NUMERICAL SIMULATION OF CONTINOUS WELDED RAILWAY RAILS

Flash Butt Welding, Fatigue and Laser Cladding

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Contents

- **Introduction - Continuous Welded Rails (CWR)**
- **The flash butt welding process (FBW)**
- **Materials testing and metallurgical evaluation**
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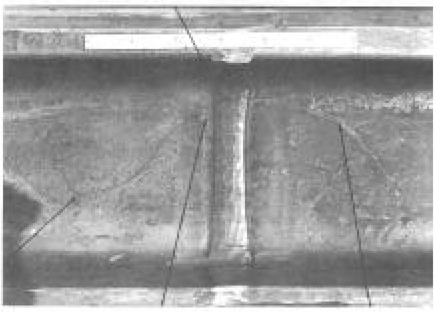
  - **Fatigue of welded rails under service load**
  - **Laser cladding of rails**
- **Summary and Conclusions**

Introduction

Rail failures



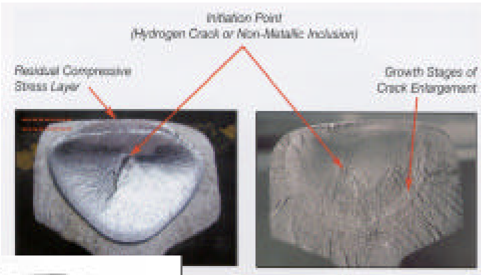
HSW (S-fracture)
Horizontal-split-web

Transverse-break fracture

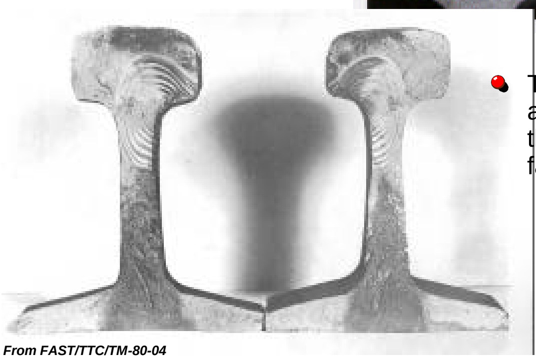
Pictures from FAST/TTC/TM-80-04

Introduction

- Failure often occurs from small pre-existing defects in the web, foot and head
- Defects in welds are hard to find in inspections and thus often lead to broken rails



From Railtrack



From FAST/TTC/TM-80-04

- The stress state in and around the weld increase the risk of contact fatigue failures

Introduction

Sawley, Reiff: Rail failure assessment for the office of the rail regulator. Transportation Technology Center, Inc., Colorado, USA

RAILWAY	Four common causes of defective rails by percentage of railway total			
	First	*Second*	*Third*	*Fourth*
Railtrack (U.K., 1999-2000)	Squats 21.7%	Vertical/transverse 20.1%	Horiz./longitudinal 12.5%	Bolt holes 9.8%
SNCF (France, 1999)	Squats 23.4%	Internal fatigue 11.5%	Shells 8.4%	Thermite welds 4.7%
HSPC – high speed (North America, 1999)	Thermite welds 31.5%	Wheel burns 17.2%	Horizontal split webs 13.3%	Bolt holes 11.3%
NS (Netherlands, 1997)	Insulated joints 59.4%	Transverse defects 18.0%	Thermite welds 15.0%	Shells, head checks 5.2%
EJR (Japan)	Shells and squats 63.9%	Head flaws 15.8%	Transverse cracks 6.7%	Rail end cracks 6.1%
DB (Germany, 1998)	Thermite welds 29%	Sudden fracture 18%	Fatigue failure (head checks and shells) 16%	Electric bonds 4%
Banverket (Sweden, 1998)	Transverse fracture 55.1%	Welded joints 32.7%	Horizontal defect 6.1%	Vertical split 2.0%
Spoornet (South Africa, recent)	Thermite welds 59.2%	Flash welds 17.7%	Head/web horizontal 16.1%	Railhead transverse 7.1%
HH1 (North America, 1999)	Vertical split heads 34.7%	Thermite welds 20.3%	Detail fractures 13.1%	Bolt holes 12.2%
HH2 (North America, 1999)	Transverse defects 23.6	Thermite welds 15.5%	Wheel burns 13.2%	Shells 9.6%

Introduction

BACKGROUND

Defects in welds are hard to find by inspections, they often lead to broken rails. Failure often occurs from small pre-existing defects in the web, foot and head. Two welding processes are used today:

- Flash butt welding – stationary to obtain longer units
- Thermit welding – final joining in the field

PROJECT AIM

To quantify the influence of welding residual stresses and deformations on the necessary maintenance of rails

- Numerical FE simulation of the flash butt welding process
- Carry out verifying experiments of process parameters during welding and of residual stresses
- Develop material model for elasto-plastic deformation at high temperatures (Determine material data at different temperatures)
- Study possible crack growth in rail welds

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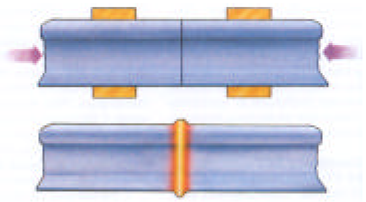
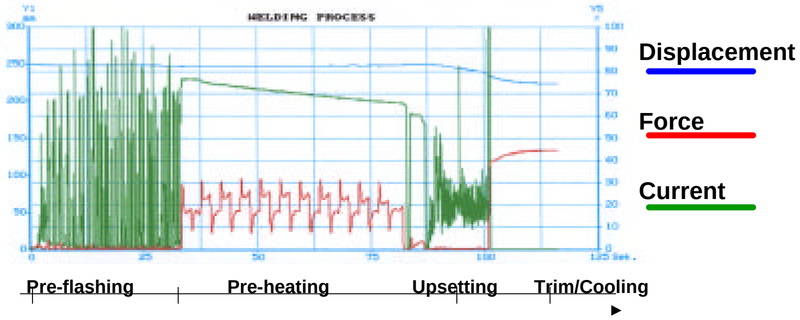
Flash butt welding process

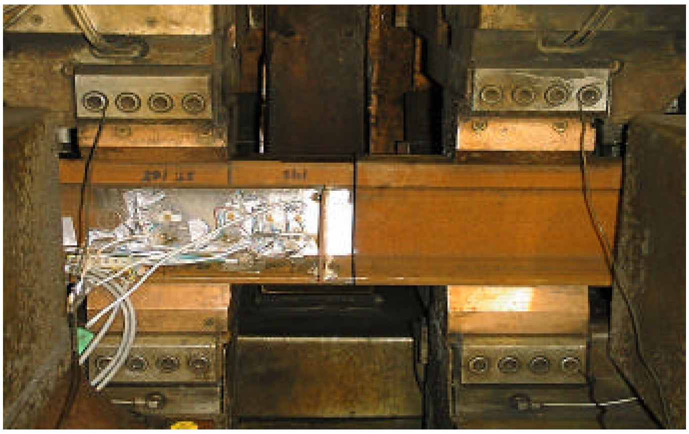
1. Pre-flashing
2. Pre-heating
3. Upsetting
4. Trimming
5. Air/Spray cooling
6. Straightening and grinding





Flash butt welding process

Full-scale measurements at Sannahed rail-welding plant



Flash butt welding process

Butt-welding test at the Sannahed plant

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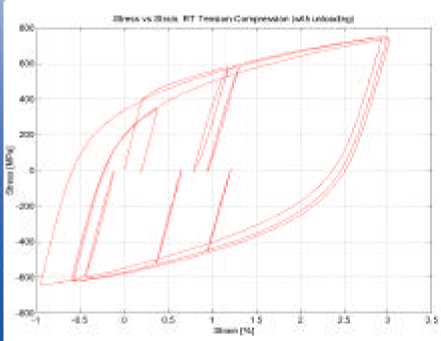
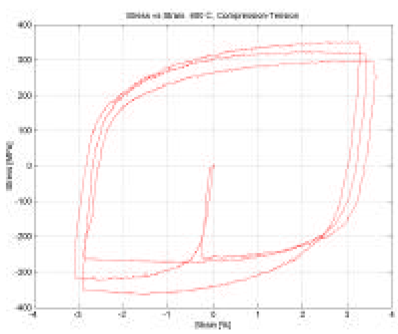
Materials testing and metallurgical evaluation

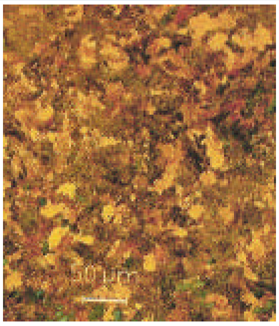
Materials Testing 900A (R260)

Cyclic stress-strain at 20°C and 600°C



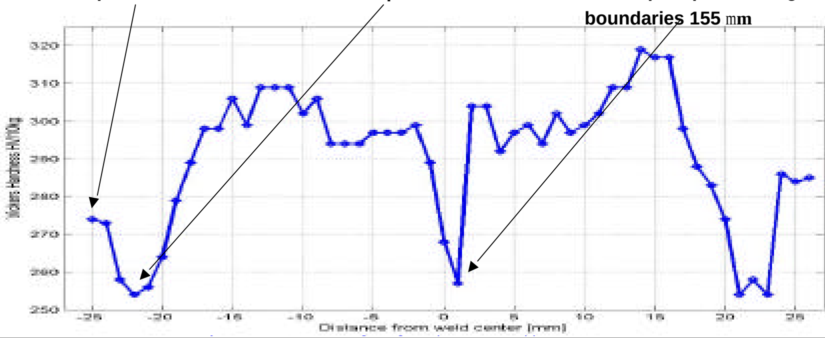


Lamellar pearlite 110 mm

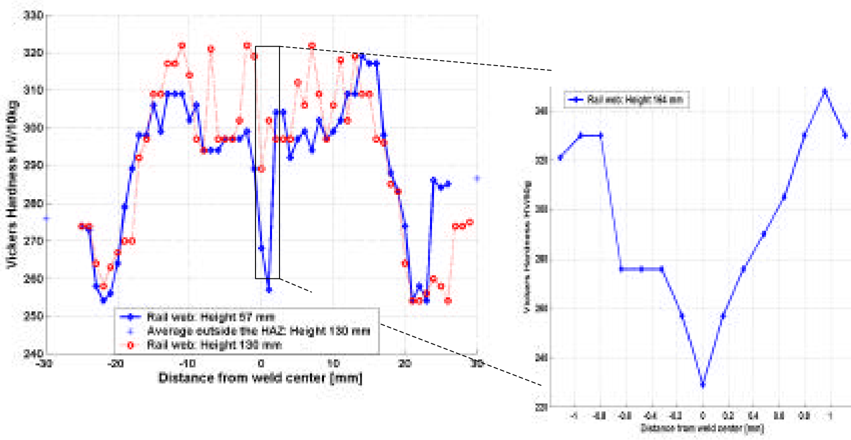


Globular pearlite 25 mm

Ferrite precipitation in grain boundaries 155 mm



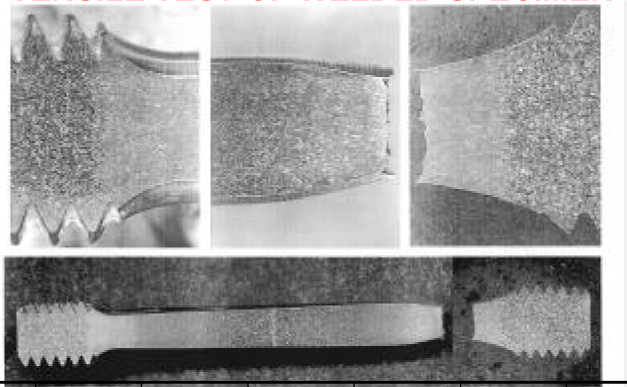
Materials testing and metallurgical evaluation
Microstructural Evaluation



- The hardness of the zone with ferrite precipitations is considerably lower that the surrounding material ~ 229 HV

Materials testing and metallurgical evaluation

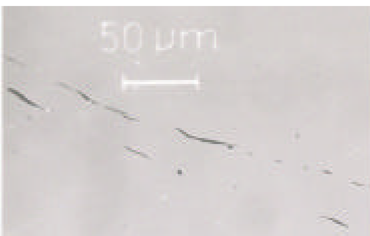
TENSILE TEST OF WELDED SPECIMEN



Specimen	Base/Weld	E (GPa)	$R_{p0.2}$ (MPa)	R_m(MPa)	A4/A5(%)	Z(%)
1	Weld	194	608.5	955.9	8.5	43.2
2	Weld	197	597.0	938.7	9.6	46.8
3	Weld	205	607.0	955.4	8.0	46.8
4	Base	207*	618.0	934.0	12.3	
5	Base	207*	575.0	963.0	12.3	
6	Base	207*	532.0	950.0	12.0	

Materials testing and metallurgical evaluation

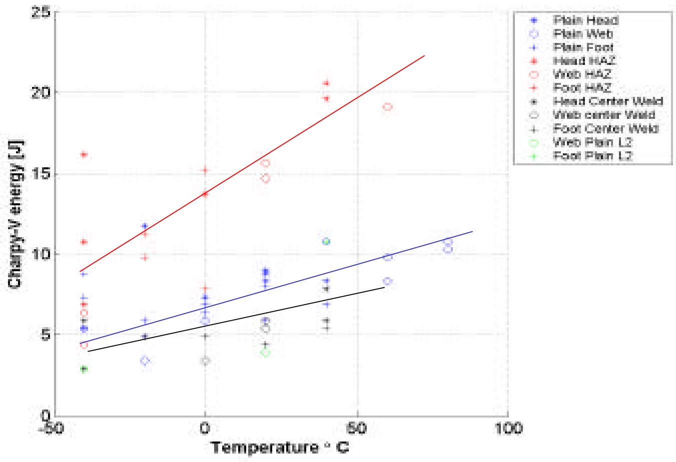
Microstructural Evaluation



- **Lamellar pearlite structure with ferrite precipitations, but No martensite**
- **MnS and SiO_2 slag exist in the fracture surface (~5mm)**
- **Cigar shaped slag (ASTM 1-2) does not affect fatigue strength**
- **Decarburization at the edge of the weld on the head**

Materials testing and metallurgical evaluation

Microstructural Evaluation



- **~85% of failure surface brittle fracture (- 40 to + 80 °C)**
- **Width of HAZ varies from 49.6 mm to 44.5 mm**
- **Base and Fusion zone are similar, HAZ more ductile**

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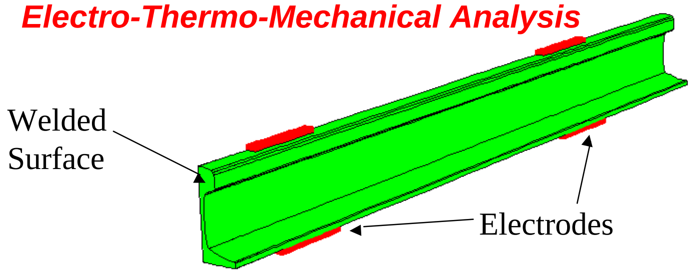
FE simulations

Electro-Thermo-Mechanical Analysis

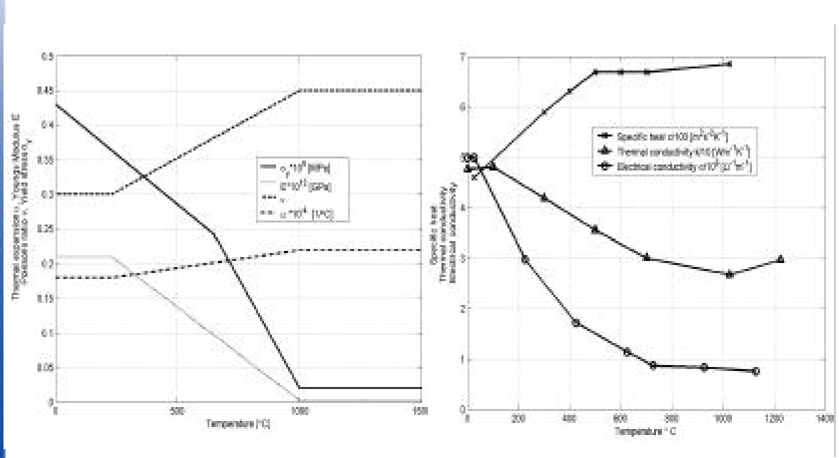


- **Coupled thermal-electrical analysis (ET)**
- **Input:**
  - **- Electrical potential and current from measurements**
  - **- Arc, rail and contact resistance are assumed R=20-200 mW**
  - **- Conductivity, convection and radiation to ambient environment**
- **Results:**
  - **- Temperature distribution in the rail**

- **Sequentially coupled thermal-mechanical stress analysis (TM)**
- **Input:**
  - **- Temperature distribution in the rail**
  - **- Residual stress from manufacturing disregarded**
  - **- Material behaviour, non-linear kinematic hardening, melting and ratchetting**
  - **- Data from welding process, upsetting and grinding**
- **Results:**
  - **- Residual stress and strain fields**

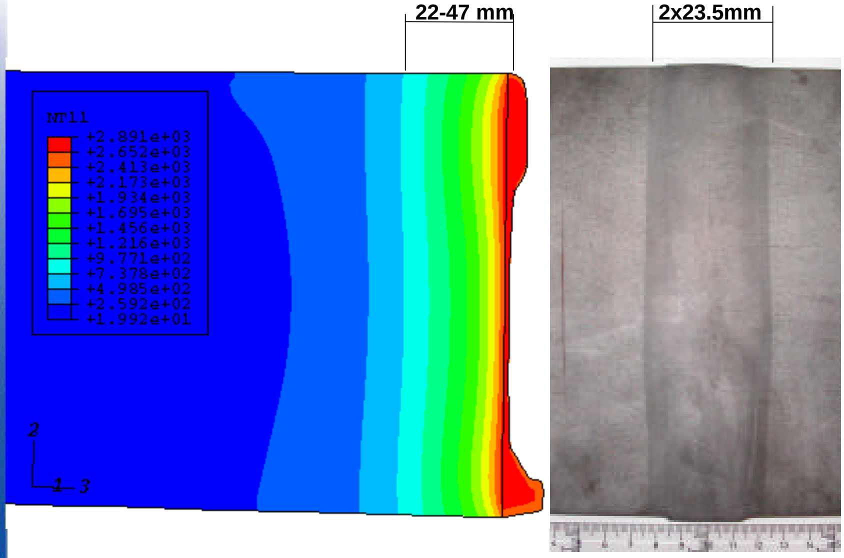
FE Simulations

Mechanical and Thermal properties



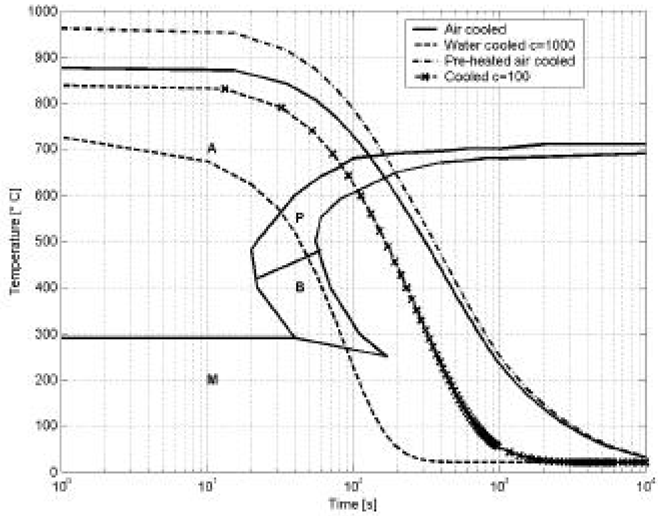
FE SIMULATIONS

Maximum temperature and HAZ



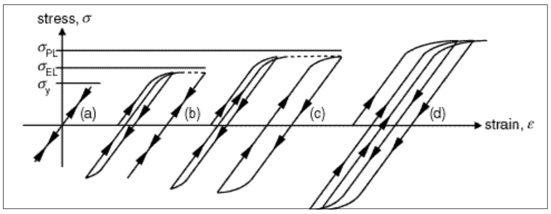
FE Simulations

Variation of welding process (present analysis air-cooled)



FE Simulations

Four material responses due to cyclic loading



(a): elastic response
(b): elastic shakedown
(c): plastic shakedown
(d): ratcheting

- **The type of material response depends on:**
  - **contact pressure (p_0)**
  - **friction coefficient (m)**
  - **shear yield strength (k)**
  - **material hardening**
  - **residual stresses**
  - **Coated specimens: the thickness of the coating material**

FE simulations

Material Model

The Constitutive model uses nonlinear kinematic hardening law with recovery of hardening and plastic strains at elevated temperatures

Total strain rate is decomposed into

$$\dot{e}^{tot} = \dot{e}^{el} + \dot{e}^{q} + \dot{\hat{e}}^{p} + \dot{e}^{Tr}$$

von Mises yield function

$$\Phi = \sqrt{\frac{3}{2}}\left| s_{dev} - X \right| - s_{y}$$

Associated flow rule

$$\dot{e}^{p} = \dot{\lambda} \frac{\partial \Phi}{\partial s} = \dot{\lambda} \sqrt{\frac{2}{3}} \frac{s_{dev} - X}{\left| s_{dev} - X \right|}$$

FE simulations - Material Model

Evolution of the yield surface

$$\dot{X} = \frac{2}{3} c \dot{\hat{e}}^{p} - g_1(\hat{X} - \hat{Y}) \dot{l} \quad \textbf{and} \quad \dot{Y} = g_2(\hat{X} - \hat{Y}) \dot{l}$$ **(Bower 1989)**

The plastic and hardening annihiliation is postulated such that

$$e^{A} = -e^{p} \qquad X^{A} = -X \qquad Y^{A} = Y \qquad at \qquad q = q_M$$

Where

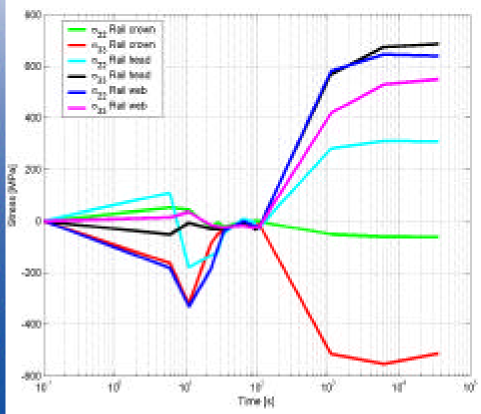
$$\begin{cases} \hat{e}^{p} = e^{p} - e^{Ap}; & e^{Ap} = e^{p} F \\ \hat{X} = X - X^{A}; & X^{A} = XF \\ \hat{Y} = Y - Y^{A}; & Y^{A} = YF \end{cases}$$

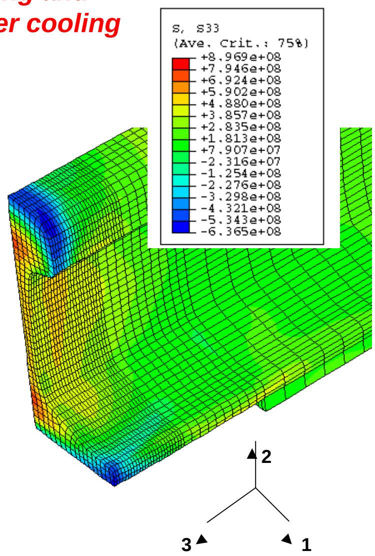
and

$$\boxed{F = \begin{cases} 0 & if \quad q < q_A \\ \left[3 - 2\dfrac{q - q_A}{q_M - q_A}\right]\left[\dfrac{q - q_A}{q_M - q_A}\right]^2 & if \quad q_A \le q < q_M \\ 1 & if \quad q \le q_M \end{cases}}$$

FE simulations

Stresses during welding and Residual stress field after cooling

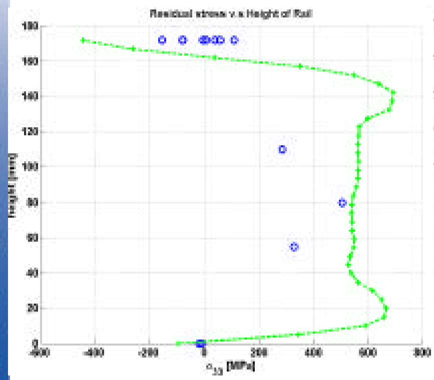


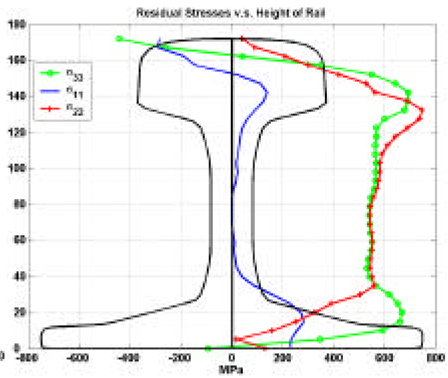


FE simulations

Measured and Calculated Residual Stresses

(Stresses as function of rail height)





Dot: Measured

Line: Calculated s_{33}

Lines:

Calculated s_{11}, s_{22} and s_{33}

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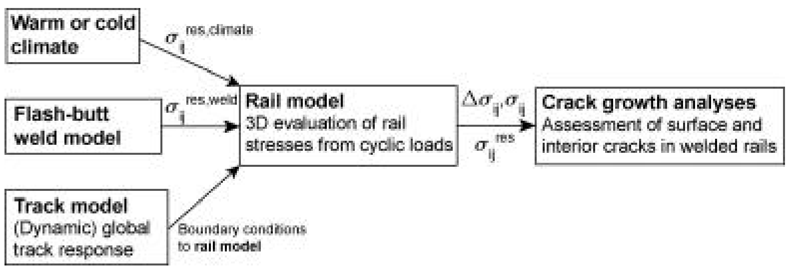
Fatigue crack growth analyses

Fatigue evaluation for different service conditions

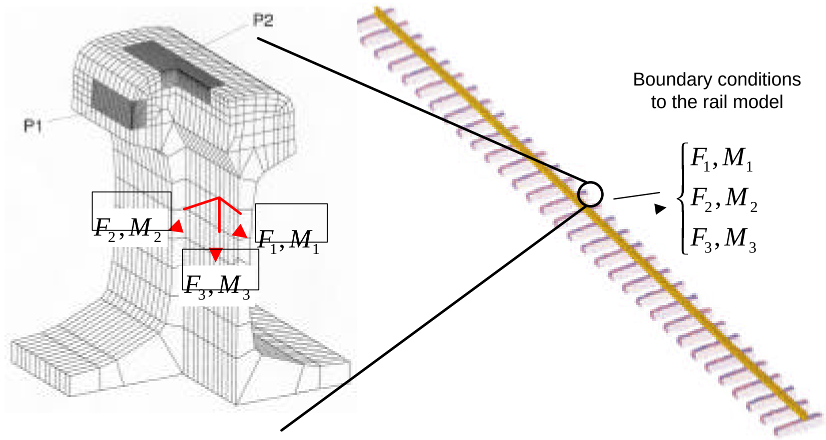


Fatigue crack growth analyses

Cross-sectional displacements and forces from train-track-interaction using the FE tool from MU6

Rail model | **Track model**

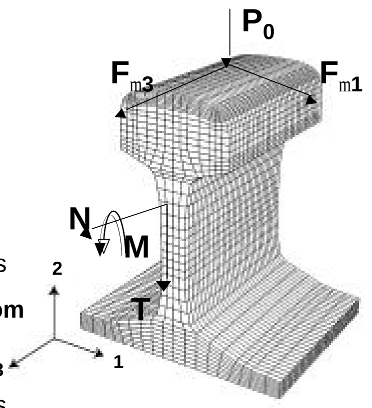
Quasi-static analysis | Dynamic analysis



Fatigue crack growth analyses

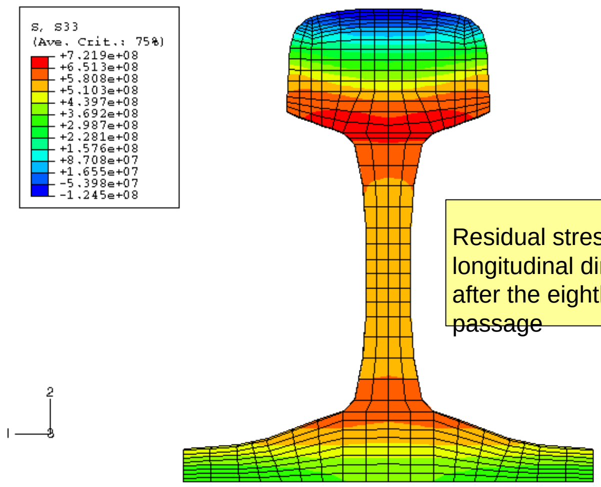
Stresses from a train pass

- **Data to track and rail models:**
  - Axle load: 30-40 tonnes
  - Hertzian load: p_0=1411 MPa (applied on the rail model)
  - Train speed: 50 km/h
  - Lateral friction factor: 0.10
  - Longitudinal friction factor: 0.35
- **Data to the rail model from a track model analysis:** Cross sectional displacements, or cross sectional forces
- **Initial conditions to the rail model from the welding FE simulations:**
  - Residual stresses from welding are included in the rail model FE analysis
  - Clamping stress from track laying (Rail is stress free at 20°C)



Fatigue crack growth analyses

Elastic shakedown after 8 wheel passes



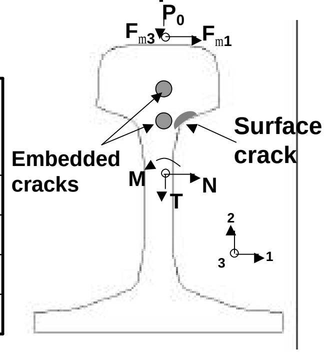
Residual stress in the longitudinal direction after the eighth wheel passage

Fatigue crack growth analyses

Fatigue crack growth calculations

- **Crack propagation data for rail steel UIC 900A**
  DK_{th}=2.0 MPa m$^{1/2}$; C=2.47*10^{-9} ; n=3.33; K_{IC}=40 MPa m$^{1/2}$
- **The welding defects are modelled as cracks in a plate:**
  Initial crack area: A_0= 10 mm^2
- **Example: Surface crack (half-elliptic)**

Axle Load [tonnes]	σ_{max} [MPa]	$\Delta\sigma_{33}$ [MPa]	N_f [cycles]	T °C	Traffic years:
35	**739**	**45**	**2.45e6**	**+20**	**2.8**
30	**735**	**38**	**5.26e6**	**+20**	**6.0**
30	**661**	**38**	**Inf**	**+40**	**Inf**
30	**957**	**38**	**>K_{IC}**	**-40**	**0**



- **Ds_{33} is the redistributed stress after eight wheel passages**
- **30-40 tonnes axle load, v = 50 km/h, 870500 axles/year**

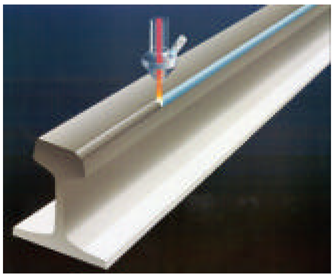
Contents

Laser cladding as a palliative

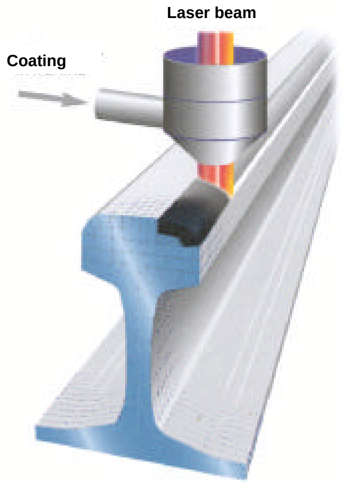
InfraStar – Charmec project EU7

The concept of a two material rail

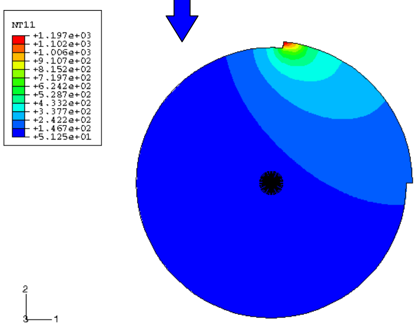
- **A two material rail was developed within the EU-project InfraStar**
  - A surface laser cladding technique is used to weld a 2-5 mm thick surface coating on to the rail head in the area of wheel-rail contact
- **The material welded to the rail has considerable higher yield limit and hardness than the base material, it is wear resistant and present lower friction in the wheel-rail contact than normal material.**
- **Result: ratcheting ? elastic (shakedown) material response**



Laser cladding of rails

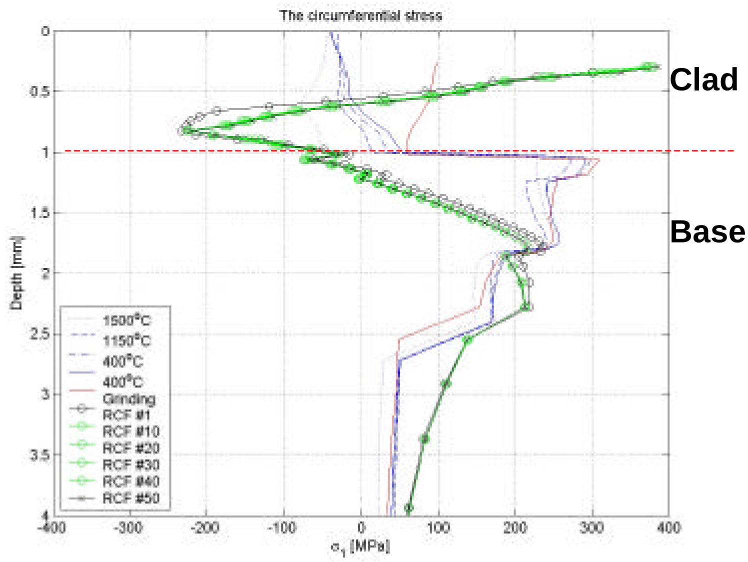


Du?ec coated disc specimen



Laser cladding of rails

Stress after laser cladding (3 passes), grinding and 50 wheel passages



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Conclusions and Future Activities

- Flash butt welding can be analyzed with respect to process parameters and RS
- The RS-field cause existing defects to grow, thus service inspection is crucial
- Elastic shakedown occur after a few wheel passages but RS are only slightly relaxed
- Small crack (5-10 mm²) may lead to failure in a few years with increased axle load
- Laser cladding is likely to work well as a palliative

- Participate in benchmark for welding residual stresses (IIW X/XIII/XV WG RSDP)
- Residual stresses with the thermit welding process

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