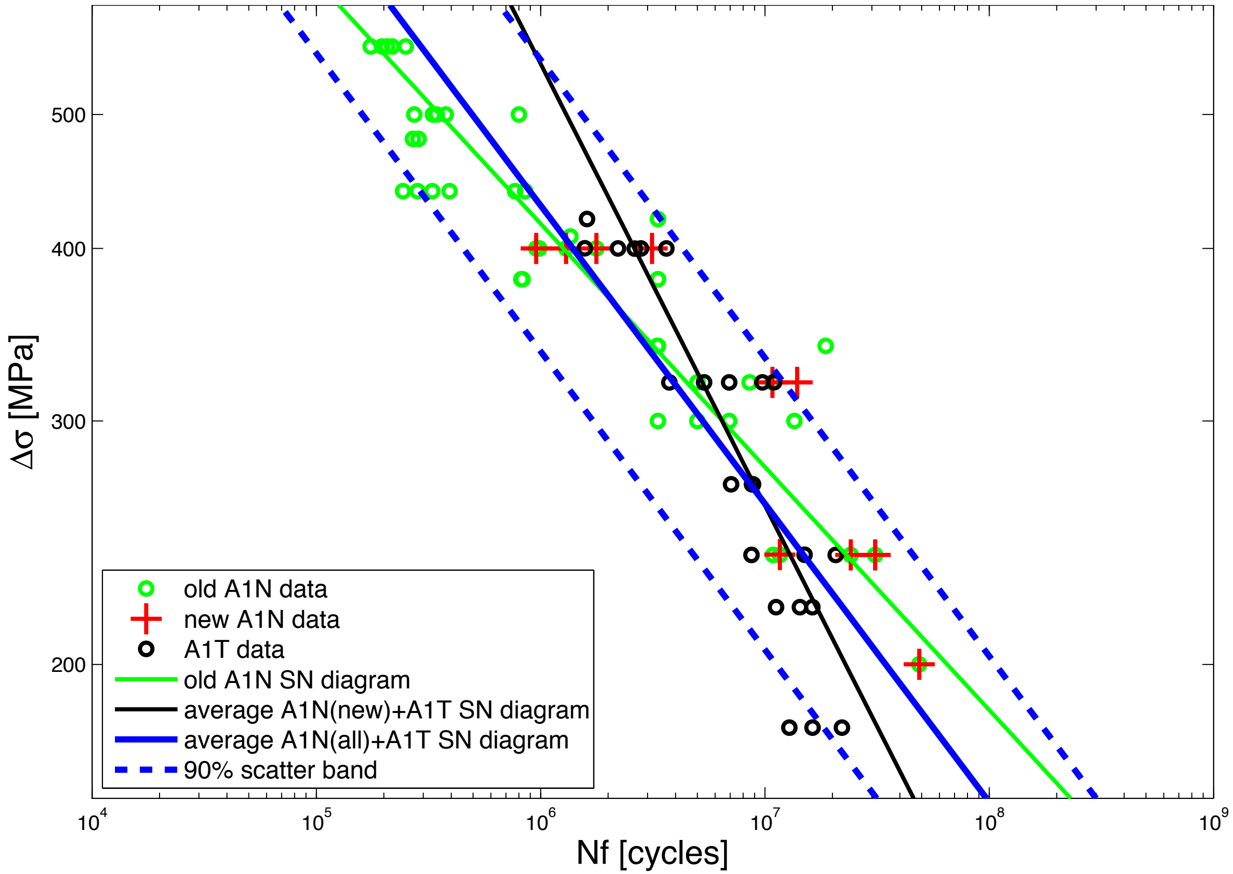
If we compared the corrosion-fatigue growth rate with simple ‘in air’ crack growth rate



from a surface length of 3-6 mm the propagation in air is more rapid !

A1T: corrosion fatigue model

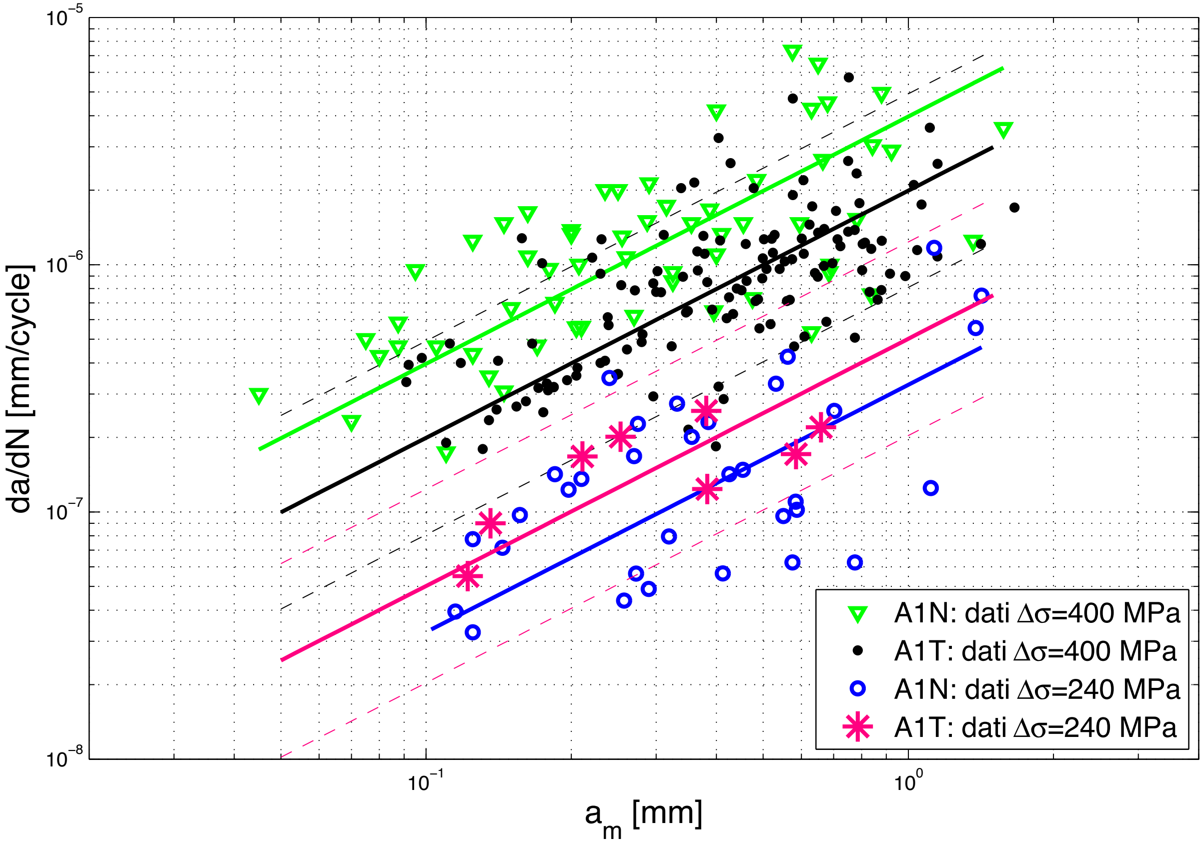
Similar experiments carried out for A1T small-scale specimens



A1T data fall within the scatter-band of A1N diagram

A1T: new experiments

Data for A1T are very close to the ones of A1N



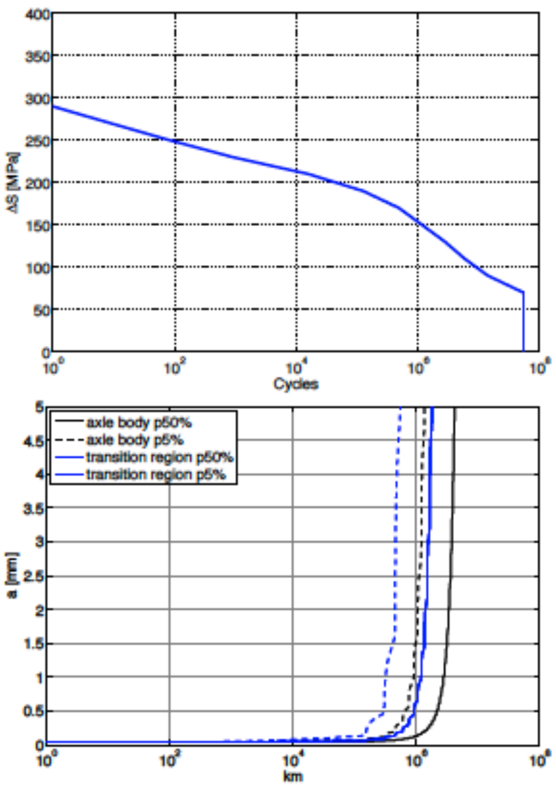
Model has been updated for a better description
(much more data than A1T data)

Application to service spectra

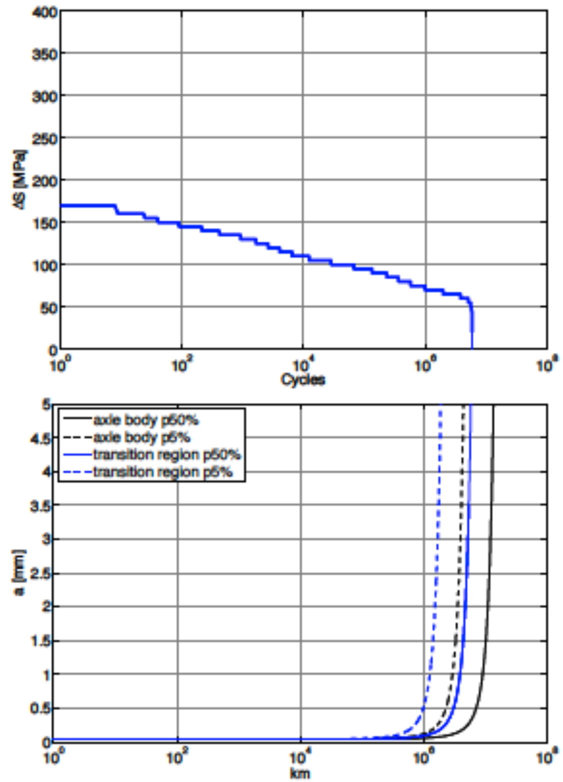
Integration of the growth curve for blocks representing a service spectrum

$$\frac{da}{dN} = B\left(\Delta\sigma\right)^{\beta} \cdot a \;\rightarrow\; dN = \frac{1}{B(\Delta\sigma)^{\beta}}\frac{da}{a} \;\rightarrow\; \boxed{\Delta N_i = \frac{1}{B\left(\Delta S_i\right)^{\beta}} \int_{a_i}^{a_{i+1}} \frac{da}{a}}$$

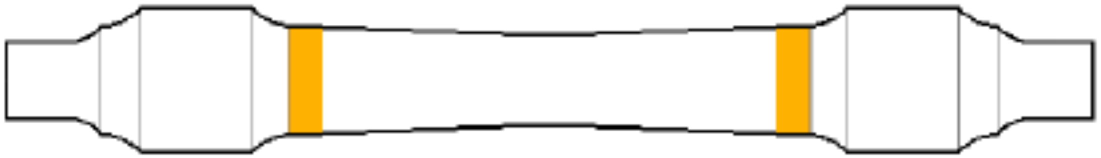
WIDEM – ETR500



Typical UK axle



Summary of application to service spectra



	Axle Body		Transition Region	
	$p_{50\%}$	$p_{0.1\%}$	$p_{50\%}$	$p_{0.1\%}$
ETR500	4,050,000	801,750	1,666,282	178,186
Locomotive	2,765,123	354,003	1,186,440	151,115
Typical UK Axle	13,052,523	1,672,503	5,607,989	717,336

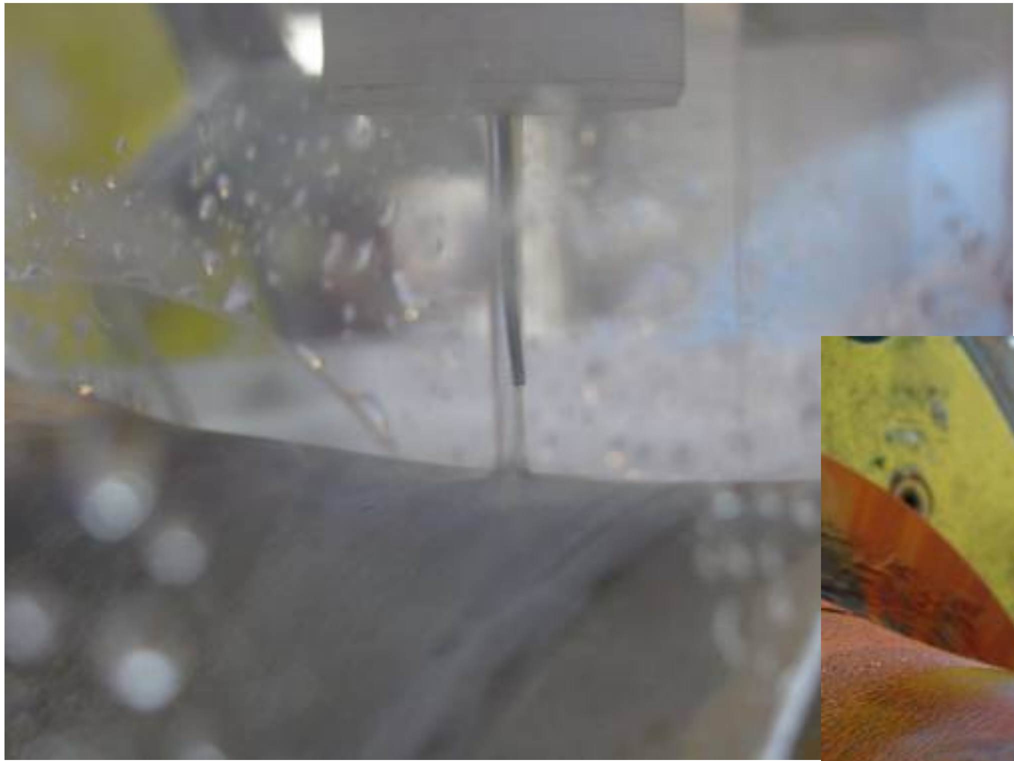
•application of model gives reasonable results (even if 100% lifetime under corrosion);

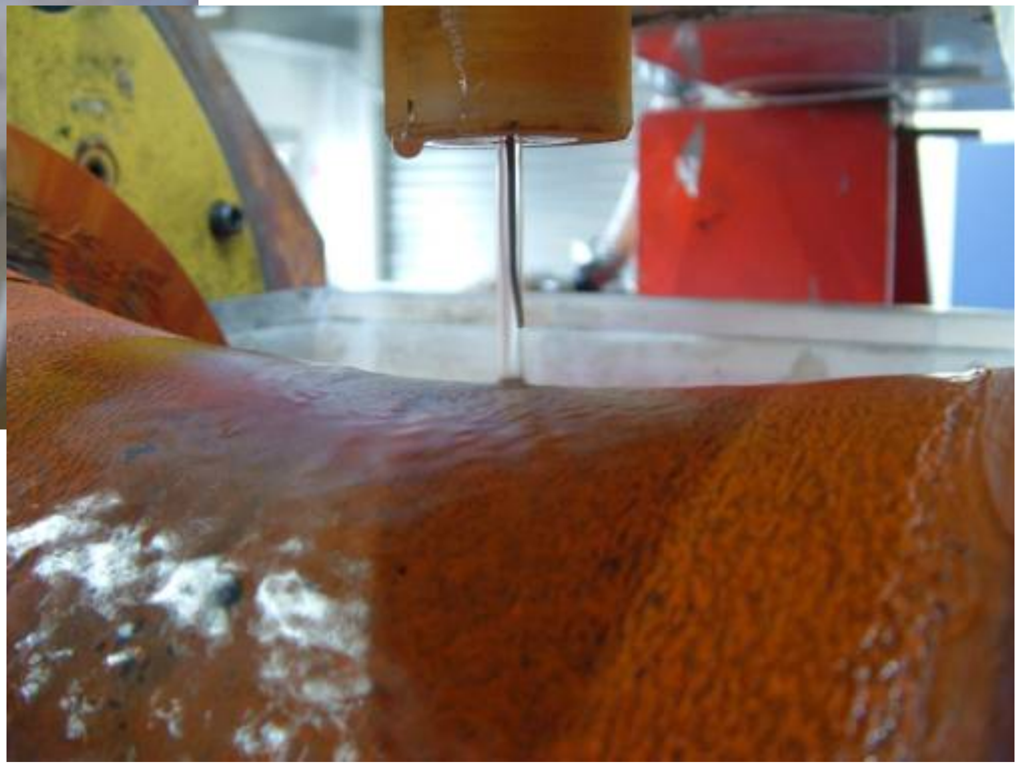
•strong effect of the stress concentration at T-transitions

Full-scale corrosion-fatigue tests

Two full scale tests on A1T for model verification: a first test run at 160 MPa (constant amplitude) a second test under block loads

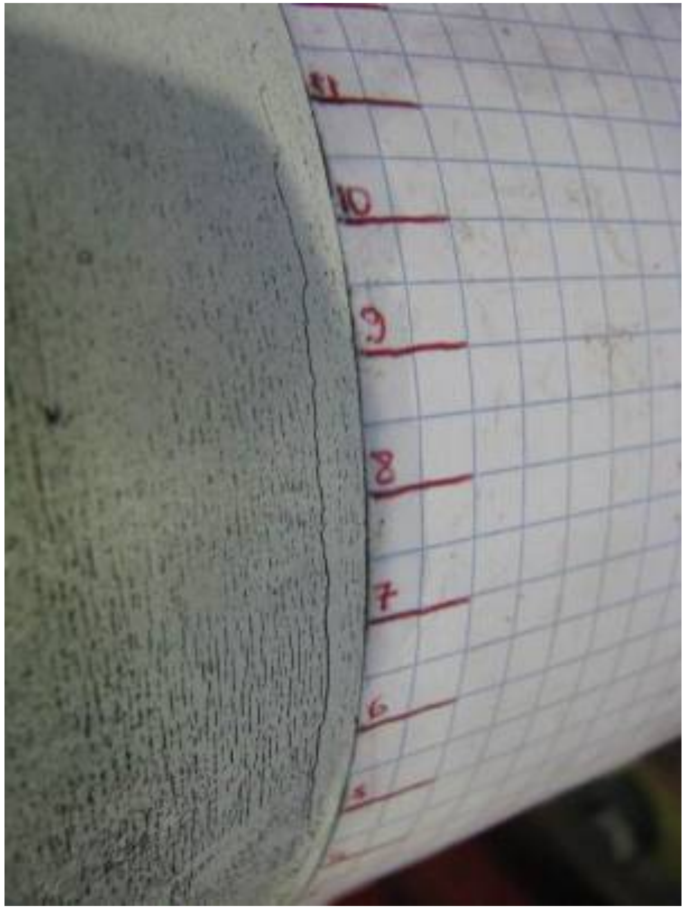
Reference electrode

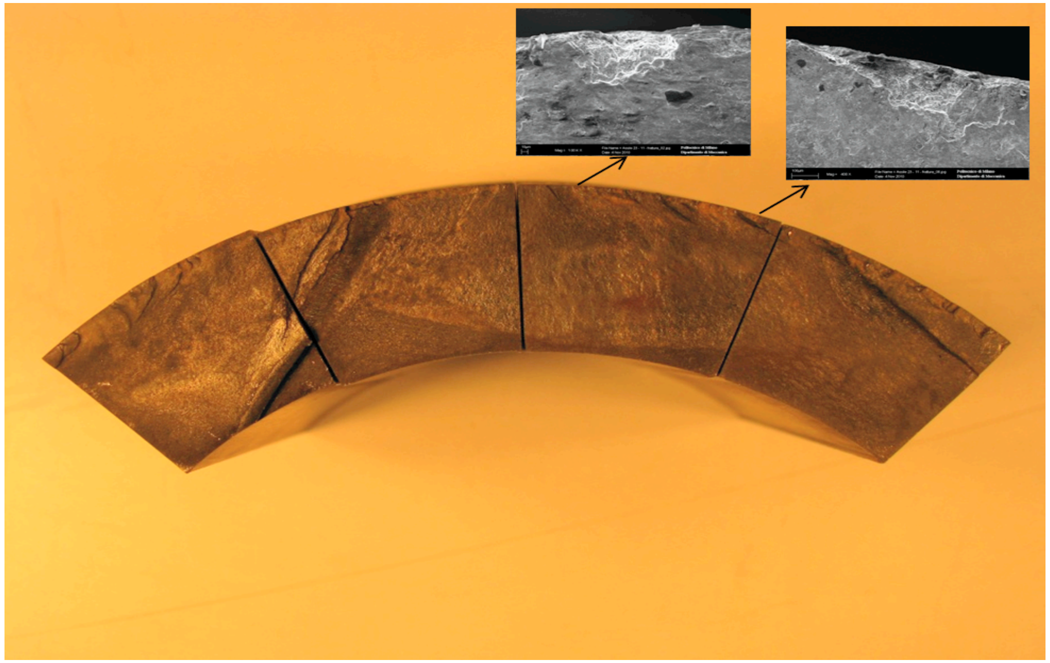




First full-scale test

The first axle broke under corrosion fatigue at 9.4 10^6 cycles with a very good agreement with predictions

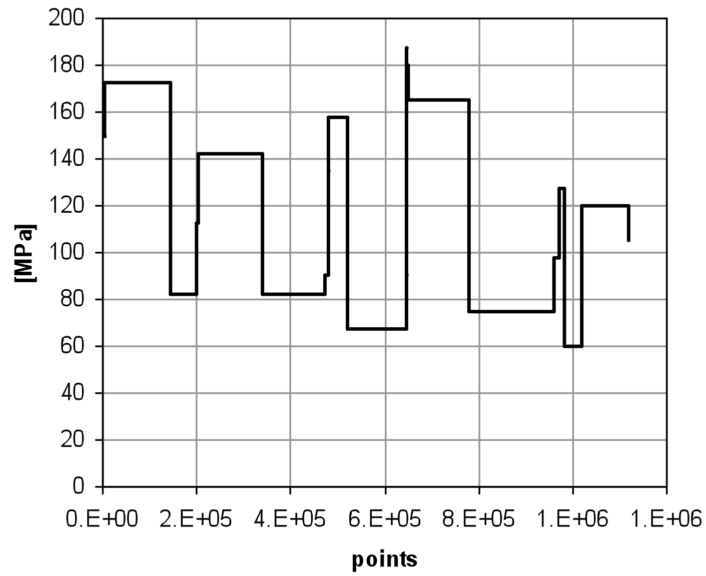


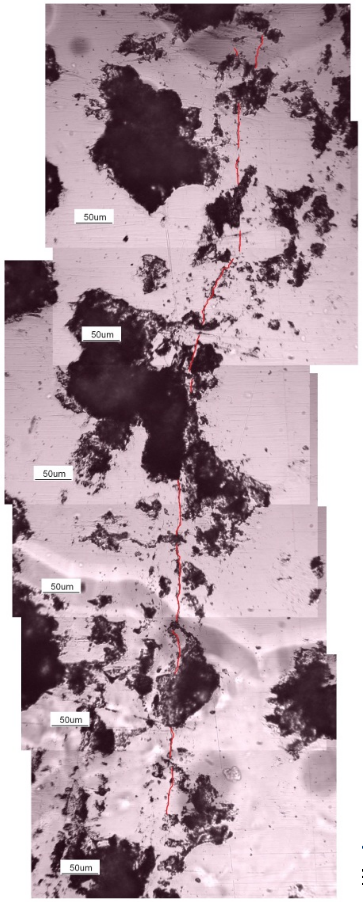


surface cracking very similar to 'Hoddinott cracking'

2nd full-scale test

- Test spectrum with a target life of 35 10^6 cycles;
- test stopped at 1.4 106 cycles





At at 14.7x10^6 cycles, 135°, first cluster of aligned small cracks, total length about 1.5 mm.

The predicted crack length is very close to experimental result

In this presentation the results obtained at PoliMI on corrosion-fatigue of full-scale axles have been shown. Main results can be summarized as:

•exposure of A1N to a mild corrosion (artificial rainwater) causes a dramatic reduction of fatigue life with the appearance of 'Hoddinott cracking';

•crack growth rate under corrosion-fatigue can be described with a simple model of the type:

$$\frac{dl}{dN} = B \cdot (\Delta S)^{\beta} \cdot l$$

•A1T has fatigue properties very similar to A1N and its corrosion-fatigue behaviour is the same;

•the propagation model obtained onto small-scale specimens could be successfully applied to full-scale tests.

Damage quantification on real railway axles:

TWI contribution to RSSB 1318 T728 – Research into the effects of corrosion on the fatigue performance of GB axles

John Davenport

Based on results of Qing Lu, Mike Gittos, John Rudlin and Yanhui Zhang

TWI
Technology
Engineering

Copyright © TWI Ltd 2011

TWI Objectives

- Focus on Grade A1 steel axles.
- Characterise the corroded axles.
- Generate crack growth data by conducting corrosion fatigue tests in air and in artificial rainwater.
- Assess probabilistic models of fatigue crack growth (not included in this presentation).

TWI Technology Engineering

Copyright © TWI Ltd 2011

Surface Damage

- Surface damage measurements:
  - Corrosion
  - Mechanical
- Techniques used:
  - Pit Gauge
  - Taking replicas
  - Micro-sectioning
  - Eddy current probe

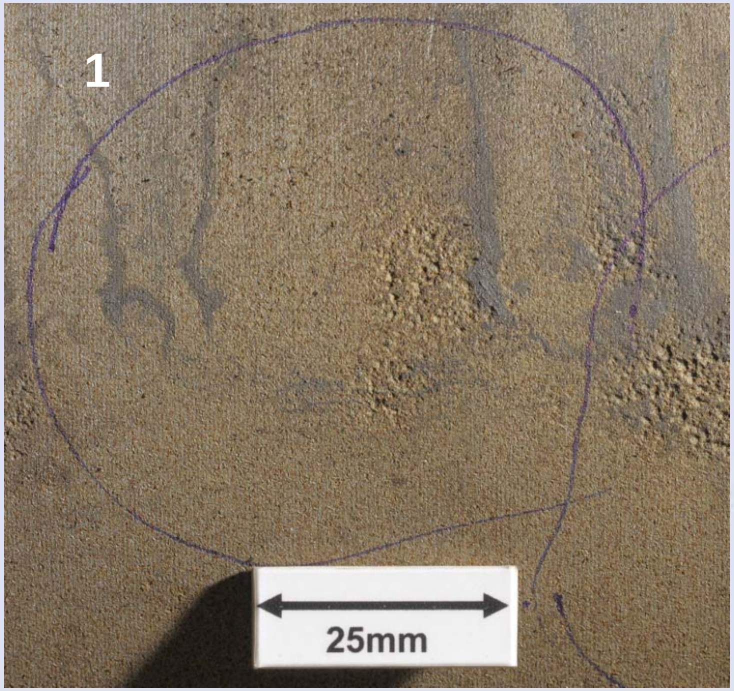
TWI
Technology
Engineering

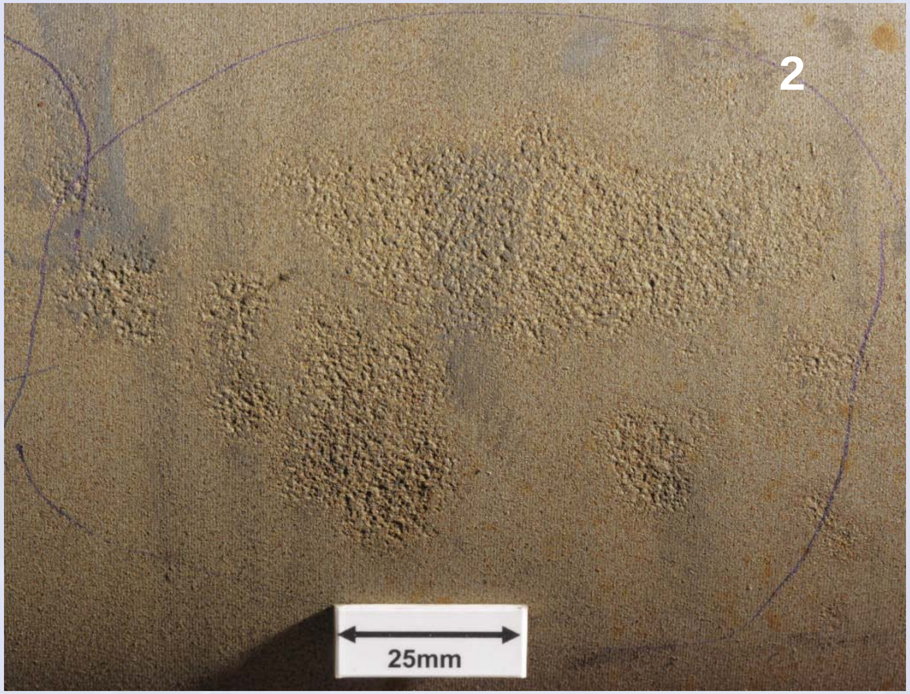
Copyright © TWI Ltd 2011

Appearance of Axles

Copyright © TWI Ltd 2011

Axle 6 As-received





Copyright © TWI Ltd 2011

Selection of Corroded Areas

- Using a very small diameter focused field 2 MHz eddy current probe (0.5mm core)

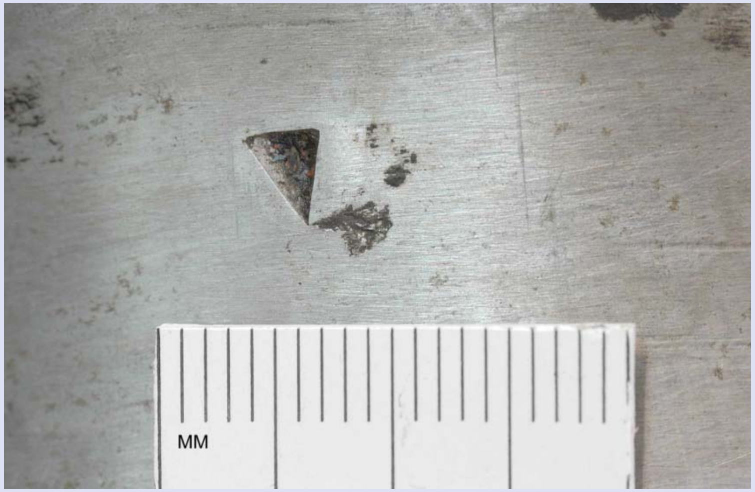
- Calibrate with lift off (50% screen height =0.140µm from 0.140µm plastic shim)
- Scan corroded areas looking for pit type signals (scan along plastic shim placed on surface)

TWI
Technology
Engineering

Copyright © TWI Ltd 2011

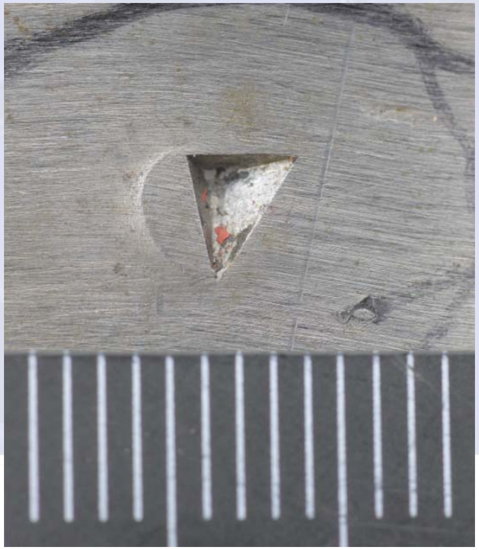
Surface Damage Measurements

- **Using a Pit Gauge**
  - **Axle 1**



Max. surface mechanical damage depth: 0.88mm

Depth ranges from 0.11 to 0.39mm

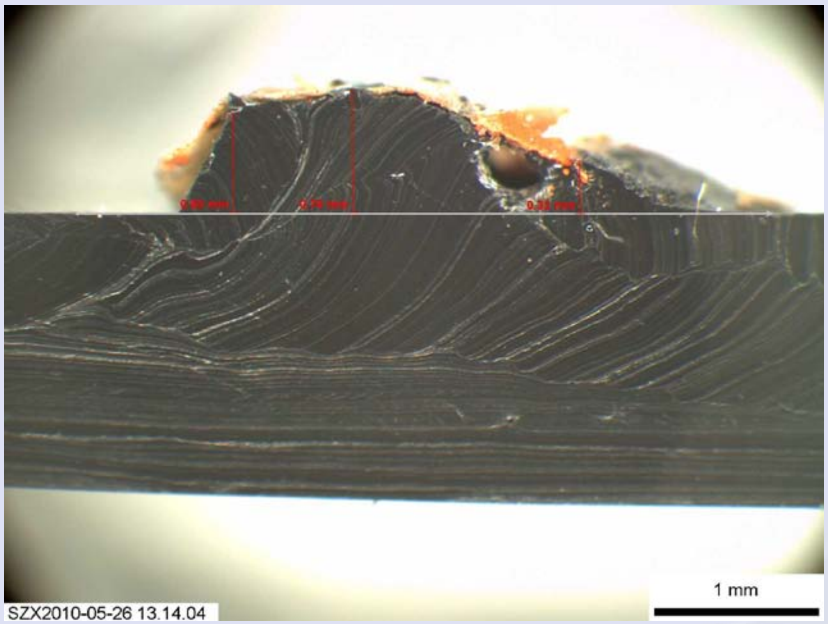


Max. depth: 0.94mm

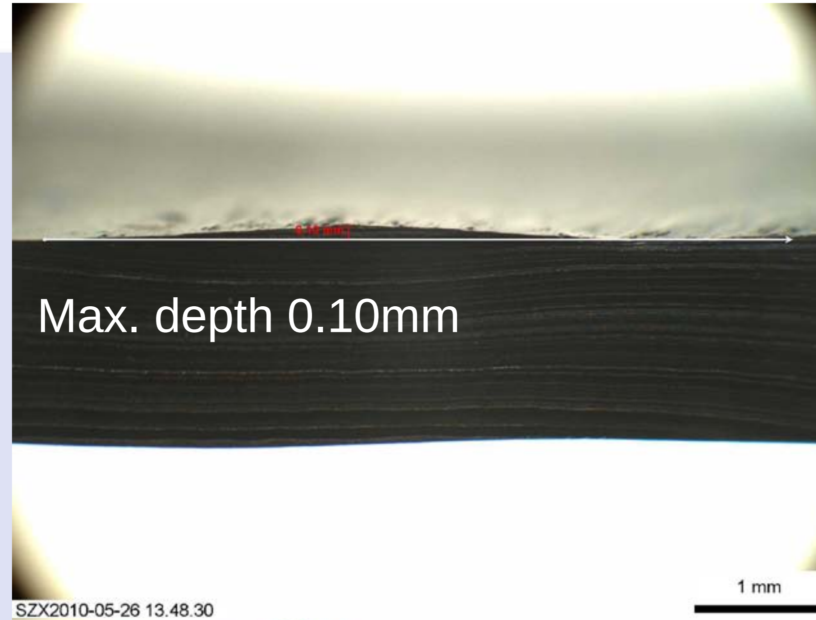
Copyright © TWI Ltd 2011

Surface Damage Measurements

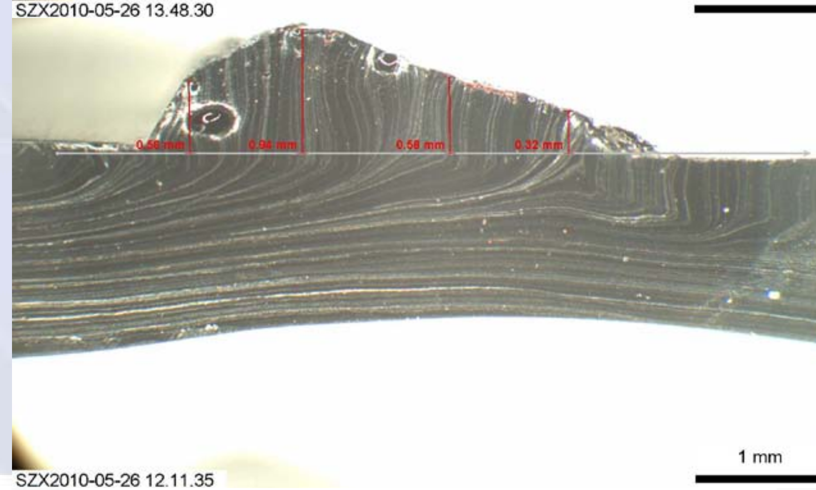
- **Taking replicas:**
  - **Axle 1**



Max. surface mechanical damage depth: 0.74mm



Max. depth 0.10mm

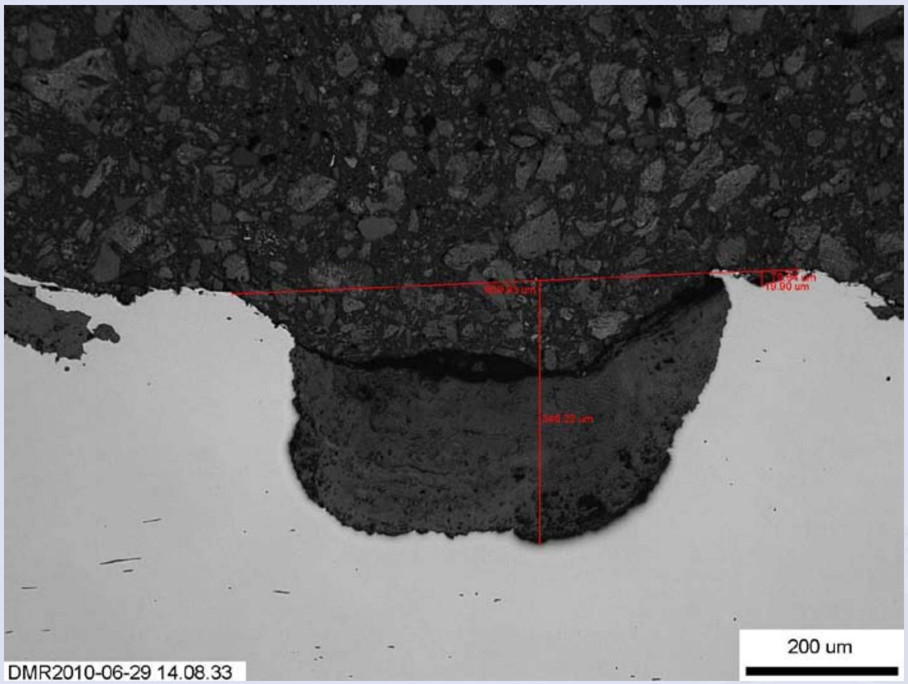


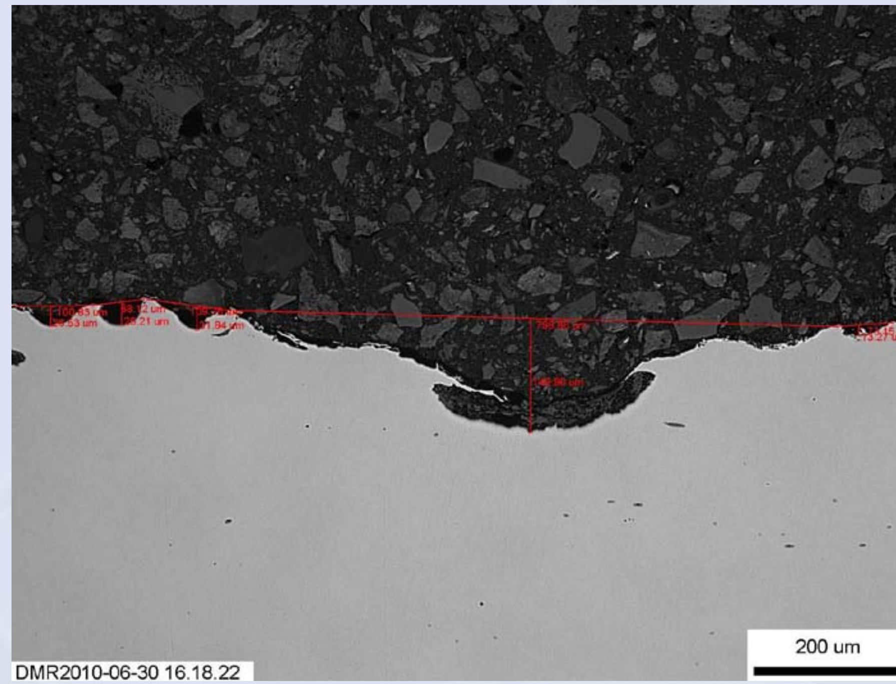
Max. depth: 0.94mm

TWI Technology Engineering

Copyright © TWI Ltd 2011

Axle 6, Area 1





TWI
Technology
Engineering
Copyright © TWI Ltd 2011

Surface Damage Measurements

- Taking replicas
  - Axles 4 and 5: as-received and after acid cleaning
  - Axle 6: as-received

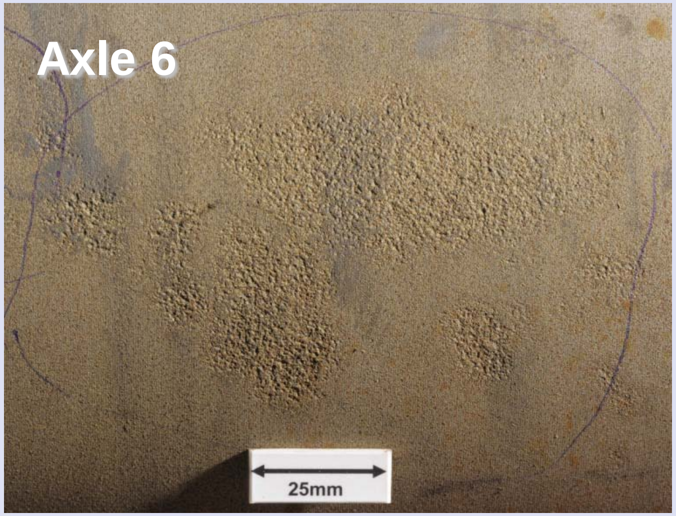


Table 1 Results of depth measurements in mm

Axle 4		Axle 5		Axle 6
As-received	After cleaning	As-received	After cleaning	As-received
0.07	0.08	0.09	0.10	0.21
0.10	0.10	0.10	0.11	0.29
0.05		0.06	0.07	0.37
0.06		0.04	0.04	0.14
0.07		0.16		0.22
0.09		0.09		0.28
0.12		0.07		0.17
		0.08		

TWI Technology Engineering

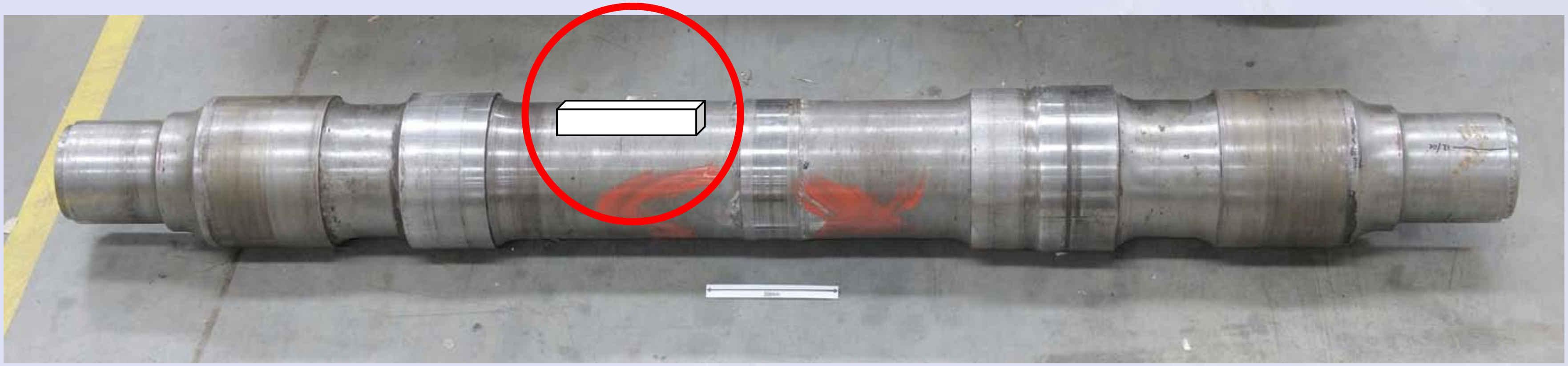
Copyright © TWI Ltd 2011

Fatigue crack growth rate tests

TWI
Technology
Engineering

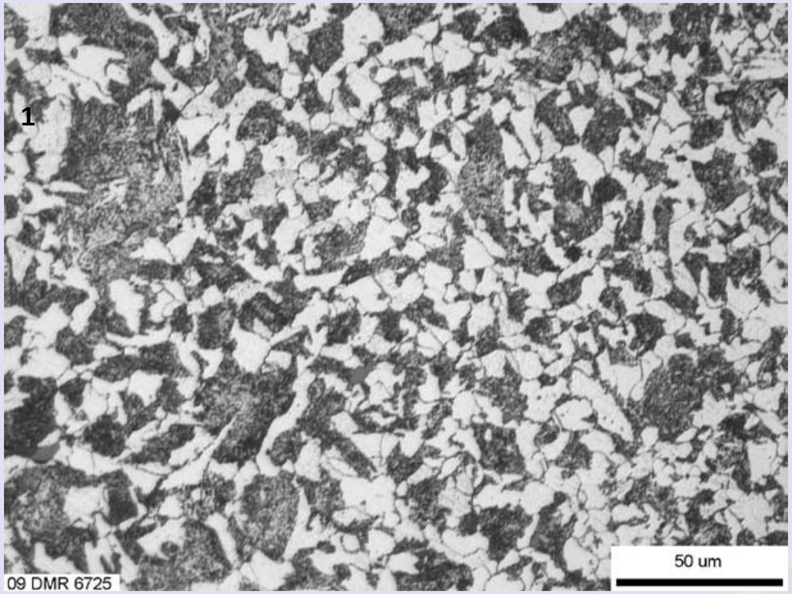
Copyright © TWI Ltd 2011

Orientation of Fatigue Crack Growth Specimens

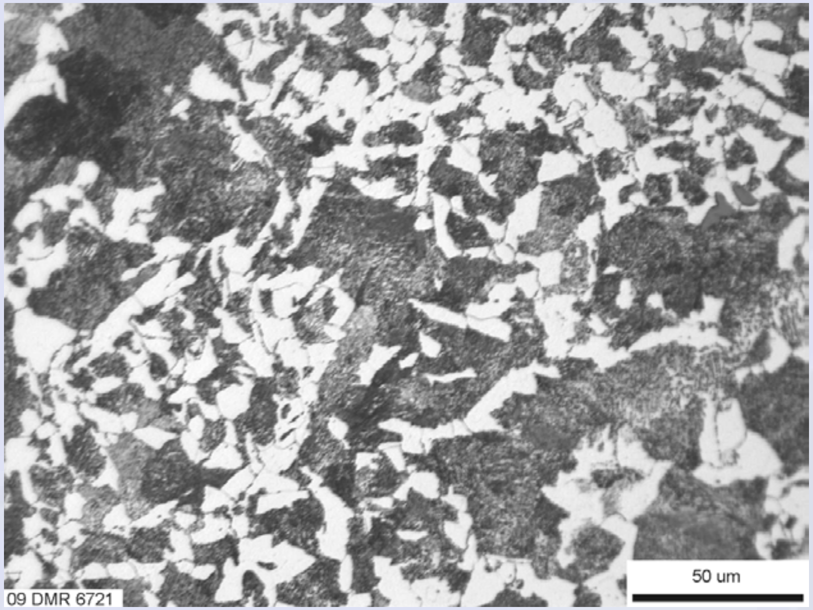


Copyright © TWI Ltd 2011

Axle 3, Polished and Etched



Close to the axle edge

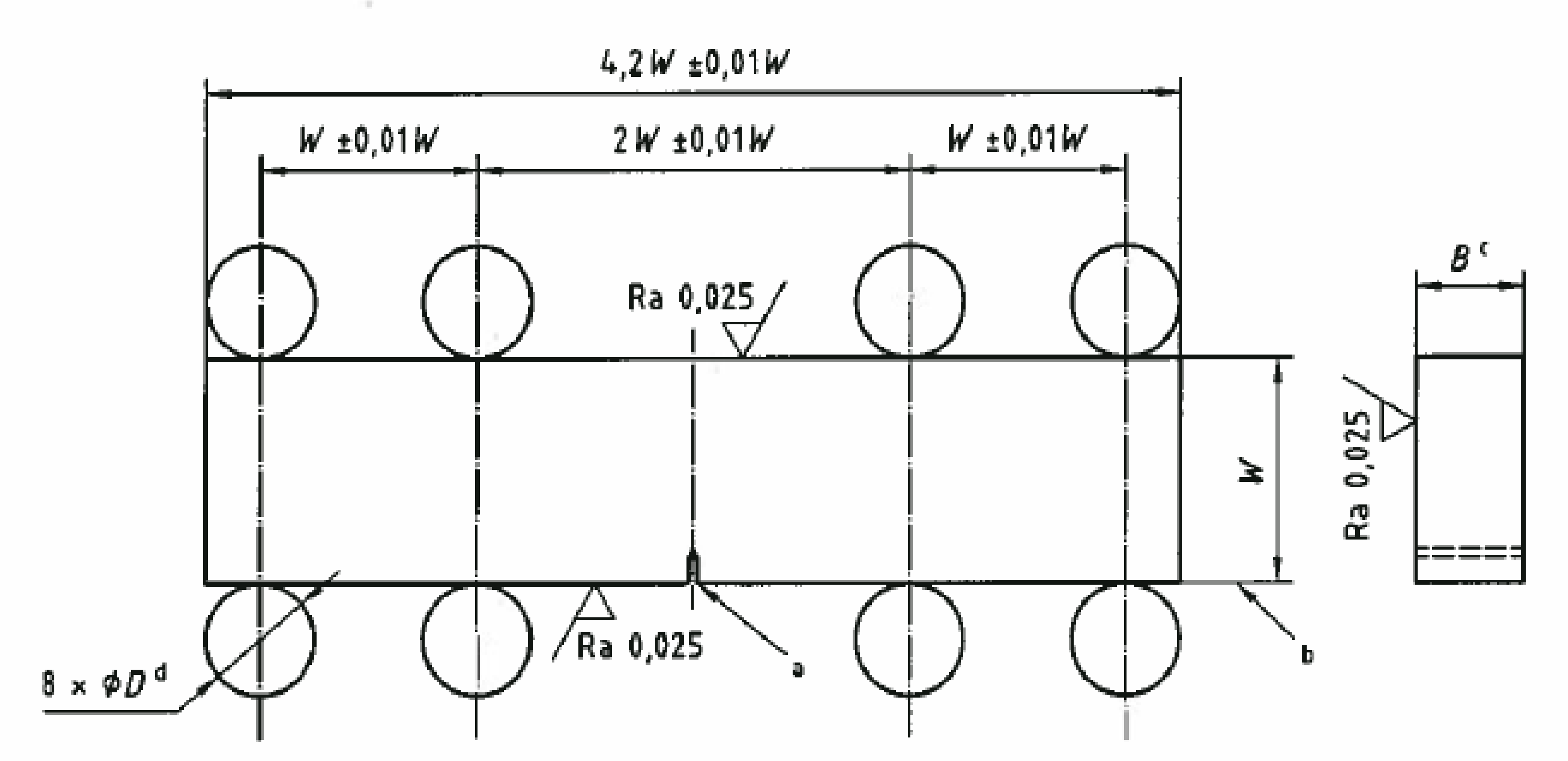


Close to the axle centre

Copyright © TWI Ltd 2011

Test Specimen

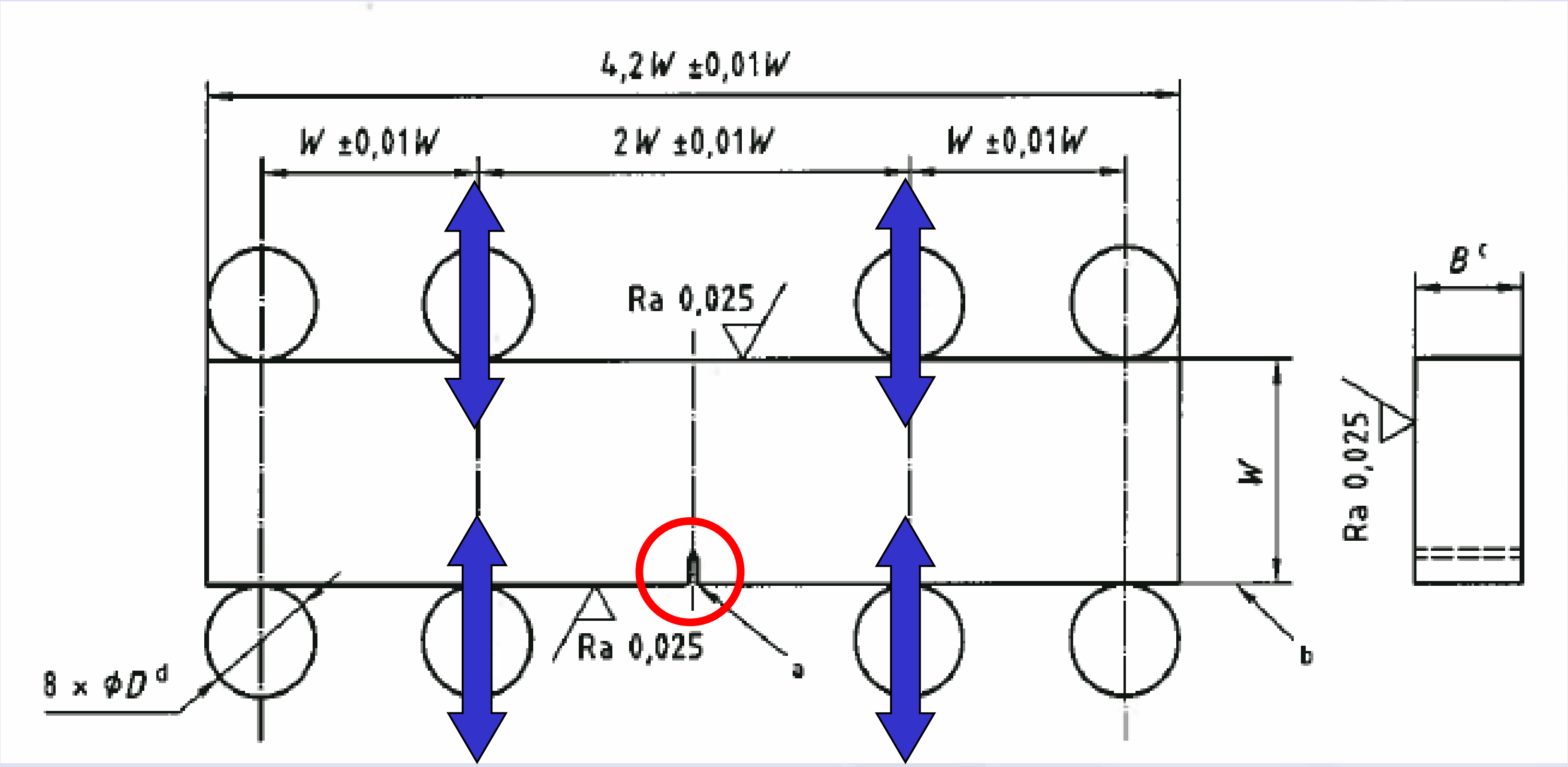
SENB8 specimen
W=25mm, B=12.5mm



Copyright © TWI Ltd 2011

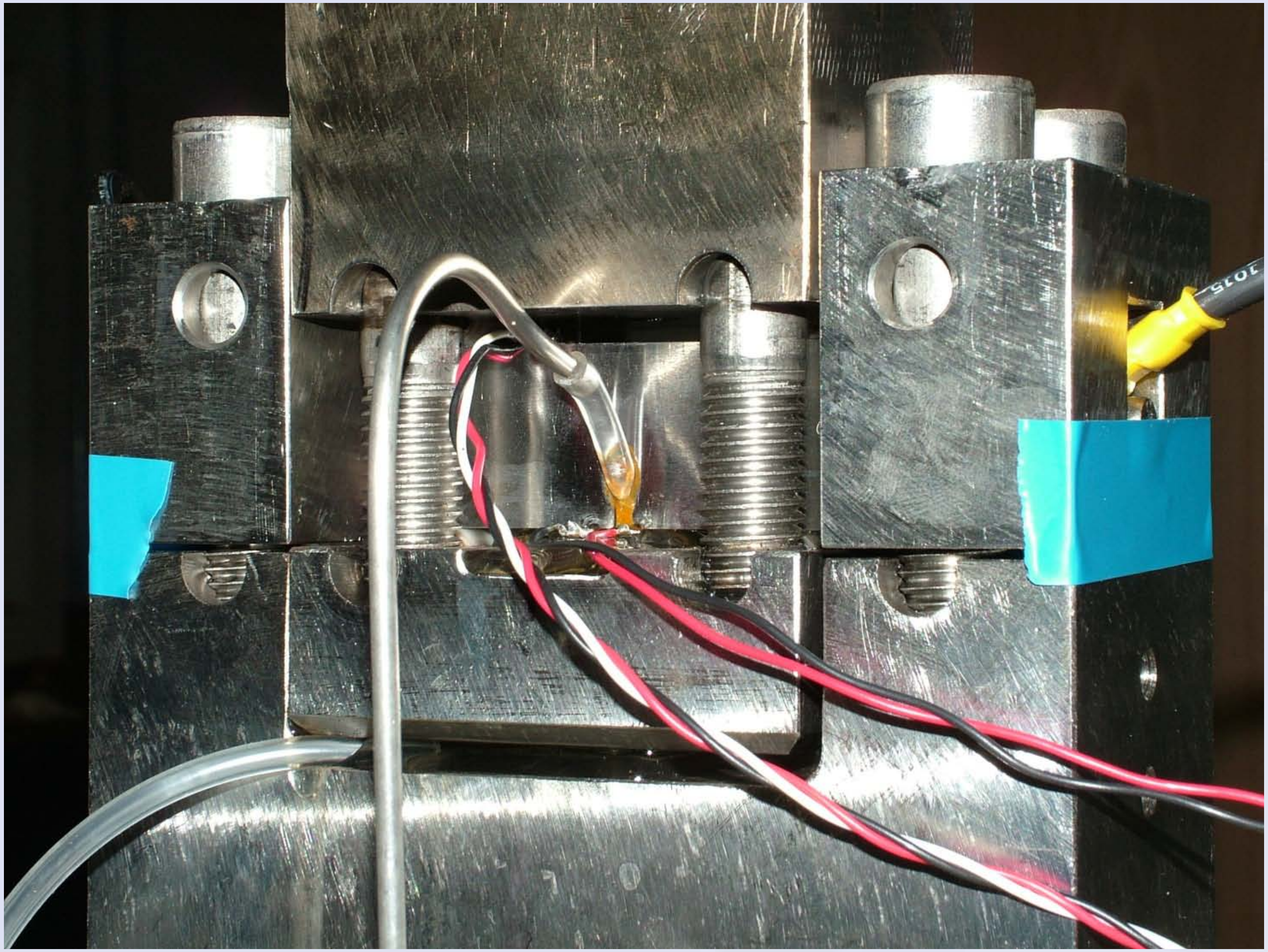
Test Specimen

SENB8 specimen
W=25mm, B=12.5mm



Copyright © TWI Ltd 2011

Set up for the Test in Artificial Rainwater



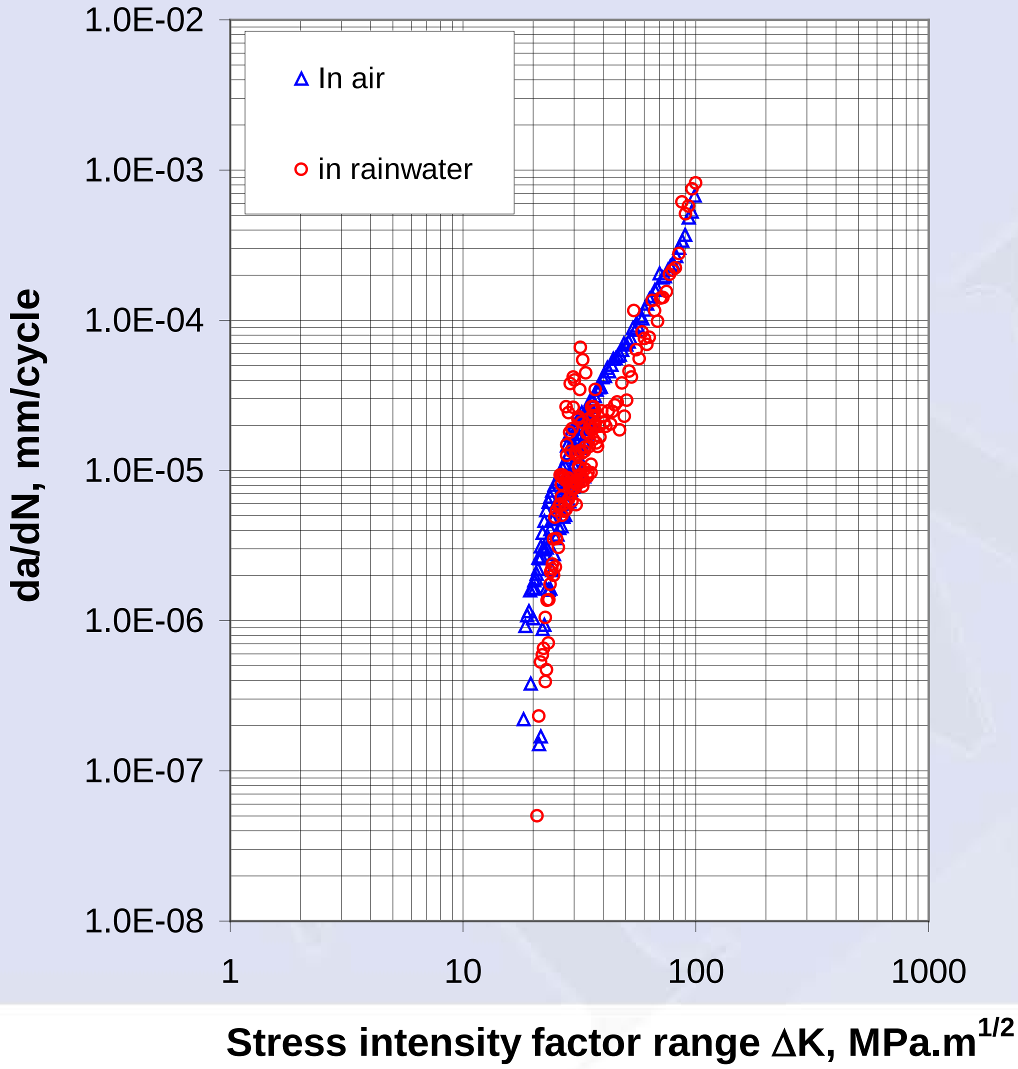
Copyright © TWI Ltd 2011

Testing Conditions

- **Tests carried out in accordance with BS ISO 12108:2002 procedures**
- **Four tests in air, loading frequency = 6Hz**
- **Four tests in artificial rainwater, rainwater dropping every 7 seconds, loading frequency = 6Hz**
- **All tests at R = -1, room temperature, 3 decreasing and 1 increasing ΔK tests for each environment.**

Copyright © TWI Ltd 2011

Fatigue Crack Growth Rate Results



TWI Technology Engineering

Copyright © TWI Ltd 2011

Main Findings – Fatigue

- The fatigue crack growth rates in air and rainwater were comparable at a test frequency of 6 Hz.
- The variations in pH values between 5 and 6.4 for the rainwater solution did not have a significant effect on the crack growth rates.

TWI Technology Engineering

Copyright © TWI Ltd 2011

Main Findings - Damage

- Corrosion products contained mainly iron and oxygen, consistent with atmospheric corrosion.
- Maximum corrosion depth measured from the individual axles ranged from 0.02mm to 0.37mm.
- Maximum depth of mechanical damage was 0.94mm.
- Eddy current measurement was not suitable for precise pit depth measurements.
- Corrosion depths measured by surface replication were in agreement with metallographic section measurements.

Copyright © TWI Ltd 2011

ESIS TC24 Workshop 3-4 March 2011

“Predicting real world axle failure and reliability”

Technical Challenges in the Axle Safety Model – A S Watson

© 2011 DeltaRail Group Limited

Background

- Current UK/European Axle Design Standards not optimum
  - Assume complete protection against corrosion and mechanical damage
  - Give no guidance about NDT requirements
- RSSB input to improved Axle Design Standards
  - Axle assessment based on probabilistic crack growth predictions
  - Will include implications of NDT
  - RSSB Project T356: Developed methodology for predicting axle stress
  - RSSB Project T550 (WIDEM): Investigated NDT Effectiveness
  - Still need to develop appropriate crack growth model
  - Still need to characterise surface condition
- RSSB Project T728 WP2 to address these remaining issues

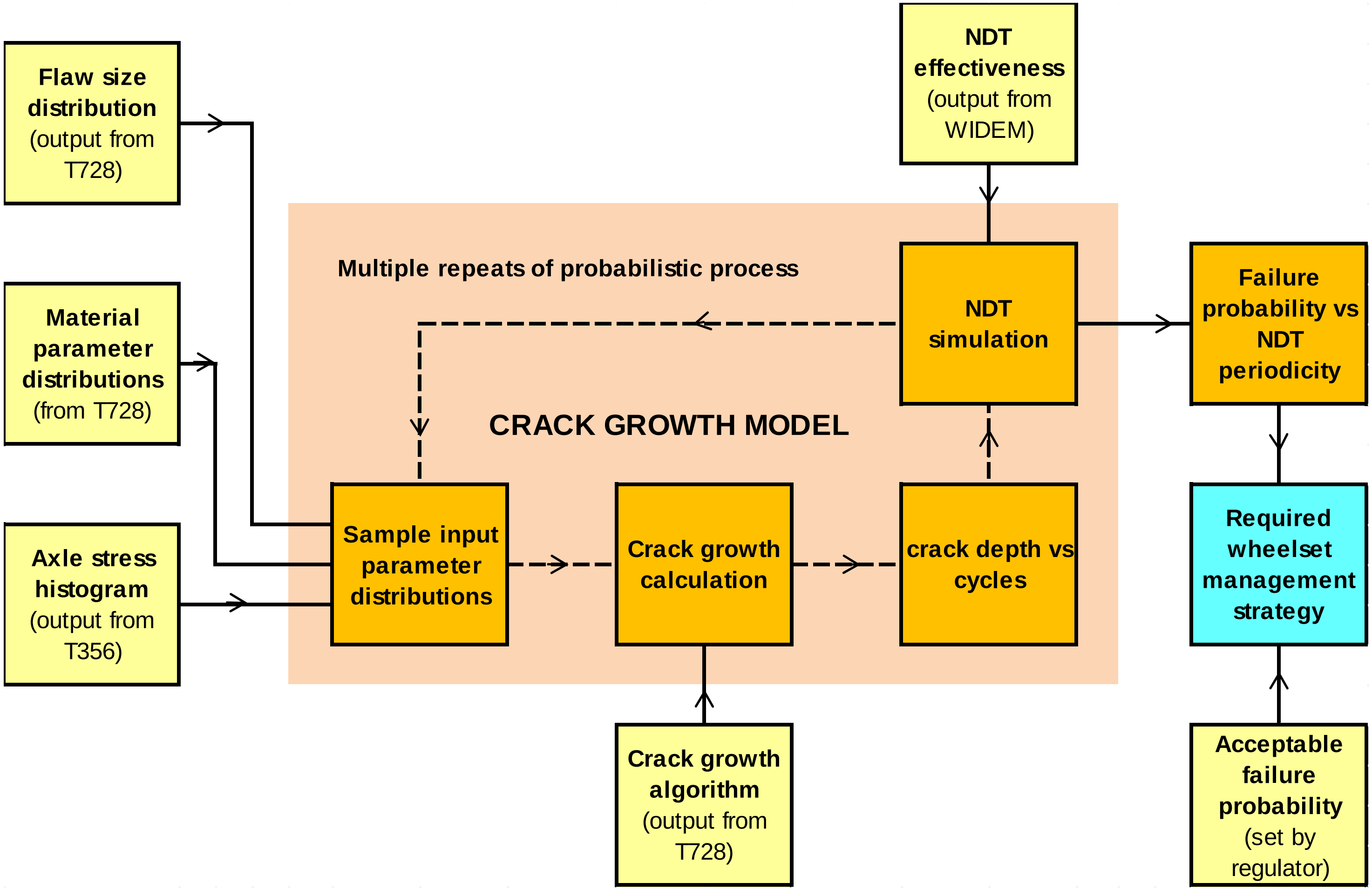
© 2011 DeltaRail Group Limited

RSSB Project T728 WP2

- "Effects of corrosion on the fatigue performance of British axles"
- Partners: RSSB, DeltaRail, Politecnico di Milano (PoliMi), TWI
- Objectives:
  - Characterisation of axle surface condition
  - Definition of crack growth behaviour for A1T axle steel
  - Development of probabilistic crack growth model for axles
  - Integration with results of RSSB Projects T356 and T550 to provide a tool to assess axle designs and NDT requirements
- Deliverables:
  - Improved methodology of axle assessment – complete process
  - Simplified Excel implementation of methodology – for immediate use by Industry Specialists

© 2011 DeltaRail Group Limited

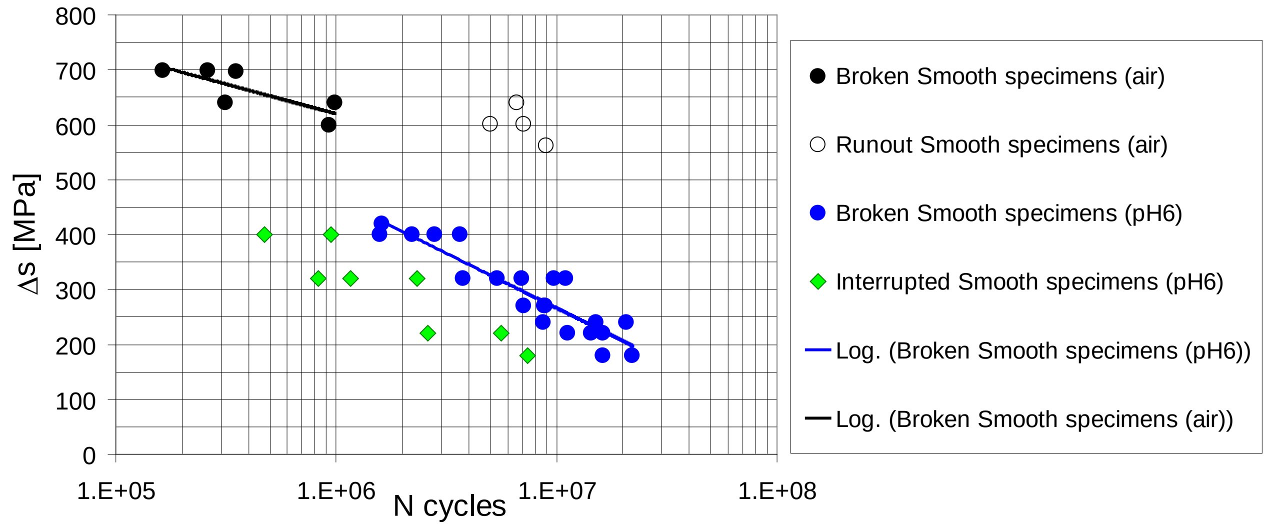
Axle Assessment Process - Overview



© 2011 DeltaRail Group Limited

Crack Growth Algorithm – Results of Material Testing for Small Cracks (PoliMi)

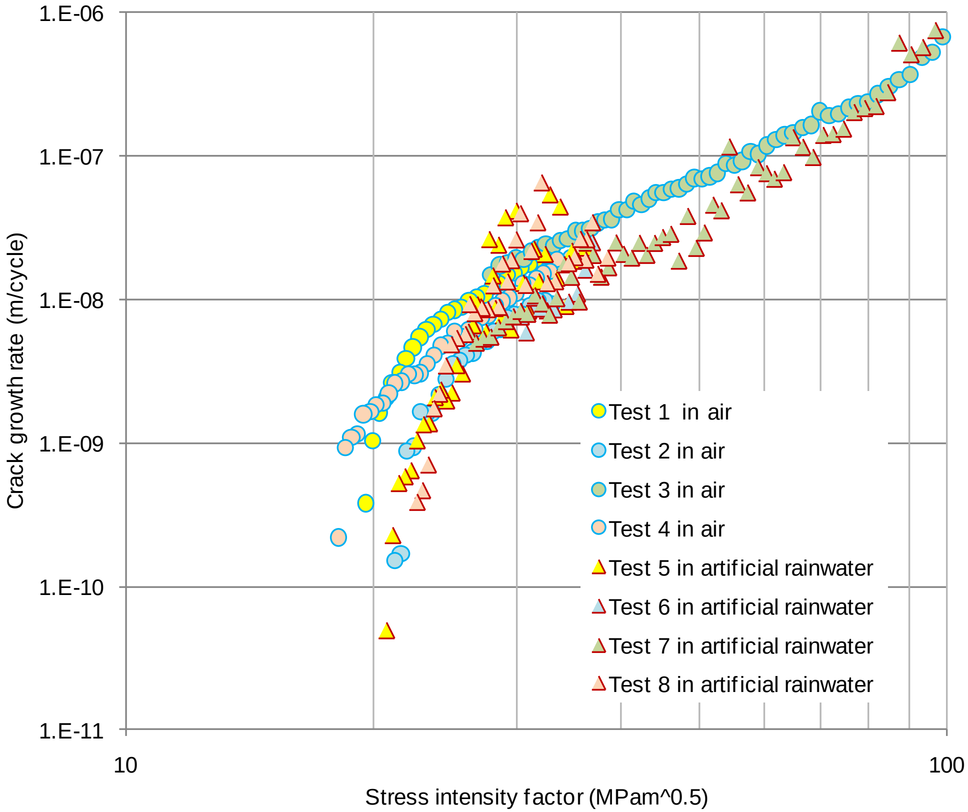
- Crack growth dominated by corrosion fatigue
- Corrosive conditions reduce fatigue limit / threshold close to zero
- Grades A1T and A1N have similar crack growth behaviour



© 2011 DeltaRail Group Limited

Crack Growth Algorithm – Results of Material Testing for Large Cracks (TWI)

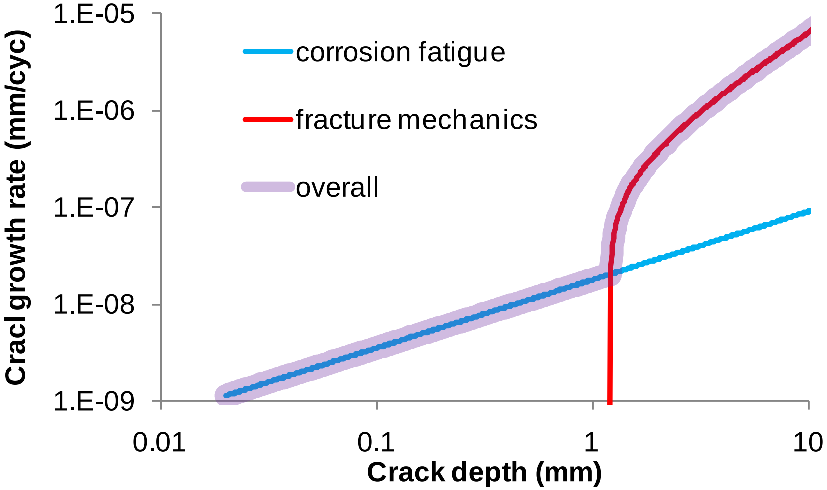
- No real difference between corrosive conditions and dry air



© 2011 DeltaRail Group Limited

Crack Growth Algorithm - Principle

- Growth of small cracks predicted using corrosion fatigue model
- Larger cracks assumed to grow according to “classical” fracture mechanics (NASGRO formulation)
- Crack growth mechanisms “change over” at 2-3 mm depth for stress levels typically seen in axles



© 2011 DeltaRail Group Limited

Crack Growth Algorithm – Dealing with Variability in Crack Growth Behaviour

- Variability in material parameters requires a probabilistic calculation
  - Best applied by a modified Monte Carlo technique where each sample is weighted according to its probability of occurrence

			Corrosion fatigue constant (B)						
			-3	-2	-1	0	1	2	3
			0.0062	0.0606	0.2417	0.383	0.2417	0.0606	0.0062
			2.72E-19	5.39E-19	1.07E-18	2.12E-18	4.20E-18	8.33E-18	1.65E-17
Threshold -3	0.0030	9.15	0.00002	0.00018	0.00073	0.00115	0.00073	0.00018	0.00002
-2.5	0.0092	9.72	0.00006	0.00056	0.00222	0.00352	0.00222	0.00056	0.00006
-2	0.0279	10.34	0.00017	0.00169	0.00674	0.01069	0.00674	0.00169	0.00017
-1.5	0.0655	10.99	0.00041	0.00397	0.01583	0.02509	0.01583	0.00397	0.00041
-1	0.1210	11.68	0.00075	0.00733	0.02925	0.04634	0.02925	0.00733	0.00075
-0.5	0.1747	12.42	0.00108	0.01059	0.04222	0.06691	0.04222	0.01059	0.00108
0	0.1974	13.20	0.00122	0.01196	0.04771	0.07560	0.04771	0.01196	0.00122
0.5	0.1747	14.03	0.00108	0.01059	0.04222	0.06691	0.04222	0.01059	0.00108
1	0.1210	14.92	0.00075	0.00733	0.02925	0.04634	0.02925	0.00733	0.00075
1.5	0.0655	15.86	0.00041	0.00397	0.01583	0.02509	0.01583	0.00397	0.00041
2	0.0279	16.86	0.00017	0.00169	0.00674	0.01069	0.00674	0.00169	0.00017
2.5	0.0092	17.92	0.00006	0.00056	0.00222	0.00352	0.00222	0.00056	0.00006
3	0.0030	19.05	0.00002	0.00018	0.00073	0.00115	0.00073	0.00018	0.00002

Key:
- (green) Standard deviations from mean
- (blue) Associated probability based on normal / lognormal distribution
- (orange) Parameter value based on lognormal distribution
- (yellow) Overall probability of occurrence

© 2011 DeltaRail Group Limited

Flaw Size Distributions – Sources of Flaws

- Potential sources of flaws in axles:
- Corrosion fatigue
  - Can predict crack growth from “perfect” surface – no pre-existing flaws required
- Corrosion pits
  - Could initiate fatigue cracks due to local stress concentration
  - But, for the high cyclic stress levels seen in axles, is this effect overshadowed by corrosion fatigue?
- Mechanical damage
  - Can be caused by impact from debris, or careless handling
  - Is known to have caused some axle failures
- Fretting fatigue in areas subject to interference fits
  - Not considered explicitly in RSSB T728. Use existing conservative model
- Scoring, electrical damage, and other exceptional cases
  - Not currently considered by RSSB T728

© 2011 DeltaRail Group Limited

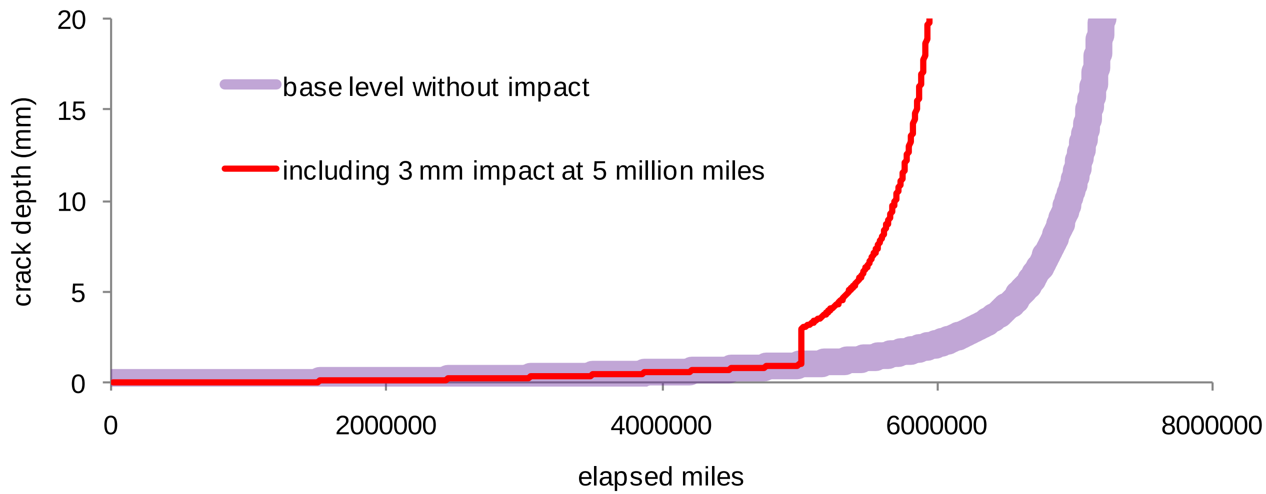
Flaw Size Distributions – Sources of Data

- Review of axle records
  - Main source of quantitative mechanical damage data
  - Previous BRR work suggests maximum corrosion pit depth of about 0.3 mm
- Visits to axle overhaulers
  - Qualitative data on probability of mechanical damage
  - Qualitative data on severity of corrosion
  - Axles usually scrapped because of damage to journals and wheelseats rather than corrosion. However, corrosion may be significant for some specific fleets
  - Insight into how overhaul documents affect axle scrapping rates
  - Six axles selected for detailed surface investigation by TWI
- TWI detailed Investigation and PoliMi Extreme Values Analysis
  - Confirmed typical maximum corrosion pit depth of 0.3 mm
  - Defined distribution of flaw depth for mechanical damage – much larger than corrosion pits

© 2011 DeltaRail Group Limited

Flaw Size Distributions – Application to Crack Growth Model

- Corrosion fatigue model predicts crack growth from “nominal” surface
  - Assume flaw size corresponding to material grain size (0.01 mm)
- Mechanical damage can occur at any time in overhaul cycle
  - Depth distribution based on Extreme Value Analysis by PoliMi
  - Probability of damage during overhaul cycle assumed to be: 30% for high speed trains, 5% for other train types



© 2011 DeltaRail Group Limited

Effectiveness of NDT – Effect of Variability between Operators

- WIDEM work found significant variability in probability of detection between operators, particularly for UAT far end scans
  - Using mean probability of detection (PoD) curve gives similar failure probabilities to explicitly taking account of the variation
  - Recommend mean PoD for far end scans, provided that there is sufficient confidence that mean PoD is on average actually achieved
  - Otherwise recommend lower bound (90% confidence) PoD curve
  - Axle geometry, UAT beam angle and frequency also affect PoD
- WIDEM work could not quantify variability for UAT near end and high angle scans
  - Appropriate lower bound PoD curves have been defined

© 2011 DeltaRail Group Limited

Effectiveness of NDT – Application to Crack Growth Model

- Probabilistic calculations carried out over axle overhaul interval
  - Probability of finding crack during overhaul (including MPI) sufficiently good that any significant cracks can be assumed to be found
  - Risk to axles is from cracks that initiate and grow to failure entirely within the overhaul interval
- NDT may be simulated between axle overhauls
  - Probability of failure is probability of missing crack in all the inspections carried out
  - PoD curves for ultrasonic techniques based on WIDEM work
  - PoD curve for eddy current based on work by National NDT Centre following Rickerscote accident
  - PoD curves currently have a limit of 95% detectability to allow for human factors

© 2011 DeltaRail Group Limited

Axle Assessment Methodology: Sensitivity to Variability in Input Parameters

- Parameters with significant influence on failure probability
  - Static axle stress
  - Route, particularly distribution of curve radius (as found with T356)
  - Overhaul interval
  - Effectiveness of corrosion protection (currently paint). This is probably the most significant uncertainty in the assessment methodology
- Parameters with less influence
  - Probability of mechanical damage
  - Initial flaw size in corrosion fatigue model
- Variability in crack growth parameters explicitly included in probabilistic process

© 2011 DeltaRail Group Limited

Axle Assessment Methodology: Uncertainty in Effectiveness of Corrosion Protection

- British Axles are currently painted
  - Paint gives some but not full protection, and the degree of protection is very variable
- Effect of protection investigated by a sensitivity study
  - Protection simulated by reducing overhaul interval in probabilistic calculation
  - Protection for half overhaul interval reduced failure probability by factor between 20 and 3000 – this degree of improvement considered unrealistic
  - Protection for quarter of overhaul interval reduced failure probability by factor between 3 and 10 – considered a reasonable approximation
  - Preliminary assumption is that paint protects axle for ¼ of overhaul interval
  - Actual degree of protection a priority in terms of future work
- Fully effective protection can be considered in model
  - No possibility of failure from axle body (also protected against mechanical damage)
  - Fretting fatigue at seats becomes the limiting factor

© 2011 DeltaRail Group Limited

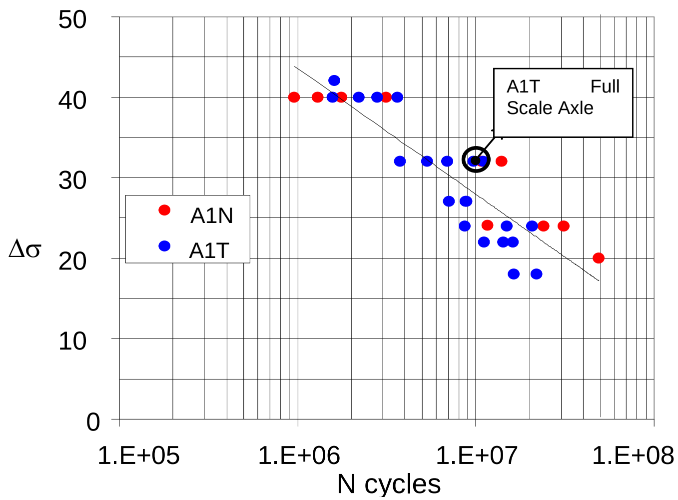
Verification of Axle Assessment Methodology - Principles

- Necessary to have two approaches to verification
  - Does the FORTRAN code operate as intended?
  - Is the model itself a reasonable approximation to actual axle behaviour?
- FORTRAN code verified by parallel Excel calculations
- Major challenges in assessing model itself
  - Not enough axle failures or properly recorded cracking data to compare predictions with reality
- PoliMi carried out two full size axle tests with realistic loading, as a validation exercise
- Also “sense checks” based on predicting current and historic axle behaviour

© 2011 DeltaRail Group Limited

Validation of Axle Assessment Methodology – PoliMi Full-scale Axle Tests

- First test at constant amplitude (+/- 160 MPa)
  - Life within scatter band of small specimen tests used to develop corrosion fatigue model
- Second test based on an axle stress spectrum
  - Stresses increased to give 40 million cycle (60,000 mile) predicted life
  - Both predicted and measured cracks about 1.5 mm long after 15 million cycles
- “Hoddinott” type stress corrosion cracking observed in both tests



© 2011 DeltaRail Group Limited

Verification of Axle Assessment Methodology – Sense Checks

- Objective: to show that the crack growth model can provide a reasonable estimate of actual axle behaviour
- Sense check 1: Corrosion pit depths from TWI/PoliMI work
  - 15 vehicles assessed. Number of overhaul intervals to generate largest pit varied from 1 to 6, i.e. right order of magnitude
- Sense check 2: No failures in passenger / locomotive axle fleets
  - 13 vehicles assessed. Only one case where predicted failure probability greater than 1 / number of axles in fleet (which was highly stressed axle)
- Sense Check 3: Historic 1/10,000 of axles found cracked
  - Same 13 vehicles assessed. Five were predicted to have failure probability greater than 1/10,000, eight smaller
  - Historic cracking rate before mandatory MPI at overhaul – probably smaller now

© 2011 DeltaRail Group Limited

Axle Assessment Methodology – Application

- Current Application by a series of separate modules
  - Excel spreadsheets to characterise route and derive axle stress histogram (T356 methodology)
  - FORTRAN program to calculate failure probability as function of NDT periodicity
  - Need to interpret FORTRAN output in terms of acceptable NDT regime
- Option to develop methodology into a stand-alone tool
- Methodology has been delivered as Excel Decision Support tool
  - Intended for use by Industry Specialists
  - Uses failure probability curves, precalculated using full methodology
  - Necessarily approximate, but intended to be conservative
- Excel tool will be demonstrated in separate presentation

© 2011 DeltaRail Group Limited

Axle Assessment Methodology – Possible Further Developments

- Further investigation into protection against corrosion and impact provided by current paint systems
- Further investigation into probability and severity of mechanical damage
- Validation of T356 stress estimation methodology to cover most main line outboard journal axles
- Extension of assessment methodology to LRT vehicles and inboard journal axles
- Extension of assessment methodology to higher grade axle materials (A4T and stronger?)
- Incorporate fretting model to cover seat areas, rather than current conservative treatment

© 2011 DeltaRail Group Limited

Thank you for listening

© 2011 DeltaRail Group Limited

ESIS TC24 Workshop: Predicting real world axle failure and reliability
3-4 March 2011 London

Railway axle failures caused by corrosion and corrosion fatigue – the German experience

Dr. Katrin Mädler, Deutsche Bahn AG, DB Systemtechnik
Brandenburg-Kirchmoeser, Dept. Material engineering and damage analysis

Deutsche Bahn AG
DB Systemtechnik
Dr. Katrin Mädler
Brandenburg-Kirchmöser

Introduction
DB Systemtechnik

DB Systemtechnik

- Provides technical engineering support to Deutsche Bahn AG and other railway traffic companies in Germany and Europe

Key aspects of DB Systemtechnik Kirchmoeser

- Vehicle and track maintenance support (technical consulting)
- Non-destructive testing (Vehicles/ Track)
- **Materials engineering and failure analysis (Vehicles/ Track)**

DB Systemtechnik locations

- Minden: near Hannover
- Munich (München)
- Brandenburg-Kirchmoeser: near Berlin

Introduction
Why a DB presentation at this workshop?

ESIS TC 24 Workshop „Fatigue strength and fatigue life of railway axles"

Berlin 11-12 October 2010

While discussing causes of axle failures following questions were asked:

- Is corrosion fatigue a common problem of axle failures in other countries than UK as well?
- Do other railway companies know the „Hoddinott phenomenon"?

⇨ Deutsche Bahn representers were asked to present their experiences

DB Experiences...

- ...are based on damage analysis work over several years as every failure event of wheels and axles and a lot of failure events regarding track components (rails, S&C) has usually to be investigated by DB Systemtechnik Kirchmöser

Introduction

Wheelset axles – philosophy of Deutsche Bahn

1st Safety level

Wheelset axles are designed according to DIN EN 13103/ 13104 to maintain a clear fatigue strength.
That means axle loads below fatigue strength do not result in axle fatigue failures in service.

In rare cases (related to the overall number of axles in service) crack initiation at surface defects (arising from axle manufacturing and service resp.) may happen.

2nd Safety level

To check the axle for surface defects and to avoid possible crack initiation and crack growth until axle failure, axles are subjected to ultrasonic testing on a regular basis.

Wheelset axles failures

Potential crack starters in general and DB experiences

Note: There is no fatigue cracking without a crack starter (surface defect)!

What could be potential crack starters?

1. Wheel seat

- Fretting fatigue dimples
- Hard non-metallic inclusions at or beneath the axle surface
- Sharp-edged blasting particles of high hardness leave indentations at the wheel seat surface

2. Axle shaft and transitions

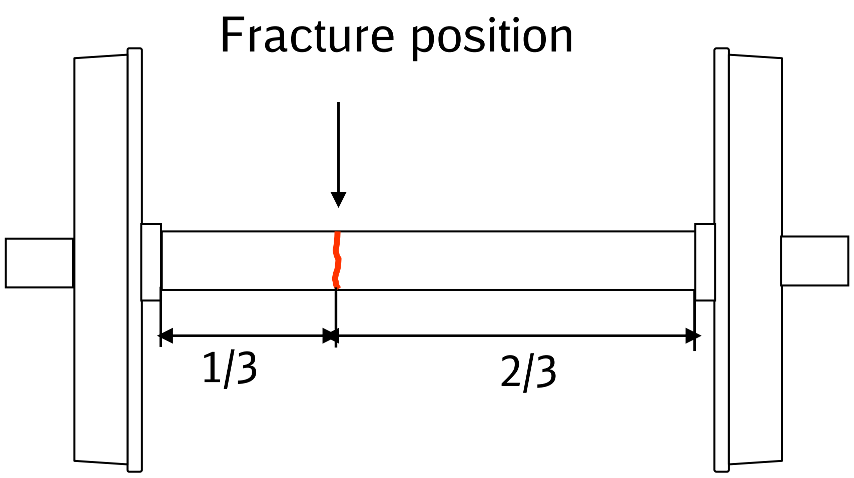
- Corrosion pits/ corrosion fatigue (if protection fails)
- Stone impacts
- Turning marks (grooves, off-sets) and increased surface roughness
- Hard non-metallic inclusions at or beneath the axle surface

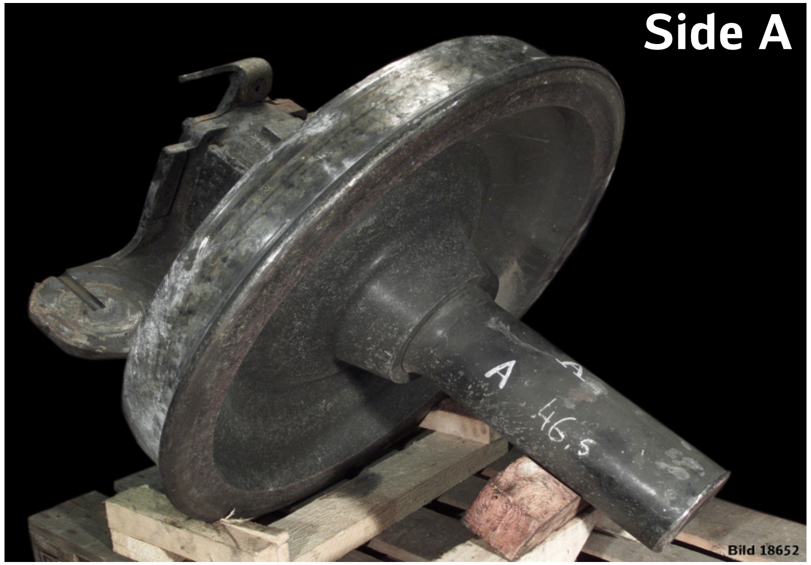
Experiences of Deutsche Bahn with real axle failures

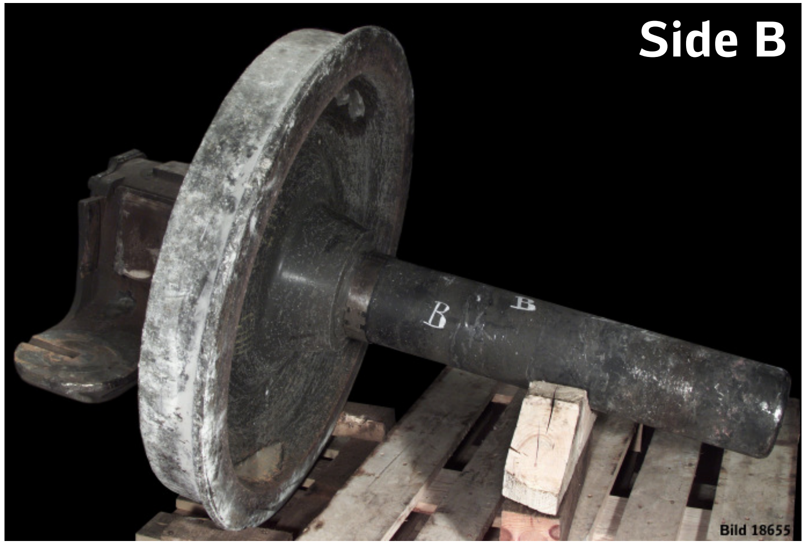
Example 1 - Freight wagon

Wheelset axle breakage

- Axle was first in salt transport service before installation in bulk transport
- Running performance since last revision:
  ~ 74,000 km



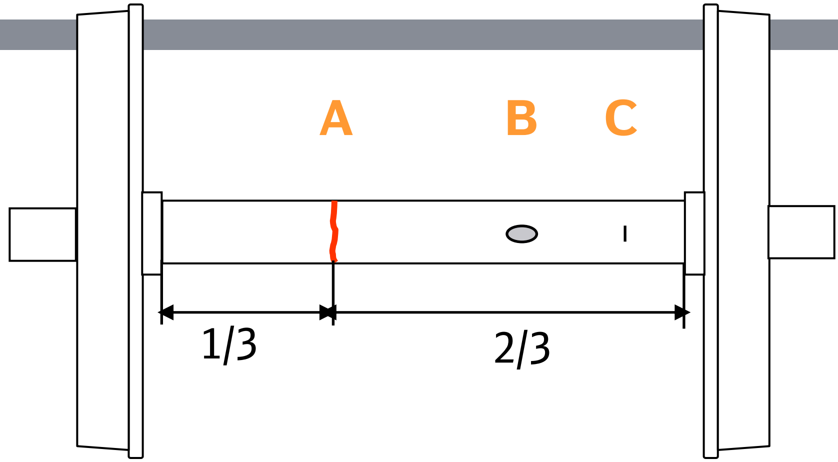


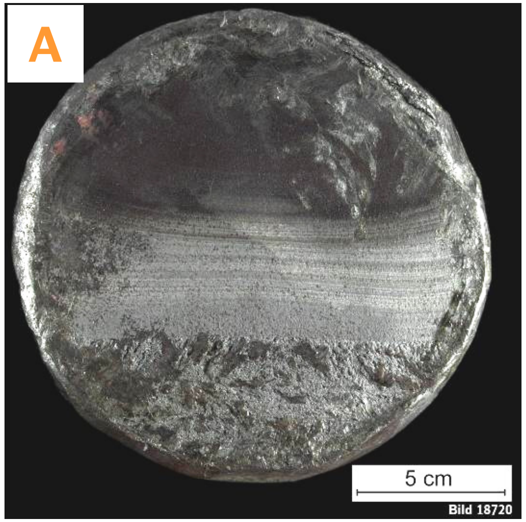


Experiences of Deutsche Bahn with real axle failures

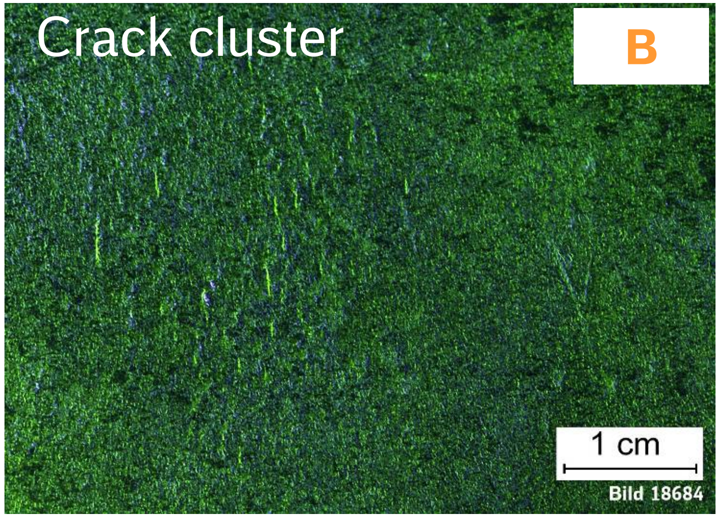
Example 1 - Freight wagon

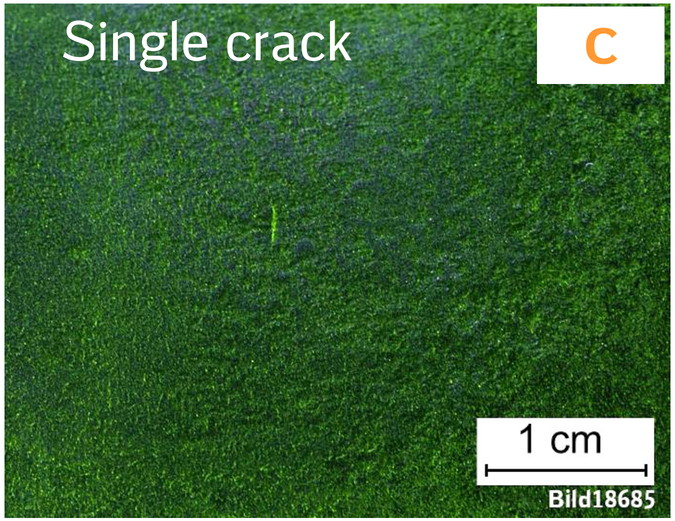
Wheelset axle breakage





Fracture surface

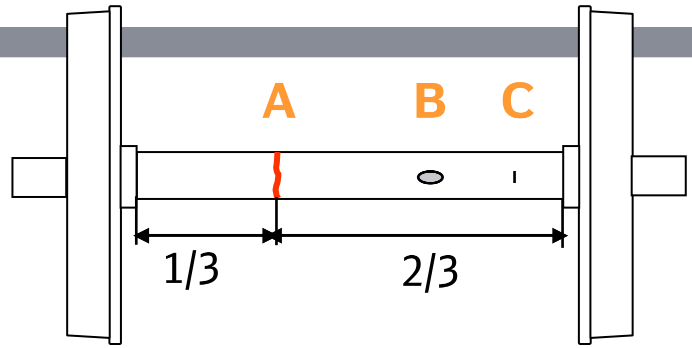




Corrosion fatigue cracks at the surface
Results of Magnetic particle testing (UV light)

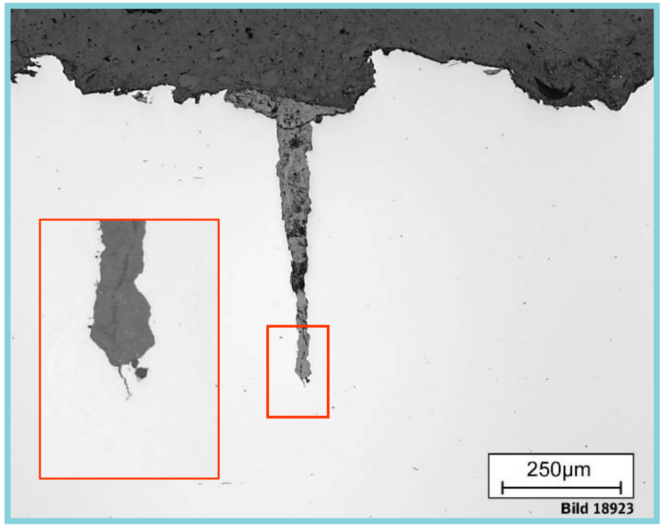
Experiences of Deutsche Bahn with real axle failures

Example 1 - Freight wagon

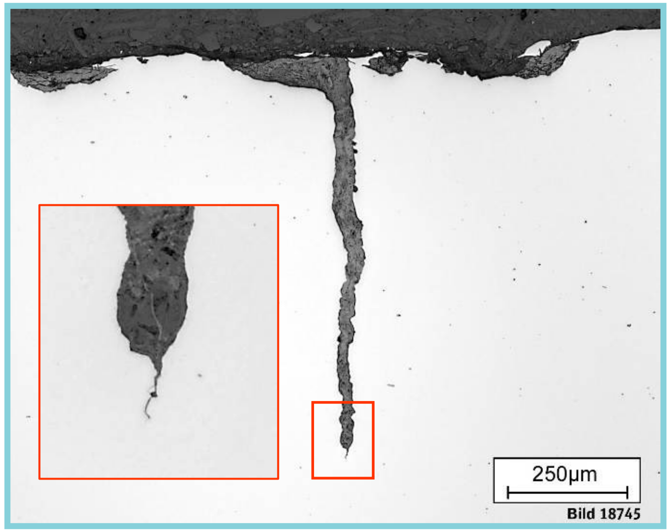


Metallographic investigation of fracture initiation area A and crack positions B and C

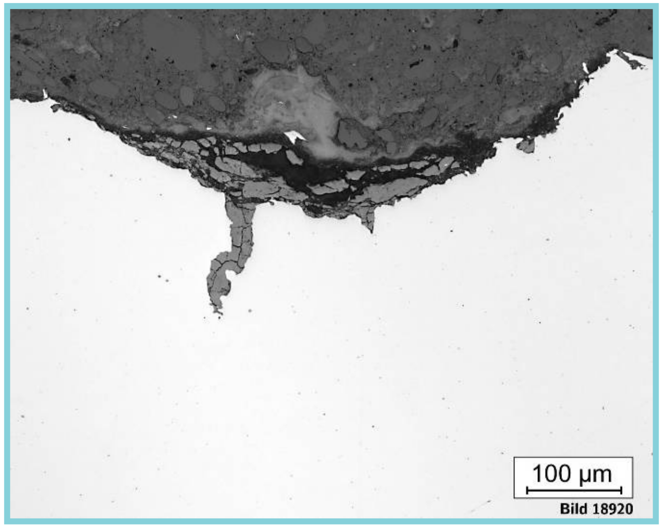
A – Near fracture position



B – Crack cluster



C – Single crack



Corrosion pits with corrosion fatigue cracks at the pit ground

Longitudinal micro-cross section (un-notched)

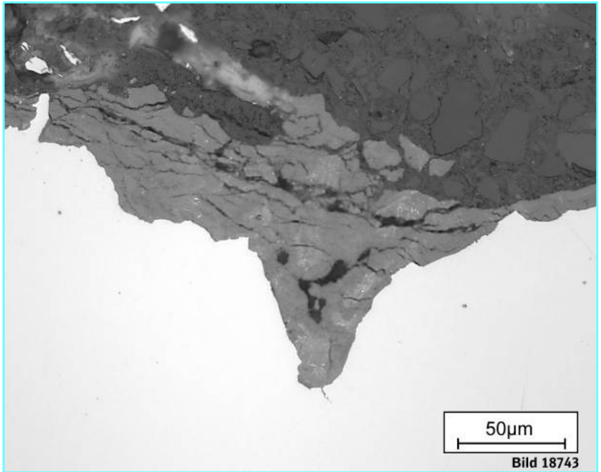
Experiences of Deutsche Bahn with real axle failures

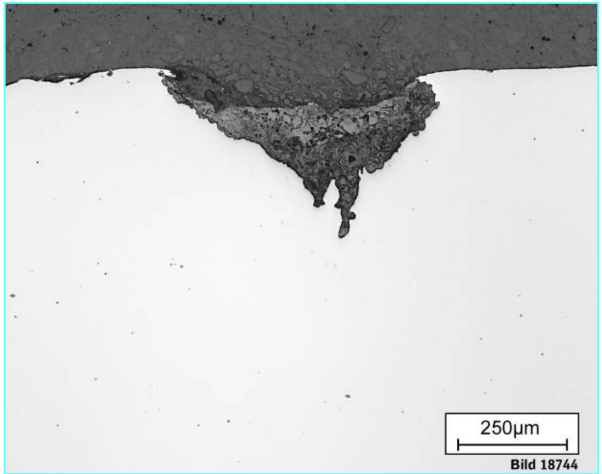
Example 1 - Freight wagon

Position B – cluster of cracks

Corrosion pits up to 0,4 mm deep at the surface

Note: sharpness of such corrosion notches is much higher than a semi-circular 0,4 mm deep flaw



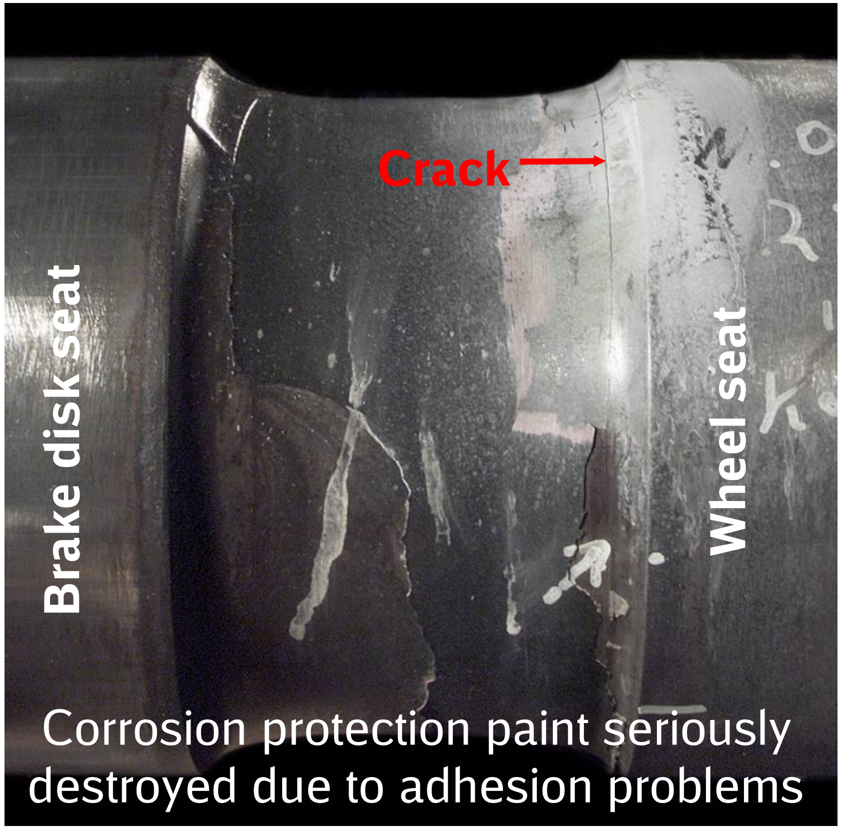


Damage mechanism

1. Local corrosion processes (salt transport wagon, aggressive medium)
2. Roughening of axle surface by corrosion
3. Superposition of mechanical loading: corrosion pits became sharper at the ground => Crack initiation at the ground of sharp corrosion pits
4. Growth of corrosion fatigue cracks and coalescence (later on as one fatigue crack)

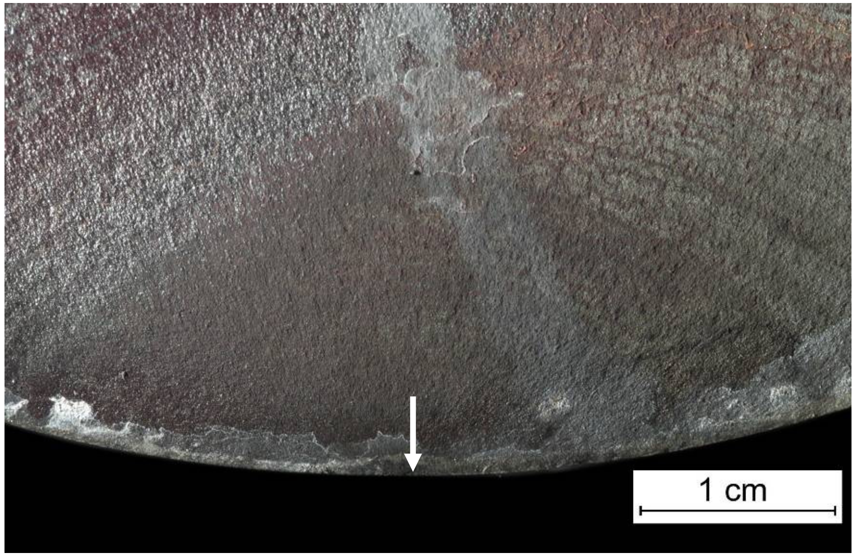
Experiences of Deutsche Bahn with real axle failures

Example 2 - Passenger traffic



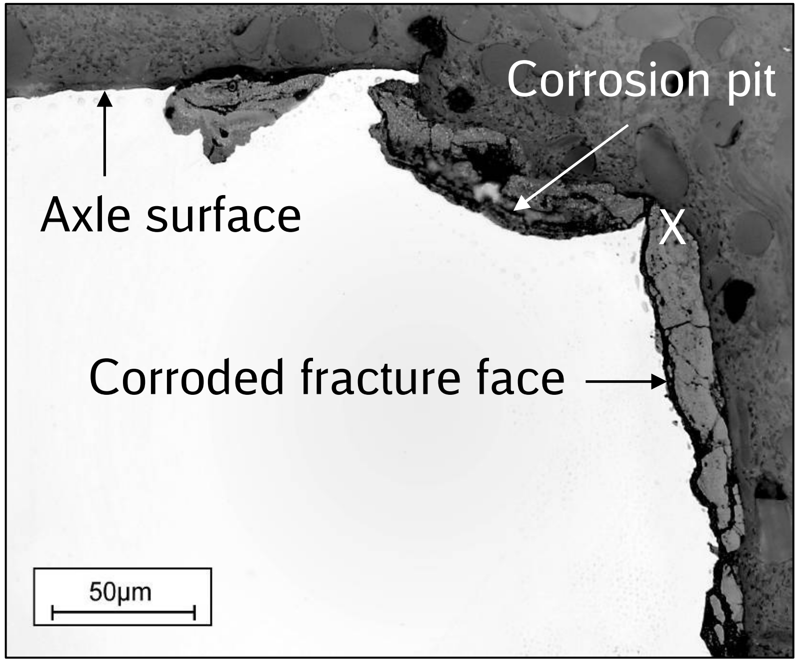
Fatigue crack between wheel seat and brake disk seat

- Trailing axle
- Total running performance: ~ 450,000 km
- Ultrasonic-testing (UT) revealed naked-eye-visible crack
- After crack opening the fracture surface was investigated



Corroded fatigue fracture surface with beach marks

Metallographic investigation of crack initiation area



Longitudinal micro-cross section through the crack initiation point (X)

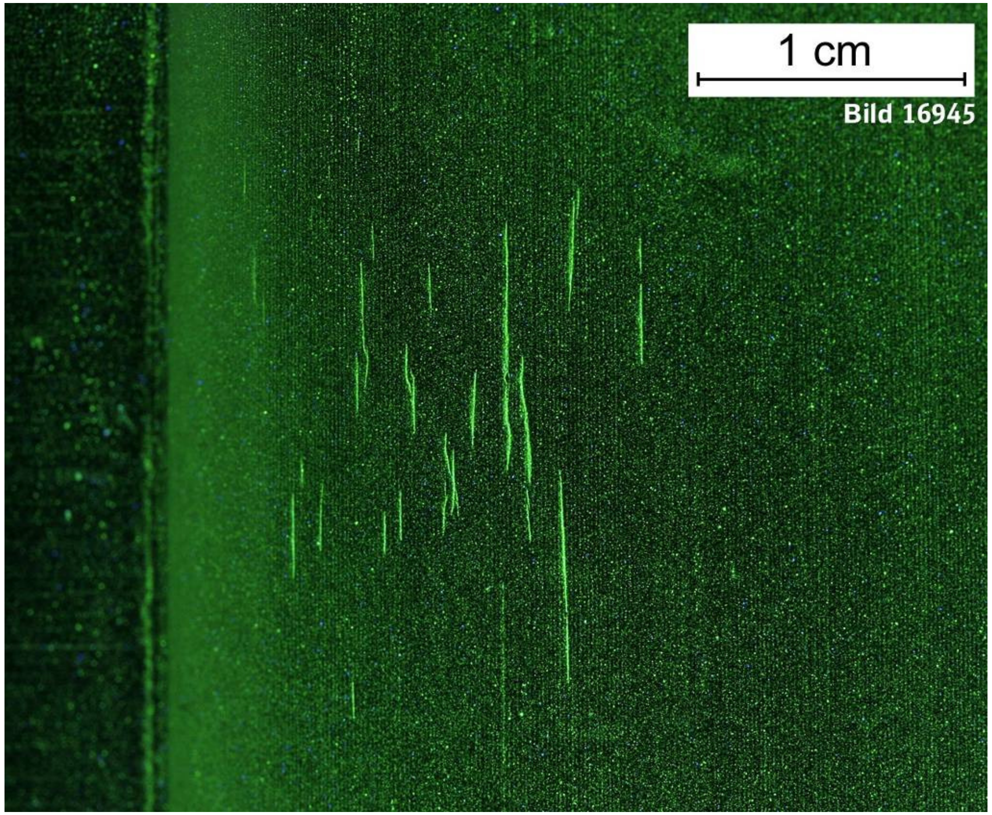
Result: Corrosion fatigue crack starting from a corrosion pit where the crack faces were deeply corroded

Damage mechanism

1. Surface corrosion protection layer was destroyed
2. Corrosion fatigue processes as described before
3. In addition: Slightly higher strength steel than A4T was used here => slightly higher notch sensitivity

Experiences of Deutsche Bahn with real axle failures

Example 3 - Passenger traffic

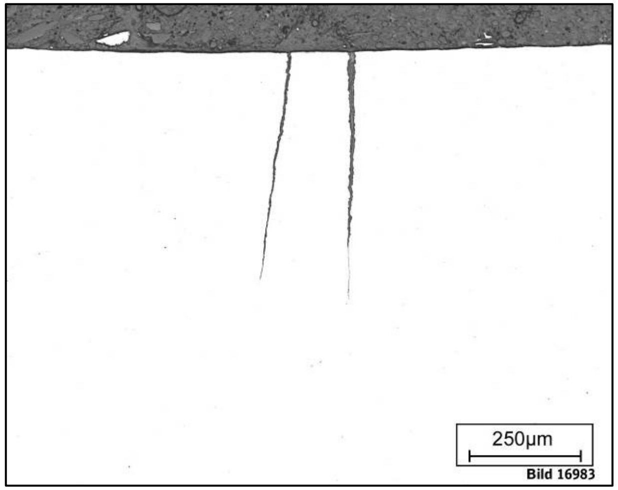


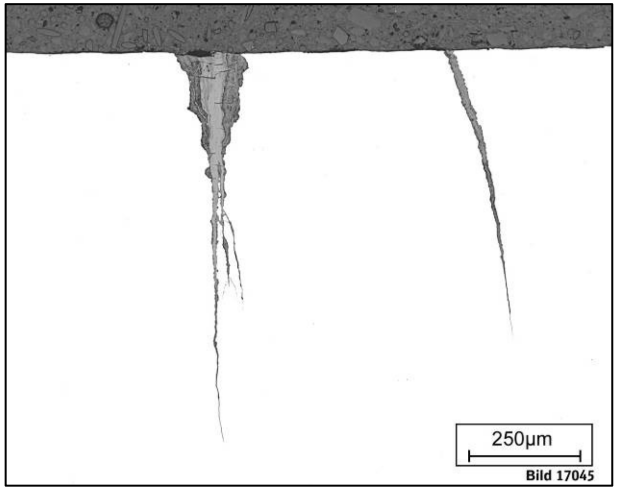
Multiple cracking in the transition range
Results of Magnetic particle testing (UV light)

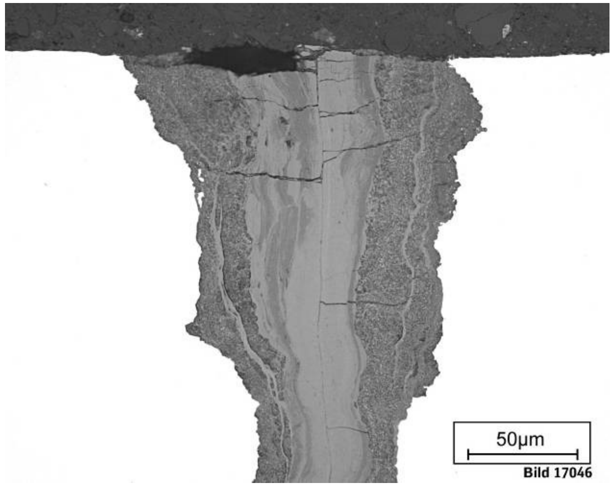
- Driving axle
- Total running performance:
  ~ 1,35 Million km
- Higher strength Cr-Ni-Mo steel
  Tensile strength: ~ 1,000 MPa
- Crack indications in the transition range were found by ultrasonic testing in the DB workshop
- Investigation of DB Systemtechnik
- Magnetic particle testing revealed crack cluster
- Detailled investigation of longitudinal micro-cross sections perpendicular to the cracks

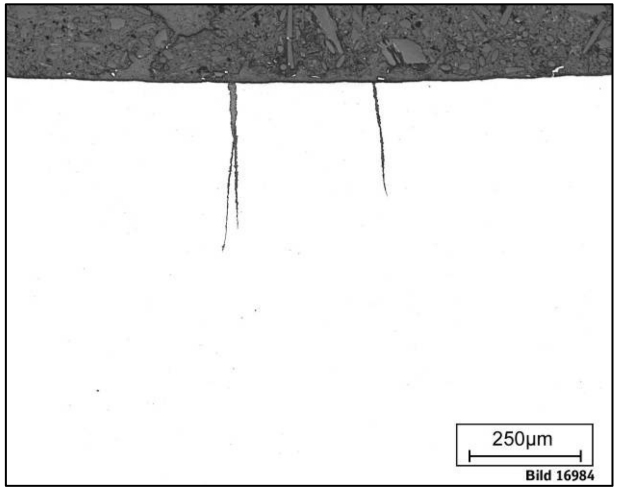
Experiences of Deutsche Bahn with real axle failures

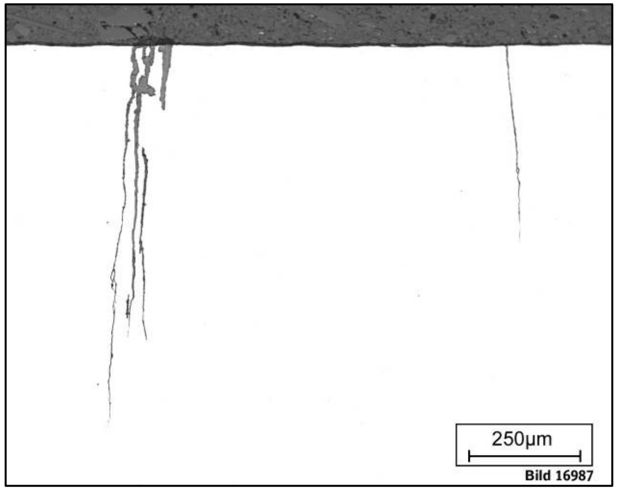
Example 3 - Passenger traffic









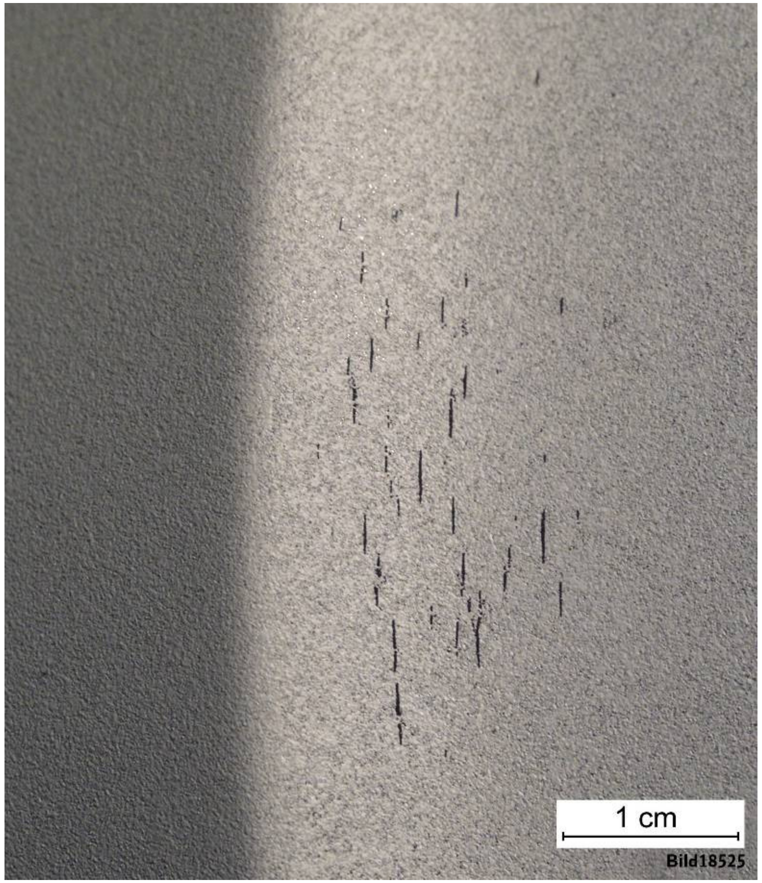


Result:

- Cluster of corrosion fatigue cracks (Multiple cracking)
- Corrosion products inside the crack reveal flowing direction of fluid corrosion medium

Experiences of Deutsche Bahn with real axle failures

Example 4 - Passenger traffic



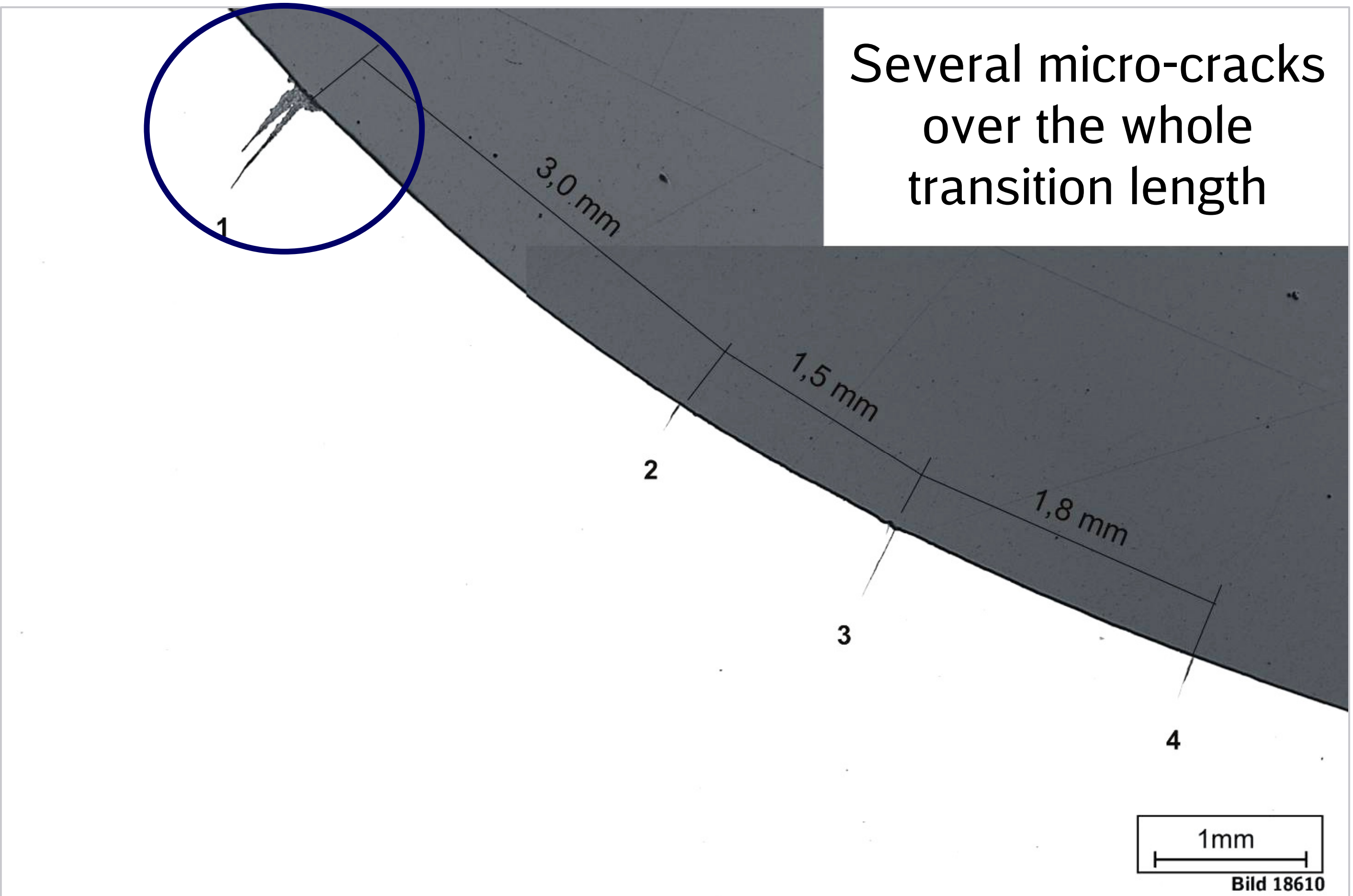
Transition range with multiple cracking
Result of Magnetic particle testing (b/w)

- Driving axle
- Total running performance:

  2,78 Million km
- MT indications in the transition range between wheel seat and shaft were found in the DB workshop and confirmed by DB Systemtechnik´s investigation
- Higher strength Cr-Ni-Mo steel was used (Tensile strength: ~ 1,000 MPa)
- Investigation of longitudinal micro-cross sections perpendicular to the cracks

Experiences of Deutsche Bahn with real axle failures

Example 4 - Passenger traffic

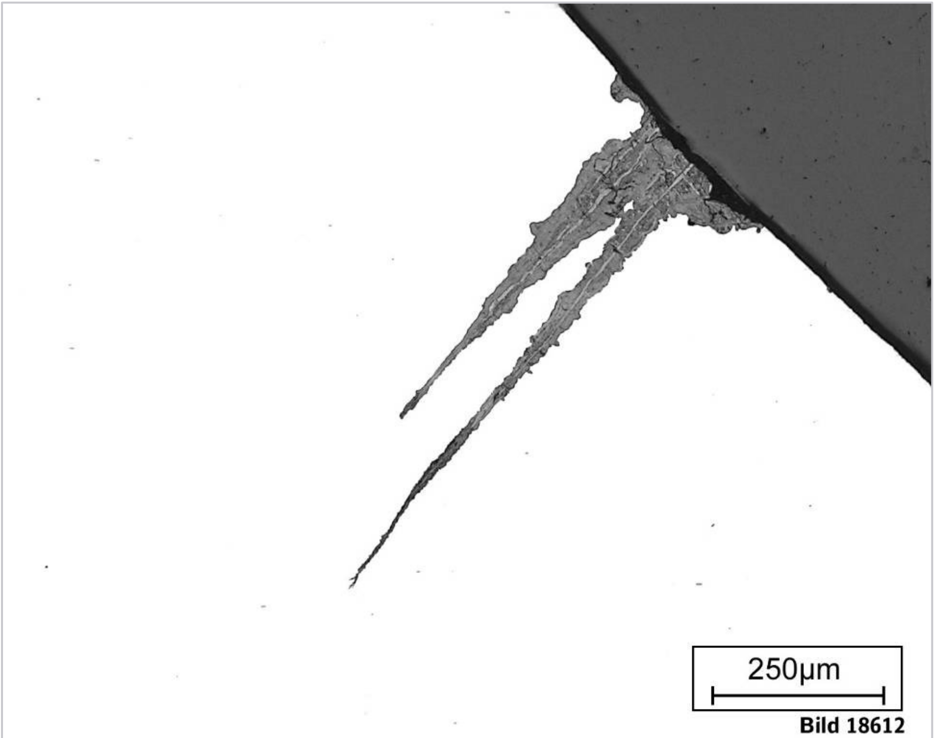


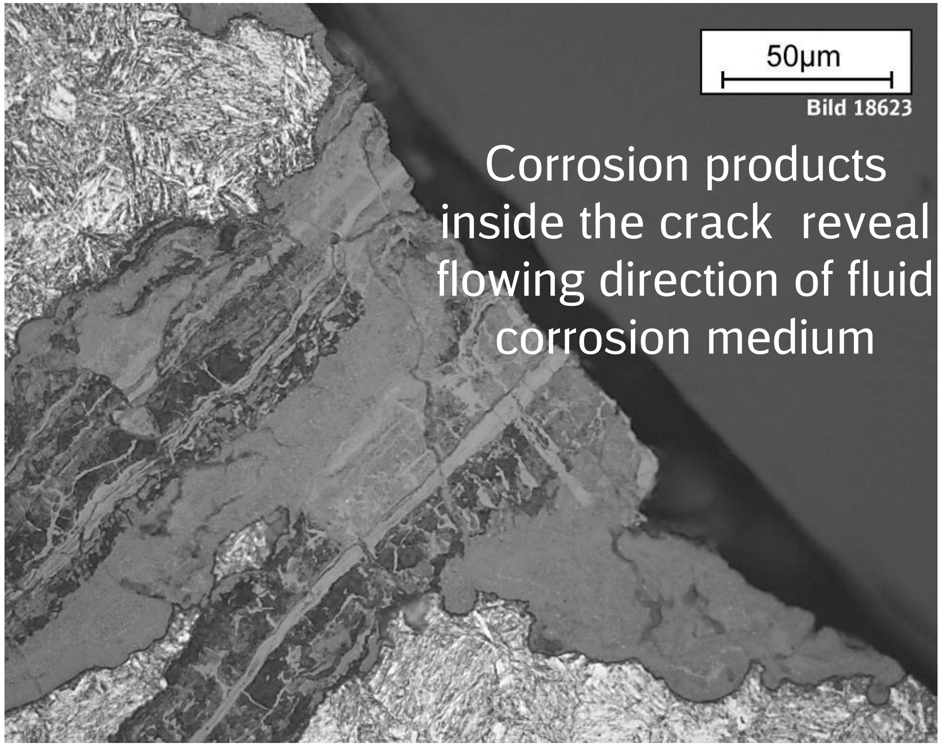
Axle transition range with multiple cracking

Longitudinal micro-cross section (un-etched)

Experiences of Deutsche Bahn with real axle failures

Example 4 - Passenger traffic





Corrosion fatigue cracking in the transition range, longitudinal micro-cross section

Left figure: un-etched

Right figure: Nital etched

Corrosion fatigue – General mechanism

Interpretation of results

Corrosion fatigue in the active state [1)]

1. Concerning non-passivating un-alloyed or low alloyed steels
2. Local corrosion attack ⇨ **initiation of micro-notches**
3. Further corrosion processes concentrate at the micro-notches
4. Concentration of mechanical stress at the notch tip (ground) shifts the electro-chemical potential to lower values and increases the metal dissolution ⇨ **micro-notch growth**

1) Spähn, H.; Wagner, G. H.: Corrosion fatigue in steels. In: Bruchuntersuchungen und Schadenklärung. Allianz Versicherungs AG, München, Berlin, 1976, p. 59-74

Corrosion fatigue – General mechanism

Mobility
Networks
Logistics

Corrosion fatigue in the active state [1)]

5. Opposite increase of mechanical stress concentration and metal dissolution

   ⇨ **fatigue crack initiation**

   ⇨ often **multiple cracking** because of presence of several micro-notches (pits)

6. Fatigue crack growth perpendicular to the normal strength
7. Final (residual) **fracture:** Fissured fracture surface due to combination of several cracks

1) Spähn, H.; Wagner, G. H.: Corrosion fatigue in steels. In: Bruchuntersuchungen und Schadenklärung. Allianz Versicherungs AG, München, Berlin, 1976, p. 59-74

Corrosion fatigue
Influencing factors

- **Stress amplitude**

  With higher amplitudes the mechanical effect of loading is prevailing and there are more cracks (multiple cracking)

  With lower amplitudes the corrosive effect becomes more important.

- **Materials strength**

  Corrosion fatigue in the active state results in numerous micro-notches at the surface thus higher strength steels are more endangered due to their higher notch sensitivity.

- **Non-metallic inclusions**

  Manganese sulfides play an important role if corrosion fatigue occurs, especially if pitting corrosion is regarded. (In contrast to normal fatigue, where MnS-inclusion do not affect crack initation/ growth so much.)

Conclusions

1. Corrosion fatigue is a common damage mechanism for wheelset axles. It occurs only if there are paint adhesion problems or if the protection paint was destroyed in service.
2. The corrosion fatigue mechanism affects probably only the first crack growth phase up to a few millimeters of crack depth. Thereafter the mechanical (pure fatigue) damage mechanism is prevailing.
3. Steels with a higher tensile strength are more notch sensitive. Accordingly, they are also more corrosion-pit-notch sensitive.
4. <u>However:</u> Corrosion fatigue also works in freight wagon axles of A1N steel. If axles of higher strength steels are designed „thick enough“, corrosion, stone impacts and other defects will not cause more problems than A1N.
5. To avoid axle failures due to corrosion fatigue, the corrosion protection of the axle surface has to be assured by maintenance workshops carefully.

Thank you!

For more questions please ak now or contact:

Katrin Mädler, Deutsche Bahn AG, DB Systemtechnik

katrin.maedler@deutschebahn.com

Phone: +49 (0) 3381 812 337

ESIS TC24 Workshop 3-4 March 2011

“Predicting real world axle failure and reliability”

GB axle failures caused by corrosion fatigue – A S Watson

TWI

DeltaRail

© 2011 DeltaRail Group Limited

Background

- Crack growth model developed in RSSB Project T728 largely based on corrosion fatigue
- "Corrosion fatigue" has been previously recognised as a cause of axle failures
  - Not clear what "corrosion fatigue" actually means in historic axle failure reports…
  - Does it refer to fatigue initiating from corrosion pits, perhaps due to local stress concentrations…
  - Or is it really corrosion fatigue, where the chemical process of corrosion forms part of the crack growth mechanism?
- How many axle failures have actually been caused by corrosion fatigue?

© 2011 DeltaRail Group Limited

Characteristics of Corrosion Fatigue in Axles

- Fatigue can occur from an undamaged surface
- Two implications for axles:
  - Because significant areas of a given axle experience similar stresses, multiple cracks are to be expected
  - Because different axles in the same fleet experience similar loadings, significant numbers of axles would be expected to develop cracks
  - Contrasts with cracks initiating from specific flaws, which are “one-off” events, normally involving only one crack in one axle
- Multiple cracks in one axle reported by Hoddinott (2003)
- One example of cracking affecting whole axle fleet is early (tapered) Mk3 coach axles

© 2011 DeltaRail Group Limited

Data for Axle Failures on UK Main Lines

- No definitive list of axle failures
- Combining available records suggests 44 failures between 1970 and 2010 associated with axle integrity, i.e. ignoring cases caused by bearing or gearbox failure
  - 23 involving wagons
  - 14 involving passenger vehicles (coaches & multiple units)
  - 7 involving other vehicles
- Axle failure rate is decreasing over time
  - Only two failures 2000-2010
  - Could be due to MPI mandated at axle overhaul as a result of Rickerscote accident

© 2011 DeltaRail Group Limited

UK Axle Failures – Overall Causes

Cause of axle failure	Vehicle type			Decade			
	passenger	wagon	other	1970-1980	1980-1990	1990-2000	2000-2010
Transition radius (stress concentration?)	1		1	1	1		
Mechanical damage (not impact)	1	2	1	1	2		
Corrosion (includes corrosion fatigue)	5	11			12	4	1
Fretting fatigue at seat	1	5			3	3	
other / not known	6	5	5	9	1	5	1

- For the 28 axle failures where the cause is known, over half (17) are due to corrosion
- How many corrosion failures due specifically to corrosion fatigue?

© 2011 DeltaRail Group Limited

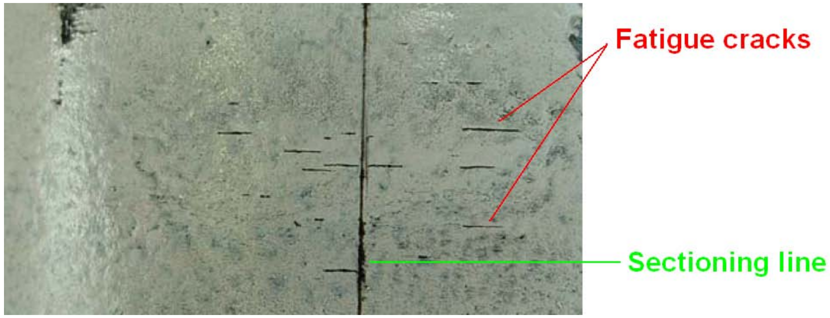
Corrosion Fatigue Case Histories – Mk3 Coach (early design)

- Original design of axle was tapered – high operating stress
- Axles suffered from corrosion, probably associated with toilet discharge
  - Some axles were skimmed to remove corrosion, leading to even higher stresses
- Two service failures in 1985 and 1990
  - Further investigation revealed cracking in another 20 axles
  - Multiple fatigue cracks found in corroded region
- Axle redesigned to reduce stress level (parallel)
- Three pointers toward corrosion fatigue
  - High operating stress
  - Multiple cracks found in one of the failed axles
  - Multiple cracked axles in fleet

© 2011 DeltaRail Group Limited

Corrosion Fatigue Case Histories – Mk3 Coach (current design)

- Axle found cracked by MPI inspection in 2003
- Cracking associated with region of heavy corrosion
- Further investigation indicated multiple cracks



- Other Mk3 axles reported with similar corrosion
- Two pointers toward corrosion fatigue
  - Multiple cracks on one axle
  - Multiple cracked axles (perhaps)

© 2011 DeltaRail Group Limited

Corrosion Fatigue Case Histories – Merehead, Norton Bridge & Shields Junction

- Three service failures of wagon axles
  - June 1985, PTA wagon at Merehead
  - August 1988, FGA Freightliner wagon at Norton Bridge
  - January 1998, PGA salt hopper wagon at Shields Junction
- Multiple fatigue cracks found in all three cases

Merehead

Norton Bridge

Shields Jn (Hoddinott, 2003)

  - Shields Jn case probably led to the term “Hoddinott cracking” for corrosion fatigue

© 2011 DeltaRail Group Limited

Corrosion Fatigue Case Histories – Class 87 Locomotive at Carlisle

- Axle failed in transition between axle body and gearseat
  - Known to be a region of high stress
- Contemporary investigation found corrosion in region of failure
- Initial conclusion was that corrosion pits had acted as stress raisers and had reduced the effective fatigue limit
  - But contemporary report also refers to “many (corrosion pits) with fatigue cracks”
  - A definite pointer to corrosion fatigue
- Note also: this type of failure may be a historical reason for not allowing corrosion in transitions

© 2011 DeltaRail Group Limited

Corrosion Fatigue Case Histories – Wagon Axle Drawing No. F-A0-3639

- Of the 11 wagons axles known to have failed due to corrosion 1970-2010, at least six cases involved F-A0-3639 axle design
- Three of these cases confirmed as corrosion fatigue
  - One further case very likely to be corrosion fatigue
  - No information easily available for the other two
- Only two wagon types involved
  - Three failures under PGA hopper (2-axle) wagons
  - Three failures under JUA hopper or iron ore tippler (bogie) wagons
  - Evidence of multiple failures in specific fleets – strengthens case for corrosion fatigue

© 2011 DeltaRail Group Limited

Corrosion Fatigue in Axles – not just a UK Problem

- 1994, China: Cracks found in wagon axle during MPI – identified as corrosion fatigue
- 2001, Canada, Broken wagon axle due to corrosion fatigue in moisture trap
- 2009, Italy (Viareggio): Broken wagon axle – same design, same cause as 2001 incident in Canada
  - Significant numbers of similar cracks found in this design of axle

© 2011 DeltaRail Group Limited

Axle Corrosion Fatigue - Summary

- 17 axle failures identified as due to corrosion:

Date	Vehicle type	Failure location	Corrosion fatigue
Jun-83	Class 114 DMU	Trowell	no detailed information
Dec-83	Class 114 DMU	Elsham	no detailed information
Jan-84	PGA wagon	Hungerford / Kintbury	Likely (F-A0-3639 axle)
Mar-85	Mk3 coach	Ashton / Bletchley	Likely
Jun-86	JUA wagon	Goring / Merehead	Confirmed
Apr-88	Cl.87 locomotive	Carlisle	Likely
Apr-87	JUA wagon	Hampstead	Confirmed
Aug-88	Freightliner wagon	Norton Bridge	Confirmed
Mar-89	PGA wagon	Wolvercot	Cited in contemporary report
Nov-89	Alumina wagon	Woodhorn Jn / Lynemouth	Cited in contemporary report
Mar-90	Mk3 coach	Greenhill	Confirmed
Jun-90	Tank wagon	Trent South Jn	Confirmed
Mar-92	Mk2B coach	Etches Park	Confirmed
Mar-96	Tank wagon	Rickerscote	No definite evidence
Jan-98	PGA wagon	Shields junction	Confirmed
Oct-98	JUA wagon	Margam	Likely (F-A0-3639 axle)
Jun-02	MGR wagon	Bennerley Jn	No definite evidence

© 2011 DeltaRail Group Limited

Axle Corrosion Fatigue - Conclusions

- 17 axle failures identified as due to corrosion:
  - 7 confirmed and 6 probably caused by corrosion fatigue, i.e. at least 13 out of 17 likely to involve corrosion fatigue
  - Other cases of corrosion fatigue where axle did not fail
- Most British axle failures from corrosion are likely to be due to corrosion fatigue
  - At least 47%, could be as large as 87%
- However, not all corrosion failures necessarily due to corrosion fatigue
  - What could be the “other” crack initiation and growth mechanism?
  - Does it need to be included in axle assessment methodology?

© 2011 DeltaRail Group Limited

Thank you for listening

© 2011 DeltaRail Group Limited

Applied Inspection Ltd

GB NDT AXLE TESTING & DEFECT TYPES FOUND

ESIS TC24 Workshop at RSSB 03/04 March 2011

Presented by Roy Archer (Technical Manager Rail - Level 3)

GB NDT Axle Testing & Defect Types Found.

- Manual ultrasonic testing used for 50 years primarily from the axle ends.
- Initially introduced for passenger coaches using a 0 deg twin probe.
- The 5 deg twin probe scan replaced the 0 deg scan to improve detection capability.
- MPI introduced in 1985 on coaches & now mandatory at overhaul for all axles.
- Eddy Current Inspection introduced in 1999 for some freight axles & since has further expanded to include some passenger classes.

GB NDT Axle Testing & Defect Types Found.

- Currently corrosion fatigue mid-span axle body and wheel seat transition radius defects only found occasionally. The NDT techniques employed are MPI / Eddy Current inspection. UAT does not find these defects unless they are gross.

- Note:- Regarding transition radii corrosion fatigue is where corrosion pitting has occurred where the two radii meet (not at radius bottom where stress concentration is deemed to be higher).

- Historically cracks found by UAT at the inner end of the wheelseat originating from poor design.

- Improved axle design and assembly methods (shrink fitting wheels) have significantly reduced the amount of cracks found in the seat areas.

- Some freight organisations now only apply MPI or similar inspection i.e. Eddy Current to wagon axles at overhaul and cease UAT at overhaul and in-service.

GB NDT Axle Testing & Defect Types Found.

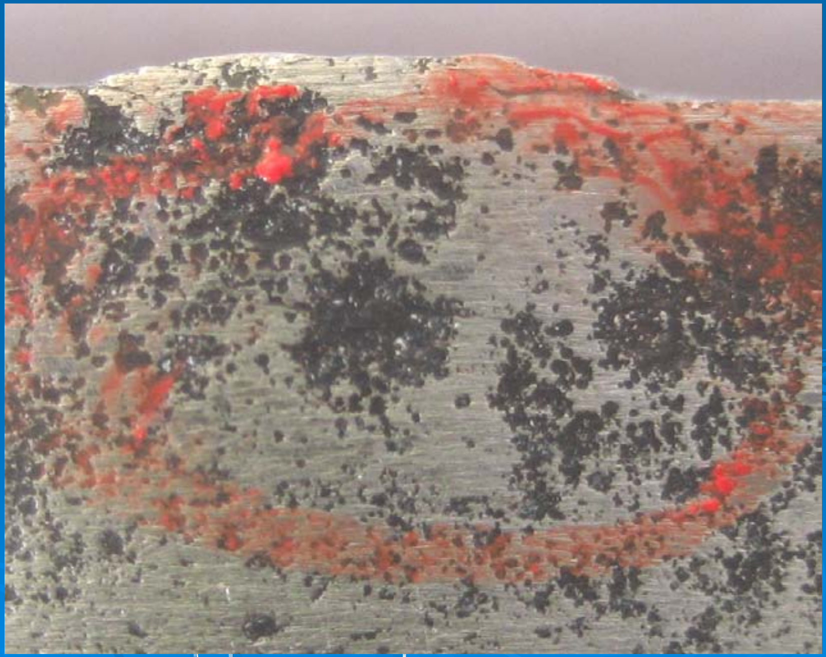
- In the past axles have suffered corrosion fatigue defects, although the issue found now is mainly corrosion. The corrosion pitting to start a crack can be quite small (See example photographs below and the actual samples here to examine or hand around).
- Examples –mid span crack – (MK 2 coach axle found in 1985). Another small crack is located next to the broken open main crack from a corrosion pitted area.
- Mk 3 coach axle (transition radii cracks)
- Potash axle severe corrosion (mid-span cracks)
- Note:- Toilet chutes adjacent to axles in the past have allowed axles to be contaminated and serious cracks have been quickly induced. This also applies to wagon axles carrying corrosive substances.

GB NDT Axle Testing & Defect Types Found.

- The corrosion levels on GB wagon axles are generally light unless they are working in a contaminated environment.
- However corrosion in the transition radii is an issue regarding wagon axles, as according to the standard it is not allowed and attempting to polish out is common, but does not always succeed.
- Sometimes skimming out of corrosion is allowed providing there is enough tolerance in the axle drawing to do so and it is accepted as OK by a Technical Competent Authority.
- In-service Eddy Current using certain equipment can identify corrosion areas under paint as well as finding fatigue defects (see photograph below).
- If the corrosion depth is above 0.5 mm then the Eddy Current technique is very noisy and cannot be applied.

GB NDT Axle Testing & Defect Types Found.

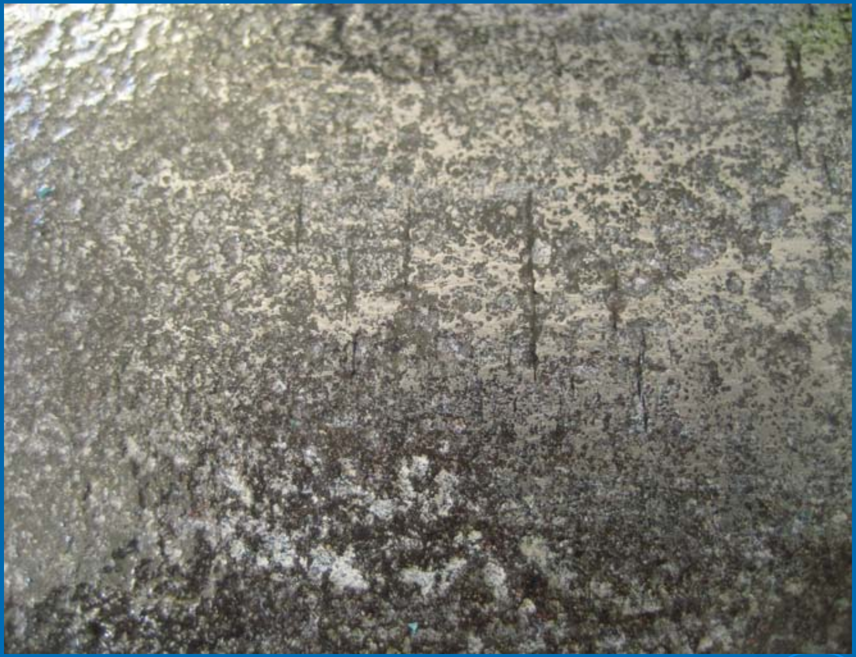
- Large fracture face (mid-span crack)
- Small crack from corrosion pore



GB NDT Axle Testing & Defect Types Found.

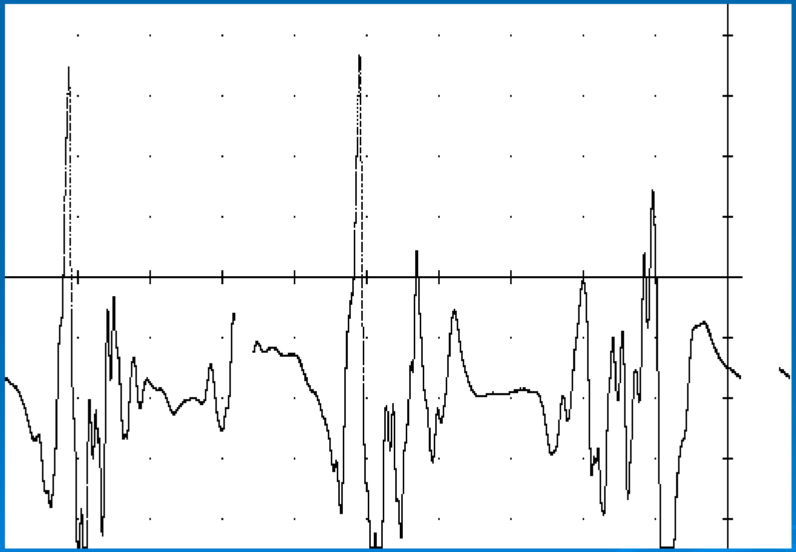
MK 3 AXLE TRANSITION RADIUS CRACKS

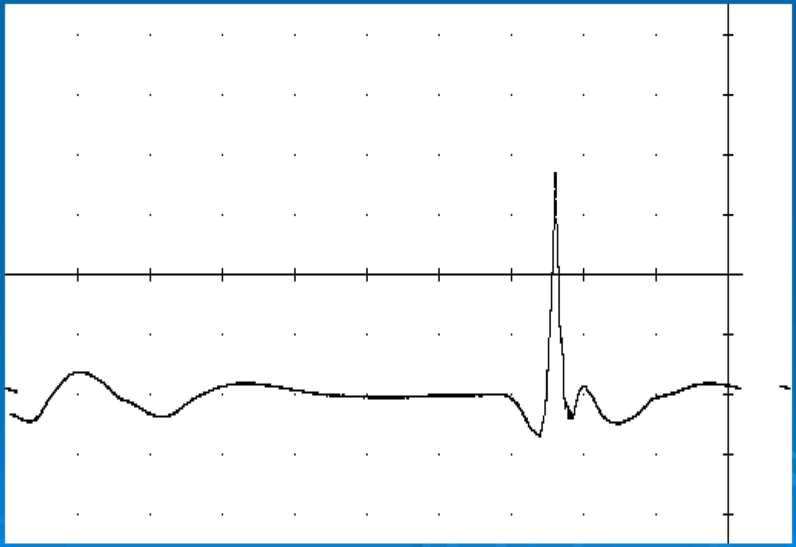
GB NDT Axle Testing & Defect Types Found. Cracks / Corrosion in potash axle sample



GB NDT Axle Testing & Defect Types Found.

- Eddy current response from potash axle cracks & severe surface corrosion noise and crack non/ lightly corroded surface.





GB NDT Axle Testing & Defect Types Found.

Passenger Vehicle Axle Testing

- Some train operators allow non –intrusive in-service testing techniques.
- This is a combination of eddy current for the
- axle body / transition radii and shear wave into seats
- This avoids the costly removal of the axle end fitments and risk involved.
- This is mainly for solid axles, but one type of hollow axle fleet has also been included where the body access is favourable.

GB NDT Axle Testing & Defect Types Found.

Passenger Vehicle Axle Testing

- Sometimes on long trains where a lot of train wheelsets are involved the body and seated area techniques are tested at split times and different test frequencies.

- The defect detection capability for the axle body is validated at 0.5mm deep natural defect as per MPI using Eddy Current and this has also allowed a relaxation of the test interval in some cases.

- An NDT operative, or a number of operatives if it is a long train, can therefore test the train overnight on maintenance, allowing no loss of train revenue regarding NDT and little involvement from the depot, therefore saving up to 4 fitters time for end fitment removal and replacement.

GB NDT Axle Testing & Defect Types Found.

Passenger Vehicle Axle Testing

- Technically regarding any trailer / mid-span gearbox motor axle at least, where access is available, a surface technique rather than conventional UAT would be preferable, for the body areas. Note: The axle should be proven clear of manufacturing defect issues, prior to UAT of the axle body being dispensed with.

- To examine the axle body tells us much more about its condition, including damage, corrosion, and paint issues, that cannot be seen when testing from the axle end.

GB NDT Axle Testing & Defect Types Found.

NDT Issues Regarding Axles in Recent Years.

- It has to be said that over the recent few years there have been a number of issues we have had to deal with regarding the quality of new axle / wheelset products being imported into GB.

- Special procedures have had to be put in place to accommodate these issues and keep the trains running.

- These issues are only coming to light at the in-service inspection, highlighting the difference in the equipment used, sensitivity & rejection criteria of procedures being used at manufacture.

- The main issue with UAT outside GB is the use of a 2 MHz single crystal forging probe (class 2 axles), which is grossly down regarding defect detection sensitivity compared with what is used in GB and does not show noise.

- Where GB use a stricter defect detection threshold, to maximise the NDT test frequency as is the current theme, the transparency of the steel requires to be of a high standard.

- Therefore NDT procurement of axles / wheelsets before delivery is an issue to consider when the order is placed outside GB.

- Where in-service testing is not carried out to the same degree outside GB, then manufacturing issues may not be identified or seen to be relevant.

GB NDT Axle Testing & Defect Types Found. NDT Issues - other than Corrosion Fatigue - Regarding Axles in Recent Years.

- Welded axles
- Opaque Axles – Various reasons-including inappropriate heat treatment / manufacturing processes.
- Introduction of specialist steels (Microstructure).
- Machining Issues – rough bore wheels.
- Noise generated from interface fits.
- Centre-line defects, cold laps & other internal defects inclusions etc.

GB NDT Axle Testing & Defect Types Found.

NDT Issues Regarding Axles in Recent Years. (Weld repaired axle)

GB NDT Axle Testing & Defect Types Found.
NDT Issues Regarding Axles in Recent Years.

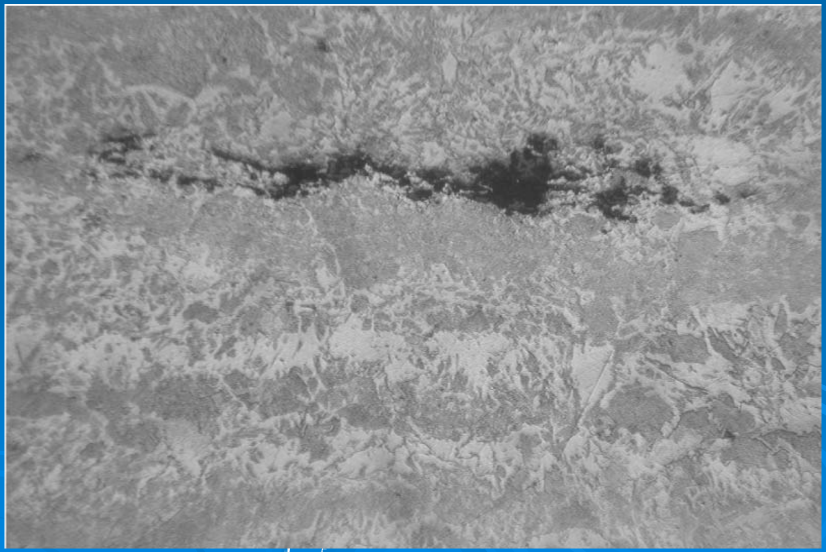
- Cold Lap in an axle body

GB NDT Axle Testing & Defect Types Found.

NDT Issues Regarding Axles in Recent Years.

Opacity Issues

- Large pearlite grains (A1N) (Left)
- Segregation & Ferrite grains & inclusion (A4T) (Right)

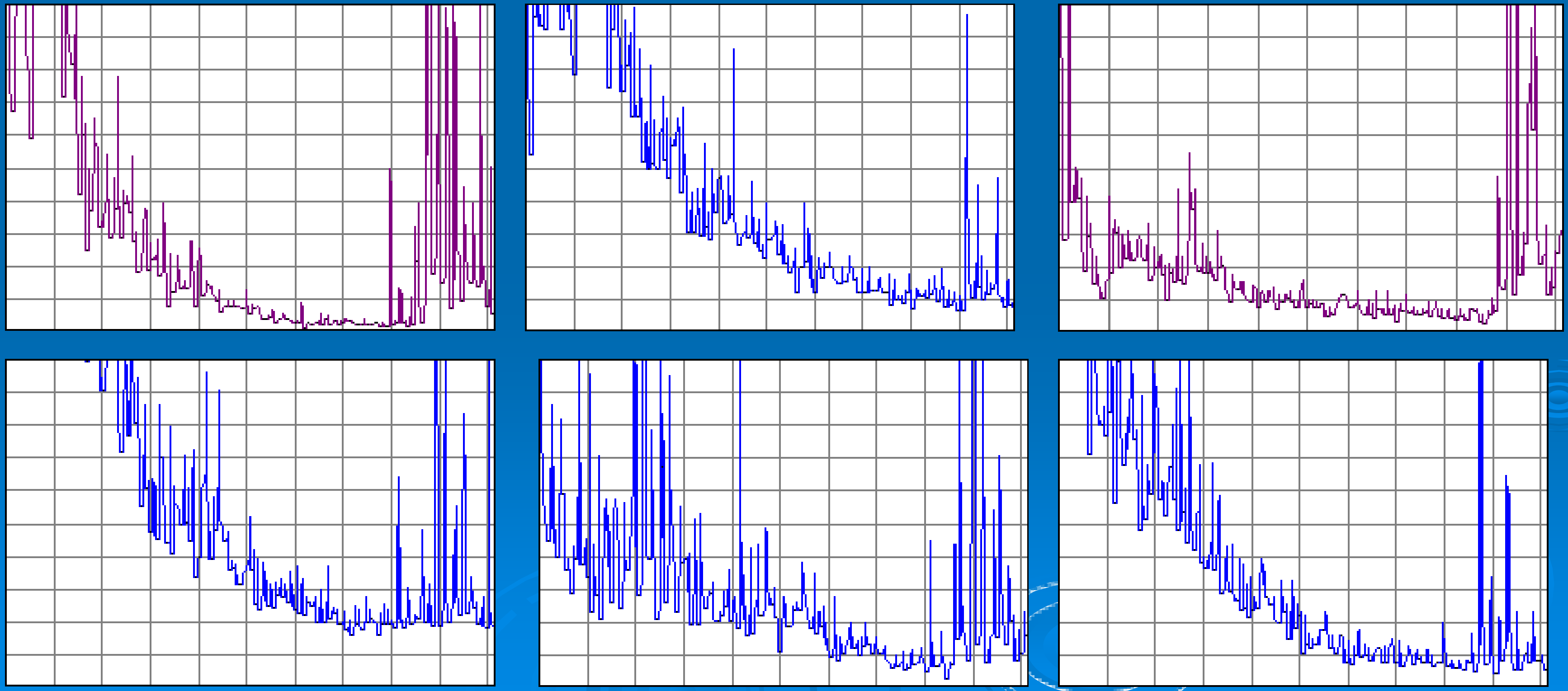


GB NDT Axle Testing & Defect Types Found.

NDT Issues Regarding Axles in Recent Years.

Opacity Issues

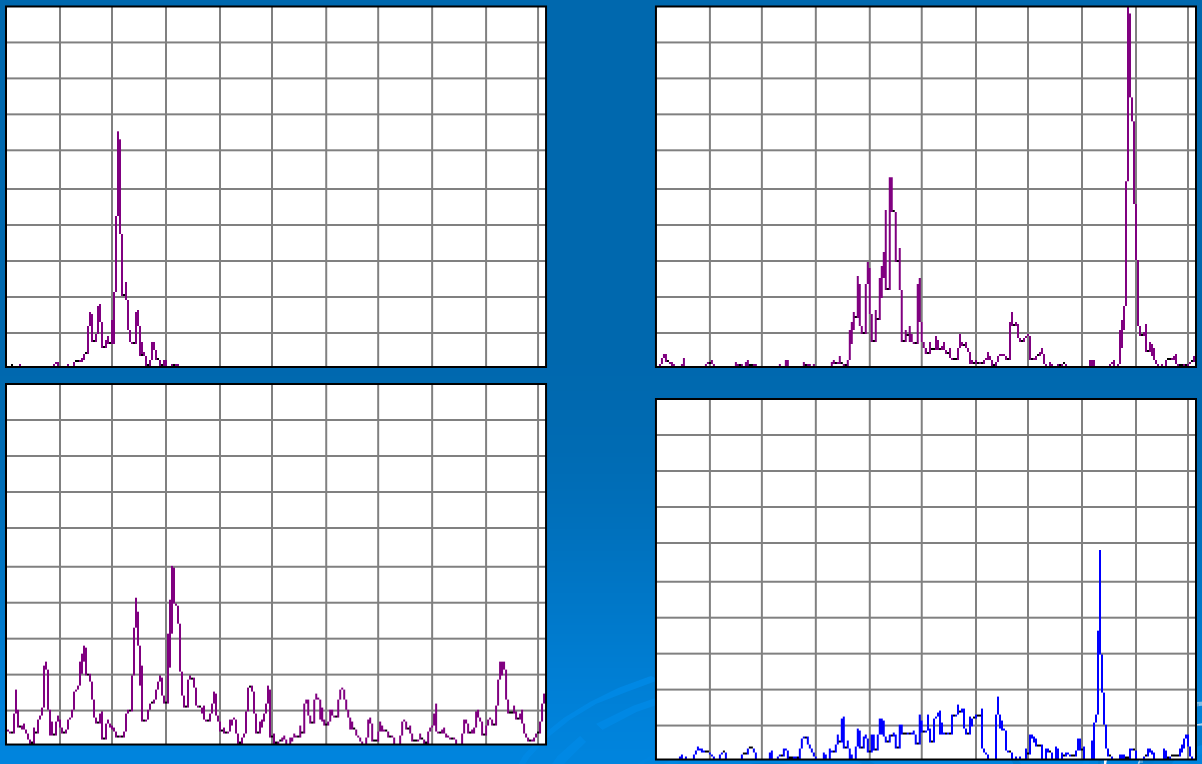
- Poor Ultrasonic traces (Opacity) different types & manufacturers / axle material.



GB NDT Axle Testing & Defect Types Found.

NDT Issues Regarding Axles in Recent Years.

- Poor ultrasonic traces (centre line defects & blocking affects) regarding HA & NE scans. Also poor wheel bore finish noise NE trace.



GB NDT Axle Testing & Defect Types Found.

Summary of Current NDT Issues Regarding Axles.

- Major corrosion fatigue cracks are now rare in GB compared with the past, as MPI at overhaul has been carried out for up to 25 years & Eddy Current 12 years.

- Light Corrosion however is available regarding freight axles and reclaiming / polishing is prevalent.

- Passenger axles are suffering with paint loss- suggested reasons (paint types used, poor preparation and bad winter weather).

- More surface techniques being applied to axle body areas in-service rather than UAT (Freight, passenger trailer & central gearbox motor axles). More types should follow on. Improved techniques and equipment should be utilised on enclosed body motor wheelsets.

GB NDT Axle Testing & Defect Types Found.

Summary of Current NDT Issues Regarding Axles.

- Less axle end fitment removal to accommodate NDT to avoid risk and save cost.
- Manufacturing defects have been on the increase over the last few years, exacerbated by the different NDT processes applied at manufacture outside GB and the in-service being here being incompatible.
- Standards including BS 5892 PT 1 and procurement regarding new axles require to be tightening up.
- The use of a 4 MHz twin probe for initial transparency checking regarding tempered axles would improve quality.
- Some UAT operators across a number of railway organisations (the majority being Level 1's in GB) have taken upon themselves to be lenient against the procedure criteria regarding noise issues causing a lack of consistency regarding the results and this issue has been recently addressed by PCN.

Bringing service to life

serco

Railway Axles – The Structural Integrity Method used by Serco

Presentation to RSSB

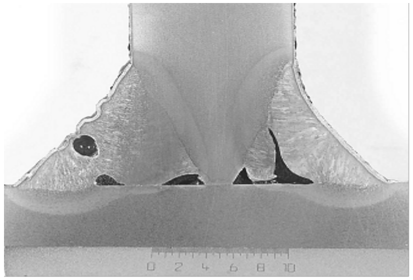
John Benyon

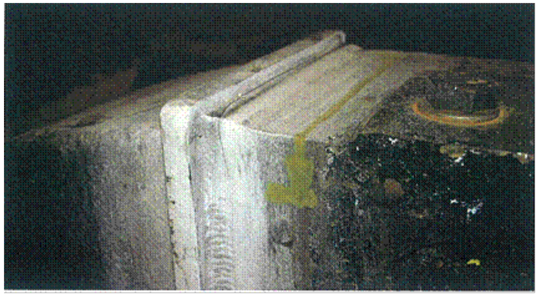
March 2011

Structural Integrity

“The science and technology of the margin between safety and failure”

- Extend asset life by developing robust technical safety cases
- re-assessment when design assumptions are wrong
  - Weld quality/Corrosion issues
  - Casting defects
  - Life extension or change in service duty
- Railway work includes gear wheels, welds and casting defects, axles etc





Methodology development

Late 70's	Mid 80's	2006 – Serco Method

- Single defect
- Crack growth data
- One shot FM
- Life to failure

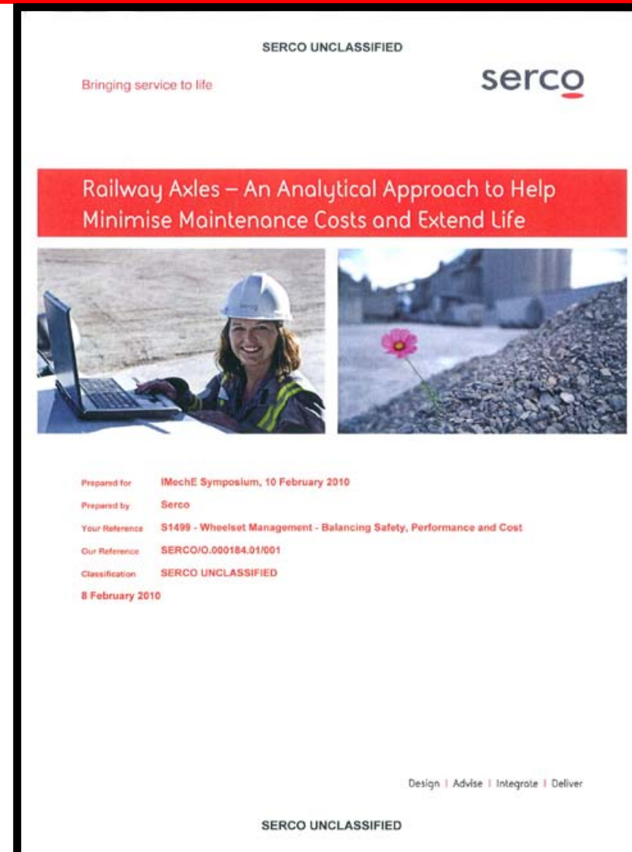
Safe inspection interval

BT10

- POD
- Material data
- Monte Carlo
- Probability or ALARP

Assessment

RICKERSCOTE


SERCO UNCLASSIFIED

Bringing service to life

serco

Railway Axles – An Analytical Approach to Help Minimise Maintenance Costs and Extend Life

Prepared for IMechE Symposium, 10 February 2010

Prepared by Serco

Your Reference S1499 - Wheelset Management - Balancing Safety, Performance and Cost

Our Reference SERCO/O.000184.01/001

Classification SERCO UNCLASSIFIED

8 February 2010

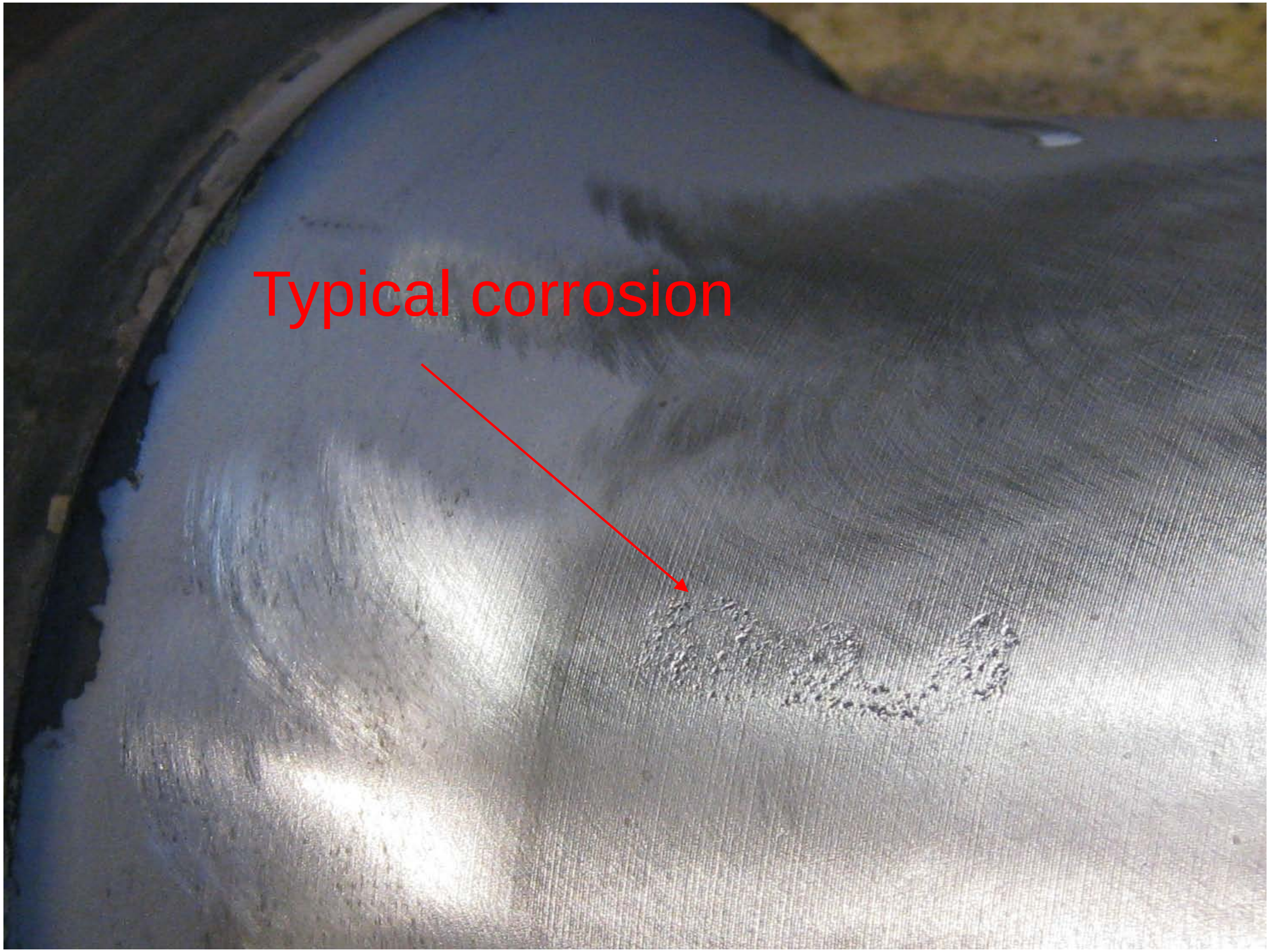
Design | Advise | Integrate | Deliver

SERCO UNCLASSIFIED

CORROSION

serco

Typical axle query



serco

Structural Integrity – process

Define defect type

Use best load data that can be obtained – measured, published, factored.

Use standard software with available data

Understand limits of NDT

Use relative rather than absolute risk

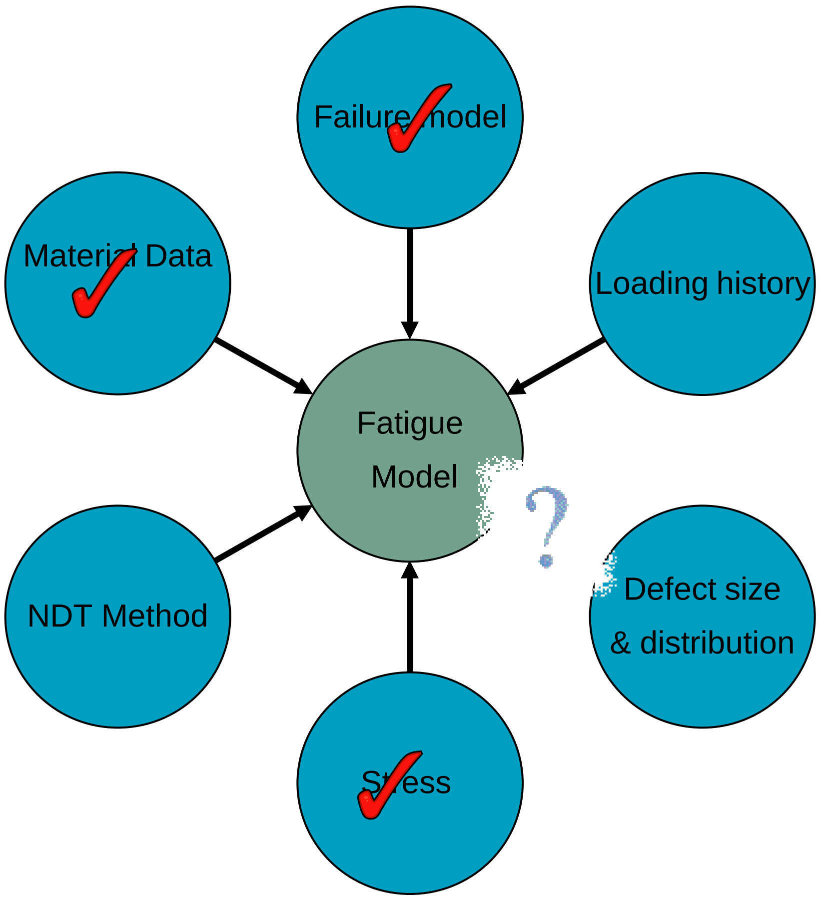
Often used as iterative process

with distinct stages

Defect distribution important

Service loads important

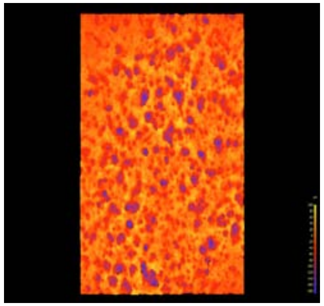
Detectability important

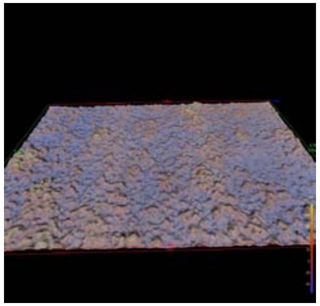


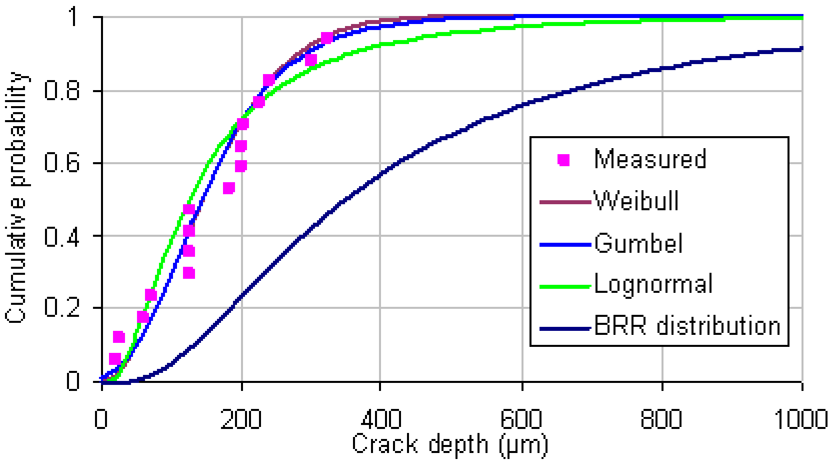
Defect size & distribution

Theoretical and actual

Alicona Infinite focus microscope







One problem is that if we use the measured distributions we predict very few failures!

serco

Material Data

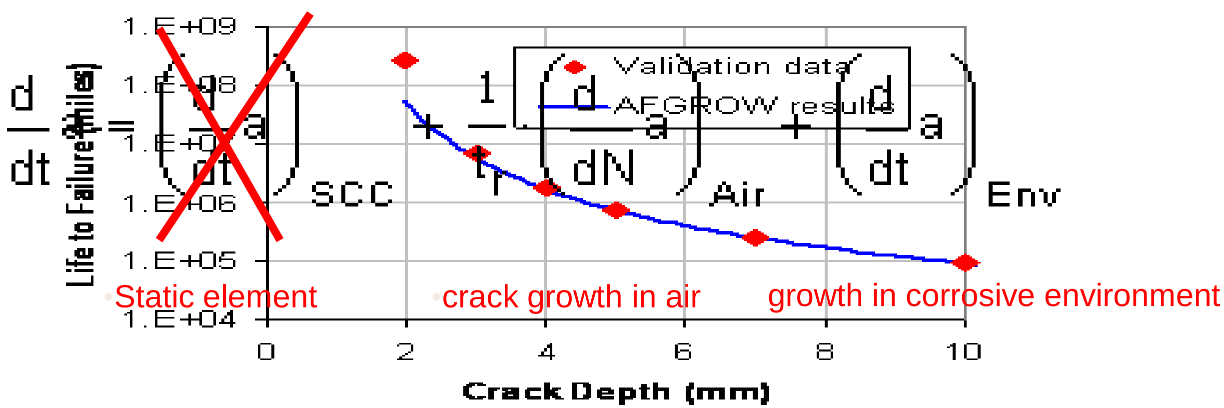
Fatigue Data

- Corrosion fatigue or the influence of corrosion on fatigue?
- There is lots of data that is surprisingly consistent!

Fatigue Model

Fatigue Model – current

- A fundamental requirement for safety critical work is traceability. Hence our use of Industry standard software which has been widely peer reviewed and is supported by a very large number of stakeholders
  - AFGROW –crack growth prediction software tool- http://www.afgrow.net/
  - NASGRO – similar capability
- In addition, AFGROW has been subjected to extensive benchmark testing against published railway axle investigations



serco

NDT Method

NDT and POD – the current weakness?

- Has there been any progress during last 30 years?
  - – Riskerscote proposed the phasing out of far end scans - a far end scan has a low probability of identifying mid span defect.
  - – I MechE conference in 1991 confirmed aspiration
    - Good POD data remains scarce.
    - Remember the PANI - 3 P's

      - People - variability between NDT operators swamps all other variables.
      - Process - NDT in the production environment has become commoditised and time pressured
      - Procedures – often updated and modified and the intellectual "ownership" becomes lost.

Loading history

Loading History

- A great deal of measured information is available to industry via RSSB – lets use it!
- It should be possible to dynamically model axle loading and hence assess wheel sets at design stage.
- Then measure during commissioning for confirmation only. This is not technically difficult and should form part of the vehicle acceptance process.

serco

Summary

- Many analytical methods make simplifications in order to obtain results. Modelling the initiation of cracks is difficult. The assumed defect distribution approach has been a good way of overcoming this problem.
- Existing models can be modified to take account of corrosion fatigue – several approaches are possible – however beware of eliminating threshold
- Very wary about simply replacing one assumption with another –improvement must be evidence based.
- NDT remains weak – Far end scans have little benefit. The fact we don’t have many failures in service is because we don’t have the populations of defects assumed that are assumed in the first place!
- Little service experience to support corrosion hypothesis. How different it would be if we had acted on the Rickerscote recommendations!
- Noted discrepancy in interpretation of procedures across industry

serco

One or two comments for discussion.....

- NDT is unreliable
  - Scan reliability is poor
  - Its a commoditised process and we risk loosing the behaviours needed
  - Independent studies show that there is huge variability between operators
- Corrosion (in terms of modelling) is not critical to obtaining safe inspection intervals
- We throw away rejected axles which contain useful information which would help us understand the true effects of corrosion
- We do not manage maintenance consistently. Scrap rates vary significantly

serco

Thanks for listening.

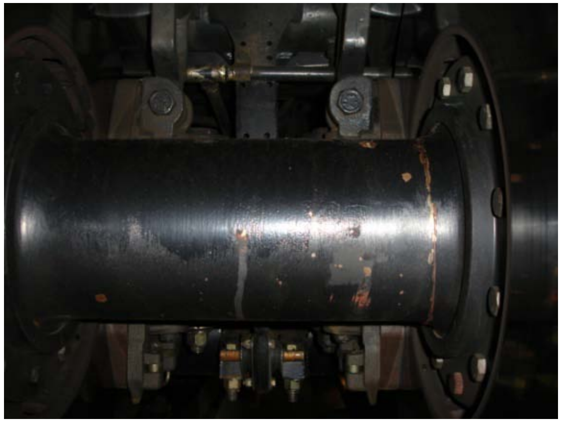
LURSAK: The new high performances axle protection

Dimitri Sala
Railway product
Research and Testing

Why protecting railway axles?

1. Wheelsets are the main safety components on the train;
2. It’s important preventing any crack on the axles surface;
3. Impacts from ballast may initiate fatigue cracks on the axle;
4. Protect against corrosion;

It’s important to keep in mind that extreme environmental conditions (e.g. ice, high temperature, etc.) may decrease drastically the performance of protective coating and so the protection of axle.



Contact with external element and starting of corrosion

Corrosion

European Standard EN 13261

Product requirements – Axle protection

LUCCHINI RS

Referring to the extreme importance of axle integrity, the European Standard EN 13261: *"All axles in service shall be protected against corrosion for the areas where there are no fitted components. For some axles, it is necessary to have protection against mechanical aggression (impacts, gritting, etc.).*

Four classes of protection are defined:

- *class 1: sections of axles subjected to atmospheric corrosion and to mechanical impacts;*
- *class 2: sections of axles subjected to the action of specific corrosive products;*
- *class 3: sections of axles subjected to atmospheric corrosion;*
- *class 4: axles subjected to atmospheric corrosion when the stresses calculated according to EN 13103 and EN 13104 in the sections ct permissible stresses;*
- *different classes are permitted on the same axle.*"

	Class 1	Class 2	Class 3	Class 4
Coating thickness	X	X	X	-
Coating adhesion	X	X	X	-
Resistance to impacts	X	-	-	-
Resistance to gritting	X	X	X	-
Resistance to salt spray	X	X	X	-
Resistance to specific corrosive products	-	X	-	-
Coating resistance to cyclic mechanical stresses	X	X	X	-

European Standard EN 13261, Table 11 - Protective coatings

EN 13261 - "Railway applications – Wheelsets and bogies - Axles – Product requirements"

Coating class 1: experience in-service of Lucchini RS

LUCCHINI RS

In 2008 Lucchini RS has began to face problems of paint detachments from the axles mounted under some high speed trains running. This happened despite all the axles were protected with a paint which totally fulfilled the EN 13261 requirements (paint certified as class 1).

	Class 1	Class 2	Class 3	Class 4
Coating thickness	X	X	X	-
Coating adhesion	X	X	X	-
Resistance to impacts	X	-	-	-
Resistance to gritting	X	X	X	-
Resistance to salt spray	X	X	X	-
Resistance to specific corrosive products	-	X	-	-
Coating resistance to cyclic mechanical stresses	X	X	X	-

European Standard EN 13261, Table 11 - Protective coatings
EN 13261 - "Railway applications – Wheelsets and bogies - Axles – Product requirements"

As example: progression of maximum running speed in service in China:

. 2008: 350 km/h -> Kin. En.: +65% in 3 years -> more critical impact, higher heating due to
. 2011: 450 km/h braking, higher centrifugal force on coating (higher "force of detachment")

From the in-service feedback, Lucchini RS concluded that the requirements of EN 13261 may be not totally representative of the real running conditions.

Axle protection

Comparison with aerospace application

Lucchini RS thinks that the **boundary conditions that an axle meets during the in-service running are similar to the conditions that the external surface of a plane meets during the take-off and landing**:

1. Presence of turbulences which can favorite the impact with similar energy to dissipate

_ Normal running speed of train: 350-450 km/h

_ Normal speed during take-off: 250-290 km/h

2. Gradient of temperature extremely high

_ Surface railway axle: in few seconds high heating, up to +90°C, due to the brake disc heating during a braking

_ Surface of plane: in few minutes high cooling, from ground temperature to -40°-50°C

3. Resistance to aggressive atmospheric condition

_ Train: possible presence of water and salt (e.g. the train running near the sea)

_ Plane: possible presence of water and salt (e.g. planes of airplane carrier)

Lucchini RS and Akzo Nobel Aerospace
Starting of collaboration

After some attempts to improve the performances of the coating with without significantly improvements, in 2008 Lucchini RS decided to take advantages of aerospace experience and know-how -> 2008, September: first contact Lucchini RS - Akzo Nobel Aerospace*

Advantages:

1. **Access to Aerospace technologies** to provide advanced rate of axles protection;

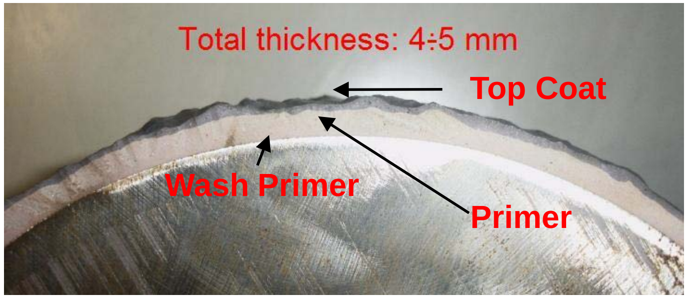
2**. Utilize typical aerospace material and coating systems to grant improved performances** like flexibility, heat resistance, impact resistances and long lasting endurance;

3. Being always **informed on the more advanced best available painting technologies** coming from Aerospace passengers and military market.

* Akzo Nobel Aerospace is the leader company in this field

With the aims to define a new protective coating which totally fulfills the **requirements (class 1) of EN 13261** Standard but it is also able to guarantee these performances both **in new and aged condition in a wider temperature range (-40°C ÷ +150°C)**, it has defined LURSAK:

- Aerospace Epoxy system based on **3 components**:
  - WashPrimer
  - Primer
  - Protective Top-coat (Finish)

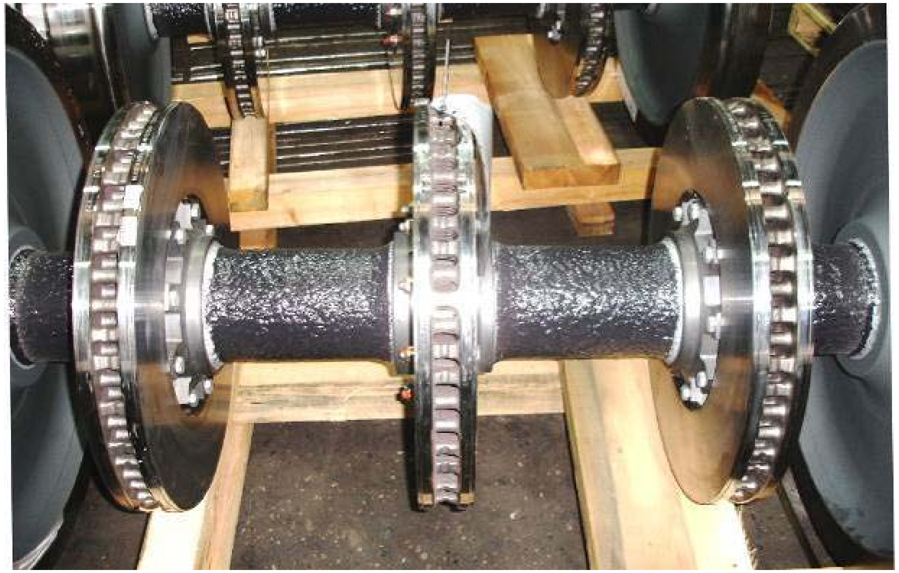


The 3 layers have, usually, a **total thickness of 4-5 mm**:

- Wash Primer, around 10 microns, for improving the adhesion to steel and protect from corrosion;
- Primer (high thickness), flexible and **reinforced with fibers**, for absorbing the impact energy;
- Protective Top-coat (Finish, high thickness), **reinforced with fibers**, for protecting against scratches and creeps.

The fibres guarantee a high level of consistence and structural resistance.

Drying of WP (first layer)



Wheelset final aspect

The surface appearance is not smooth, like a classic paint, but rough.

Research & development of LURSAK

Test campaign carried out

During the period 2009-January 2011, LURSAK has been subjected to an intensive laboratory test program in order to verify its performance in different external conditions:

Tests in accordance with European Standards EN 13621, class 1 coating

- **Coating adhesion** (pull-off test)
- **Impact test at -25°C and ambient temperature**
- **Gritting test**
- **Salt spray test**
- **Coating resistance to cyclic mechanical stresses**

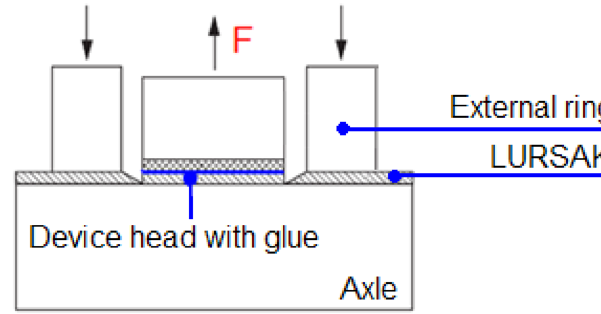
Further tests carried out

- **Impact test at -40°C, -30°C and +150°C**
- **Thermal stress test – Ageing and then Impact test at ambient temperature**
- **Dynamic test** (braking test) in new and aged condition
- **Full-scale fatigue test** in aged condition
- **Flame test**

Lucchini RS and Akzo Nobel Aerospace
Research & development of LURSAK
EN 13621, class 1 coating – tests carried out

Coating adhesion (pull-off test)

No detachment of protective coating observed in the most severe condition (up to 25 MPa applied)



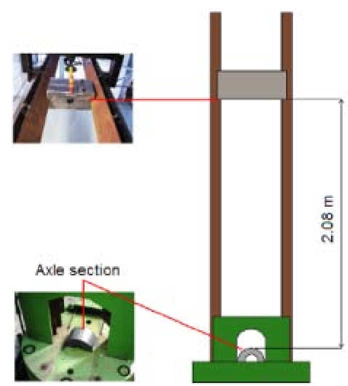
Impact test @ -25°C and R.T.

_ Projectile Mass M: 0.587 kg

_ Height of fall h: 2.08 m,

_ Impact energy E: 12 J

No hole found in the protective coating and no alteration of axle surface has been detected.



Gritting test

The gritting test defines the ability of a coating to protect the axle from damage due to repeated sand or grind blasting.

_ Projectiles: 1 kg of steel nuts dropped on the painted axle surface;

_ Height of fall h: 5 m

According to EN 13261, **LURSAK can guarantee the maximum level of protection to the axle (Coating loss level 1*) against the repeated sand or grind blasting**.

* Coating loss level 1: level of protection if the percentage of coating came off in flakes is less than 10%

Lucchini RS and Akzo Nobel Aerospace

Research & development of LURSAK

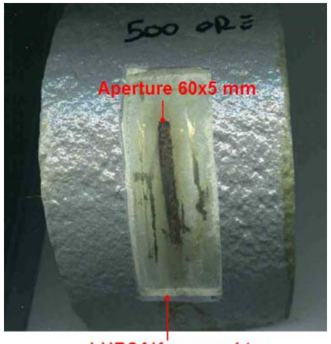
EN 13621, class 1 coating – tests carried out

Salt spray test (ISO 9227, Corrosion tests in artificial atmospheres)

_ Atmosphere: 5% of NaCl in water

The maximum progress of corrosion, from the edges of the artificial aperture, after 1000 hours is about 0.70 mm: the limit allowed by EN 13261 is 2 mm;

LURSAK guarantees the protection against corrosion.



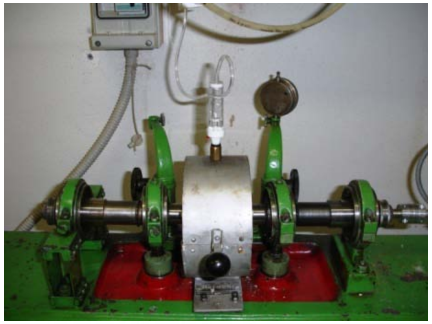
LURSAK removal to check the corrosion

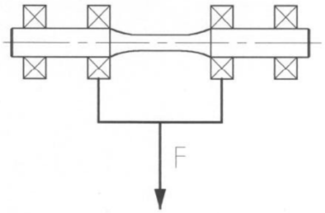
LURSAK removal to check the corrosion

Coating resistance to cyclic mechanical stresses

Fatigue tests on specimen in A1N steel grade covered with coating determining the ability of the coating to resist cyclic mechanical stresses combined with a corrosive product (demineralized water "drop by drop") dropping on specimen surface.

Each of the 4 specimen have completed the 5 stress levels required (170 -> 210 MPa) without showing any failure.





Lucchini RS and Akzo Nobel Aerospace

Research & development of LURSAK

Test campaign over EN 13261

LUCCHINI RS

Impact test at -40°C and +150°C (EN 13261 required -25°C and R.T.)

_ Impact energy E: 12 J, as required by EN 13261.

No hole found, no alteration of axle surface has been detected.

Impact test at R.T. after coating ageing

_ Impact energy E: 12 J, as required by EN 13261

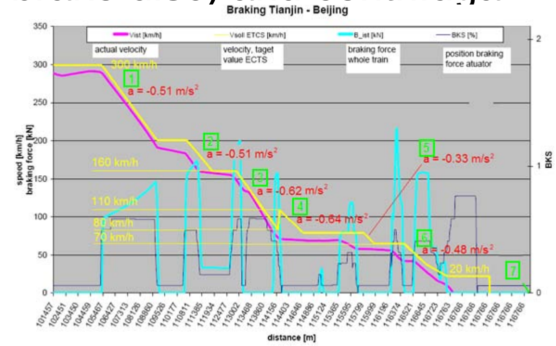
_ Ageing: 10 days of heating and cooling from +150°C to -30°C.

No hole found, no alteration of axle surface has been detected.

Research & development of LURSAK

Test campaign over EN 13261

The aim of the dynamic braking tests carried on BU300 test rig is the check of LURSAK behaviour when subjected to the combination of the actions of heating (from the brake disc) and centrifugal force.

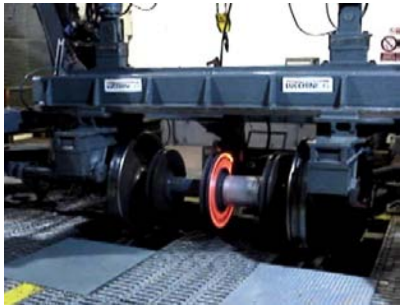


<u>The test program</u>

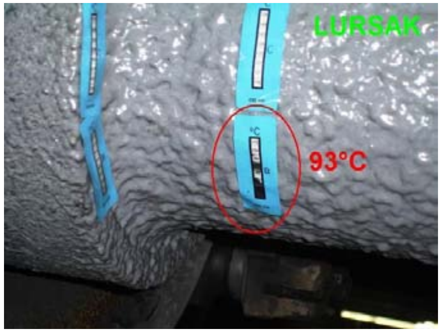
_ Simulation of track section of a Very High Speed train, repeated 40 times (240 brakes, 6 for each section);

_ 6 braking of stops ($a = -0.67\ m/s^2$), starting from three different speed (150, 220, and 300 km/h)

_ Maximum temperature measured: +93°C



The absence of any detachment, confirms that **this type of protective coating is able to tolerate the combination of heating and centrifugal force acting at 300 km/h**.



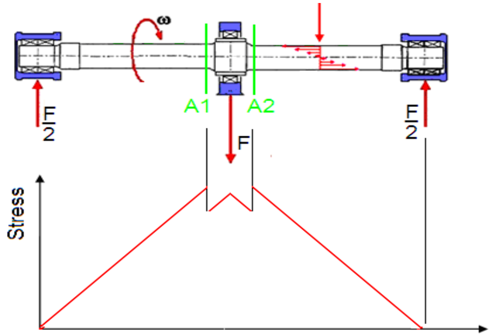
Lucchini RS and Akzo Nobel Aerospace

Research & development of LURSAK

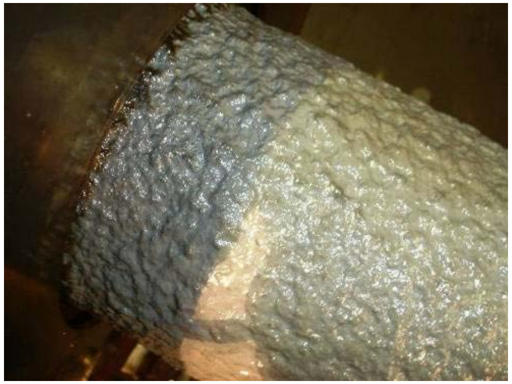
Test campaign over EN 13261

The aim of the fatigue test is the verification of LURSAK resistance when the axle is subjected to very high level of stress: a full-scale test axle painted with LURSAK, in aged condition, has carried out a fatigue test with the application of a completely reversed stress cycle (amplitude of 180 MPa) for 10 millions cycles.

The Visual and Ultrasonic Tests carried out at the end of fatigue test have confirmed that **LURSAK is able to resist for 10 millions cycles to the application of an high level of stress without any failure point.**



F: Force applied by the actuator
A1 and A2: sections with maximum stress applied



Research & development of LURSAK

Test campaign over EN 13261

A flame test campaign have been performed on plates and specimen painted with fire proof version of LURSAK. In this test campaign, they are evaluated:

_ fire behaviour, smoke emission and dropping behaviour according to DIN 54837;

_ smoke toxicity in the test chamber ISO 5658-2 (evaluation according to DIN 5510-2).

The results are satisfying.

Test campaign results

Test	Method	Results	Comment
Coating adhesion	EN 13261 & EN ISO 4624	✓	Resistance σ > 6 MPa: at this stress value there is the partitioning of glue and no coating detachment
Impact test @ R.T.	EN 13261	✓	No hole in the coating and no alteration of axle surface detected
Impact test @ -25°C	EN 13261	✓	
Impact test @ -40°C	EN 13261 @ lower T.	✓	
Impact test @ +150°C	EN 13261 @ higher T.	✓	
Gritting test	EN 13261	✓	No evidence of coating come off in flakes
Salt spray test	EN 13261 & ISO 9227	✓	Preliminary (after 500 hours) and final results (after 1000 hours) OK
Coating resistance to cyclic mechanical stresses	EN 13261	✓	No failure of any of 4 specimens
Thermal test – Ageing	Internal procedure	✓	No defect detected
Impact test at +25°C after thermal test	EN 13261 after Thermal test	✓	No hole in the coating and no alteration of axle surface detected
Braking test	Simulation of track section Tianjin – Beijing	✓	No problem of coating detachment Maximum temperature measured: +88°C
	Braking stop from 150, 220 and 300 km/h	✓	
Fatigue test	Application of 180MPa for 10 millions cycles	✓	No failure point of LURSAK found
Flame test	DIN 54837, ISO 5658-2 and DIN 5510-2	✓	Product conformed

Thanks for your kind attention

ESIS TC24 Workshop 3-4 March 2011

"Predicting real world axle failure and reliability"

The RSSB Axle Safety Model – A S Watson

© 2011 DeltaRail Group Limited

Axle Assessment Methodology - Principles

- Full Application by a series of separate modules
  - Excel spreadsheets to characterise route and derive axle stress histogram (T356 methodology)
  - FORTRAN program to calculate failure probability as function of NDT periodicity
  - Need to interpret FORTRAN output in terms of acceptable NDT regime
- Methodology has been delivered as Excel Decision Support tool
  - Intended for use by Industry Specialists
  - In general conservative
  - Failure probability curves precalculated for reference vehicles and routes
  - Considers a range of NDT techniques and axle protection options
  - Indicates appropriate NDT periodicities with associated costs

© 2011 DeltaRail Group Limited

Excel Decision Support Tool – Passenger Vehicles and Locomotives

- Most British main line passenger vehicles are included explicitly
- Vehicles categorised into five reference cases
  - **Class 142 DMU**: covers all 14x type 2-axle DMUs
  - **Class 317 EMU**: covers most DMUs and EMUs (not high speed)
  - **Mk4 coach:** covers Mk3/4 coaches and high speed DMUs/EMUs
  - **Class 91 locomotives:** covers locomotives and driving trailers
  - **Class 86 Locomotives**: covers all other locomotive classes
  - Appropriate passenger load spectra for coaches and multiple units
- Not all passenger vehicles have been considered:
  - Eurostars have unique articulated bogie configuration and unique route
  - Extremely rare vehicles ("Heritage" DMUs, Mk2 coaches)
  - Vehicles with inboard axle journals

© 2011 DeltaRail Group Limited

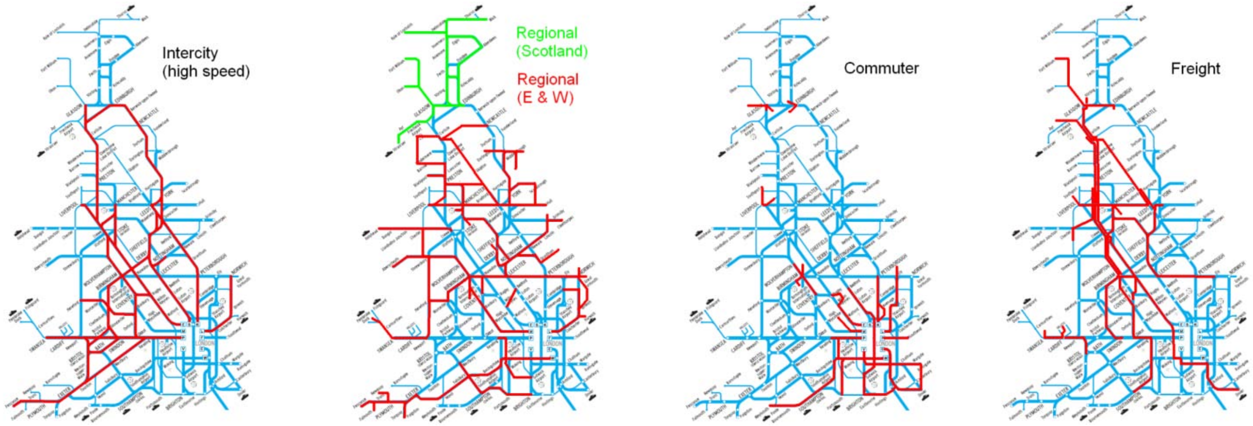
Excel Decision Support Tool – Freight Vehicles

- Too many types to include explicitly
- Freight vehicles categorised into two types: 2-axle and bogie wagons
- Excel tool calculates axle bending stress as a function of:
  - Laden axle load
  - Journal centres
  - Rail centres
  - Minimum axle diameter between wheels
- This approach could be extended to passenger vehicles (in addition to the defined list) in future versions of the tool

© 2011 DeltaRail Group Limited

Excel Decision Support Tool – Reference Routes

- All vehicles are assigned to one of five reference routes

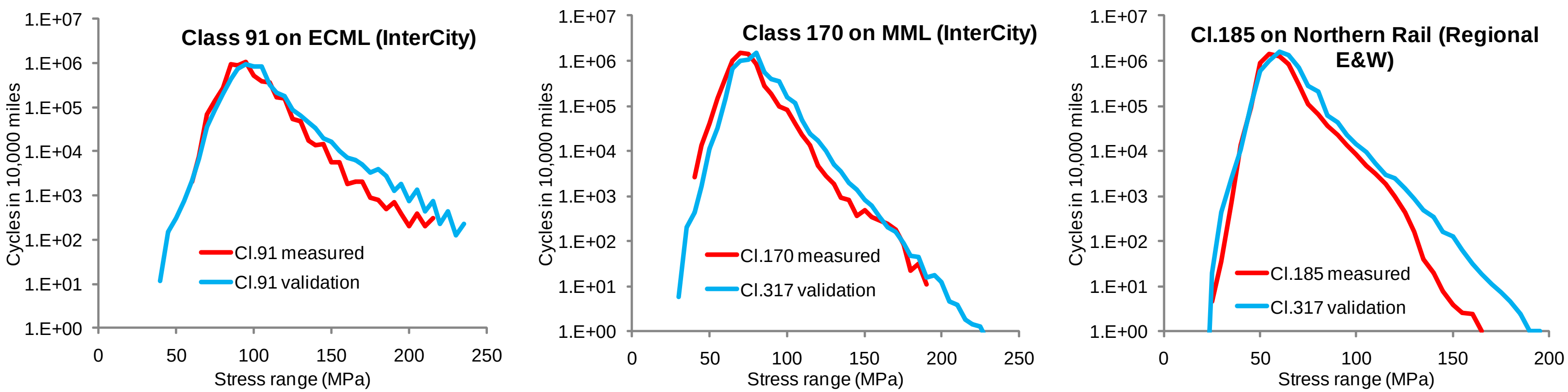


- Not all combinations of reference vehicle and reference route are appropriate
  - E.g. , High Speed Train running over freight network

© 2011 DeltaRail Group Limited

Excel Decision Support Tool – Verification of Vehicles and Routes

- Compare predicted and measured axle stress histograms



- Resulting predictions from Excel tool are generally conservative
  - However, this cannot be guaranteed for all cases
  - Excel tool to be used for preliminary axle assessments
  - Carrying out a full axle assessment will usually result in less restrictive NDT / protection requirements than Excel tool

© 2011 DeltaRail Group Limited

Excel Decision Support Tool – Axle Protection Options

- The Excel tool provides three options:
- Complete protection against corrosion and mechanical damage
  - No possibility of crack growth from axle body
  - Fretting fatigue from wheelseat becomes limiting factor
- Current paint systems – partial protection
  - Limiting factor is crack growth in axle body
  - Paint assumed to protect axle for ¼ of overhaul interval
  - Level of protection is preliminary estimate – may be refined in future
- Unpainted axle – no protection
  - Limiting factor is crack growth in axle body
  - Corrosion fatigue assumed to begin immediately after entry into service or overhaul
  - Some axles have been designed to operate in this condition (US wagons)

© 2011 DeltaRail Group Limited

Excel Decision Support Tool – NDT Options

- The Excel tool provides four options:
- Only MPI at axle overhaul
  - Mandated for all British main line axles by Railway Group Standards
- MPI at axle overhaul and Eddy Current between overhauls
  - Use high angle UAT (wheelseats) for “protected” axles
- MPI at axle overhaul and UAT far end scan (mean detectability)
  - Use this option if confident of UAT operator(s) achieving mean PoD
  - Near end scan for (wheelseats) for “protected” axles
- MPI at axle overhaul and UAT (lower bound detectability)
  - Use this option if not confident of UAT operator(s) achieving mean PoD
  - Near end scan for (wheelseats) for “protected” axles

© 2011 DeltaRail Group Limited

Excel Decision Support Tool – Cost Data

- Excel tool outputs costs for one axle over one overhaul interval
  - Includes cost of protection and NDT between overhauls
  - Does not include cost of MPI at overhaul (assumed always carried out)
  - Does not include possible consequences of axle failure – this is handled by defining a maximum acceptable failure probability
- Most costs currently estimates
  - Can be changed by user to their own values
- Assumed costs of axle protection, per overhaul cycle
  - Complete protection: £1200 (needs to be renewed at overhaul)
  - Current paint system: £50
- Assumed costs of NDT, per inspection, per axle
  - Eddy current: £200
  - UAT: £100

© 2011 DeltaRail Group Limited

Excel Decision Support Tool – Acceptable Axle Failure Probability

- Intention that this is prescribed by RSSB or other rail regulatory body
  - However, acceptable failure probability for axles has not yet been set
- Interim values used in Excel tool
  - 0.00002 for passenger vehicles, based on no failures in current British passenger fleet of about 50,000 axles
  - 0.0002 for wagons. Ten times larger, because casualties in freight derailments usually arise only from secondary collisions
  - 0.00004 for locomotives used **only** for freight workings. Locomotives that may also work passenger trains are restricted to 0.00002
  - Value of acceptable failure probability may be changed by user

© 2011 DeltaRail Group Limited

Excel Decision Support Tool – Live Demonstration

- RSSB_T728-02_Model_Version_1.0.xlsm

© 2011 DeltaRail Group Limited

Appendix – Passenger Vehicles Mapped to Class 317 (bogie DMU/EMU)

- Class 150, 153, 155, 156, 158 Sprinter
- Class 159, 165, 168 DMU
- Class 170 (original & revised), 171, 175, 180, 185 DMU
- Class 313, 314, 315, 317, 318, 319, 320, 321, 322 EMU
- Class 323, 325, 332, 333, 334 EMU
- Class 350, 357, 360, 365, 375, 376, 377 EMU
- Class 442, 444, 450, 455, 456, 458, 460, 465, 466 EMU
- Class 507, 508 EMU

Available routes: Regional (E&W), Regional (Scotrail), Commuter

© 2011 DeltaRail Group Limited

Appendix – Other Vehicle Mappings

- **Class 142 (2-axle DMU):** Class 142, 143, 144 DMU
  - Available routes: Regional (E&W)
- **Mk4 coach (high speed passenger):** Mk3 coach, Mk4 coach, Class 221 Voyager, Class 390 Pendolino
  - Available routes: Intercity, Regional (E&W)
- **Class 91 (low dynamic stress locomotive):** HST power car, Class 67, 91, Mk3 DVT, MK4 DVT
  - Available routes: Intercity, Freight
- **Class 86 (other locomotive):** Class 47, 57, 60, 66, 73, 86, 90, 92 locomotives
  - Available routes: Intercity, Freight

© 2011 DeltaRail Group Limited

Appendix – Available Static Stress

Reference vehicle	Axle geometry for UAT	Static stress range (MPa amplitude)
2-axle DMU (Class 142)	Simple	32.4 - 40.5
bogie unit (Class 317)	Simple	21.0 - 42.0
	Complex	21.0 - 36.0
High speed passenger (Mk4 coach)	Simple	23.4 - 29.1
	Complex	21.0 - 33.0
Low dynamics locomotive (Class 91)	Complex	33.0 - 45.0
other locomotive (Class 86)	Complex	24.0 - 48.0
Bogie wagon (FSA)	Simple	30.0 - 78.0
2-axle wagon (SPA)	Simple	30.0 - 78.0

© 2011 DeltaRail Group Limited