Structural and magnetic properties of cast iron for cyclotrons

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- Magnetic measurements
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- Efficiency of heat treatment and internal stress
- Conclusions

Introduction

Context and purpose

- IBA CYCLONE230® cyclotron magnet iron is cast, cooled, roughly machined, annealed, machined, transported, precisely machined, transported, assembled etc.
- The suppression of only one operation = cost reduction by few percent
- IBA: one permeameter to routinely measure the magnetization *BH* curve
  - Quality control related to different certifications
  - Created library allows different studies and analyses
- Istituto Nazionale di Ricerca Metrologica (INRIM), Torino, Italy
  - Optical microscope, Scanning Electron Microscope SEM, Energy Dispersive Spectrometer X-ray Diffraction detector + software tools + highly skilled people
- Let's analyse the cyclotron magnet iron more extensively…

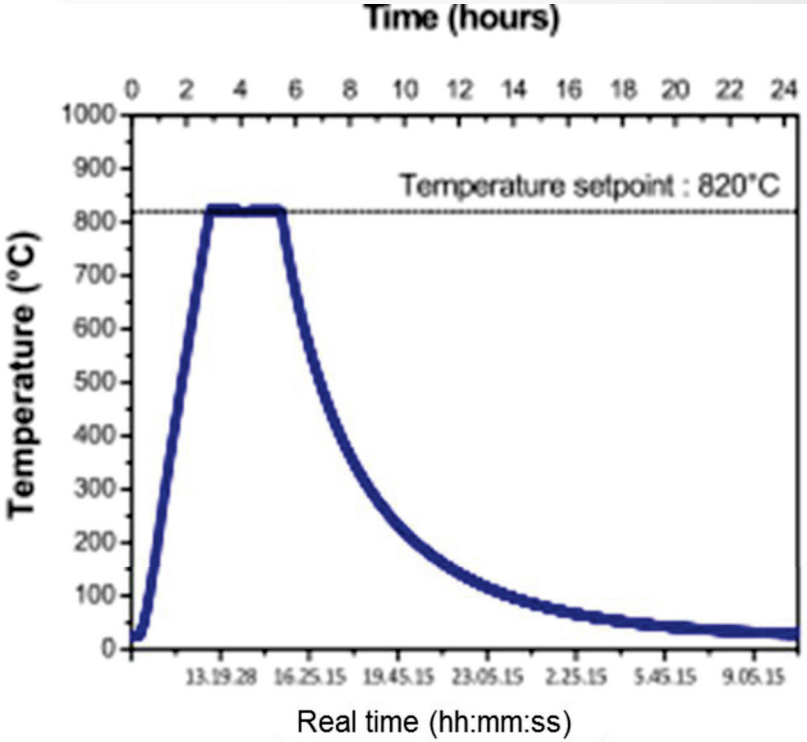
Iron samples

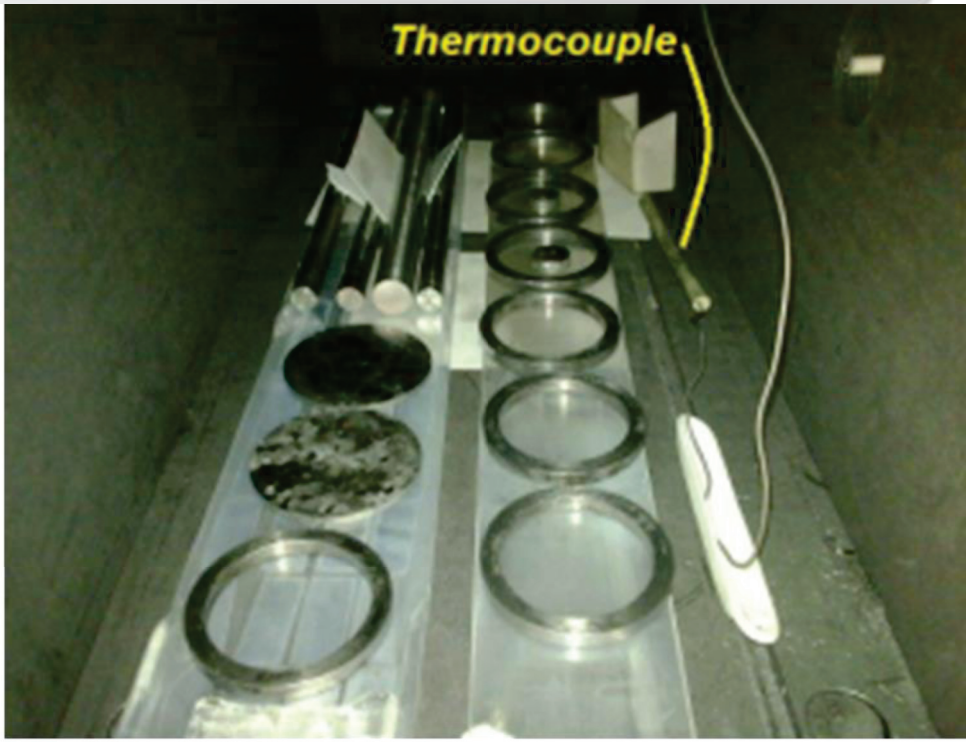
Variety

- Iron castings from the preferred IBA supplier
- Samples additionally treated:
  - thermal treatments:
    - unannealed
    - annealed
  - different shapes
  - surface preparations:
    - as it is = lathe machined
    - ground, polished and cleaned
    - etched or unetched

Thermal treatment

Annealing



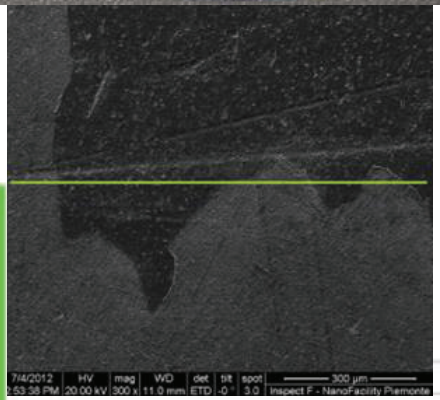


- Annealing temperature profile and samples in the oven chamber

Investigations of the microstructure

Grain size and measurement problems

- 50 mm diameter, etched disks from different castings
- Intersections between grain boundaries and arbitrarily selected test lines give
  - the average intercept length $\overline{x}$
  - standard deviation σ



- Observations using an optical microscope and an SEM
- Irregularly shaped large grains and inclusions of impurities produce:
  - multiple intersections with an arbitrarily selected test lines
  - underestimate of average intercept length

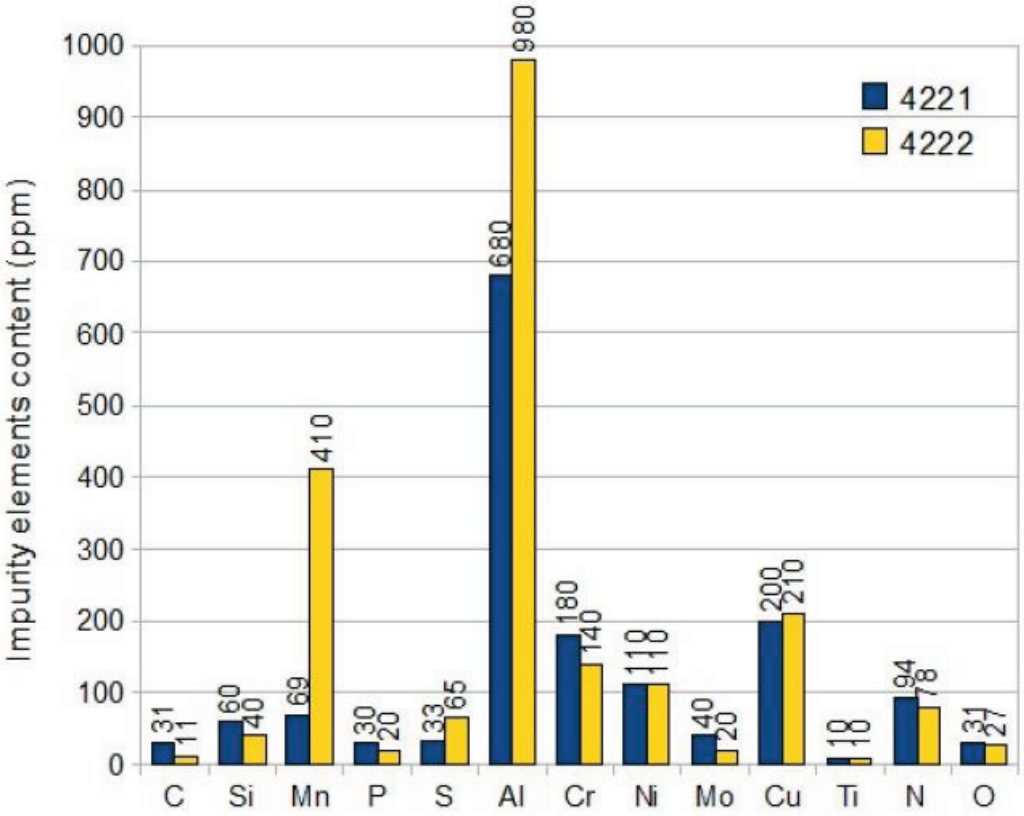
Investigations of the microstructure

Grain size

- The average intercept length $\overline{x}$ is related to the grain size
- The relation $\sigma >\approx \overline{x}$ indicates the large variation in the grain size
- 0.77 mm < $\overline{x}$ < 1.52 mm, x_{max} = 8 mm; 0.84 mm < σ < 1.64 mm
- No changes observed between the as-cast state and the fully annealed state
- Conclusion: The heat treatment does NOT produce:
  - recrystallization in samples
  - grain growth in samples

Investigations of the microstructure

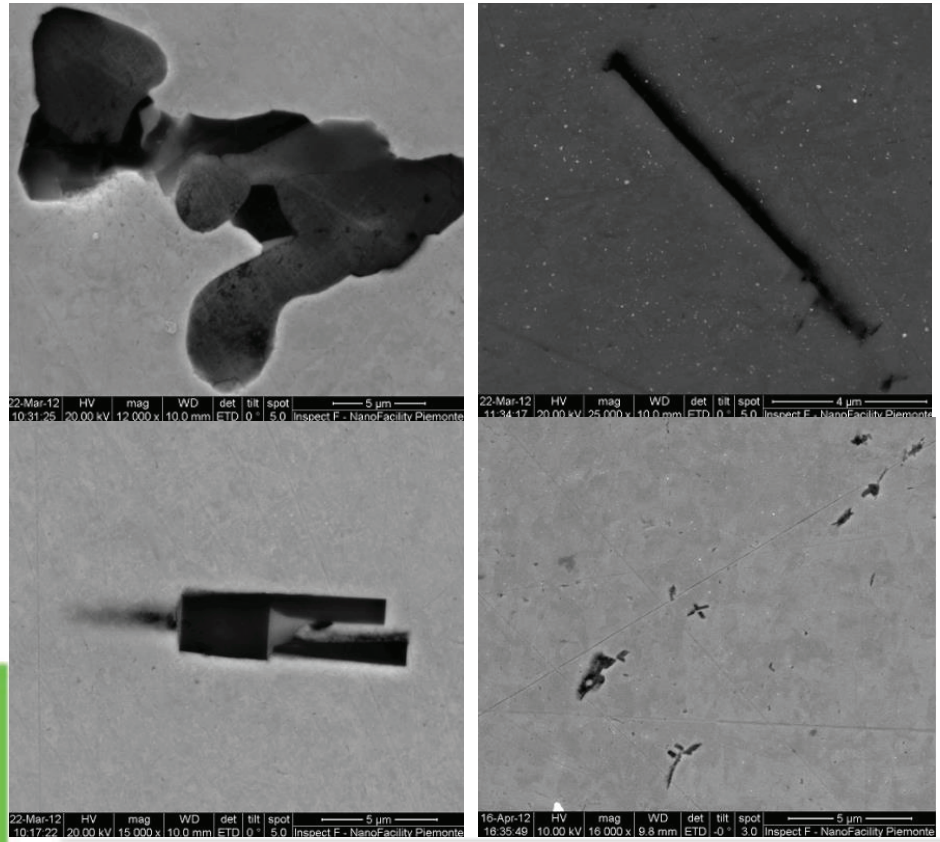
Chemical composition of impurities



- The chemical composition of the cast iron provided by the supplier
- The impurity content independently determined using an EDS X-Ray Diffraction detector
- EDS XRD analysis regularly detected chemical compounds:
  - AlN – aluminum nitride
  - MnS – manganese sulfide
  - Al_2O_3 – aluminum oxide
- Agglomerates of any 2 or all 3 compounds created most of inclusions

Investigations of the microstructure

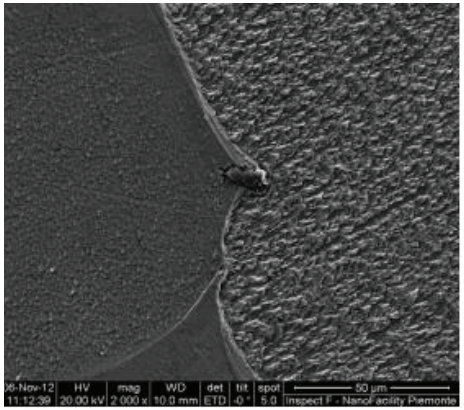
Examples of inclusions in unetched samples

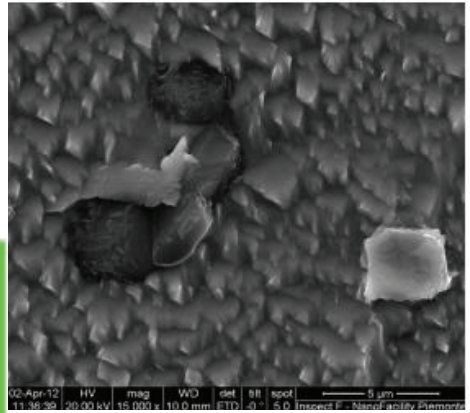


- Unetched samples
- Agglomerates of irregular crystals (different compounds)
- Sharp edge crystal agglomerates
- Bar monocrystal or multicompound agglomerates
- Cross-shaped crystals

Investigations of the microstructure

Examples of inclusions in etched samples



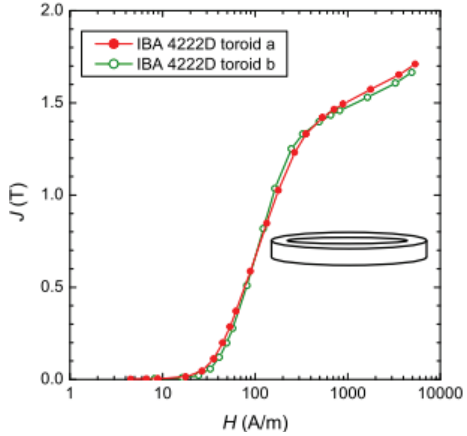


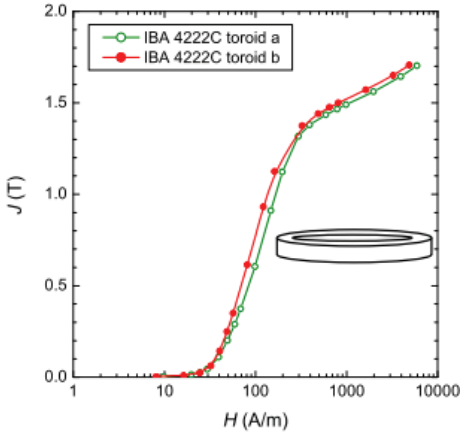
- Inclusions at the grain boundary or within the grain are better revealed by etching
- Surface differences and the strong hardening are observed due to machining in the layer up to 100µm
- Conclusion: After removal of a work-hardened layer there is not any difference between samples as-cast and samples after thermal annealing

Magnetic measurements

Ring samples

- The point-by-point « ballistic » method and the continuous hysteresisgraph measurements used

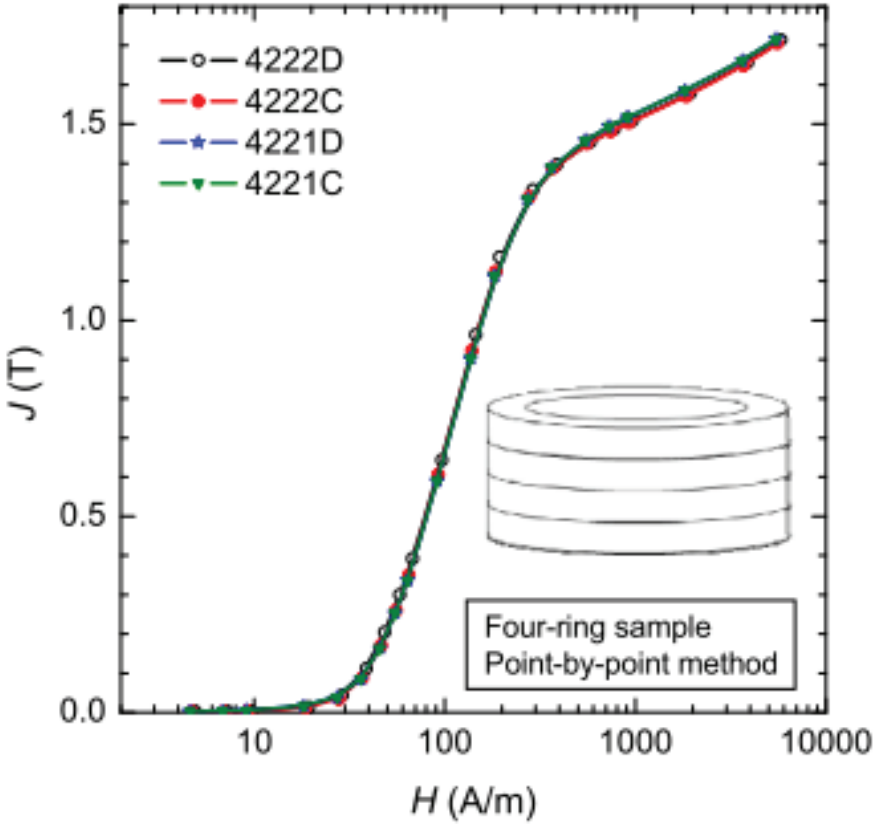




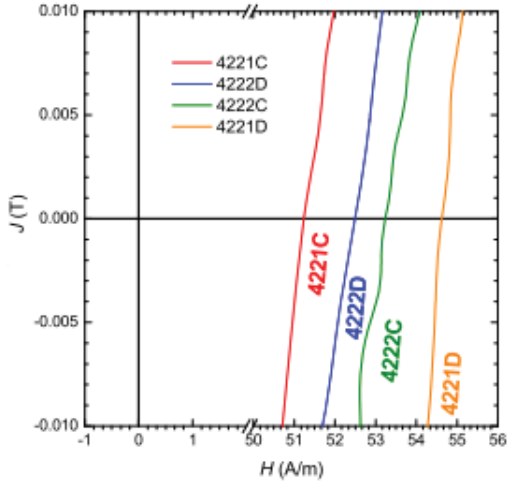
- For one ring sample, a lack of reproducibility of the hysteresis curve is observed due to coarse grain structure

Magnetic measurements

Ring samples

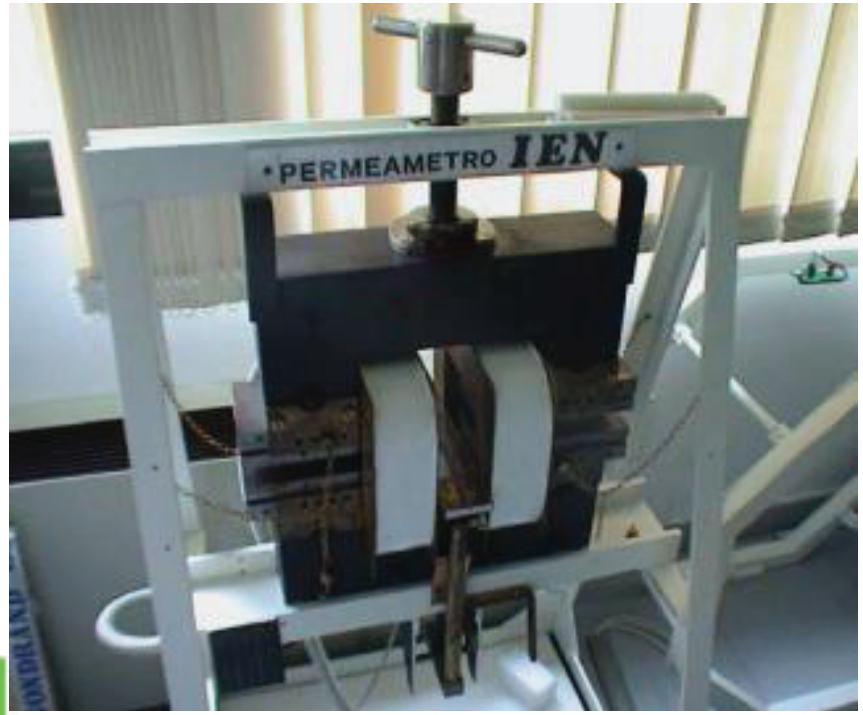


- Grouping (stacking) of the ring samples from the same batch and location produces nearly identical hysteresis curves
- Coercivities between 51-54 A/m observed after grouping



Magnetic measurements

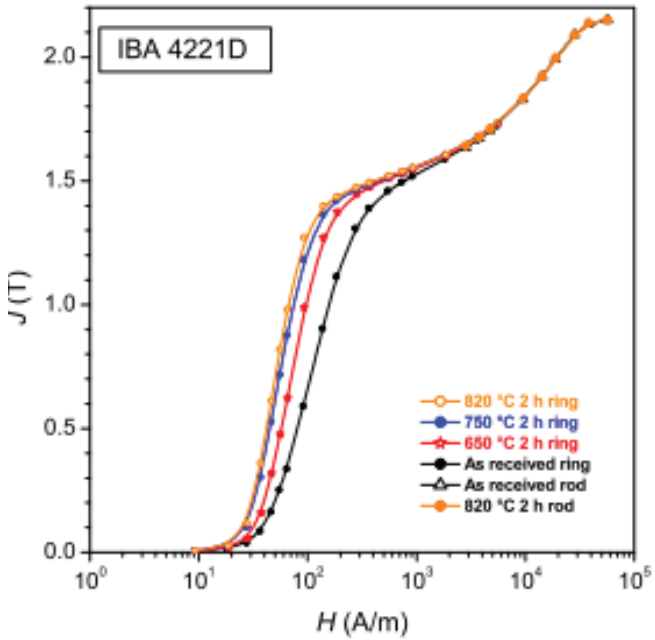
Rod samples – experimental set-up

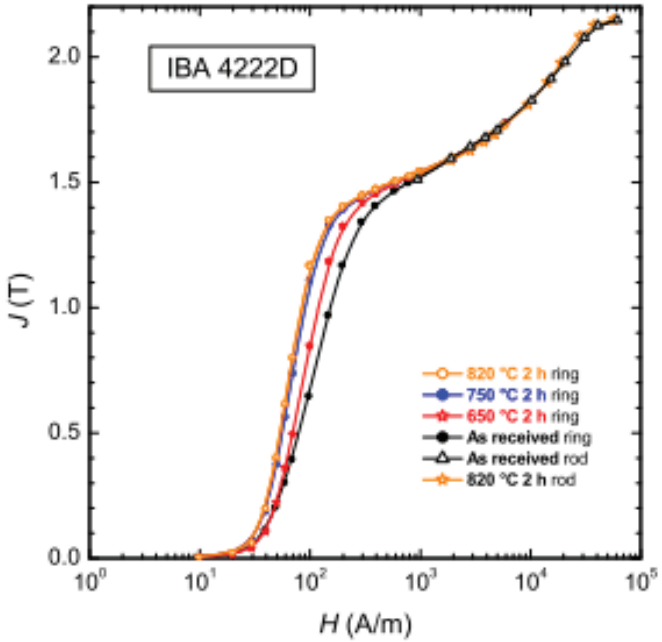


- Permeameter set-up
- The coarse grain structure produced important differences in the hysteresis curve at different points along the rod
- Averaging with respect to rod segment length was necessary
  - Magnetic flux measured by over the central 30 mm segment of the rod
  - Three Hall probes at different positions over 30 mm segment
- Chemical etching slightly reduces magnetic response at low magnetic field intensity *H*

Magnetic measurements

Magnetization and annealing temperature

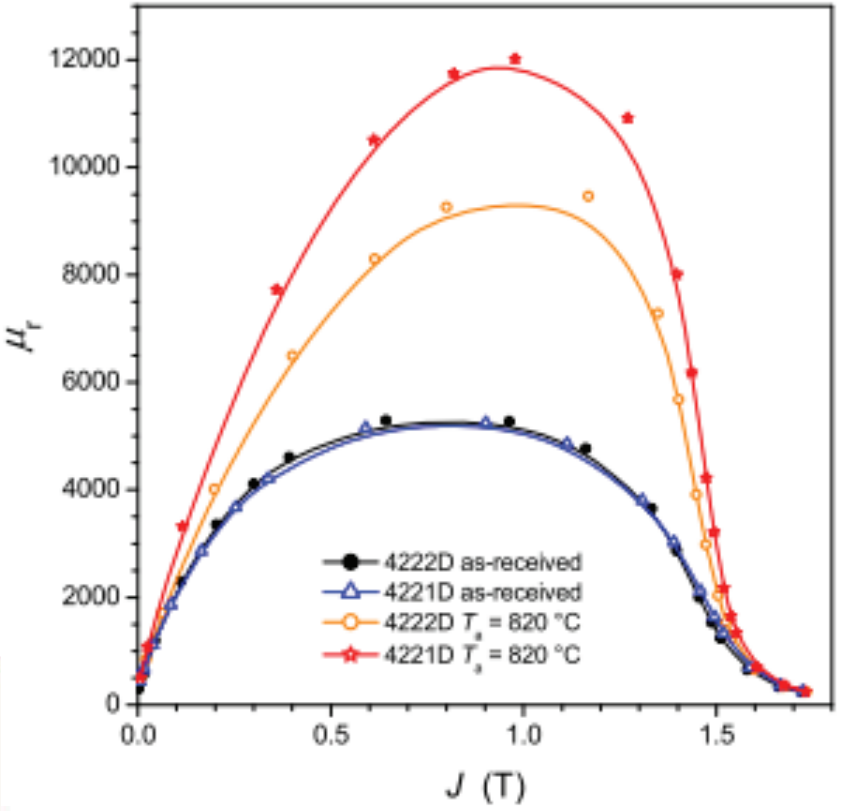




- Magnetization curves for different annealing temperatures, different sample types and locations

Magnetic measurements

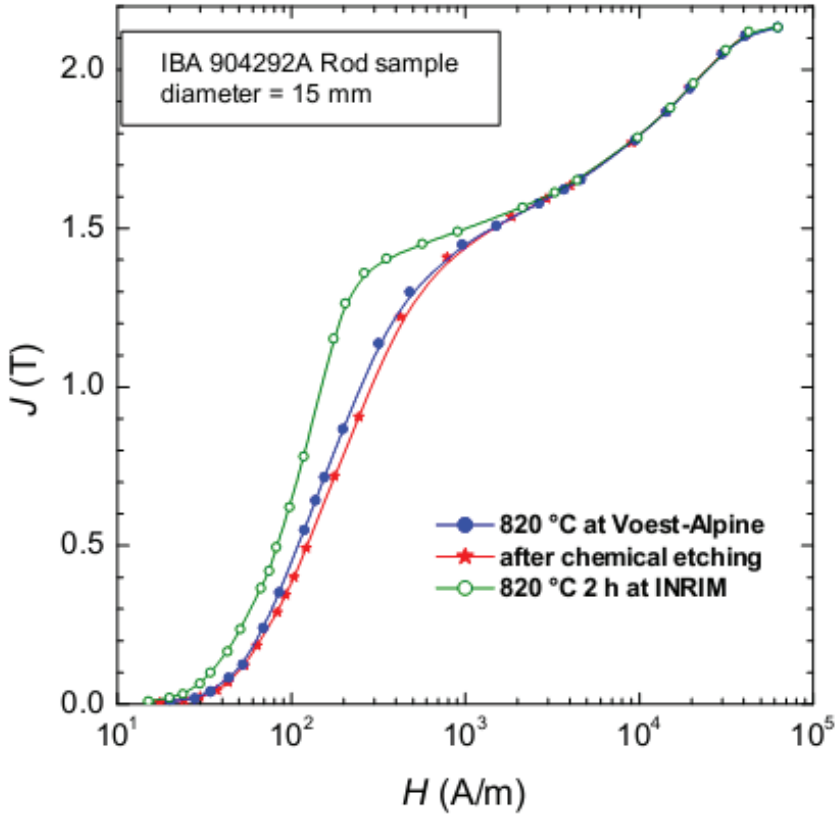
Magnetization and annealing temperature



- The relative permeability μ_r increases with annealing temperature
- All magnetization curves are unaffected by annealing for the magnetization
  $J = B - \mu_0 \cdot H > 1.6$ T
- The increase of the relative permeability is interesting for production of IBA PET cyclotron magnets where acceleration of negative ions requires lower fields
- Unfortunately IBA PET cyclotrons are produced from laminated and/or forged iron slabs

Efficiency of heat treatment and internal stress

Re-annealing has an effect



- Annealing at 820C effectively releases the stress probably accumulated during non-uniform cooling of cast iron
- Re-annealing in the lab typically has the same effect as on non-annealed sample

- IBA protontherapy C230 cyclotron has a magnetic field induction $B > 1.75$ T in the machine center
- Therefore reannealing is practically without significant effects for C230

Conclusions

Summary

- Thermal annealing as performed up to date:
  - No effects on the grain size. The grain size already big for « as cast » iron
  - No migration of inclusions, no shape change of inclusions, no changes of directional orientation of inclusions and a good chemical composition confirmed
  - Iron softening observed on magnetization curves but only at magnetic fields induction *B* below 1.6 T.
  - Modest effects due to the annealing performed by the iron supplier
- The annealing treatment of the iron cast for CYCLONE230® cyclotrons can be suppressed in the future without significant changes of iron quality
  - Reduced cost of production
  - The know-how gained for other and future IBA cyclotrons…

Thank you