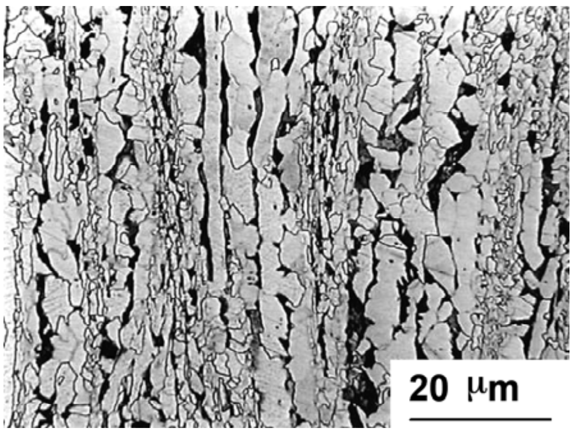
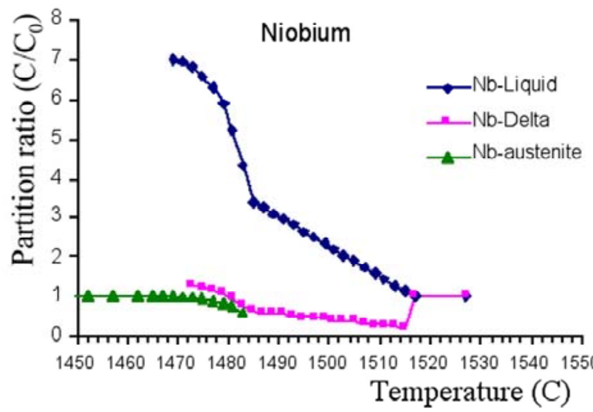
• Development of bimodal grain structures in microalloyed steels:
Niobium and titanium are added to high strength low alloy (HSLA) steels to provide grain boundary pinning precipitates to help produce the desired fine-grained microstructure. Niobium and titanium segregate strongly between the liquid and solid phase during steel solidification, with vanadium and aluminium showing much more limited segregation behaviour. Hence, macro- and micro-segregation of niobium and titanium occurs during thick slab casting resulting in a spatial distribution of precipitates and solute element. This precipitate and solute spatial distribution has significant effects on grain size development during processing (slab solidification, reheating and rolling) and can result in a bimodal grain size distribution (abnormally large grains in a matrix of smaller grains). Work is on-going to model the segregation behaviour during solidification and the subsequent microstructural development during processing.

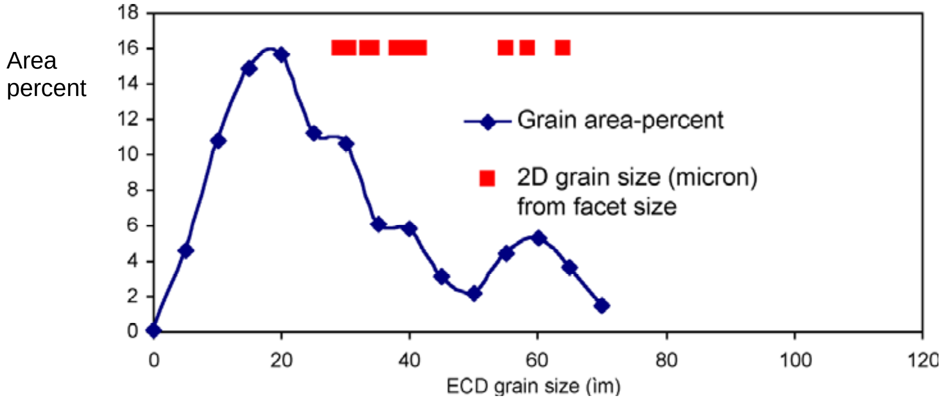




Optical micrograph showing a thermo-mechanically control rolled plate with a bimodal (banded coarse and fine) grain size, and Thermo-Calc prediction showing the strong segregation behaviour of niobium in steel.

• **Effect of bimodal grain structures on fracture properties:**

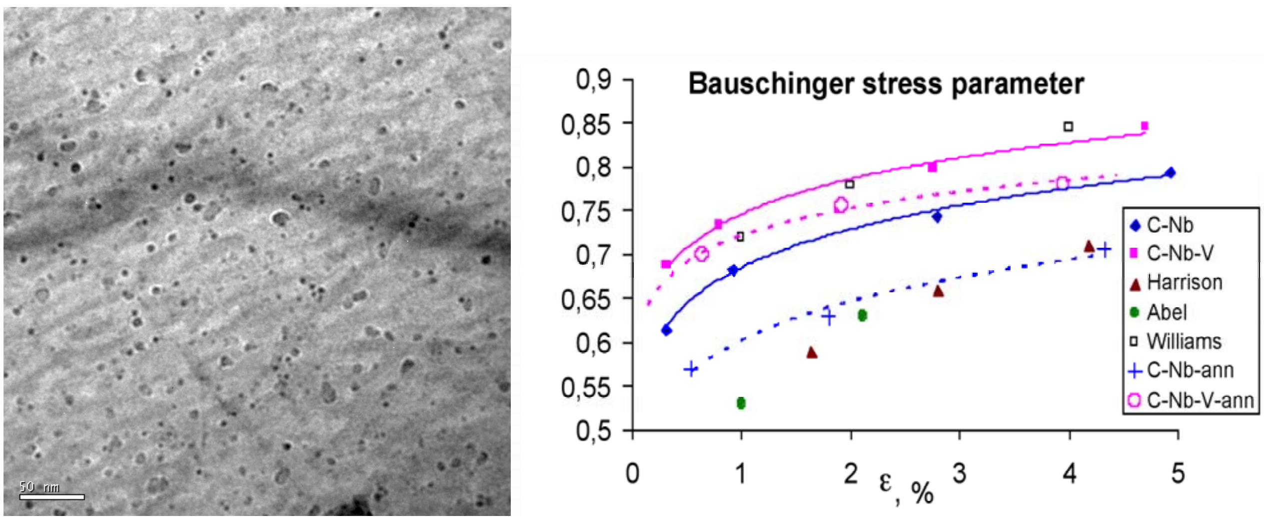
Toughness is an important property for engineering applications and specifications often require steel plates and sections to meet stringent values. Repeat testing is performed to ensure that the plate meets the minimum requirement and if the steel shows scatter in its properties one poor result may force the downgrading of the entire batch. It is therefore important to understand what causes scatter in toughness properties, and what can be done to minimise it. Notch-bend tests were performed at –160 °C to investigate the effect of a bimodal ferrite grain size distribution in steel on cleavage fracture toughness by comparing local fracture stress values for heat-treated microstructures with uniformly fine, uniformly coarse and bimodal grain structures. Analysis of fracture stress values indicates that bimodality can have a significant effect on the toughness by generating high scatter in the fracture test results.



Cleavage originating grain size values superimposed on the corresponding ECD-grain size distributions identifying the part of the bimodal grain size distribution responsible for cleavage fracture initiation.

• Predicting linepipe steel strength:

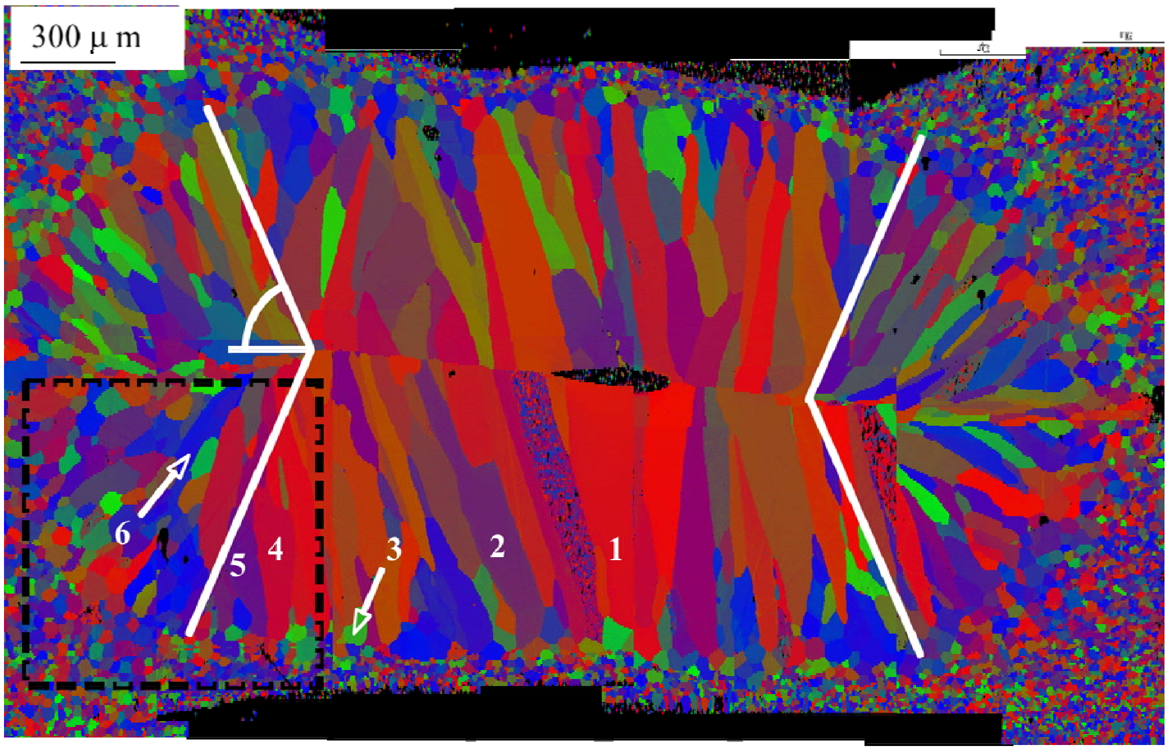
Mechanical properties of large diameter welded pipes depend on the hot-rolled plate microstructure and cold deformation schedule during forming from plate to pipe. Previous research on the UOE forming process has shown strength increase (due to work-hardening) or strength decrease (due to the Bauschinger effect) from plate to pipe. The magnitude of the Bauschinger effect has been found to be dependent on steel composition and plate processing history. The Bauschinger effect parameters is being quantitatively related to the particle number density and starting dislocation density using thin foil TEM analysis to examine the interaction between dislocations and precipitates (coarse Nb-rich particles and fine, <10nm diameter, V-rich particles) during single direction and reverse straining.



TEM image showing population of <10nm diameter V(C,N) particles in the C-Nb-V steel and compression-tension test results for as-rolled and annealed C-Nb and C-Nb-V steels showing that the yield drop in the direction of reverse strain increases with an increase in the particle number density and initial dislocation density.

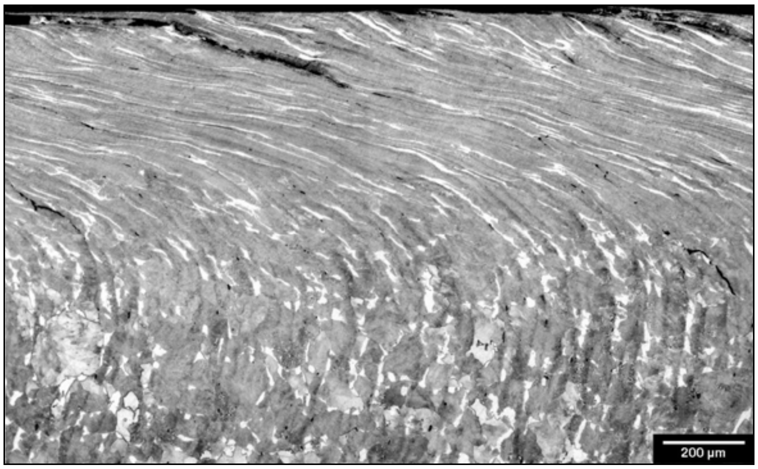
- **Modelling HAZ and weldmetal microstructures:**

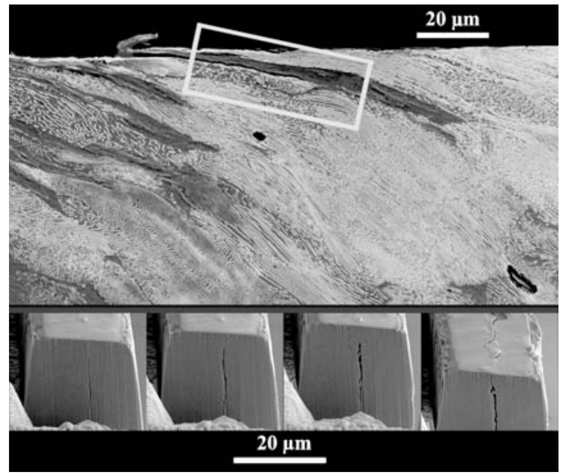
Welding is the most commonly used joining method for sheet metals and there are a number of models available for predicting the thermo-mechanical conditions associated with the various welding processes (e.g. spot, MIG, laser) used. In addition, the solid-state transformations within the weldmetal can also been modelled, although these aspects often require the solidification grain size to be assumed or used as an input. Currently, this reduces the ability of models to predict weldmetal microstructure (and properties) without either the production of a trial weld or for a narrow range of conditions around a well-characterised weld structure. Work is on-going to model the weldmetal columnar grain size based on the development of texture and grain size in the heat affected zone and the maximum misorientation between the preferred <100> grain growth orientation and the maximum thermal gradient (∇T_{max}).



EBSD map of basemetal, HAZ and weld nugget in a 430 stainless steel spot weld showing the high proportion of predicted {110}<001> oriented grains (coloured red) in the central section of the weld.

• **Microstructural influences on rolling contact fatigue crack initiation in rails:**
Wear-fatigue interaction, especially crack truncation, plays an important role in determining the life of rails. When the cracks are long, crack propagation is driven by the distribution of stress within the railhead whereas crack truncation, caused by wear, is dominated by the stress at the rail-head surface. For short cracks, however, these mechanisms are not distinct. An existing model shows how failure at the surface leads to wear, as well as crack-like features. Further research is on-going using this model to include detailed microstructural and mechanical property data for the steels of interest at the micron (x 10^{-6}m) and nanometre (x10^{-9}m) scales. Detailed micro- / nano-hardness and ductility values from the surface are being obtained, along with microstructural characterisation of the steel both before service and during service. This information, along with the links to the micro-mechanisms of fatigue crack initiation, form an input into the model of wear-fatigue interaction during crack initiation and early growth.

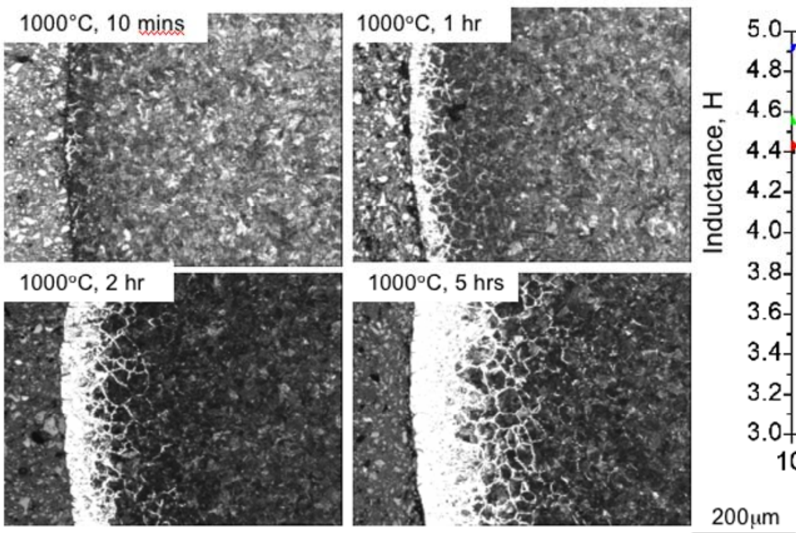


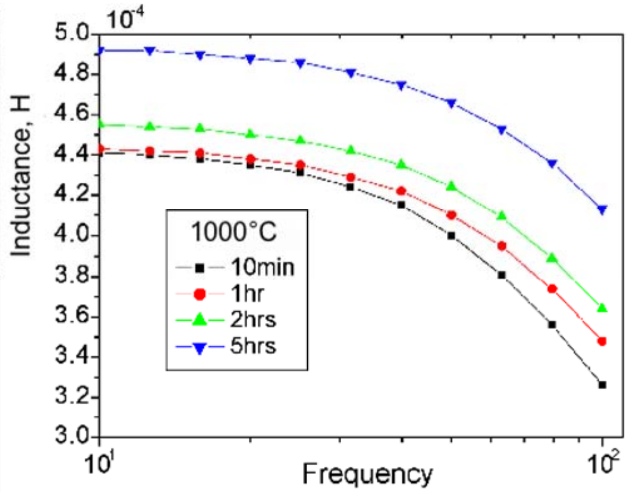


Circumferential section through a rail twin disc test sample showing gross plastic deformation and a rolling contact fatigue crack. Focussed ion beam examination of 3D crack shape approaching the tip of a twin-disc sample.

• Materials characterisation using electromagnetic sensors:

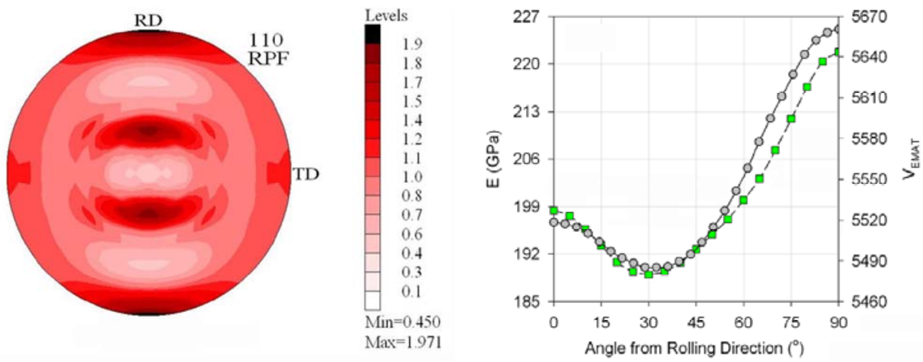
Multi-frequency electromagnetic (EM) sensors offer the possibility of measuring steel microstructure in a non-destructive and non-contact manner allowing on-line processing control. The EM sensor can be used to measure the ferrite fraction during transformation from austenite to ferrite below the Curie temperature (approx 770°C) using the low frequency inductance and zero crossing frequency. This has applications in both strip and rod processing where controlled cooling is used to achieve the desired microstructure and hence direct phase balance measurement is beneficial for process optimization. Another application is for decarburisation measurement since this can have significant effects on the mechanical properties of the final product, e.g. rod, and needs to be monitored. EM sensors can take advantage of the fact that the low carbon surface layer will transform from austenite to ferrite before the high carbon interior. If a sensor is located at the correct position in a rod mill decarburisation should be detectable. The next stage is to detect decarburized layers in the cold rod, here the sensor needs to distinguish between the surface low carbon ferrite (relatively high initial permeability) and the interior high carbon pearlite (lower initial permeability). Work is ongoing to model the EM sensor output – microstructure relationship and develop commercial systems for industrial use.





Optical micrographs showing rod samples with varying decarburisation depths and the EM sensor output for cold measurements indicating that at selected frequencies the different samples can be distinguished.

• Materials characterisation using ultrasonic sensors:
The formability of sheet metals is strongly influenced by, and can be predicted from, crystallographic texture, and is generally assessed in terms of an r-value and / or n-value off-line from tensile test samples. There is interest in the development of non-destructive, cheap and simple to operate systems for texture assessment. Ultrasonic velocity is directly related to a material's elastic modulus and metal single crystals can have significantly different elastic properties along their principal crystal axes. Hence, if a polycrystalline sample has preferred texture then variations in ultrasonic velocity with angle to the rolling direction are expected. In this project the ultrasonic velocity anisotropy, measured using a non-contact electro-magnetic acoustic transducer (EMAT) system, with respect to sheet rolling direction is being determined and compared to calculated elastic modulus anisotropy, using quantified texture components (from X-ray diffraction or EBSD and their known individual anisotropies), and mechanically measured modulus values.

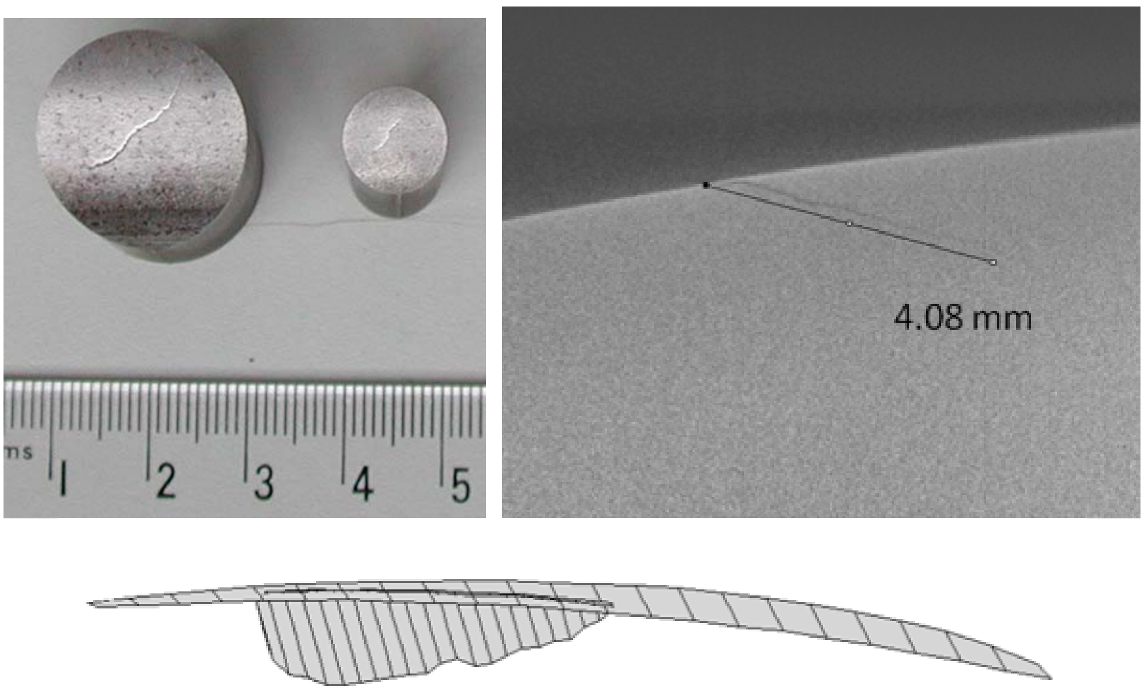


X-ray pole figure from a deep drawing steel sheet and graph showing the predicted elastic modulus and measured ultrasonic velocity anisotropy with respect to the rolling direction.

• 3D characterisation of RCF cracks in rails:

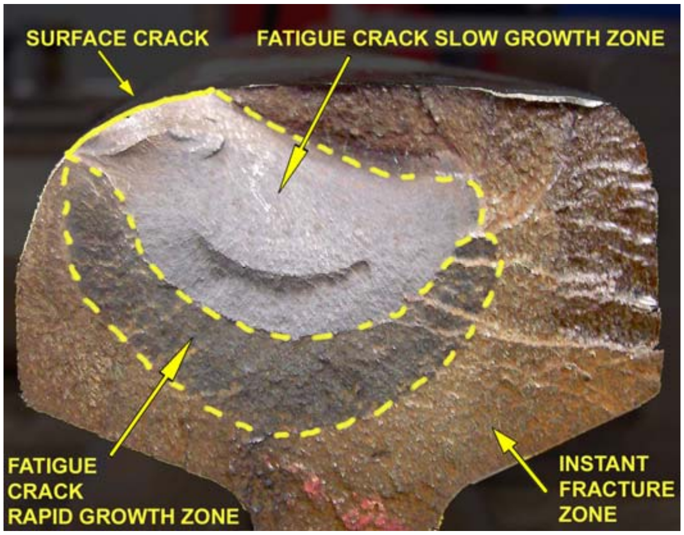
Rail tracks are subjected to intense bending and shear stresses, plastic deformation and wear, leading to degradation of their structural integrity with time. To achieve maximum reliability of the railway network and enhance the efficiency of the maintenance procedures it is necessary to conduct sufficient and reliable inspection of the rail tracks. For that reason, in-service rails are systematically inspected for internal and surface defects, using various NDE techniques, including ultrasonics, magnetic induction (or magnetic flux leakage - MFL), eddy current sensing and visual inspection. Rolling contact fatigue (RCF) cracks are surface breaking and typically grow at an angle to the running direction as well as at a shallow angle into the rail. The cracks propagate at the shallow angle until they reach a certain depth into the railhead before turning down and potentially growing to a critical size resulting in rail break. However, there is no single relationship between surface length and depth and as the cracks grow they develop complex shapes.

Research is being carried out to characterise the 3D shape of RCF cracks to use as input into computer modelling to link NDE sensor signals to actual crack shapes and sizes.

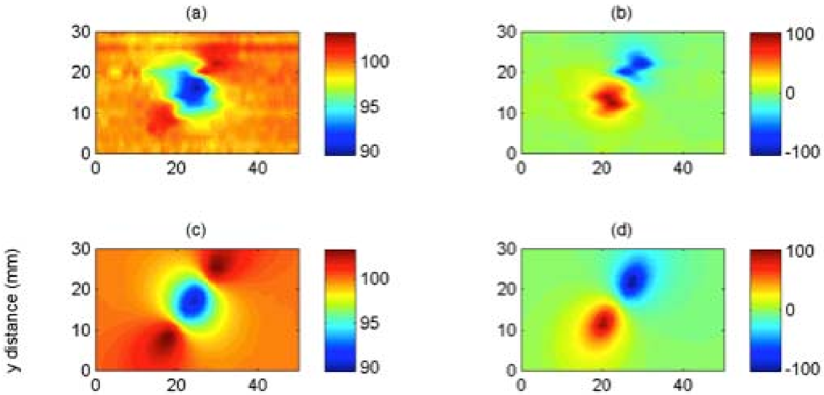


Two RCF cracks removed from a rail taken from service; X-ray tomography image of the larger RCF defect and 3D representation of the smaller RCF defect.

• Non-destructive testing of cracks in rails:
Alternating current field measurement (ACFM) sensors can be used to detect surface breaking defects in metal components. In rails, rolling contact fatigue (RCF) cracks form due to the wheel-rail contact stresses, these cracks are surface breaking and can have complex shapes. A COMSOL model has been developed for a commercial ACFM system in order to link the ACFM signal to the complex RCF crack shapes that can develop. The RCF crack shape has been determined by serial sectioning and X-ray tomography.



Broken rail showing complex shape of an RCF crack.



ACFM contour plots for a light RCF crack showing experimentally measured (plots a and b) and modelled (plots c and d) data where the plots in a) and c) represent the Bx values and in b) and d) the Bz values.