Non-destructive non-contact microstructural characterization

Claire Davis

University of Birmingham

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Current state-of-the-art
(electromagnetic, EM, sensors)

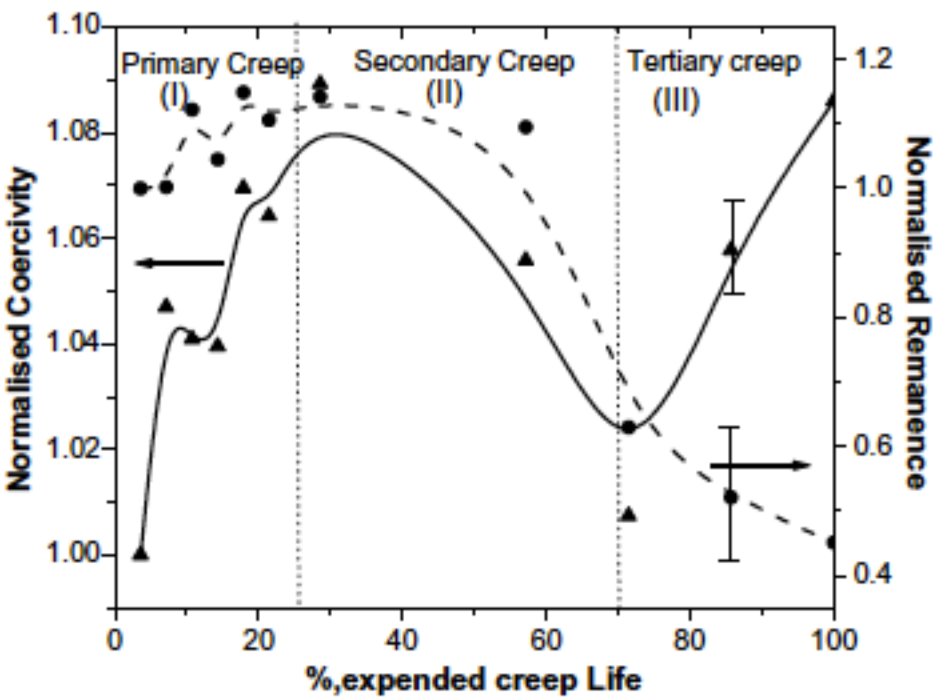
Commercial systems (e.g. IMPOC, HACOM) for use in strip mills with correlations between signal output and mechanical properties.

Laboratory systems and numerous empirical relationships for properties or microstructure changes (valid for specific steels).

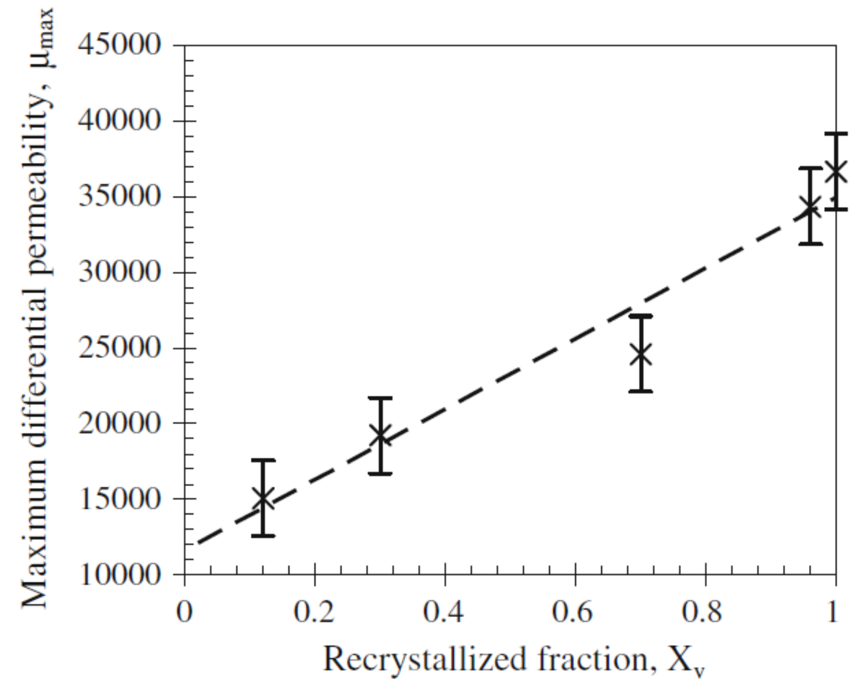
IMPOC system for cold rolled strip product for tensile strength prediction

Requirements

To develop the technology there is a need for more physical models to move away from empirical relationships.



Variation in normalised coercivity with creep life in P91 steel (A. Mitra et al. 2007) .



Variation of max differential permeability with recrystallised fraction for a low carbon steel (Gurruchaga et al. 2010).

Motivation and Challenges

- On-line inspection of steel microstructure in harsh environments (e.g. steel processing mills) using electromagnetic (EM) sensors.
- In-situ inspection of microstructure for in-service components (e.g. power plant components).
- Complex microstructures and fundamental relationships.

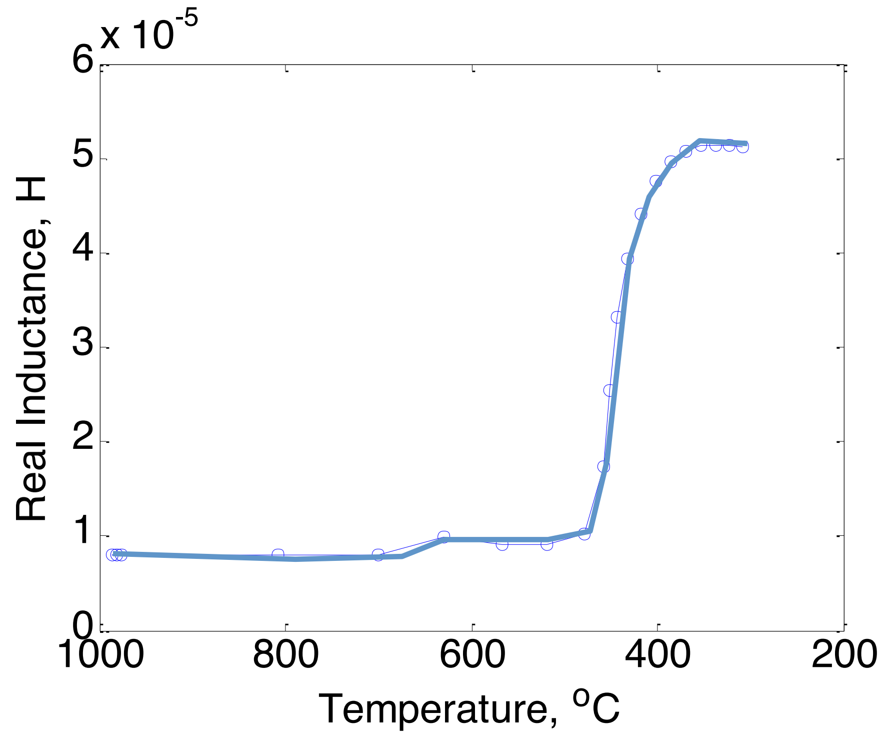
http://www.metal-supply.com

http://www.trinityndt.com

Phase transformation monitoring

Austenite is paramagnetic and ferrite / pearlite / bainite / martensite are ferromagnetic (below the Curie temperature, ≈ 770°C).

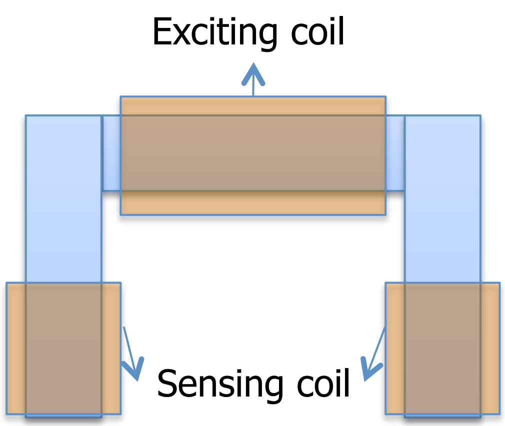
Phase transformation can be clearly observed during controlled cooling experiments.



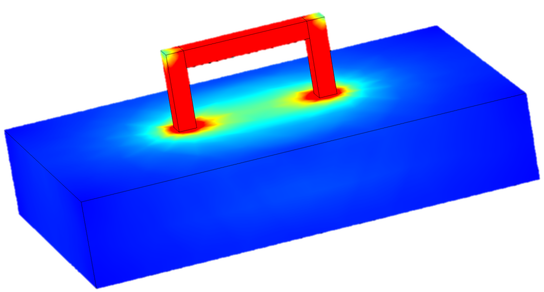
EM sensor output during cooling of 2 ¼ CrMo steel in a laboratory test

Phase transformation monitoring

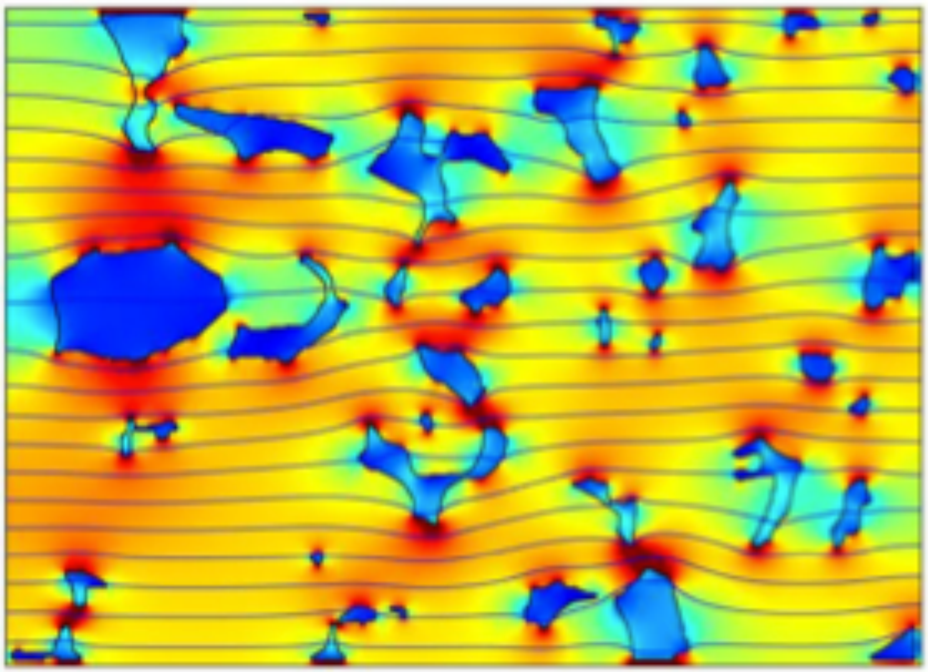
Sensors designed to operate at large (10's mm) lift off and sensor values have been predicted based on transforming microstructure.



EM sensor system



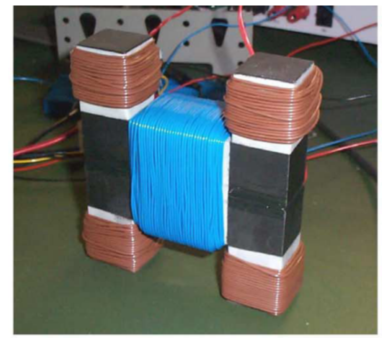
Model of EM sensor and target steel

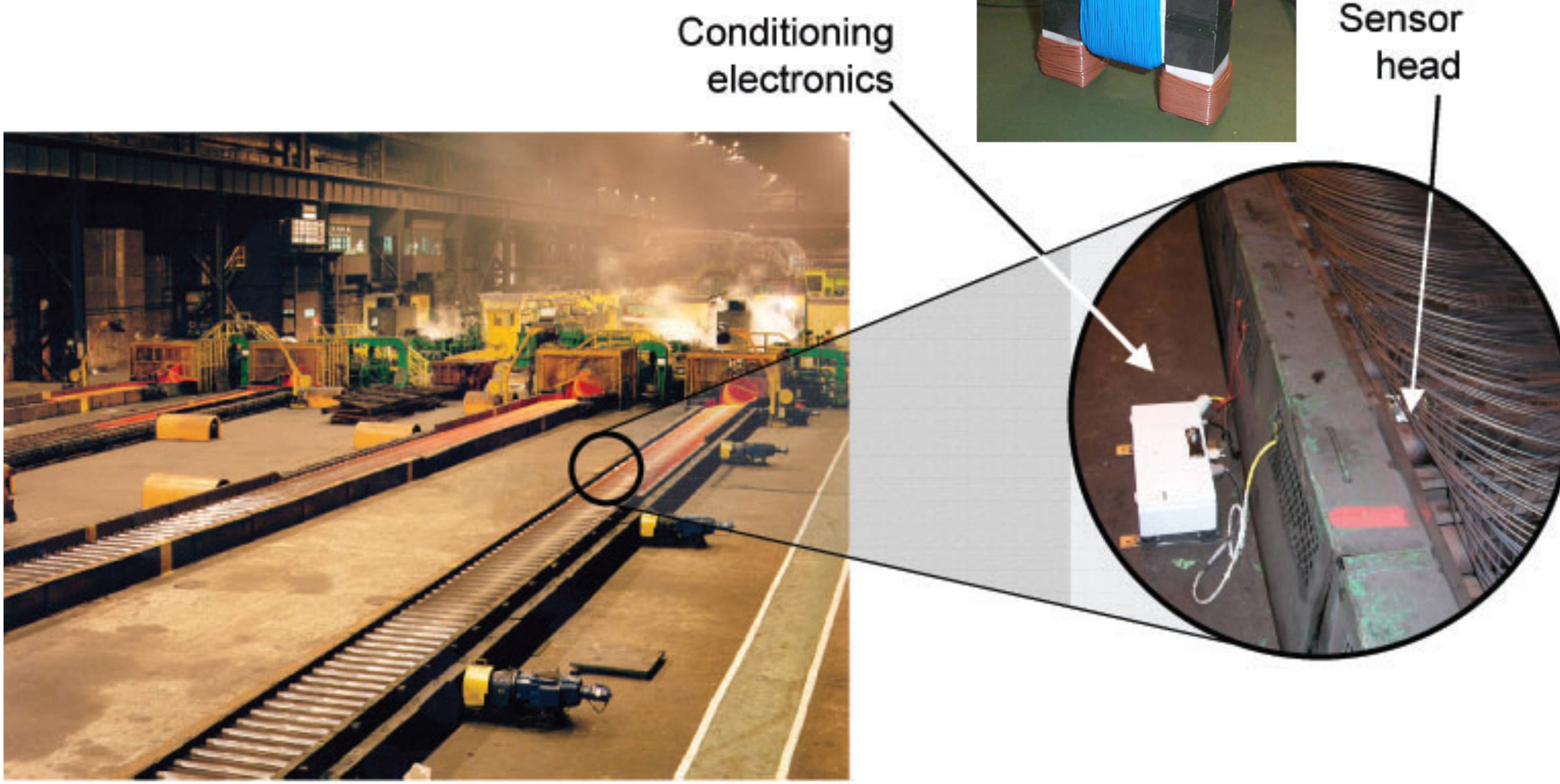


EM model for a given microstructure (magnetic field intensity shown - paramagnetic phase appears blue, magnetic lines of flux shown)

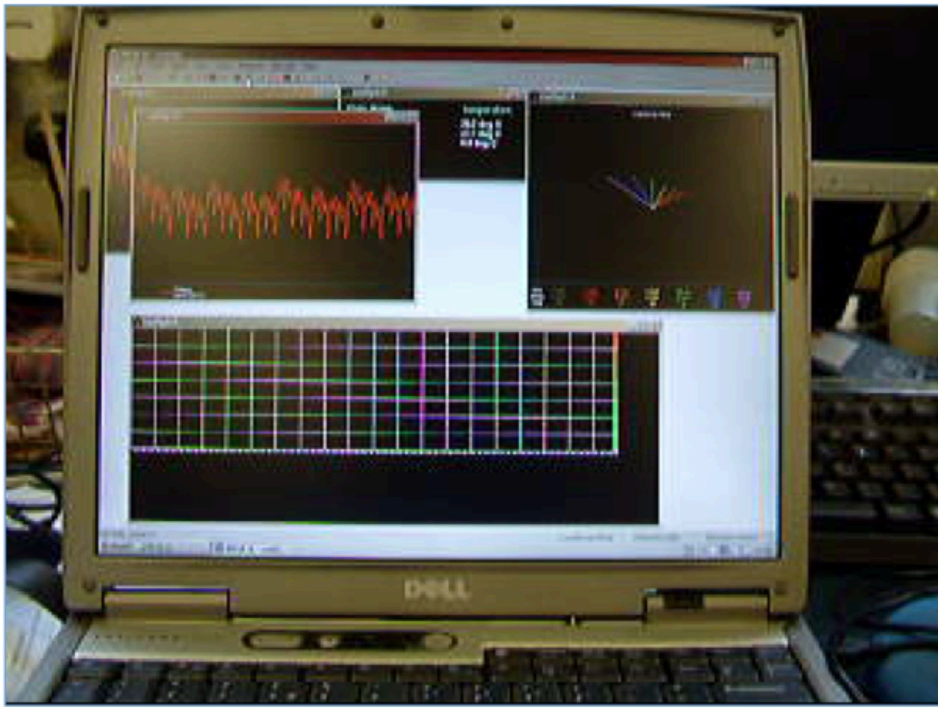
Practical application of EM technology

Installation of EM sensor in the rod mill at Tata Steel Scunthorpe.

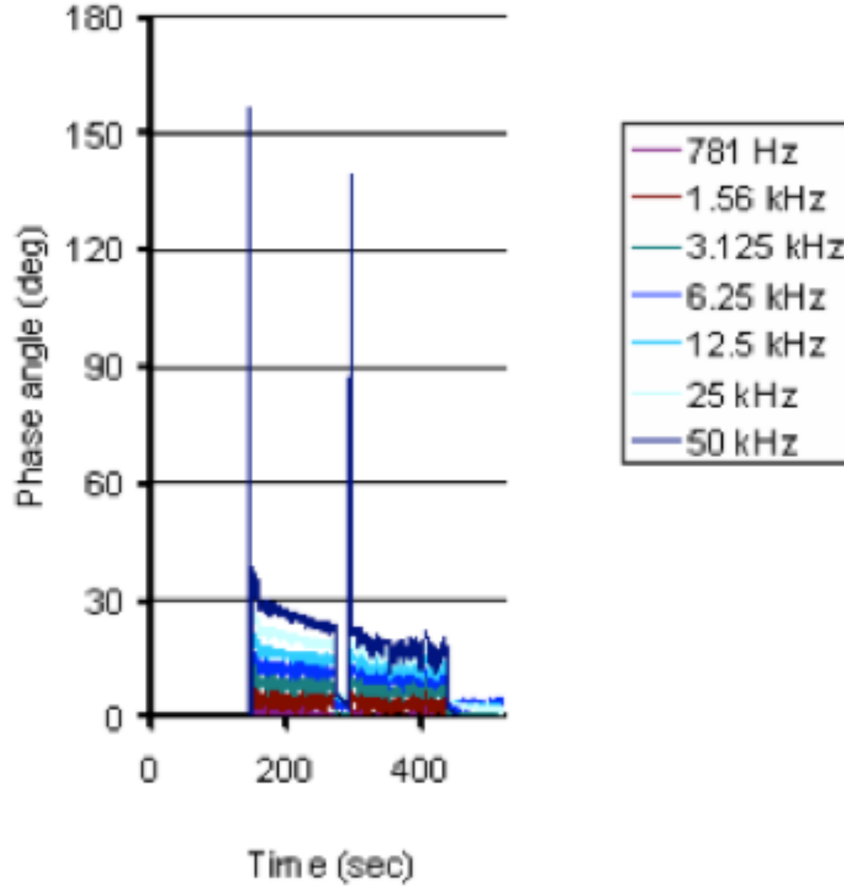




Output from practical application



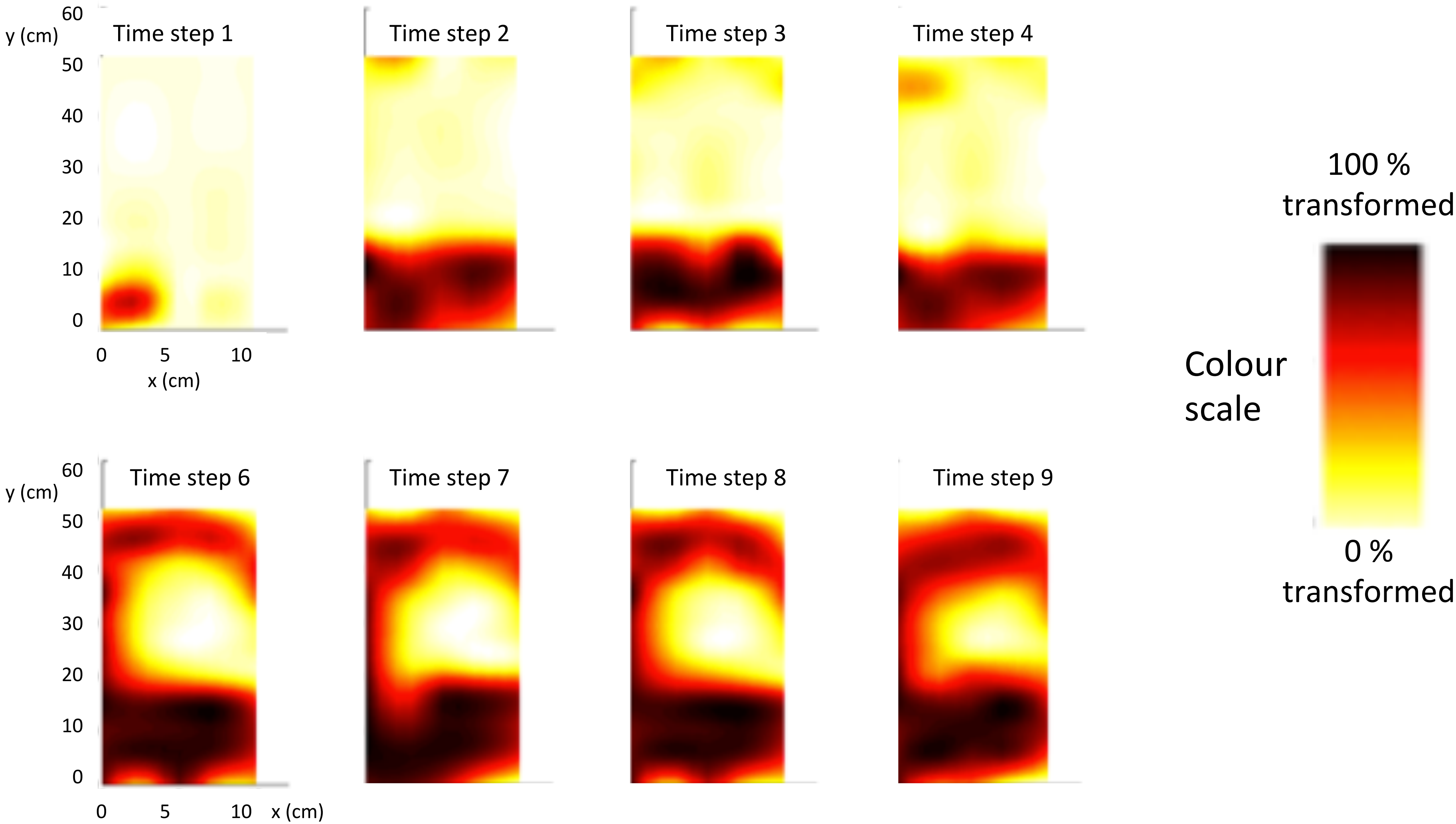
Real time display of phase angle, inductance and phasor values



Phase angle plot for two steel coils (boron steel) showing front of coil is untransformed – high phase angle.

Output from practical application

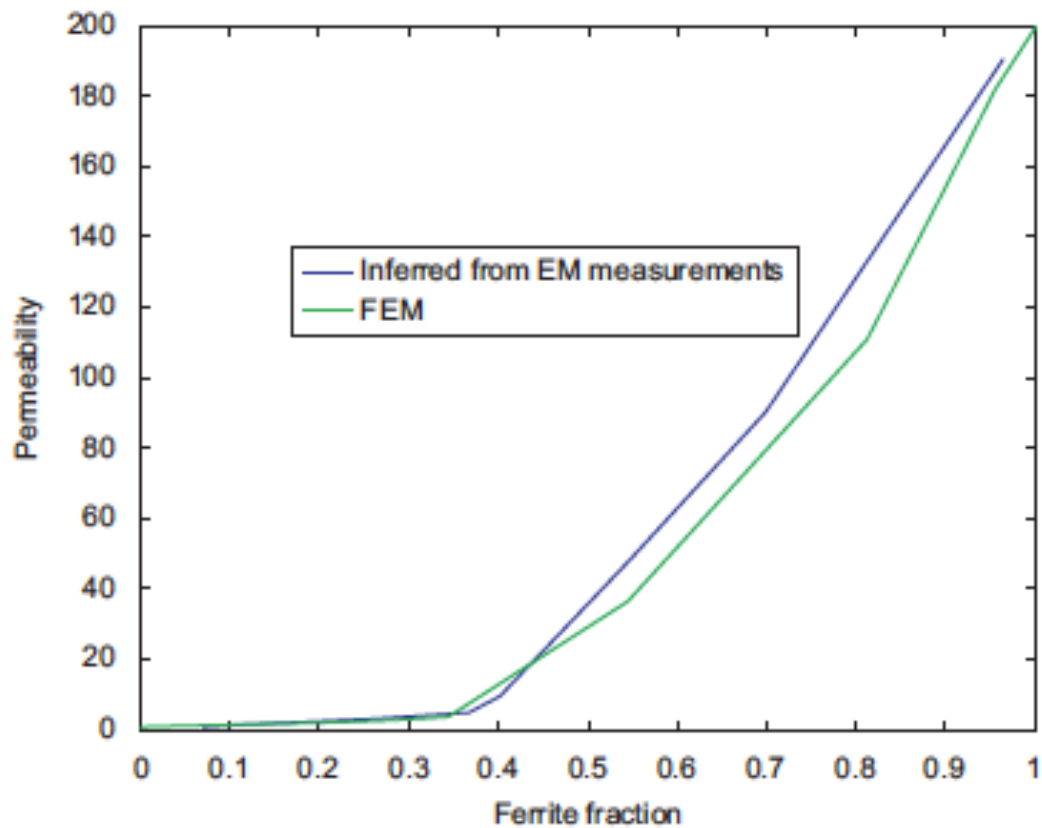
Maps of the progression of transformation for a hot rolled plate held over a sensor array as it cooled (pilot plant mill).



Summary

• On-line systems for phase transformation monitoring are currently being trialed.

• Relationship between sensor signal and phase fraction can be modelled, including taking into account phase distribution.

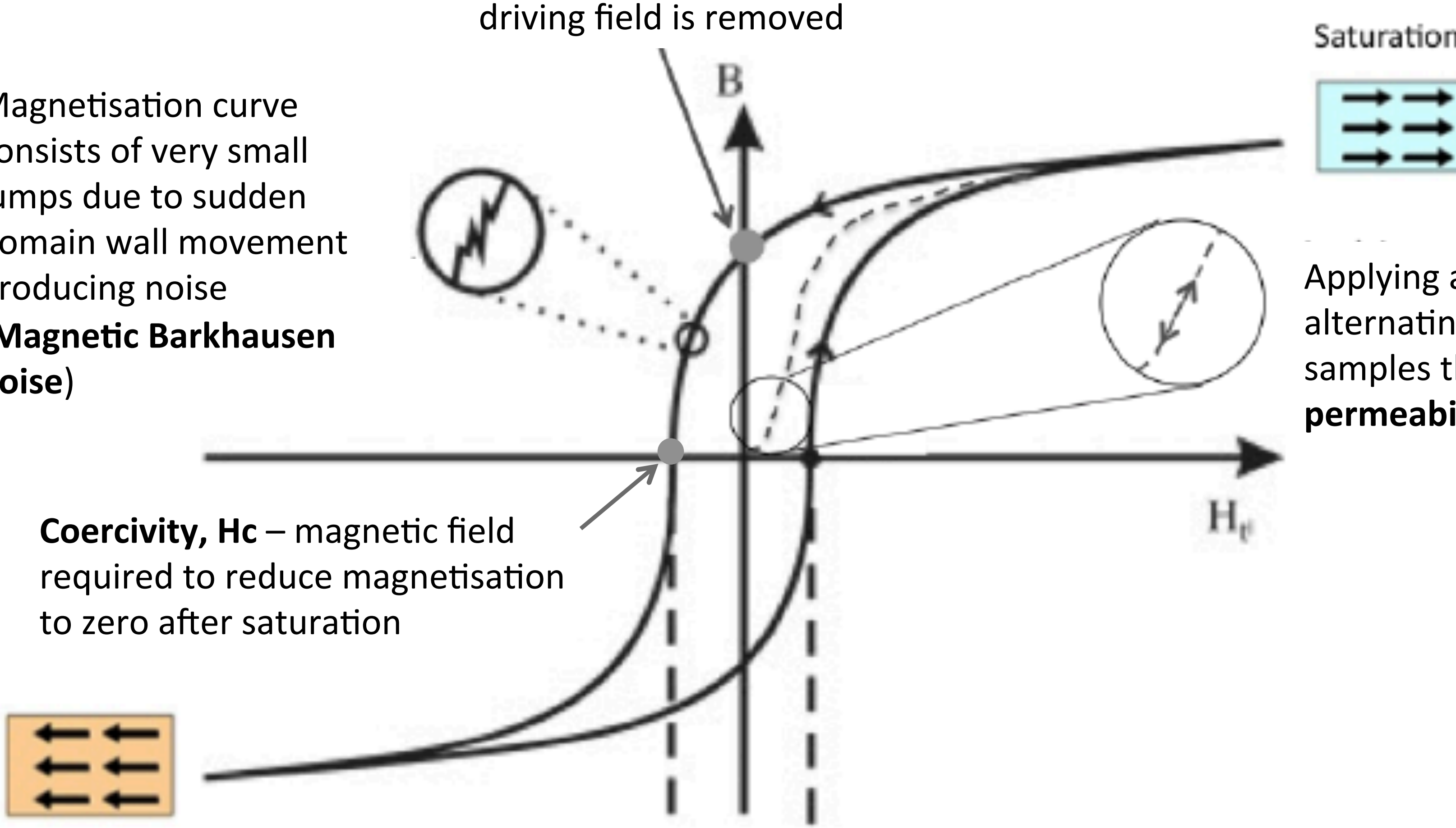


• Future need is for sensor systems for more complex microstructures which requires better fundamental understanding and alternate measurement parameters.

Scientific principles - BH curve

Remanence, Br – a measure of the remaining magnetisation after the driving field is removed

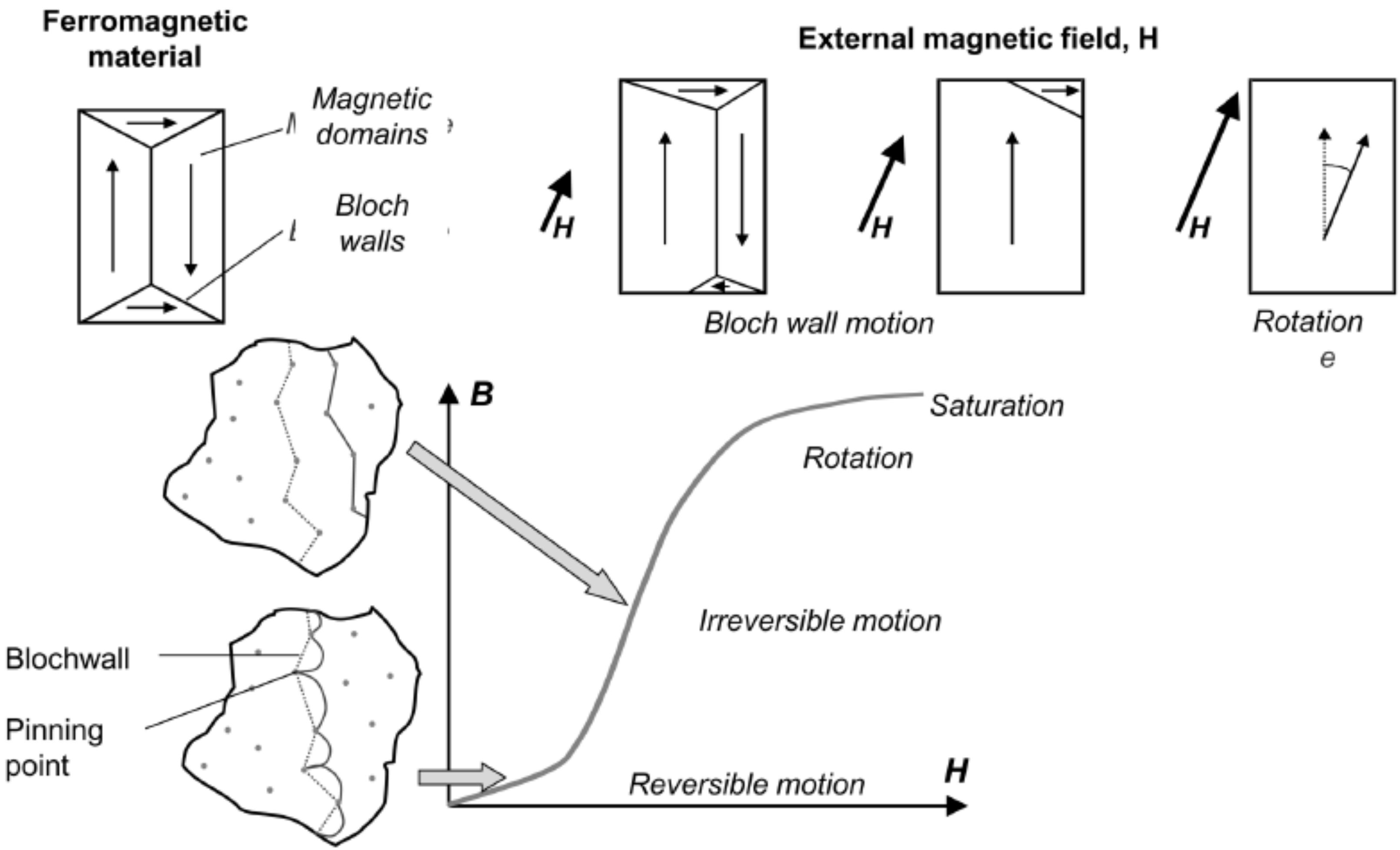
Magnetisation curve consists of very small jumps due to sudden domain wall movement producing noise (**Magnetic Barkhausen noise**)



Applying an alternating low field samples the **initial permeability, μ_i**.

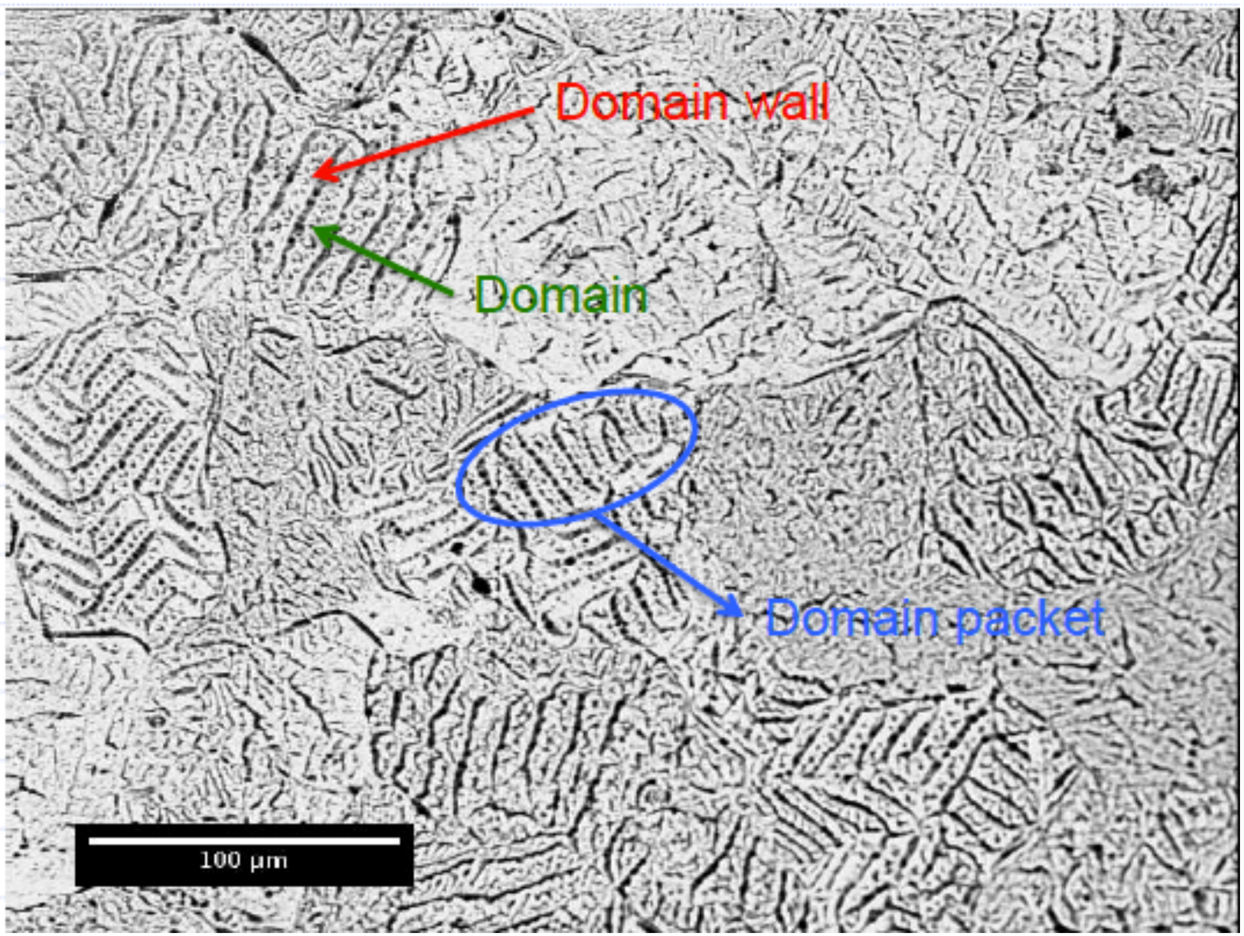
Coercivity, Hc – magnetic field required to reduce magnetisation to zero after saturation

Scientific principles – domain movements



Boller, C., et al., Materialwissenschaft und Werkstofftechnik, 2011. 42(4): p. 269-278.

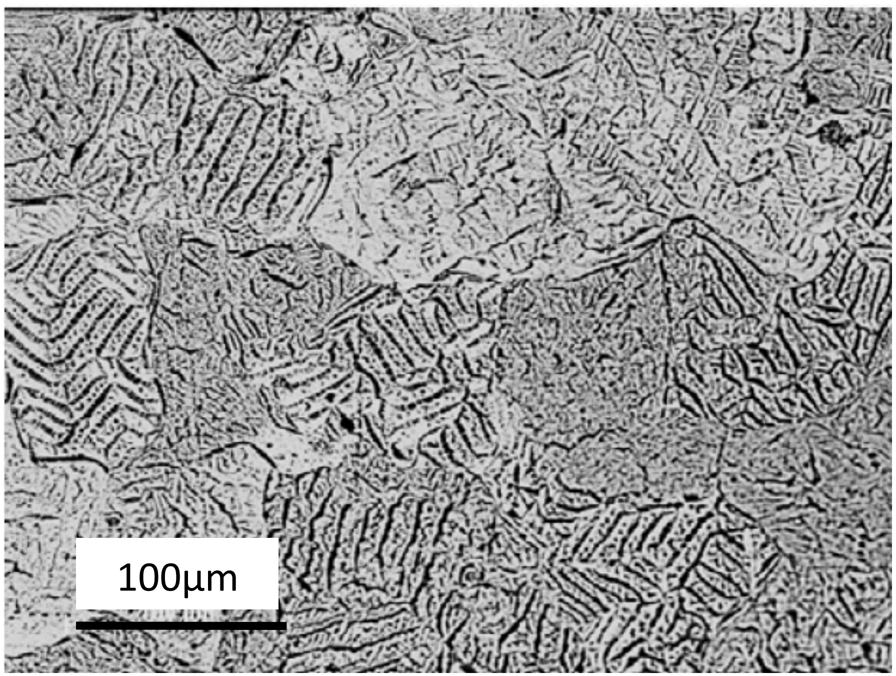
Domain observations in steels



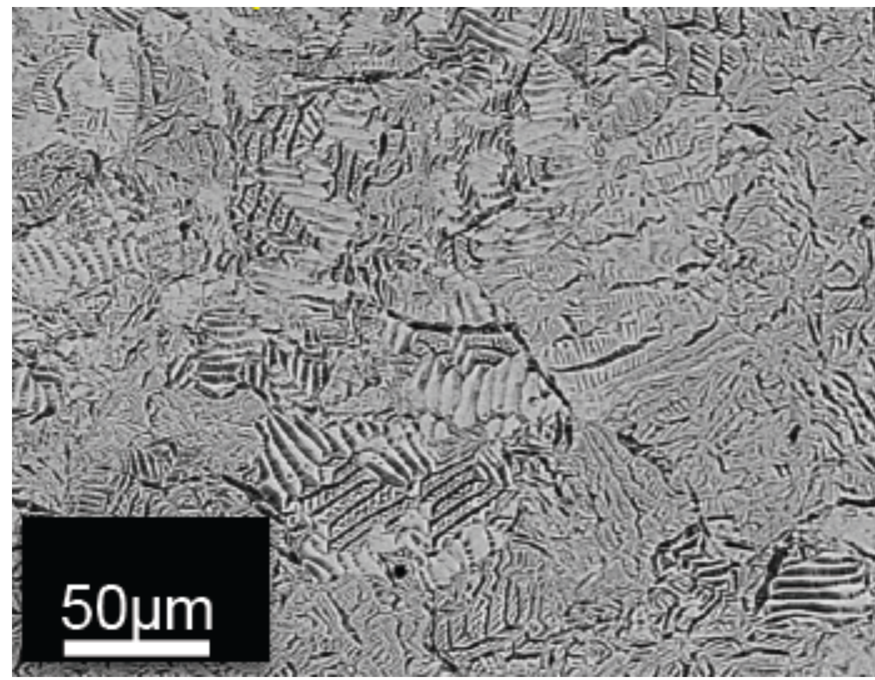
Magnetic domain observations in ferritic steels using ferro-fluid

Relationship between domains and microstructure in steels

One domain packet is observed per ferrite grain …



Pure iron sample, grain size approx 150 µm



Low carbon steel sample, grain size approx 50 µm

Relationship between domains and microstructure in steels

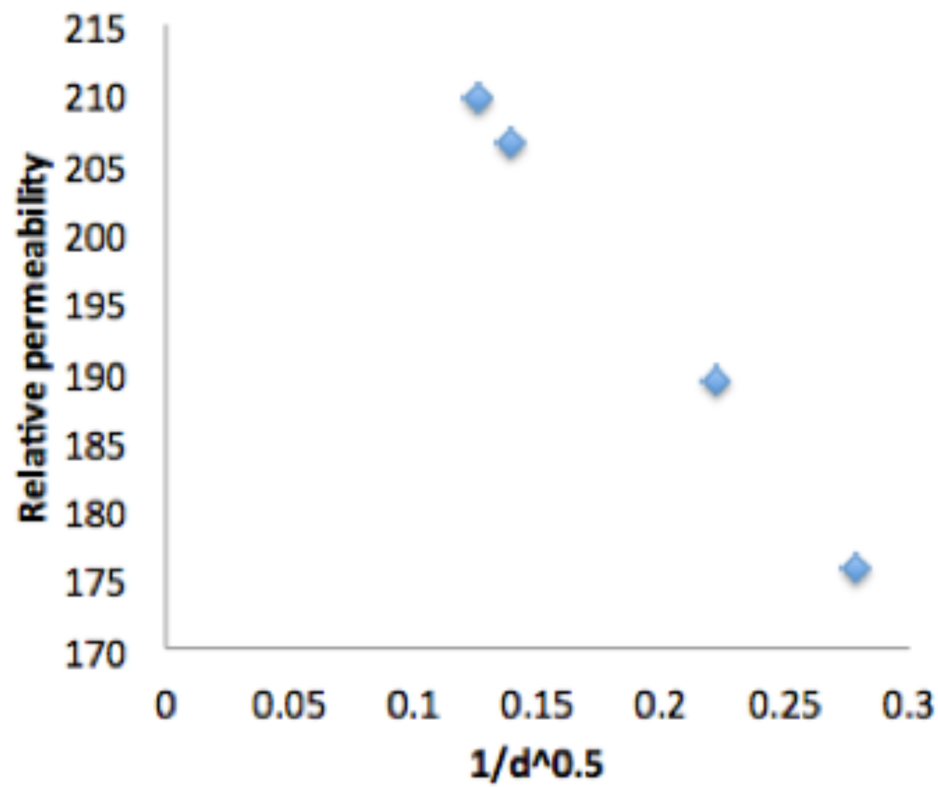
One domain packet is observed per ferrite grain … except at large ferrite grain sizes where multiple domain packets are seen.

Pure iron sample, grain size approx 220 µm

Relationship between domains and microstructure in steels

Materials property of relative permeability is related to the ferrite grain size (in the absence of other microstructural changes) in the regime where each ferrite grain contains one domain packet.

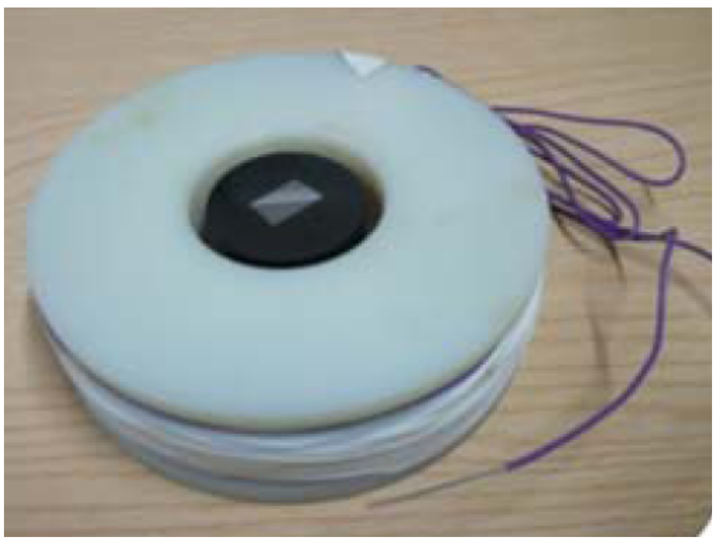
Relationships with other individual microstructural parameters are reported and under development.



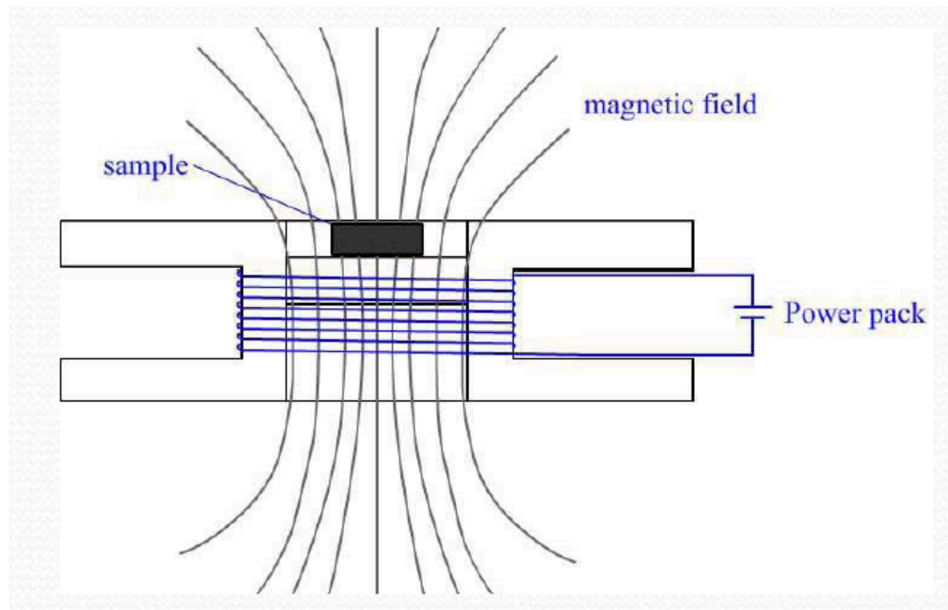
Dynamic observation of domain walls

Application of a magnetic field with in-situ observation using a high speed camera.

The magnetic flux density on the sample is approximately 4.9 - 17.6 mT for an operating current of 2~7A



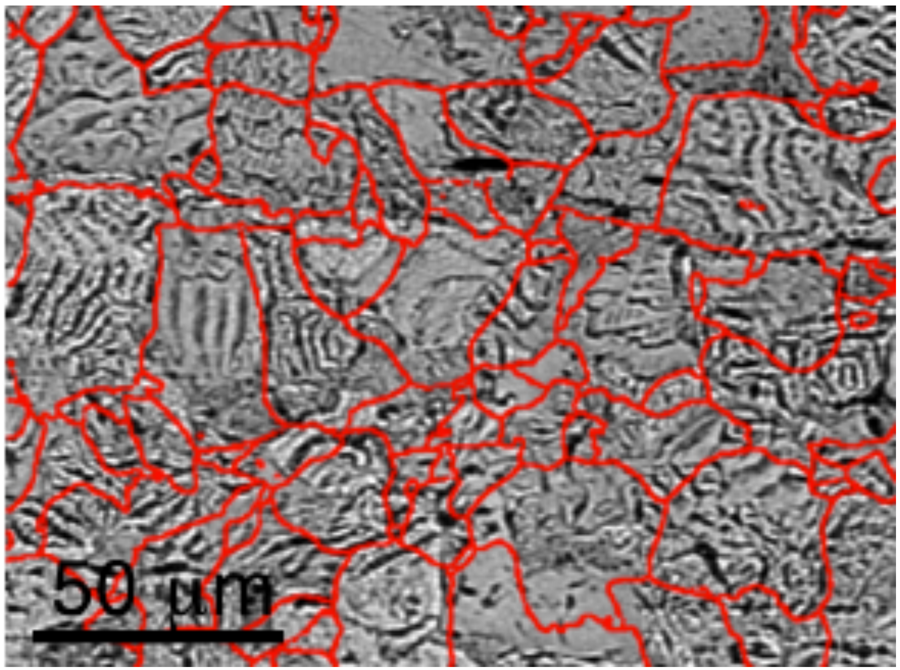
Experimental arrangement



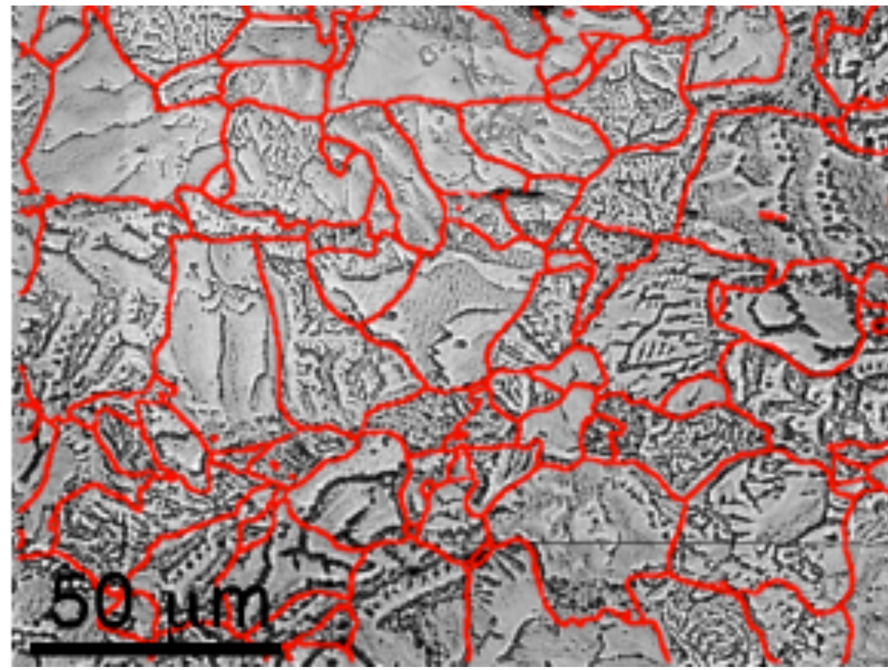
Magnetic field with respect to sample

Dynamic observation of domain walls

Dynamic observations have allowed the relative strength of the pinning points in the domain walls to be observed.



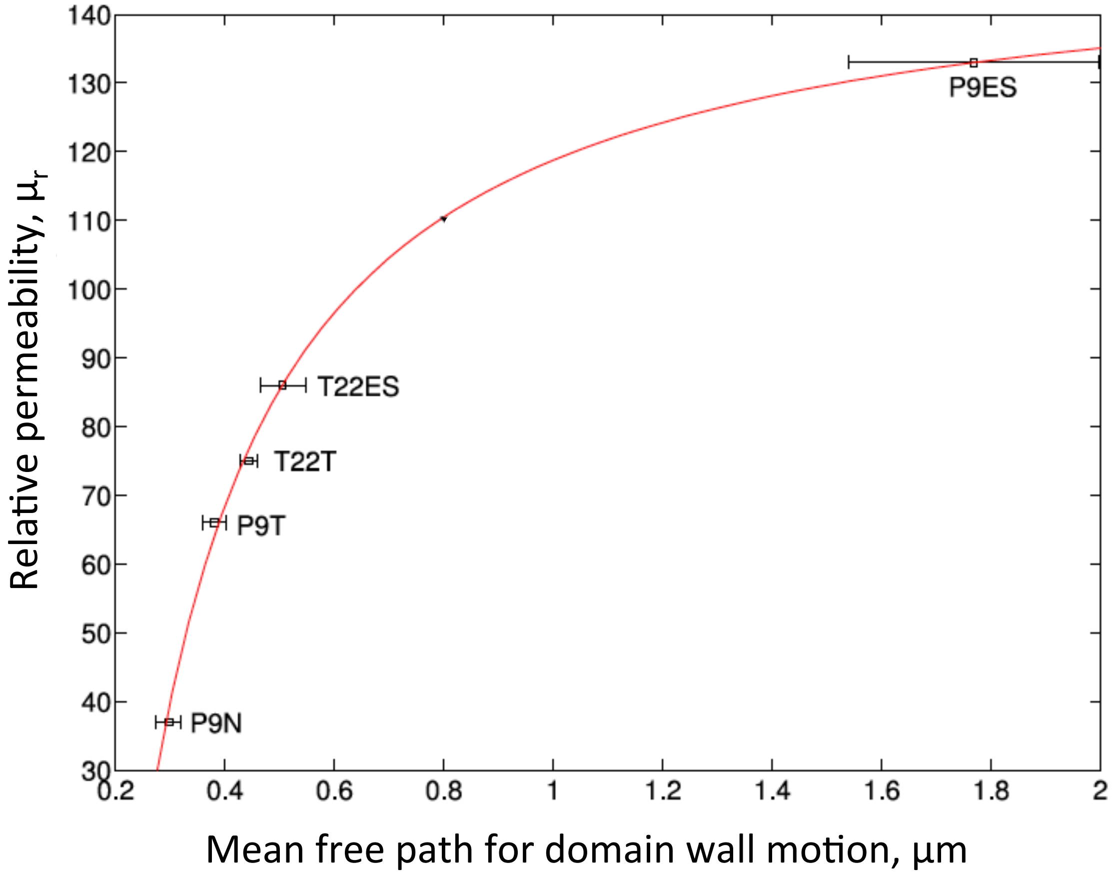
Domain structure and overlaid grain boundaries in the absence of any applied magnetic field for a low carbon steel



Domain structure and overlaid grain boundaries in a strong magnetic field for a low carbon steel

Effective pinning points in power generation steels

For domain wall motion under low applied field (related to the material's relative permeability, μ_r) there is a relationship between the spacing between the pinning points (lath boundaries and / or precipitates) and μ_r.

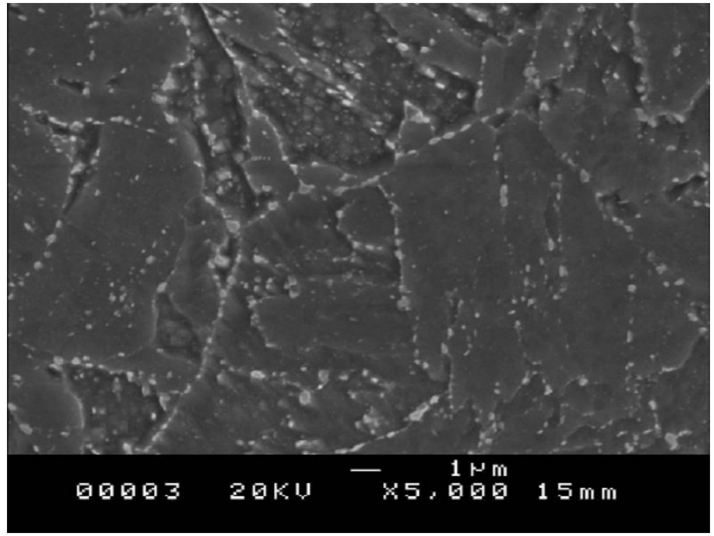


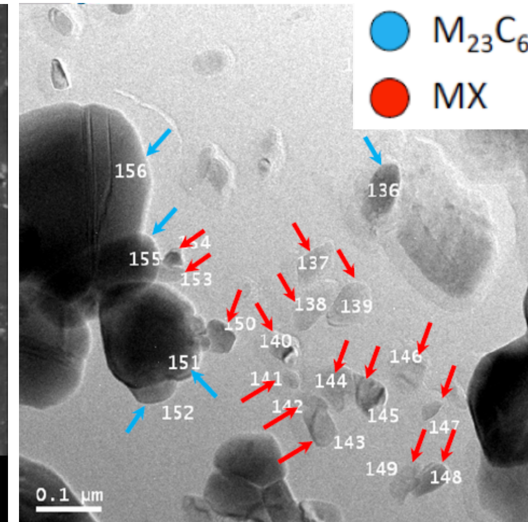
Data for P9 and T22 power plant steels in the normalised (N), normalised and tempered (T) and ex-service (ES) conditions.

Case study for P91 steels

G8 sample

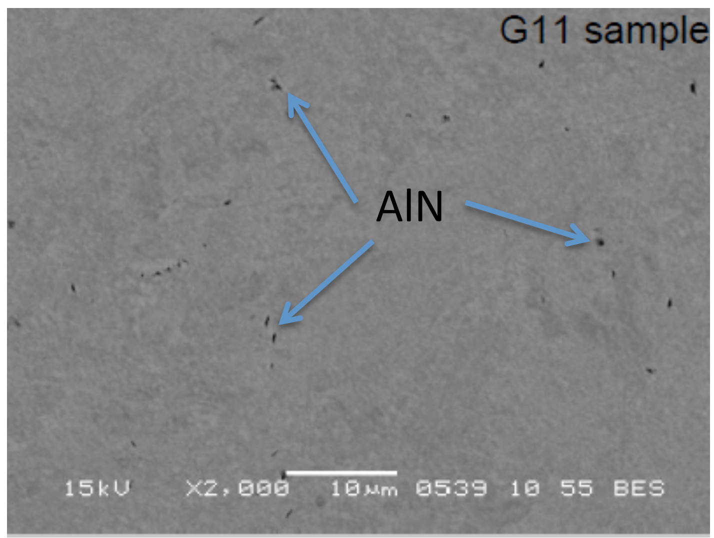
- AlN absent;
- $M_{23}C_6$ on lath boundaries
- High density of MX within laths – reducing mean free path to domain wall motion

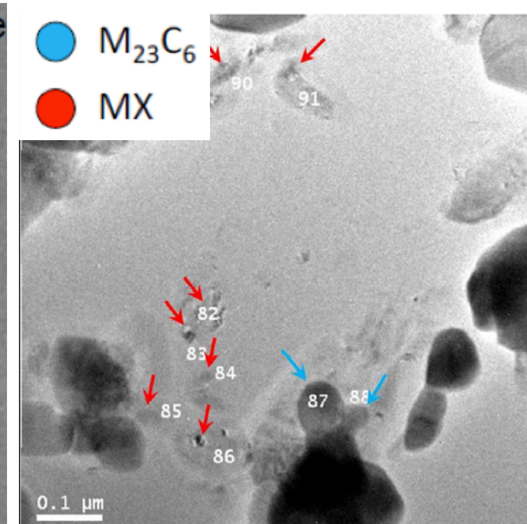




G11 sample

- AlN coarse and widely separated – insignificant pinning.
- Many fewer MX – less pinning

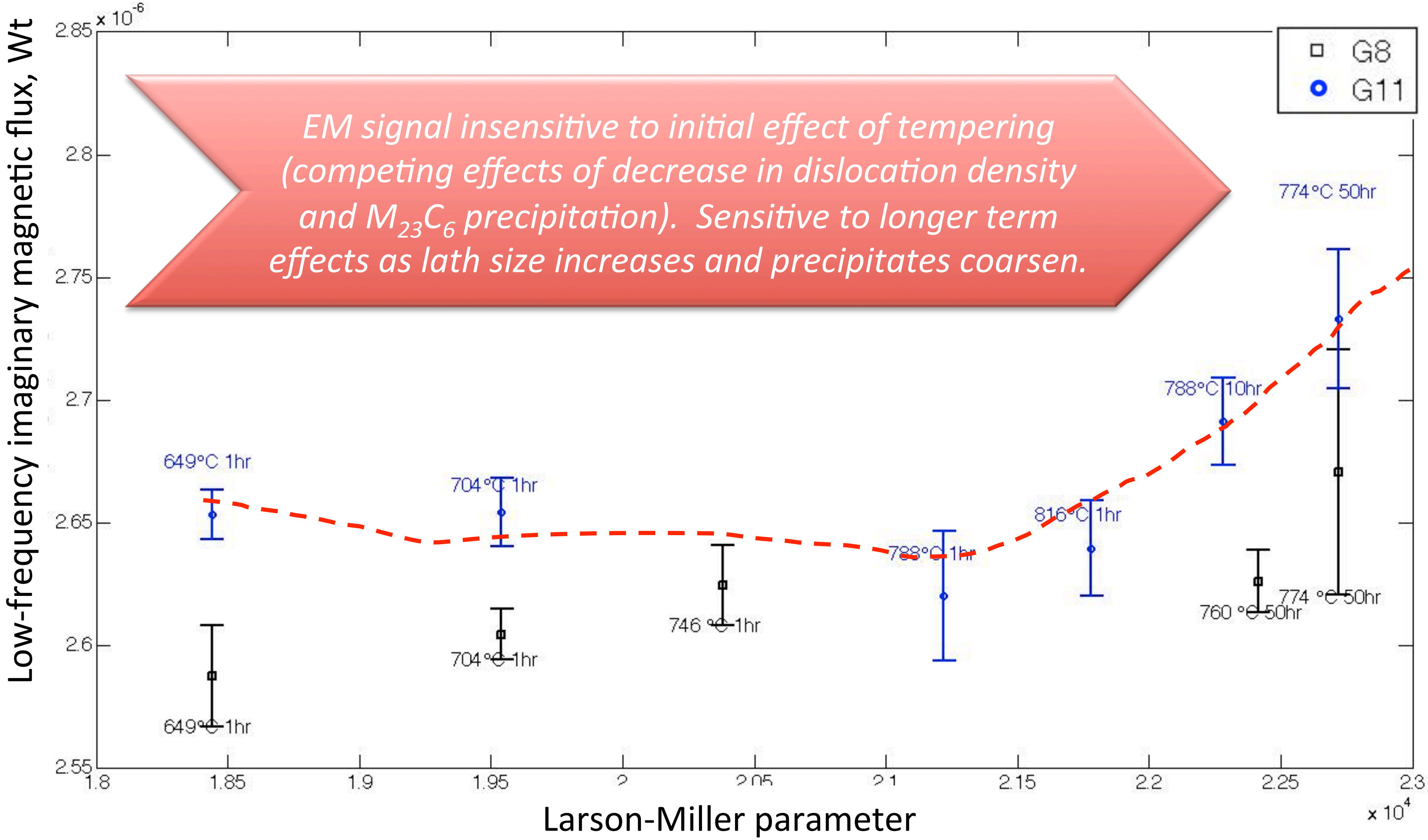




Courtesy of EPRI.

L.Cipolla, Centro Sviluppo Materiali, Italy, June 2010 (internal presentation)

EM testing of P91 steels



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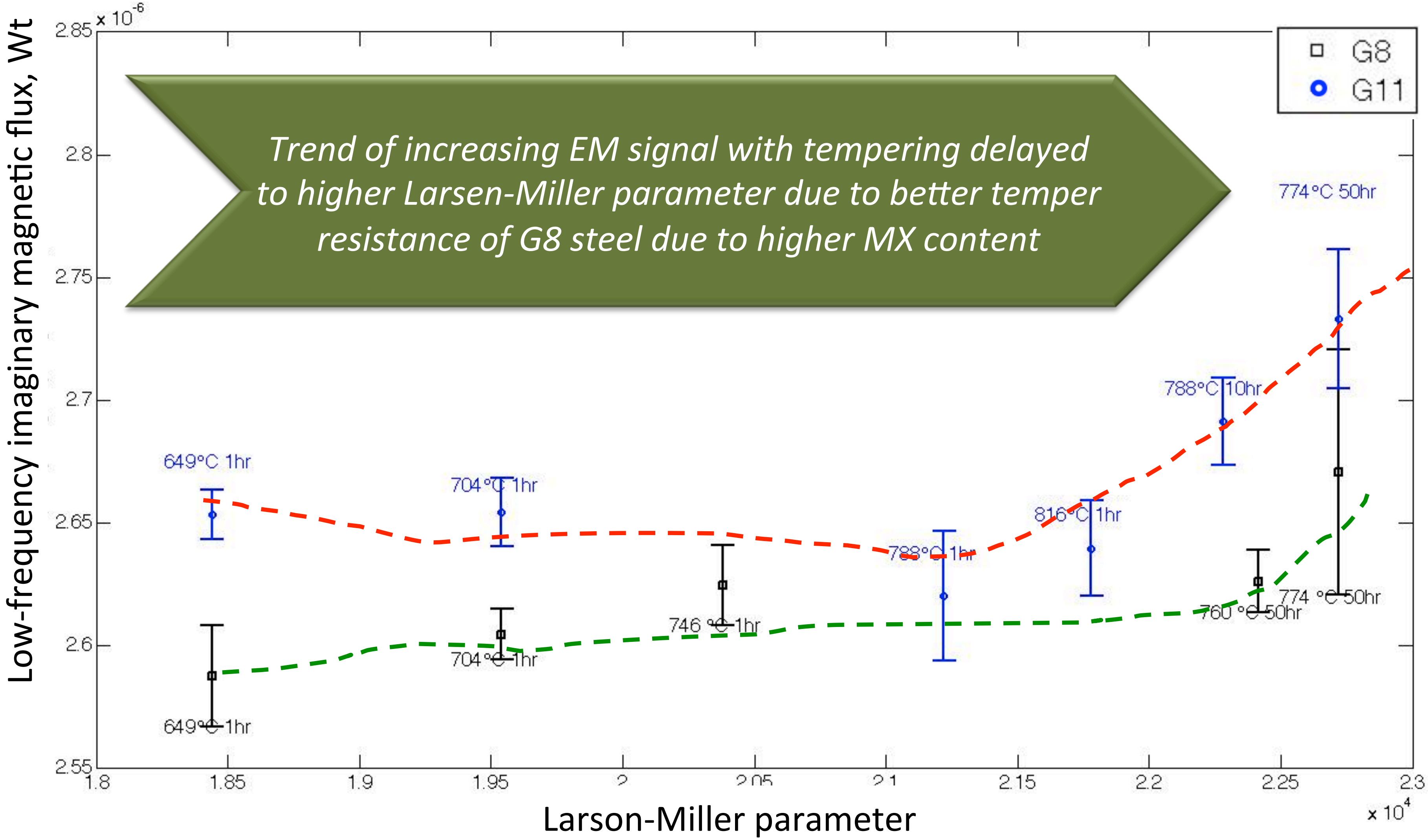

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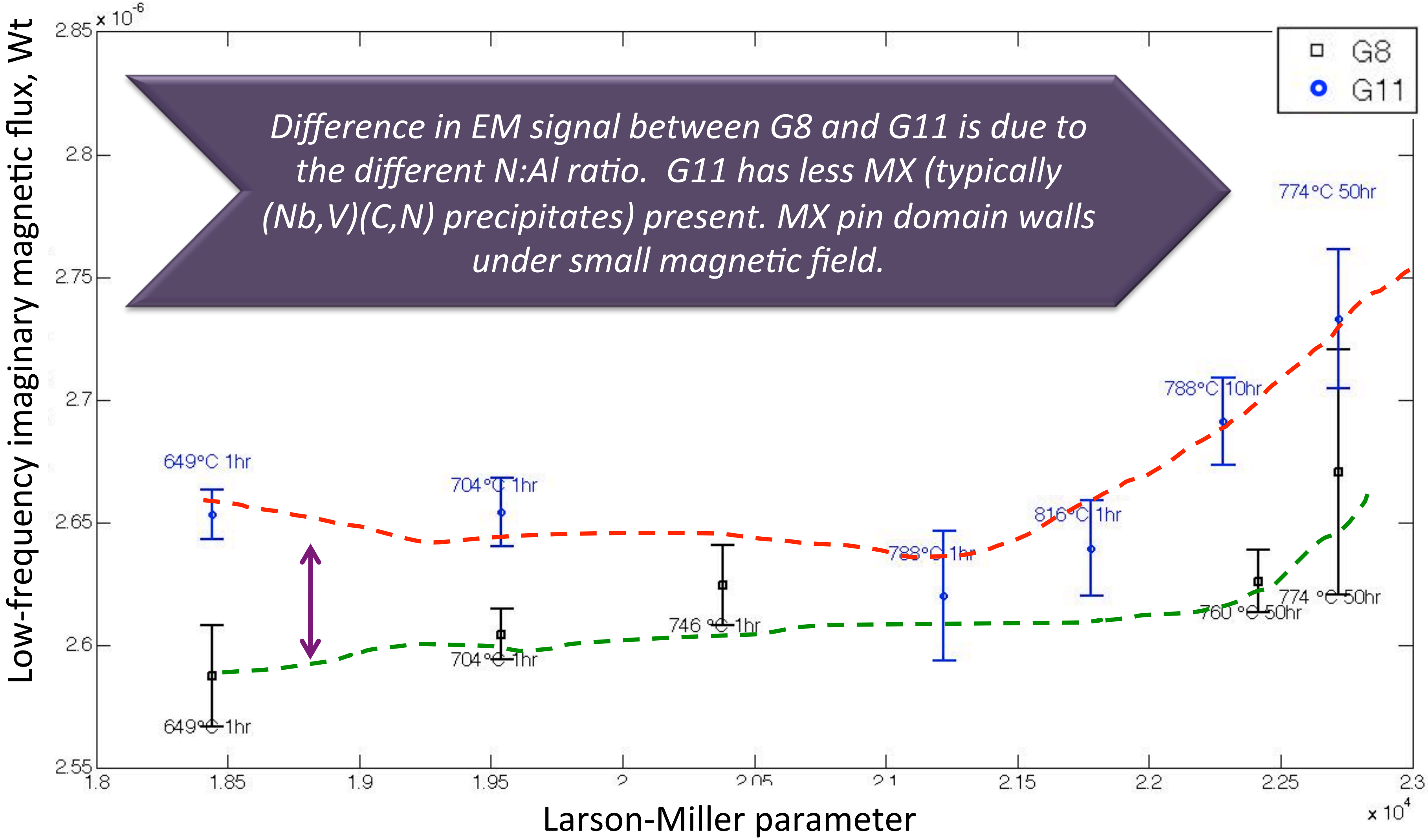
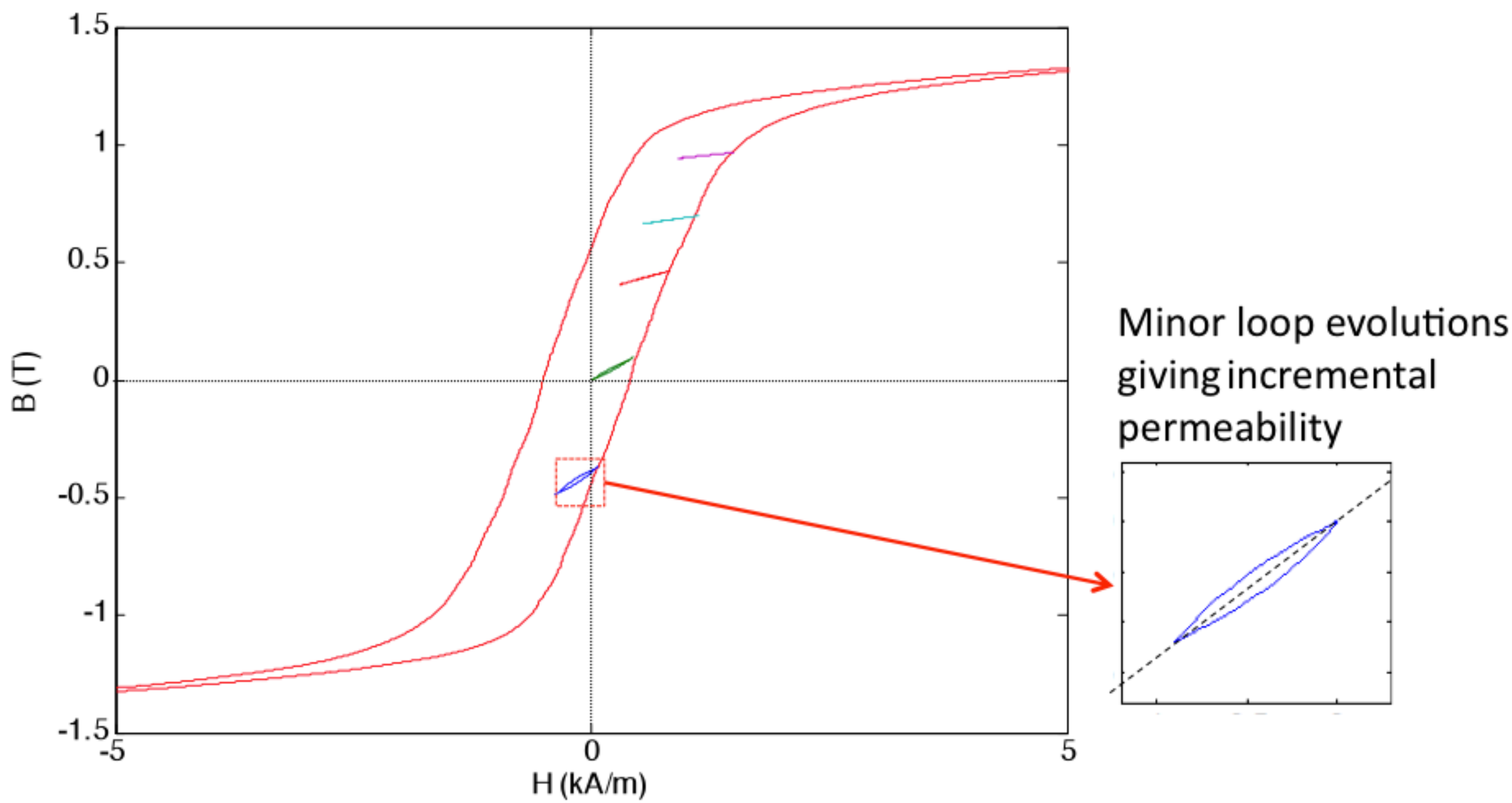


FUTURE - exploitation of magnetic information

Microstructures are complex, therefore a single magnetic property output is insufficient. Analysis of the minor loops on a BH curve should allow much more detailed microstructural characterisation.



Conclusions

- Sensor systems exist for on-line and off-line materials characterisation. However, most systems rely on (semi-) empirical relationships to give a mechanical property or microstructural feature for certain steels.
- Fundamental relationships between specific microstructural features and magnetic measurements exist.
- Using measurements of multiple magnetic parameters using new deployable sensors will allow the characterisation of complex microstructures in the future.

How far can sensors go in replacing metallography and mechanical testing in the future?