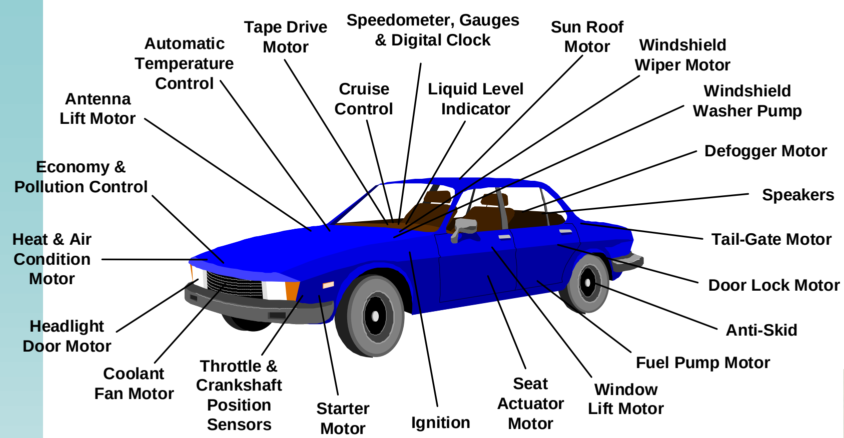
High-Performance & High-Temperature Permanent Magnets

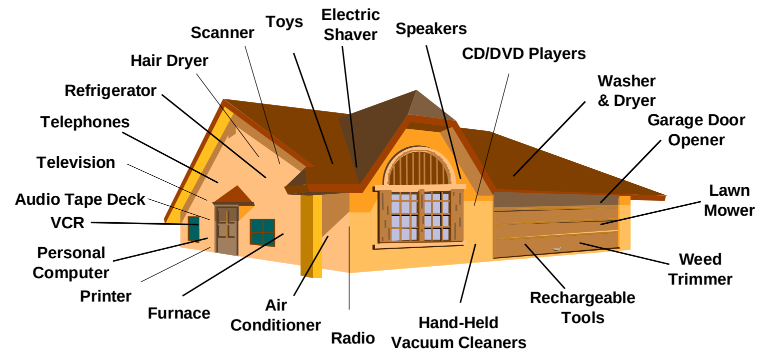
May 2007，Purdue University

高性能、高温永磁材料

2007年5月于普度大学

Magnetic Material Applications





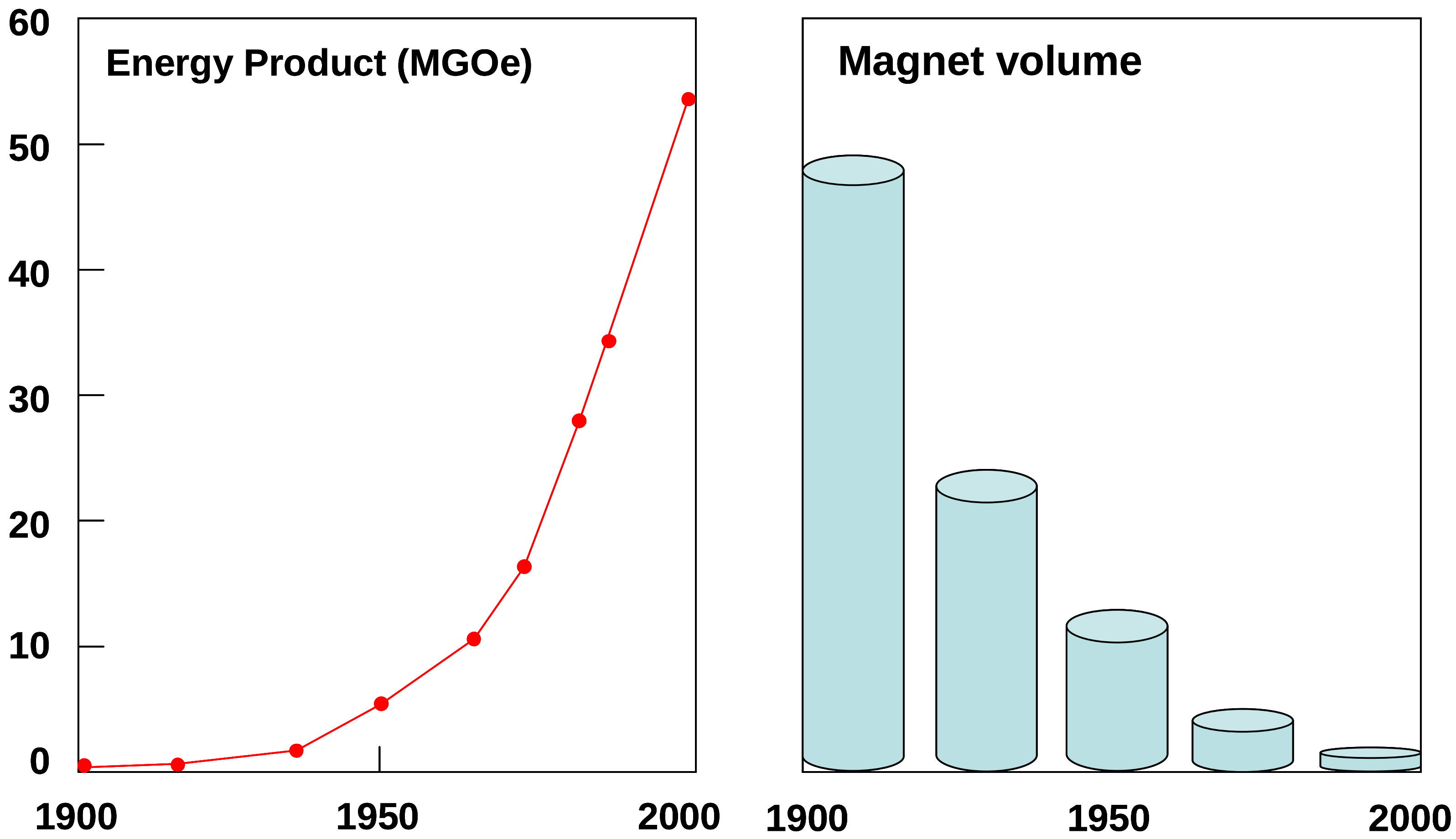

AGM-84 HARPOON (SVG I PD)

Air Force Applications and Requirements

- ***Applications***
  - *Power system*
  - *Control system*
  - *Weapon*

- ***Requirements***
  - *High performance: $(BH)_{max}$ > 50 MGOe*
  - *High operating temperatures: up to ~450°C*

Advance of Permanent Magnets



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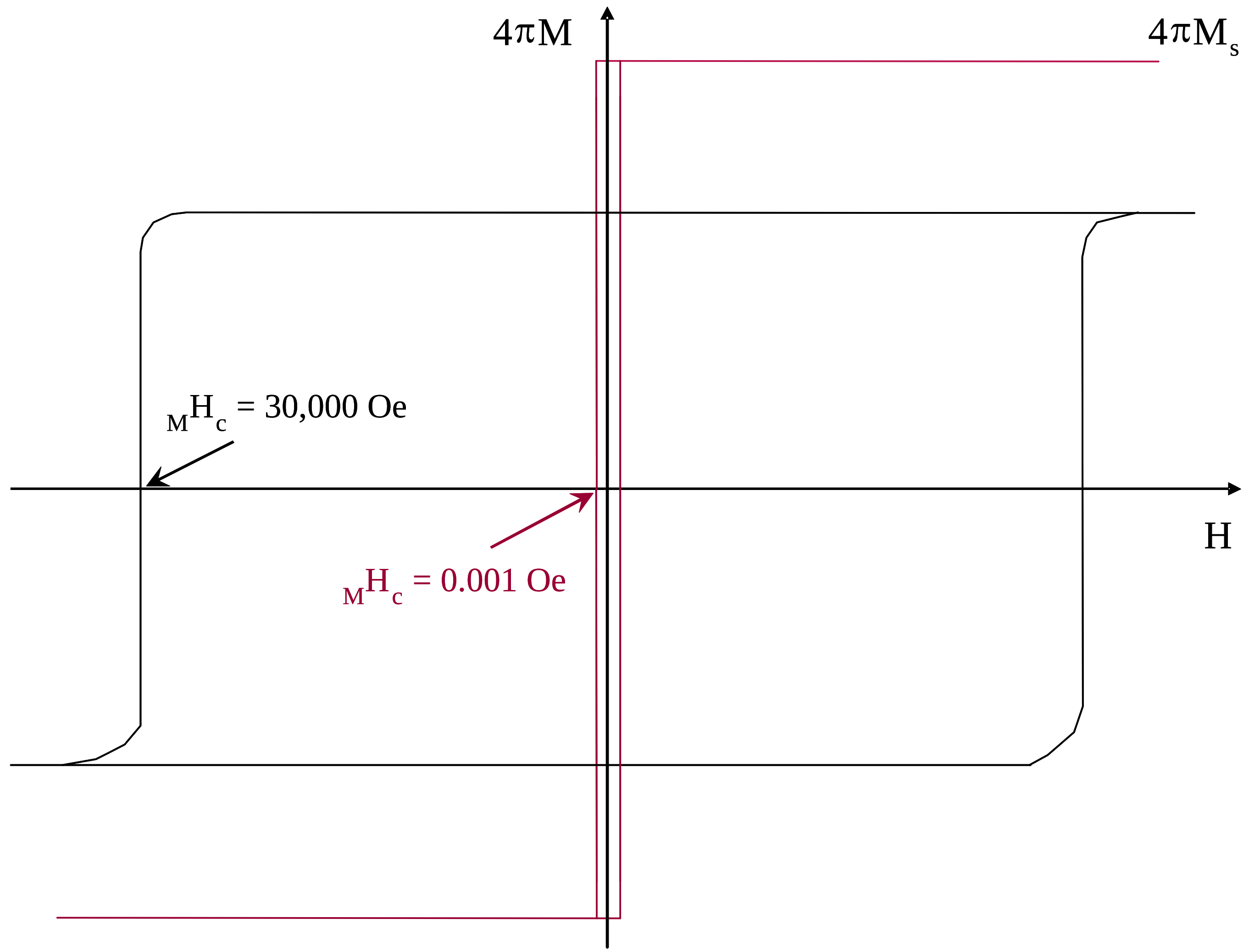
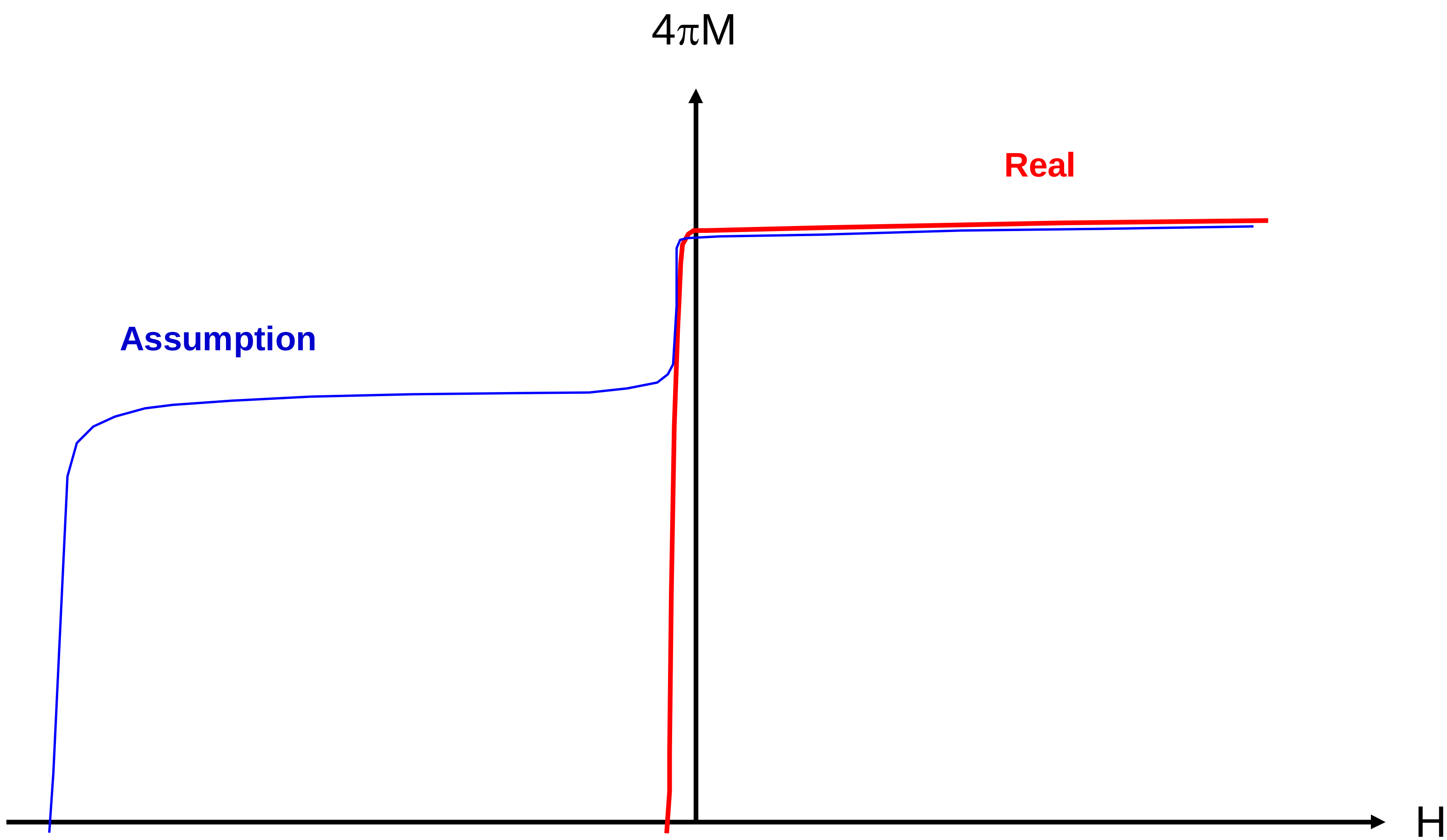
Approach to Further Advance

- *Maximum energy product $(BH)_{max}$*
- *Saturation magnetization: $4\pi M_s$*
- ***$(BH)_{max} \propto (4\pi M_s)^2$***
- *Permanent magnet with highest $4\pi M_s$ and $(BH)_{max}$*
  - ***$Nd_2Fe_{14}B$***
  - ***$4\pi M_s$ = 16 kG***
  - ***$(BH)_{max} \approx$ 26 – 45 MGOe*** *(commercial),* ***53 – 56 MGOe*** *(lab)*
- *$4\pi M_s$ of soft magnetic materials*
  - ***Fe: 22.5 kG***
  - ***Fe-Co: 24.5 kG***
- *Approaches*
  - *Search for new compounds with $4\pi M_s$ > 16 kG*
  - *Make* ***composite $Nd_2Fe_{14}B$/Fe-Co*** *magnets*

Concept of Hard/Soft Composite Magnets



Conventional Composite $Nd_2Fe_{14}B/\alpha$-Fe Magnets



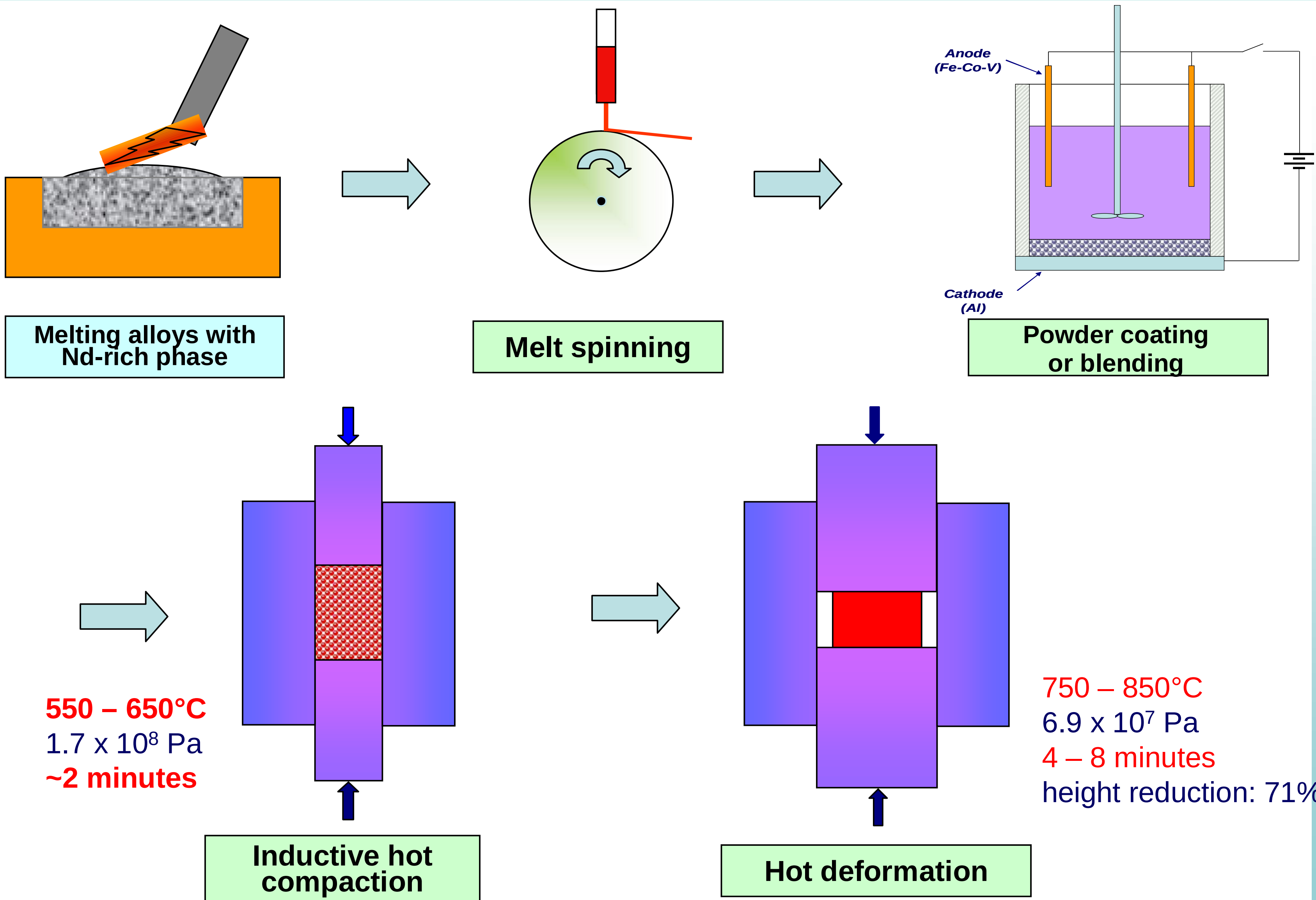
Previous Status of Nanocomposite $Nd_2Fe_{14}B/\alpha$-Fe Magnets

- *In 1988, the Philips group obtained $_MH_c$ = 3 kOe in **nano**composite $Nd_2Fe_{14}B/Fe_3B$ alloy*
- *Worldwide extensive R&D had been followed in 1990s with expectation of $(BH)_{max}$ ~ 80 – 100 MGOe*
- ***Two major technical difficulties** in developing nanocomposite magnets*
  - *How to make a **bulk, fully dense** nanocomposite magnet?*
  - *How to make a high-performance **anisotropic** magnet?*
- *Status of nanocomposite magnets prior to UD/FutureTek's R&D*
  - *Only **ribbons, thin films, or powders** could be made*
  - *Only isotropic materials could be made with **$(BH)_{max}$ = 10 – 20** MGOe*
  - *Bulk bonded magnets with $(BH)_{max}$ = **5 – 10** MGOe*

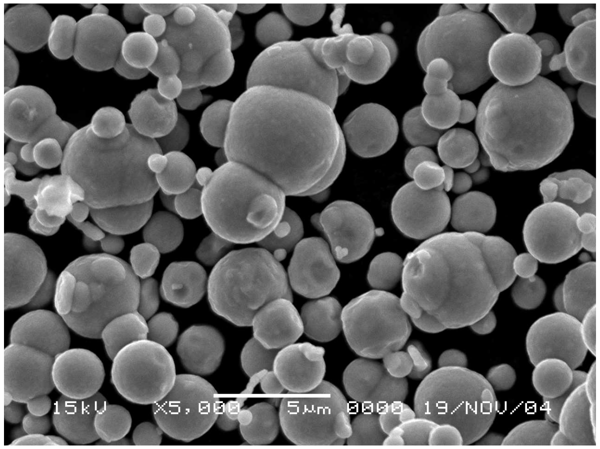
Innovative Approach

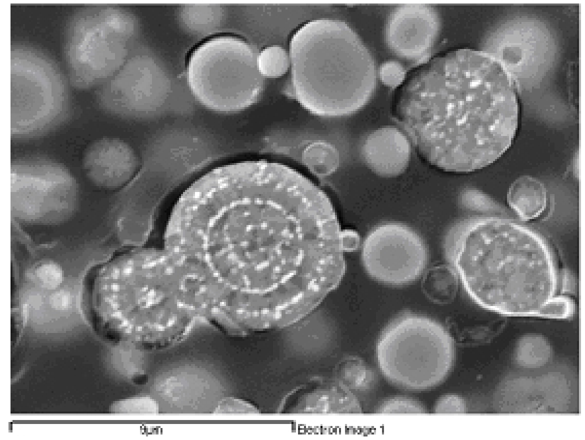
- ***Melting*** *alloys* ***with Nd-rich phase***
- ***Melt spinning****: amorphous Nd-Fe-B alloys*
- ***Blending or coating*** *Nd-Fe-B power with soft magnetic material powder, such as α-Fe or Fe-Co*
- *Rapid inductive* ***hot compaction:*** *to form a bulk isotropic magnets*
- ***Hot deformation****: to form anisotropic magnets*

Approach and Process

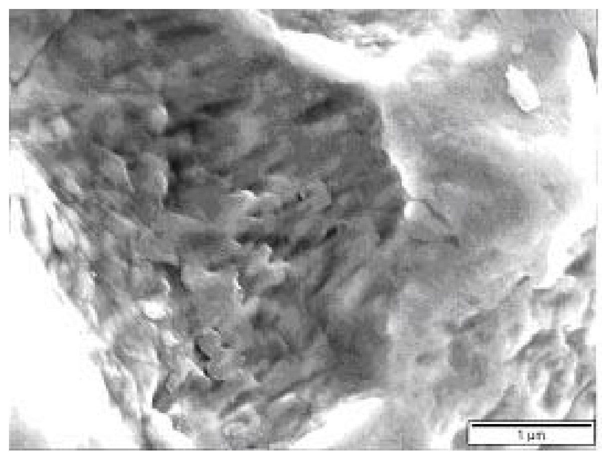


α-Fe and Fe-Co Powder Particles



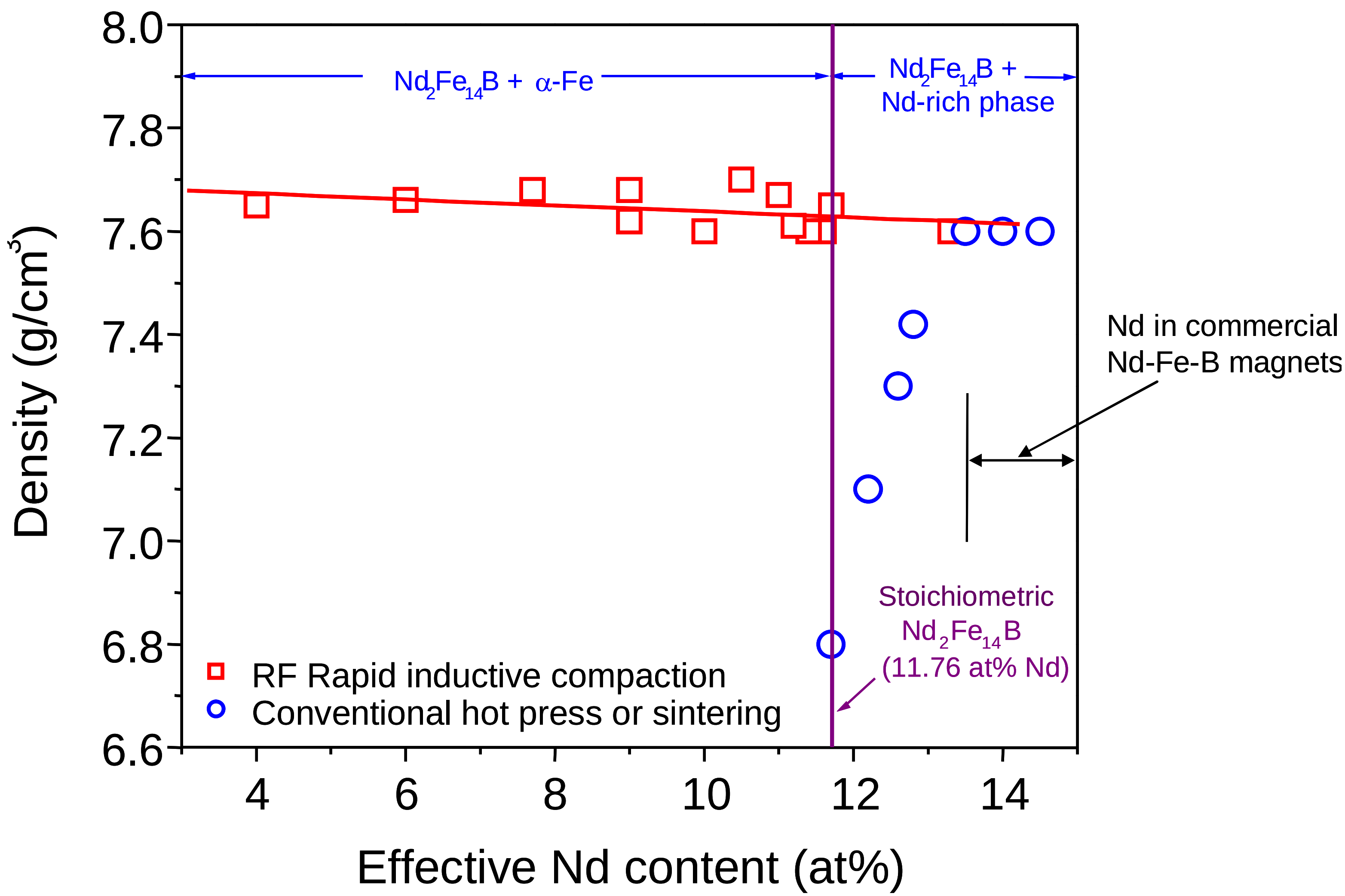


α-Fe
3 – 5 microns

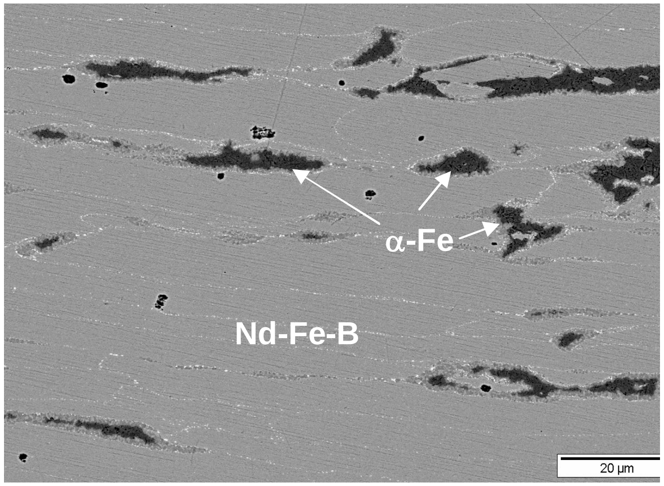


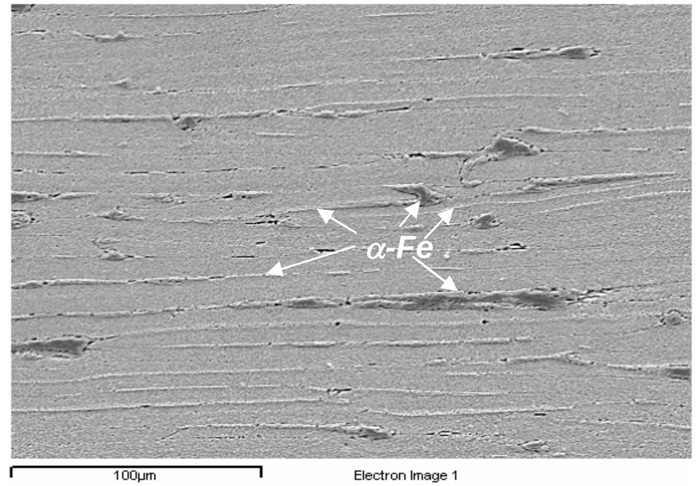
Fe-Co
20 – 50 microns

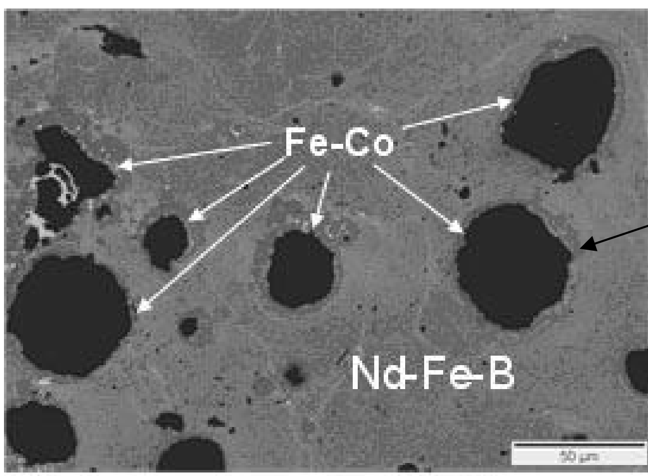
Comparison of Compactions

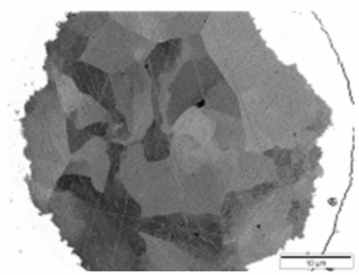


Microstructures after Hot Deformation









The soft phase is more than 1000 times as large as the upper size limit predicted by the current model of exchange coupling

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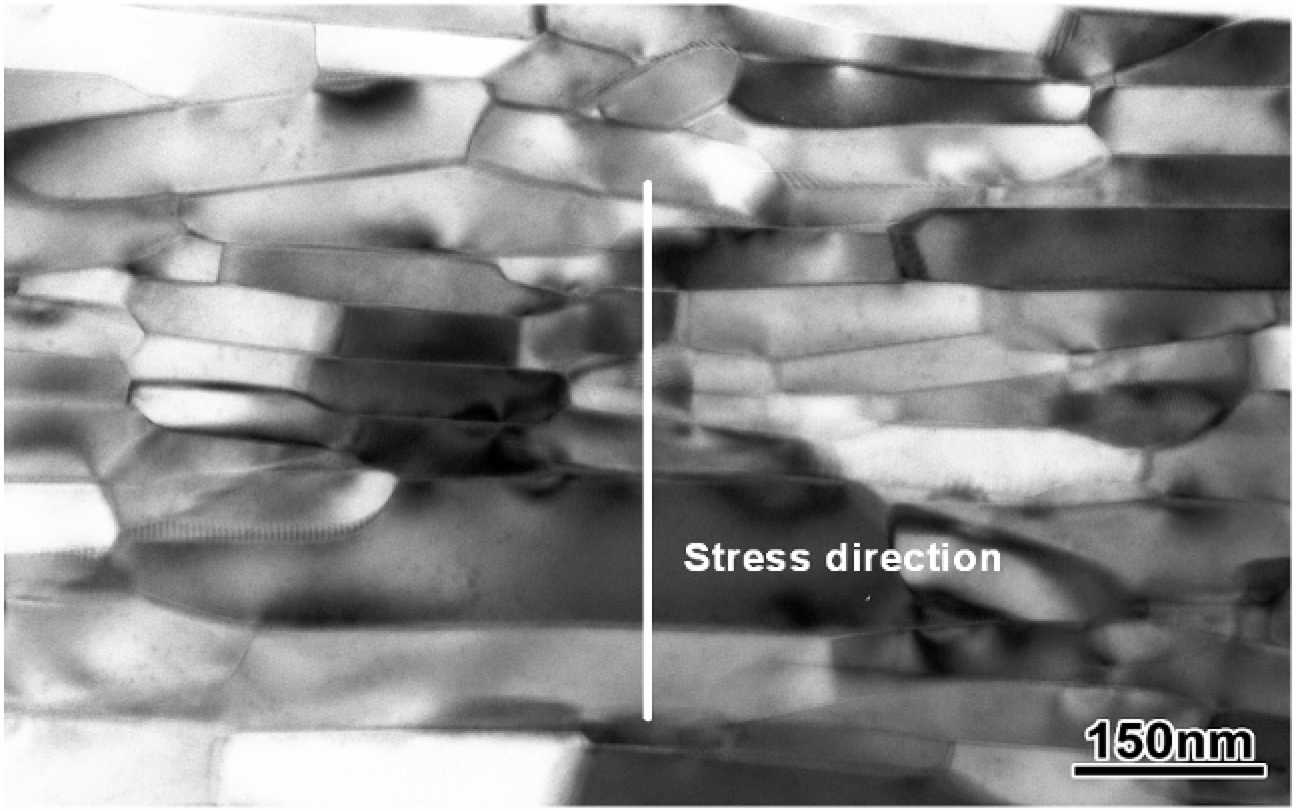
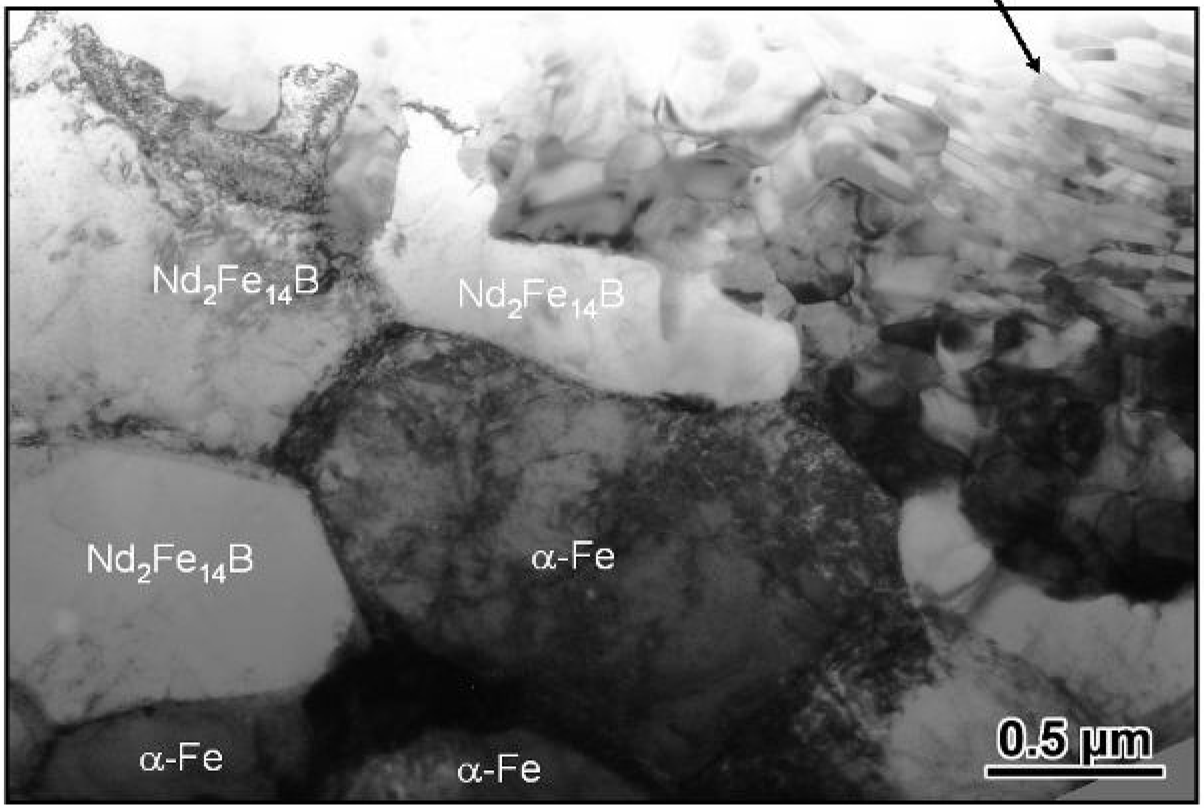
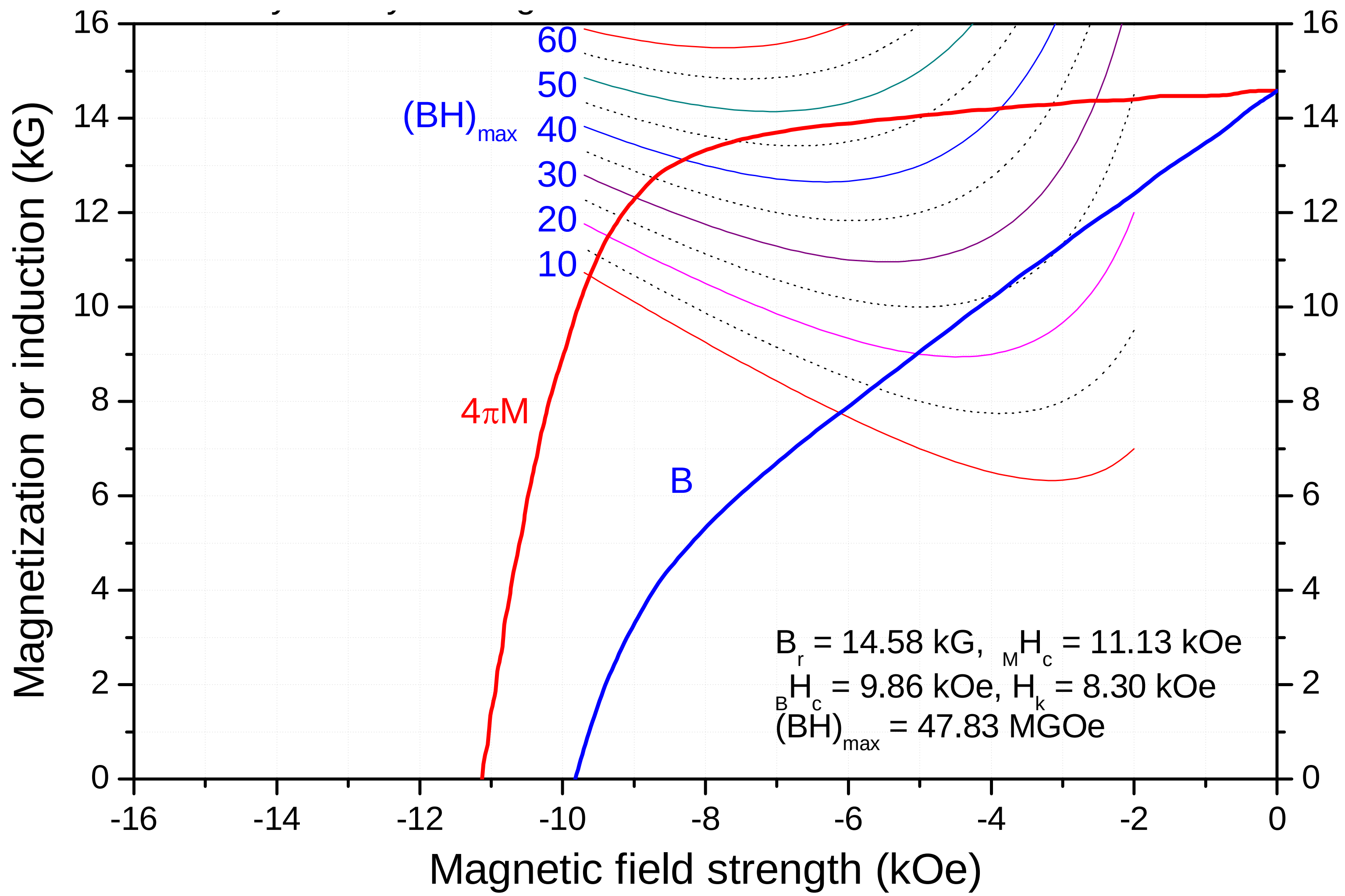
TEM Micrograph of Matrix Phase of $Nd_{13.5}Fe_{80}Ga_{0.5}B_6$/α-Fe (95%/5%)



TEM Micrograph of Hard/Soft Interface of $Nd_{13.5}Fe_{80}Ga_{0.5}B_6$/α-Fe (95%/5%)



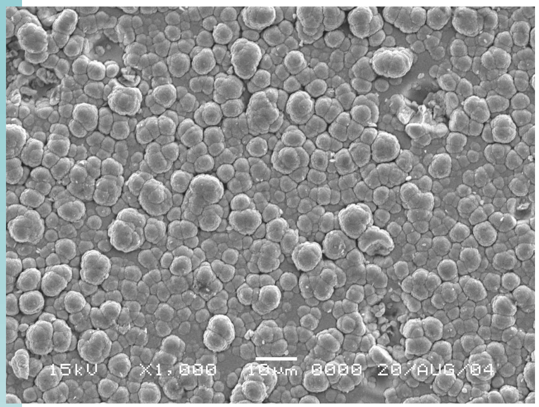
Magnetic Properties of a $Nd_{13.5}Fe_{80}Ga_{0.5}B_6/\alpha$-Fe (95%/5%) Magnet prepared by Powder Blending



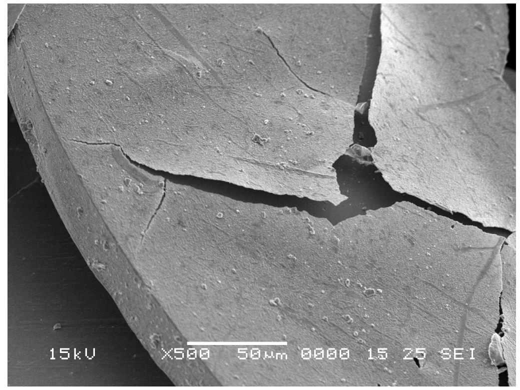
Various Coating Techniques

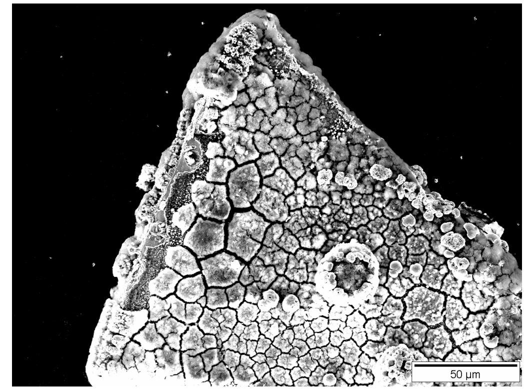
- ***Sputtering and PLD***
  - *Low deposition rate*
  - *Low oxygen pickup*
- ***Chemical (electroless) coating***
  - *Low deposition rate*
  - *Low oxygen pickup*
  - *Low cost*
- ***Electrolytic coating***
  - *High deposition rate*
  - *High oxygen pickup*

Microstructures of Coated Surfaces

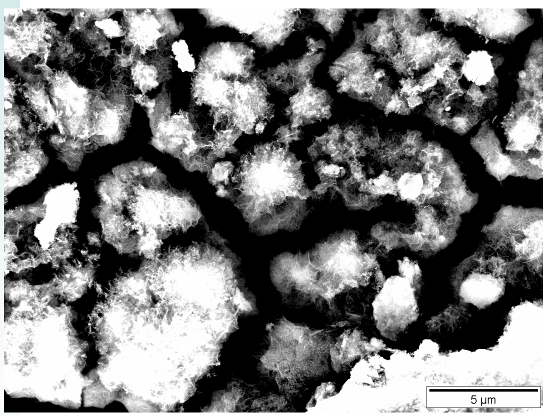


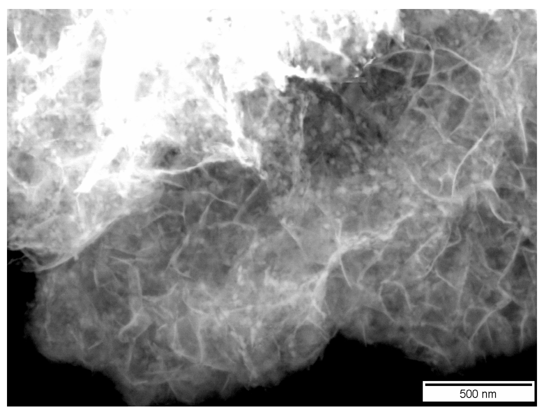
Sputtering for 20 hrs

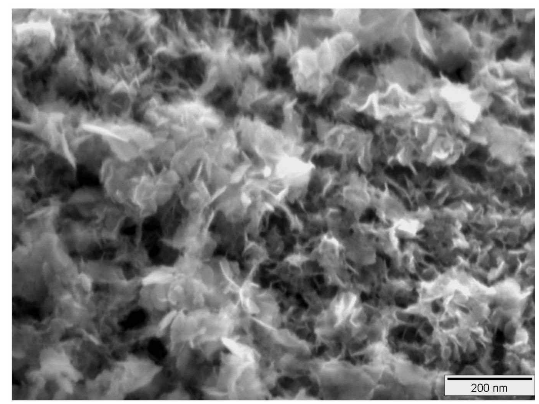




Electrolytic coating for 1 hr







Electrolytic coating for 1 hr

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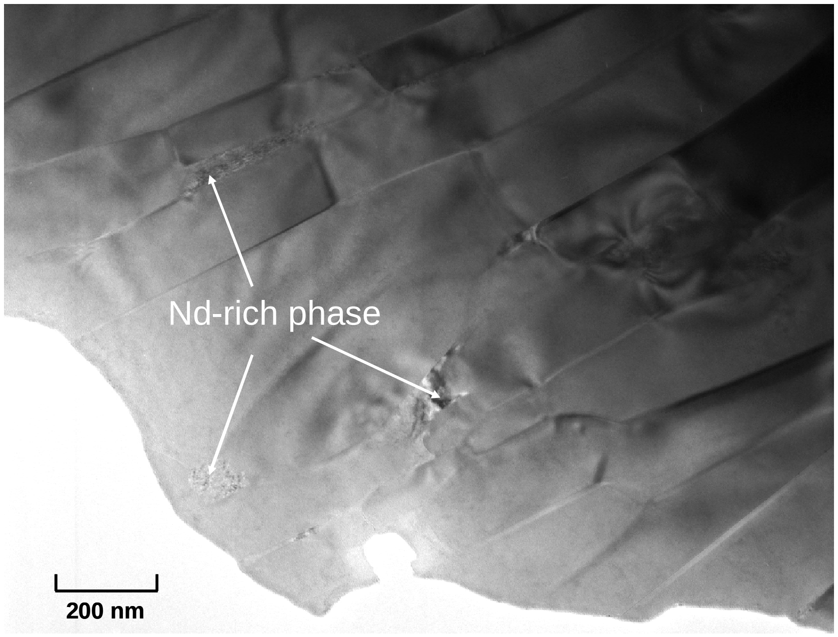
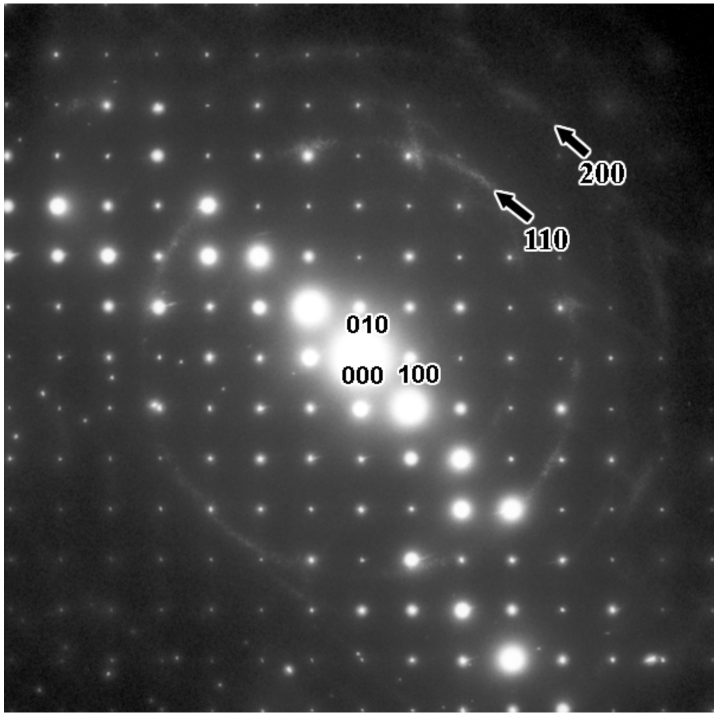
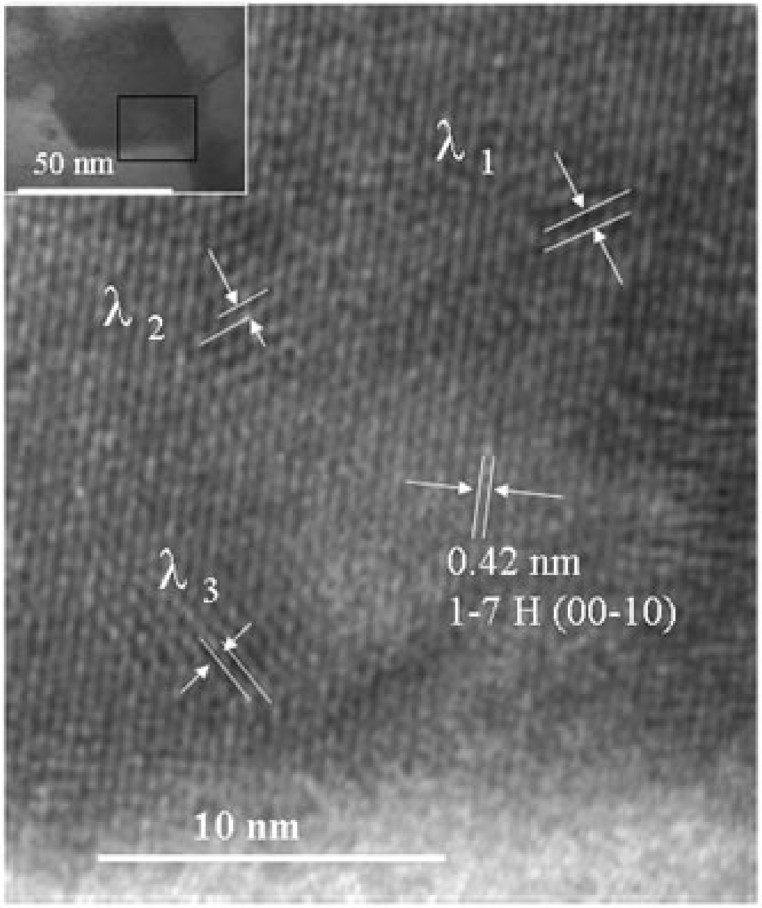
TEM Microstructures of a Composite Magnet Prepared by Electrolytic Coating

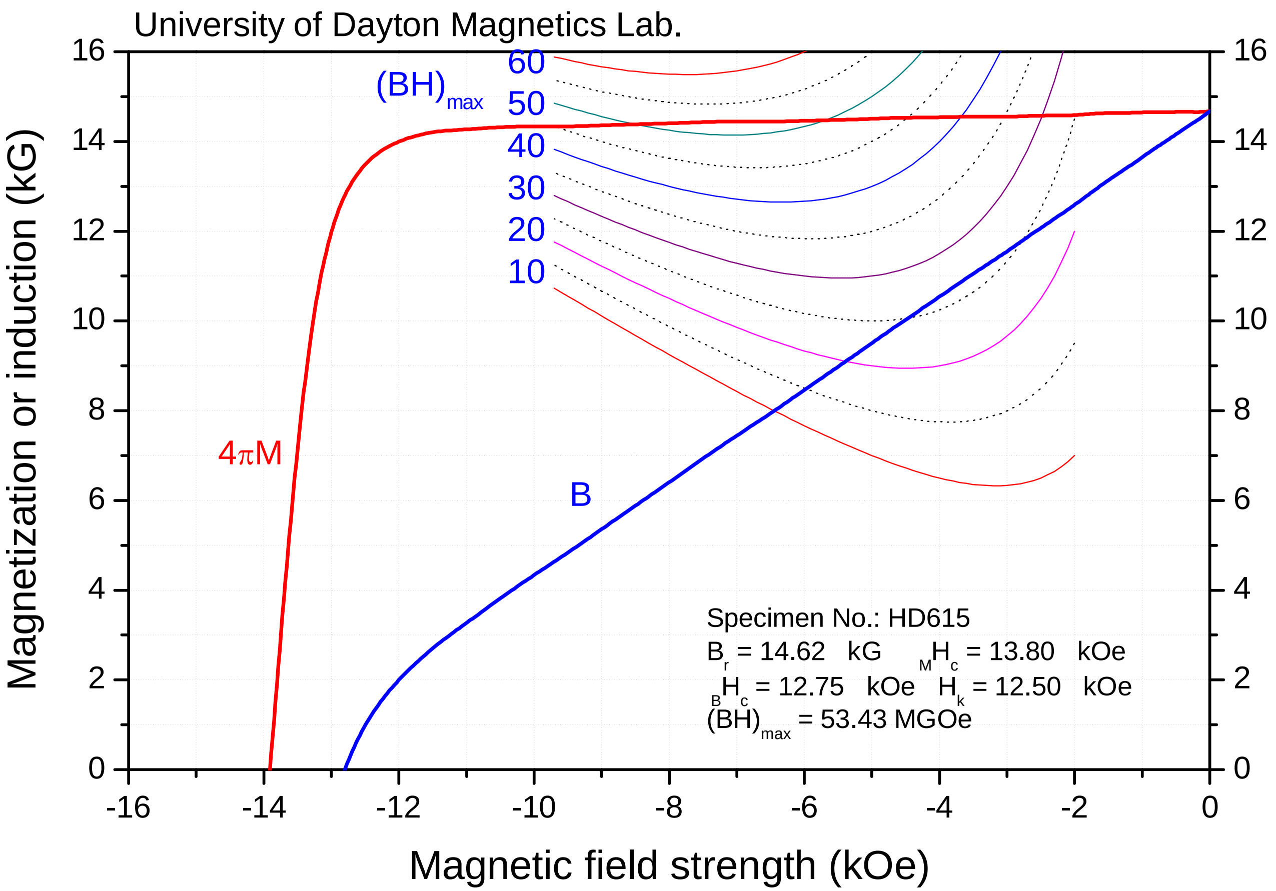




Fine Structure within a Nanograin

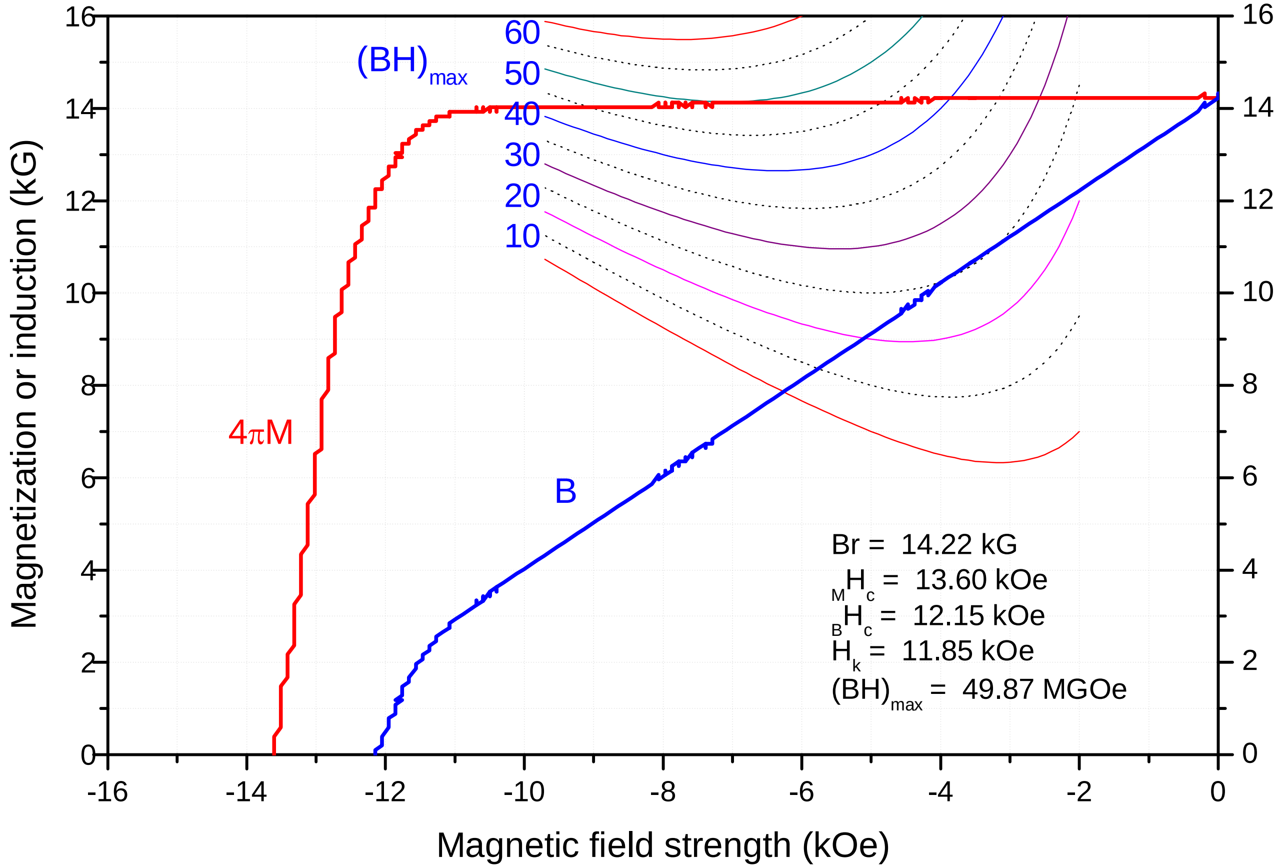


Magnetic Properties of a Composite Magnet Prepared by Sputtering



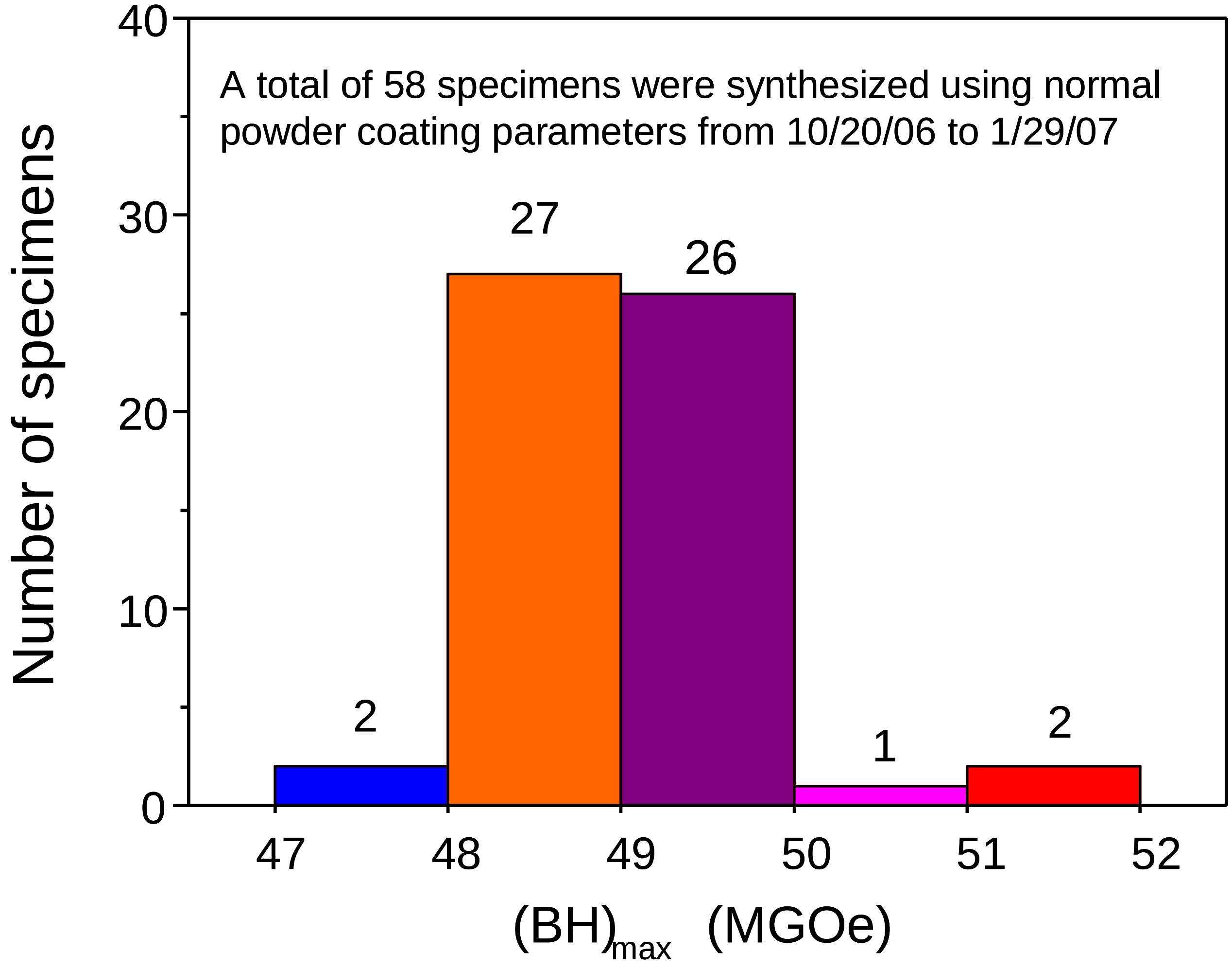
$Nd_{14}Fe_{79.5}Ga_{0.5}B_6/\alpha\text{-}Fe$, DC sputtering for 20 hours,
hot compacting at 630°C for 2 minutes,
and die upsetting at 930°C for 4 minutes

Magnetic Properties of a Composite Magnet Prepared by Electrolytic Coating



$FeSO_4/CoSO_4$ solution, I = 0.8 A, V = 15 – 22 volt, time = 20 m.

$(BH)_{max}$ Distribution of Specimens Prepared by Electrolytic Coating



Comparison of Processing

Conventional Nd-Fe-B

1. Melting
2. Strip casting
3. Crushing
4. Milling to 3 μ
5. Fine powder alignment — *Anisotropic material Formation*
6. Compaction — *Room-temperature Consolidation*
7. Sintering — *1100°C- 2 hrs*
8. Heat treatment — *560°C – 1 hr*

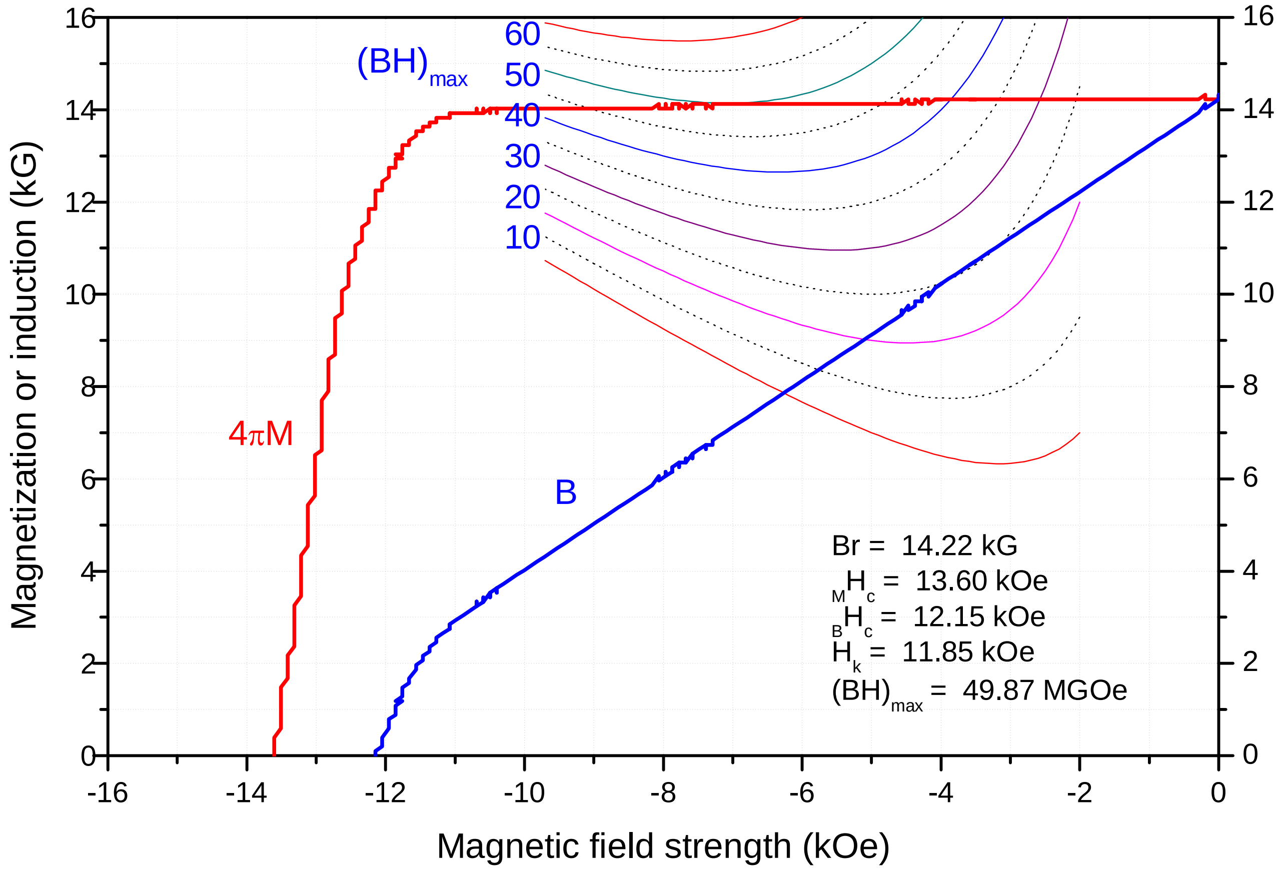
Nanocomposite Nd-Fe-B/α-Fe

1. Melting
2. Melt spinning — *Amorphous powder*
3. Crushing to 300 μ
4. Powder coating
5. Hot compaction — *550°C – 2 minutes*
6. Hot deformation — *850°C – 4 minutes Anisotropic material Formation*

In the new process, the advantage of nanograin structure is fully utilized without the trouble of making and handling nanoparticles

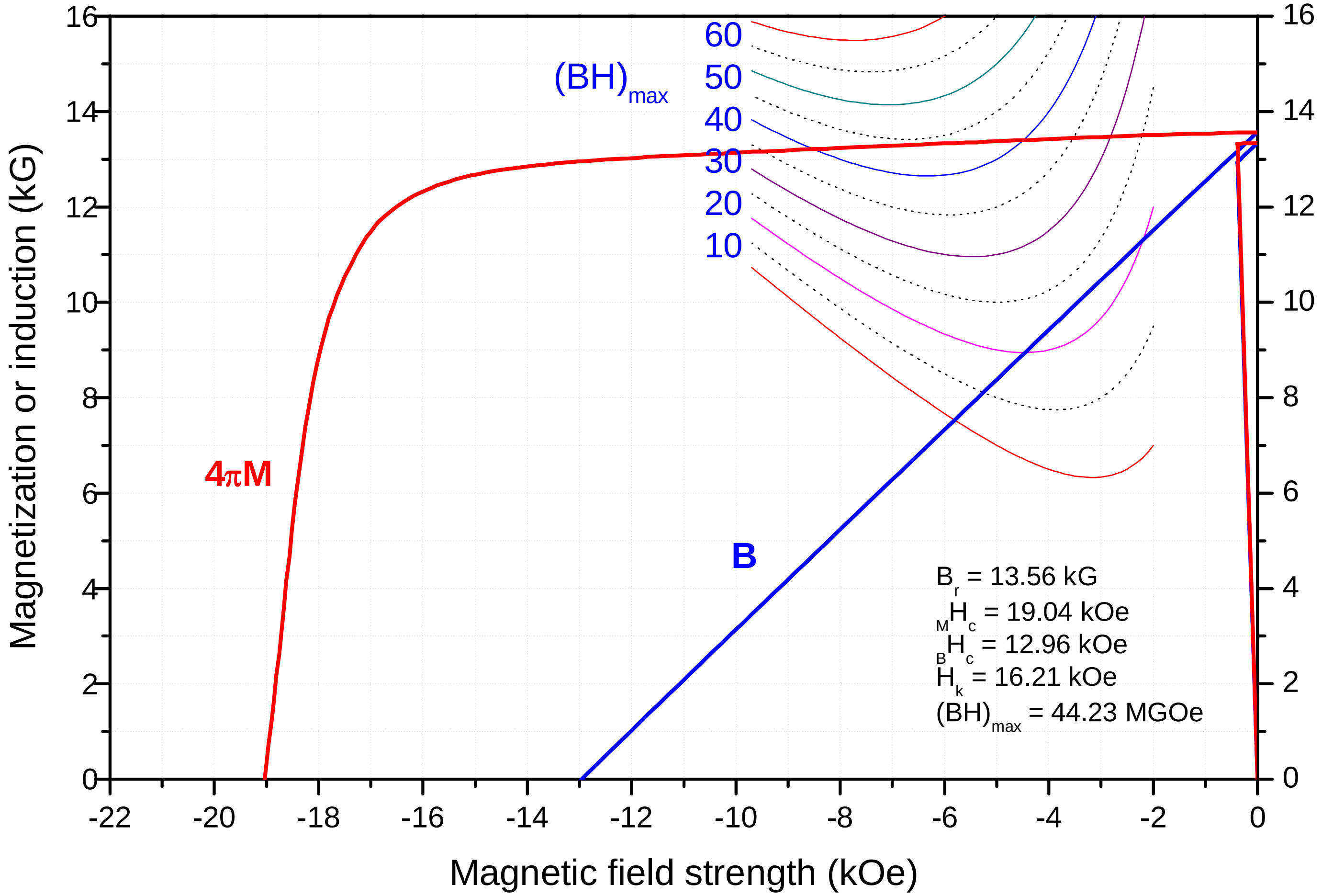
Low $_{M}H_{c}$ leads to Non-Linear B Curve

$B = 4\pi M + H$



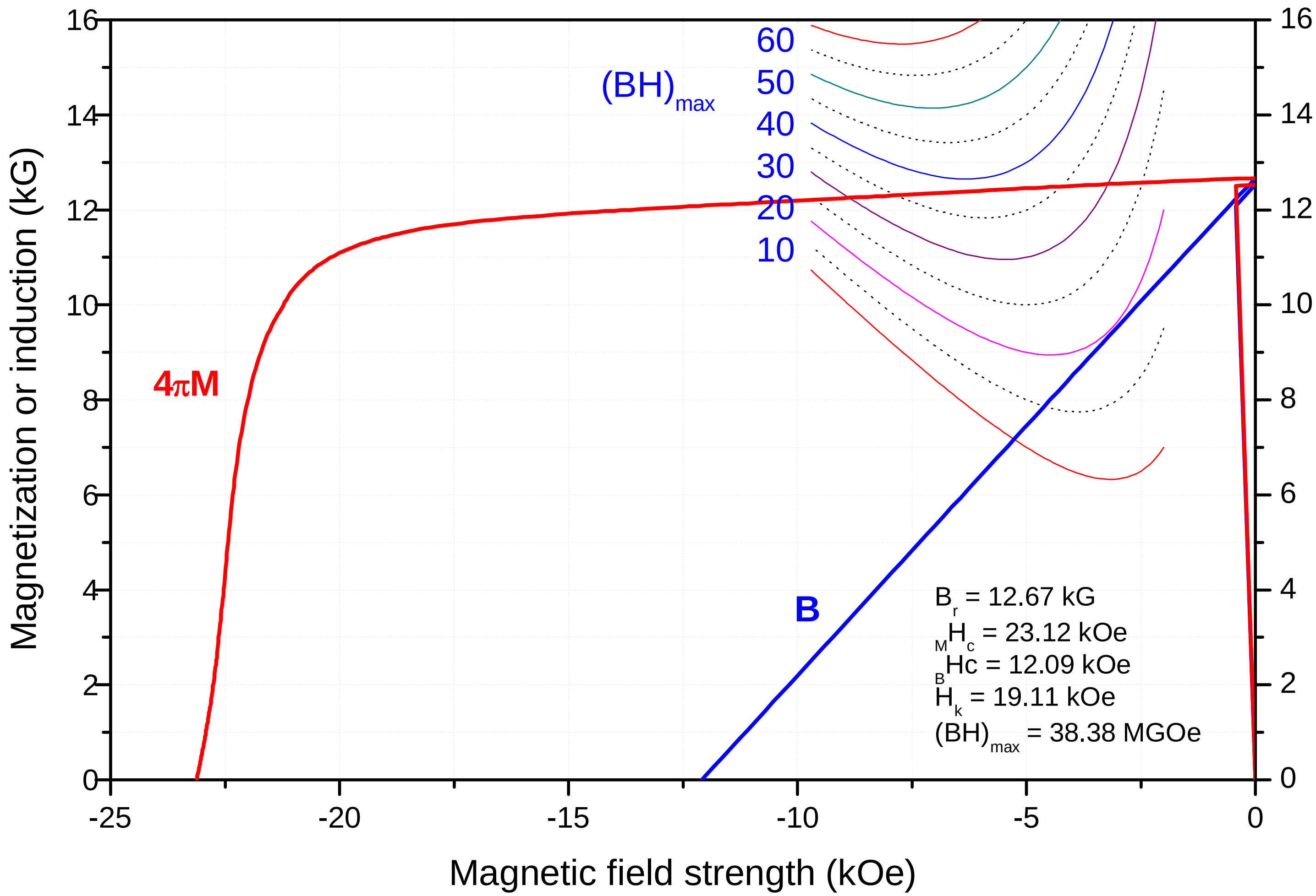
$FeSO_4/CoSO_4$ solution, I = 0.8 A, V = 15 – 22 volt, time = 20 m.

Nanograin Composite magnets for Elevated Temperature Applications - 1



Operating temperature: up to 130°C

Nanograin Composite Magnets for Elevated Temperature Applications - 2



Operating temperature: up to 180°C

Conclusions

- ***Bulk, anisotropic, nanograin composite magnets*** *have been successfully obtained*
- *Using* ***powder blending technique****, $(BH)_{max}$ = ~ 40 to ~ 50 MGOe has been accomplished*
- *Using* ***powder coating*** *$(BH)_{max}$ can reach ~45 to ~ 55 MGOe*
- *Better powder blending and powder coating techniques are yet to be developed*
- *Hot compaction and hot deformation parameters for coated and blended powders need optimized*
- *High-performance magnets for 450°C applications are to be developed*

Acknowledgement

- *Research projects have been sponsored by the US Air Force under contracts FA8650-07-C-2725, FA9550-07-C-0028, and F33615-02-D-2299*
- *Microstructure analyses were performed by Magnetics Lab., Wright-Patterson Air Force Base*