Development of Improved Powder for Bonded Permanent Magnets

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Development of Improved Powder for Bonded Permanent Magnets

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Sintered vs. Bonded (RSP) RE-Fe-B (2-14-1) Permanent Magnets

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Sintered

Cast/homogenized/crushed/pressed/sintered

Anisotropic (Aligned)

crystallographic

magnetic

- Plus:
  - -high energy product
- Minus:
  - -magnetize each part
  - -difficult assembly of segments
  - -corrosion (plate each part)

Bonded

RSP: Melt spun (flake), Atomized (spherical)

Crystallization annealed/compounded/formed

Isotropic (Microcrystalline)

- Plus:
  - -net shape molding (full assemblies)
  - -magnetize assembly (multi-sector)
  - -corrosion resistance (encapsulated)
- Minus:
  - -reduced energy product

Project Objectives:

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- Develop high performance permanent magnets (PM) for traction motor with internal PM rotor :
  - requires elevated temperature (180-200˚C) operation, minimize cooling needs
  - increased high temperature magnetic performance more critical than RT
- Reduce manufacturing cost of PM traction motors:
  - bonded PM can utilize injection or compression molding technology
    - net shape forming for mass production of rotors
- Achieve high performance and reliability for bonded magnets:
  - increase volumetric loading
  - minimize irreversible magnetic losses (oxidation)

Magnet Production Techniques

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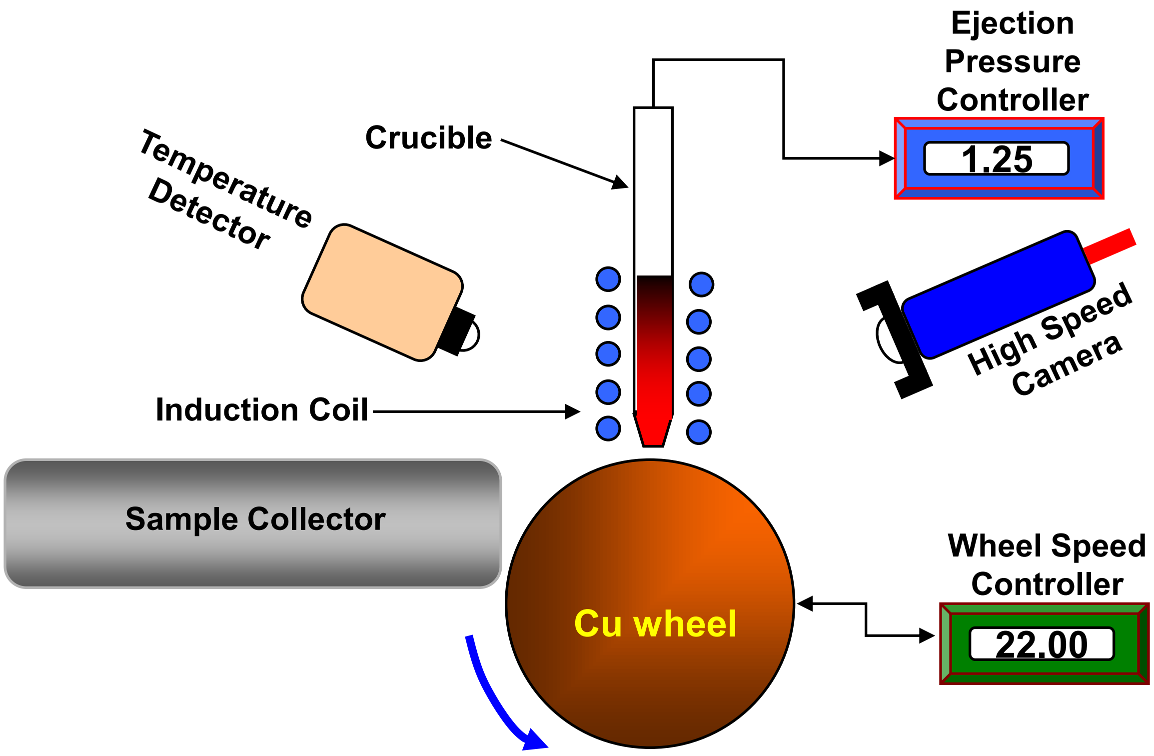
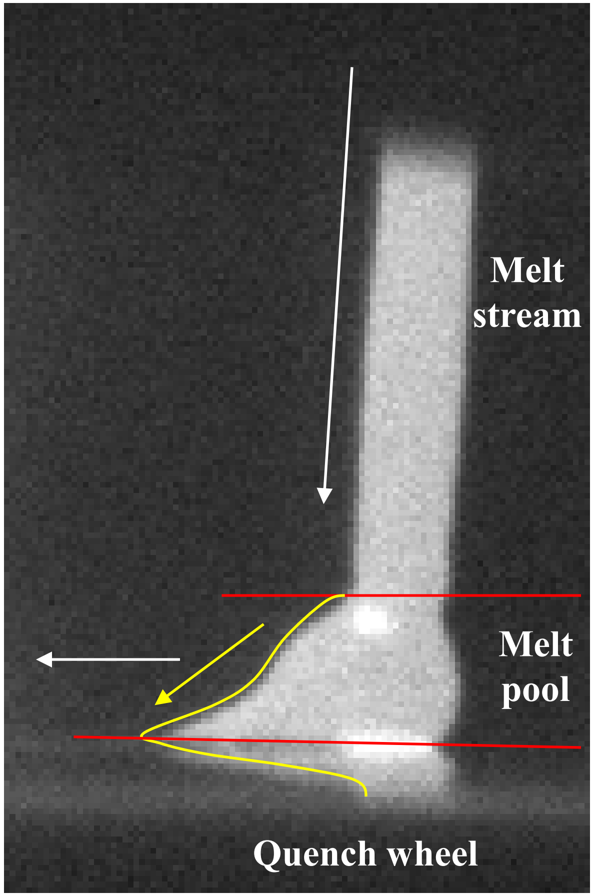
Melt Spinning Technique





Alloy Design

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$Nd_2Fe_{14}B$

- Plus
  - Nd
    - relatively abundant RE
    - large magnetic moment
    - low vapor pressure
    - reactivity not bad
  - High saturation magnetization
- Minus
  - low Curie temperature
  - large temperature dependence of the magnetocrystalline anisotropy
  - peritectic compound
    - difficult to form pure compound
    - In equilibrium with a low melting liquid

Theory versus Practice

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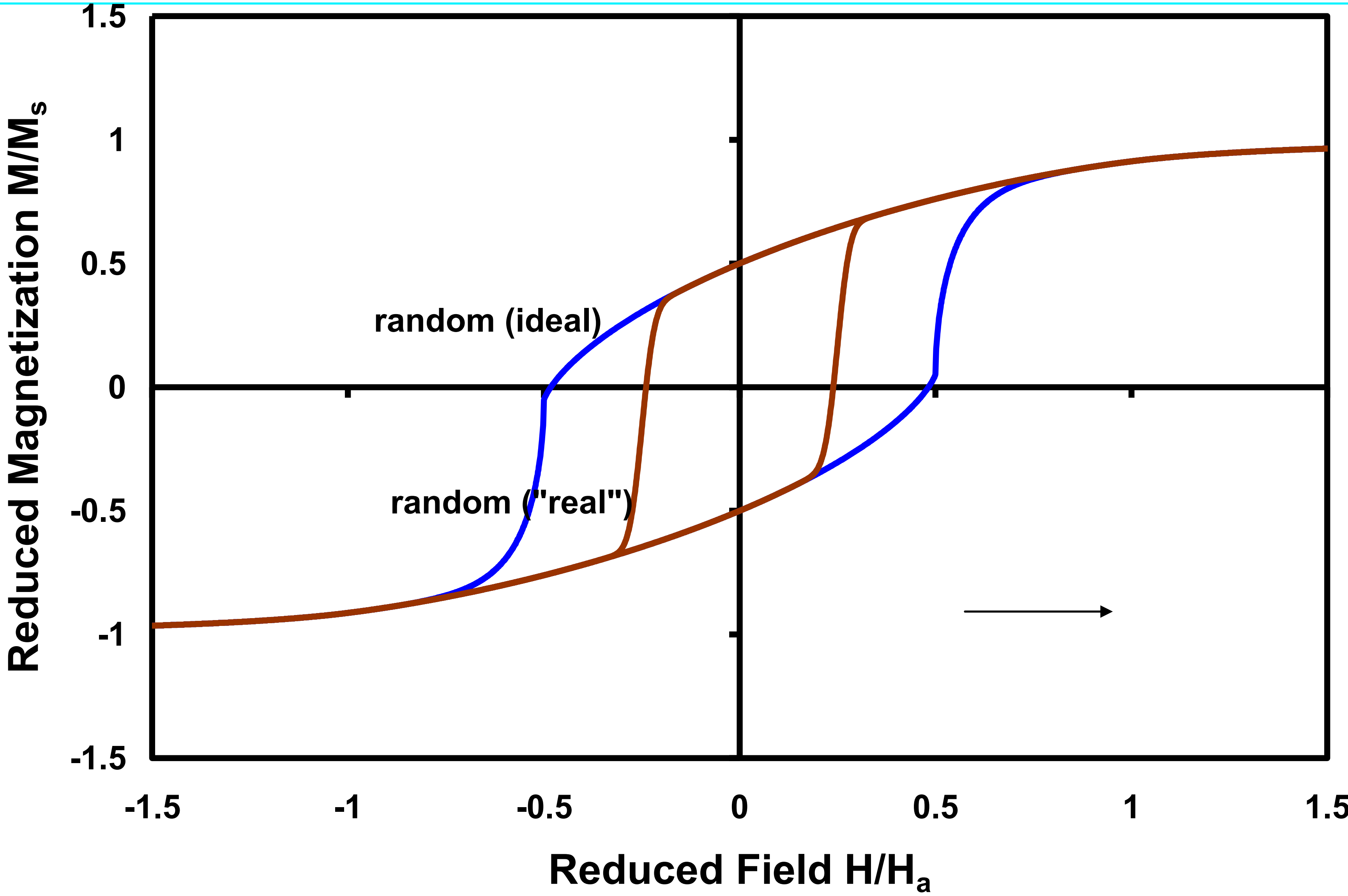

Pseudo-conservation of mediocrity

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- Given the qualities
  - Magnetic
    - T_c, B_r, α, H_{ci}, β, BH_{max}
  - Physical
    - Ductility, toughness, hardness
  - Financial
    - Cost, ease of assembly
- The sum is essentially constant

What are the factors that determine B_r?

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- Magnetic moment of the hard phase
  - $Nd_2Fe_{14}B$
    - Nd=3.3 μ_B/atom, Fe~2 μ_B/atom
    - Ferromagnetic coupling
    - ~35 μ_B/formula unit
  - $Dy_2Fe_{14}B$
    - Dy=10μ_B/atom, Fe~2 μ_B/atom
    - Antiferromagnetic coupling
    - ~8 μ_B/formula unit
- Degree of orientation of the hard phase
- Volume percent of the hard phase

Alloy Design

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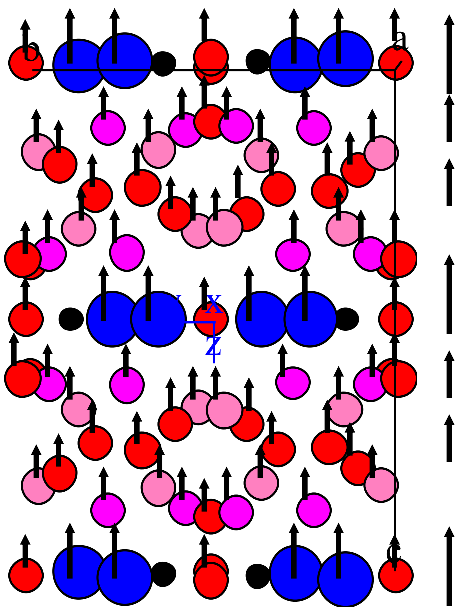
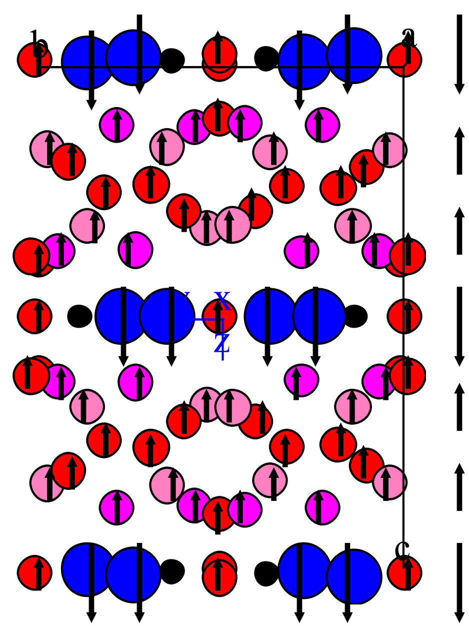
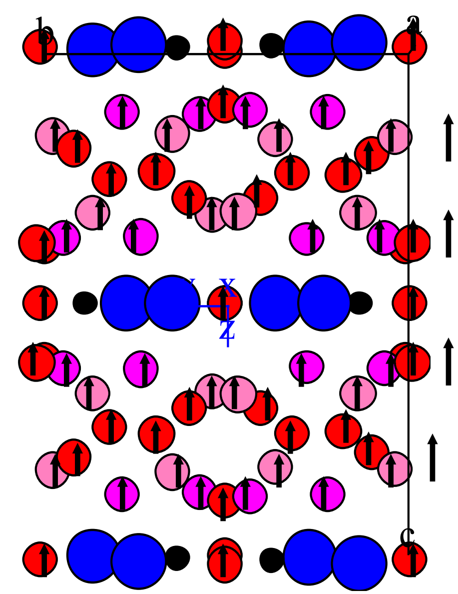
$Nd_2Fe_{14}B$ $Dy_2Fe_{14}B$ $Y_2Fe_{14}B$







Alloy Design

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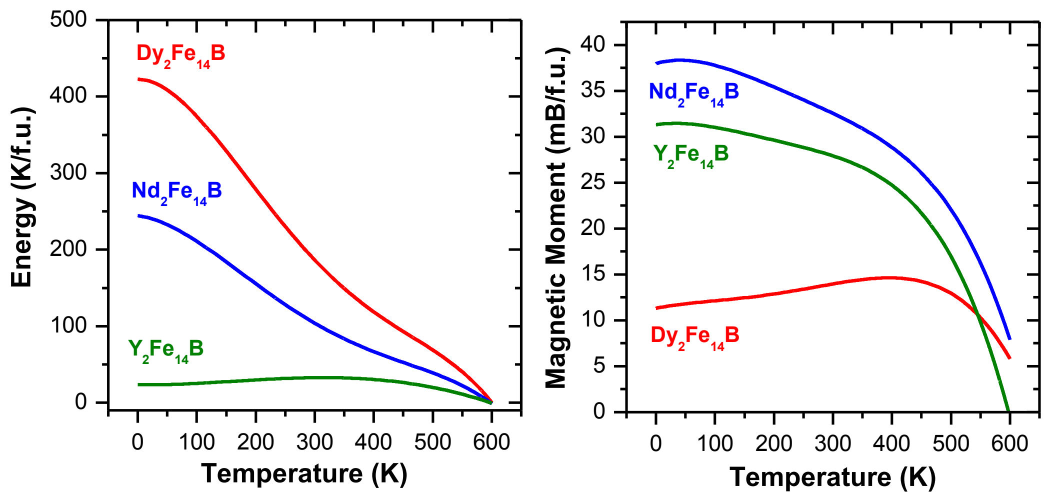
➢Why YDy-based $R_2Fe_{14}B$?

Intrinsic magnetic properties of $R_2Fe_{14}B$ compounds

	M_s (kGs)	H_a (kOe)
$Nd_2Fe_{14}B$	16	73
$Y_2Fe_{14}B$	14.1	26
$Dy_2Fe_{14}B$	7.1	~150

Temperature dependence of anisotropic energy and magnetic moment of $R_2Fe_{14}B$ compounds



(After R. Grössinger [2], S. Hirosawa [3], E. B. Boltich [4], D. Givord [5])

- **The H_a of $Y_2Fe_{14}B$ and the M_s of $Dy_2Fe_{14}B$ exhibit a weak temperature dependence which initially rises above room temperature before decreasing as the Curie temperature T_c is approached.**

Effect of the ratio of Y to Dy

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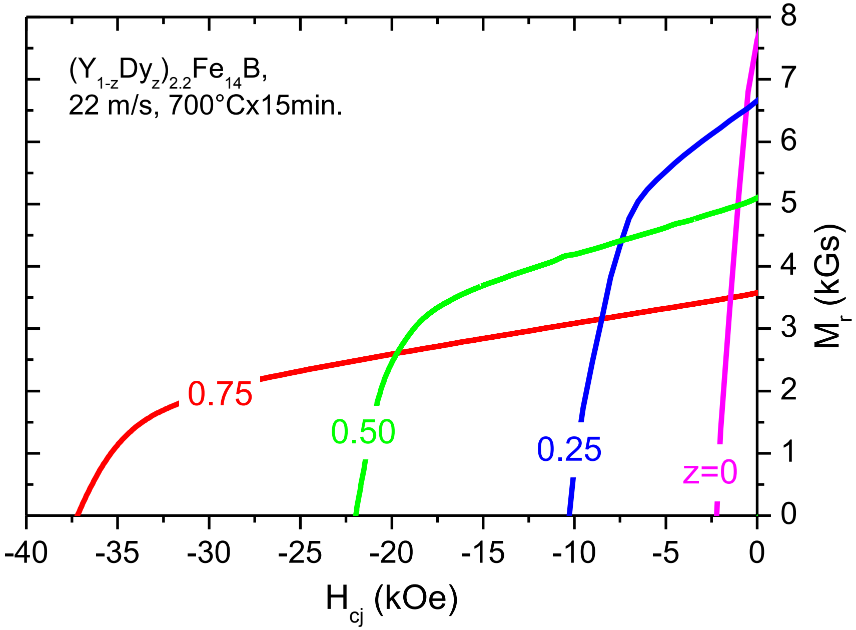
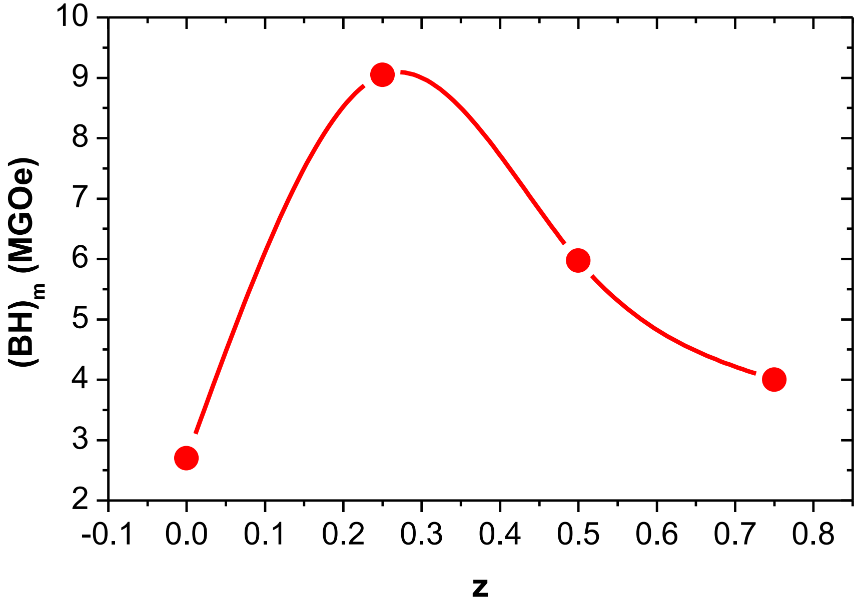
Demagnetization Curves

Annealed $(Y_{1-z}Dy_z)_{2.2}Fe_{14}B$ ribbons with different z





- **As predicted by the intrinsic properties of $Dy_2Fe_{14}B$ and $Y_2Fe_{14}B$ compounds, the covercivity of the ribbons increases, but the remanence decreases with increasing z.**
- **(BH)max first increases and then decreases with increasing Dy content, z.**

Effect of the ratio of Y to Dy

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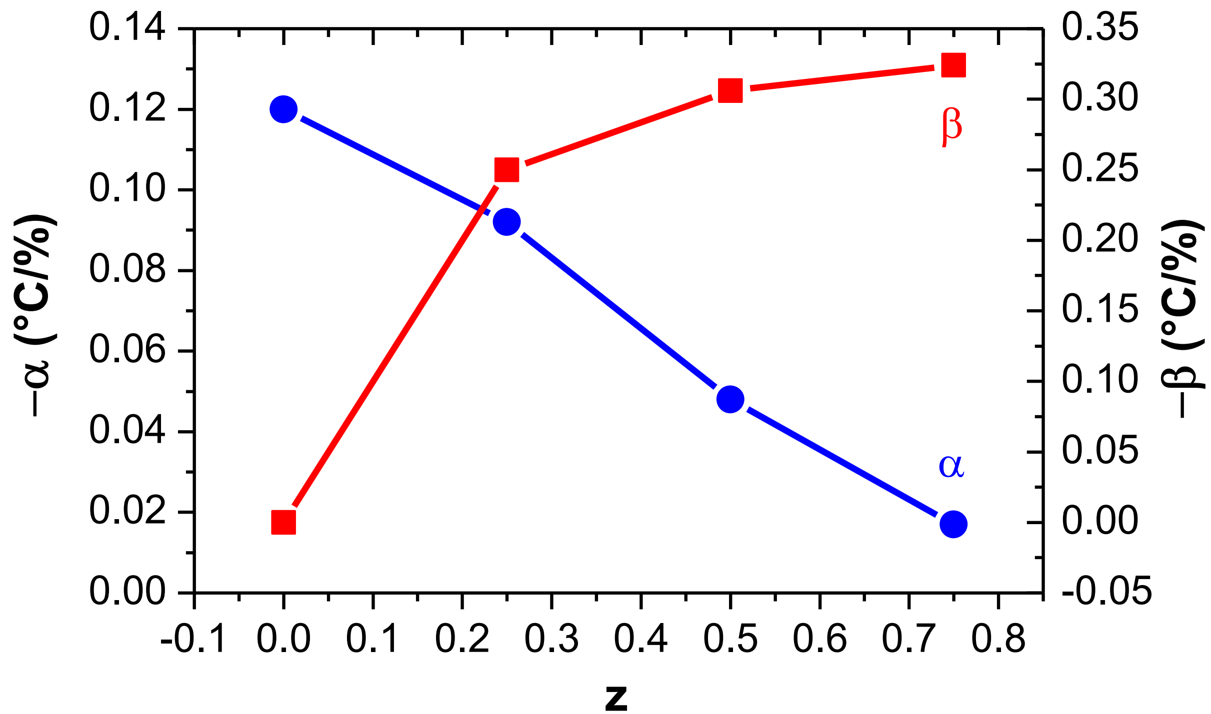
Temperature Coefficients as a Function of z

Annealed $(Y_{1-z}Dy_z)_{2.2}Fe_{14}B$ ribbons with different z



- **With increasing z from 0 to 0.75, α monotonically decreases from -0.12 to -0.02 %/°C, while β increases from 0 to -0.33%/°C.**

Effect of Nd-Substitution

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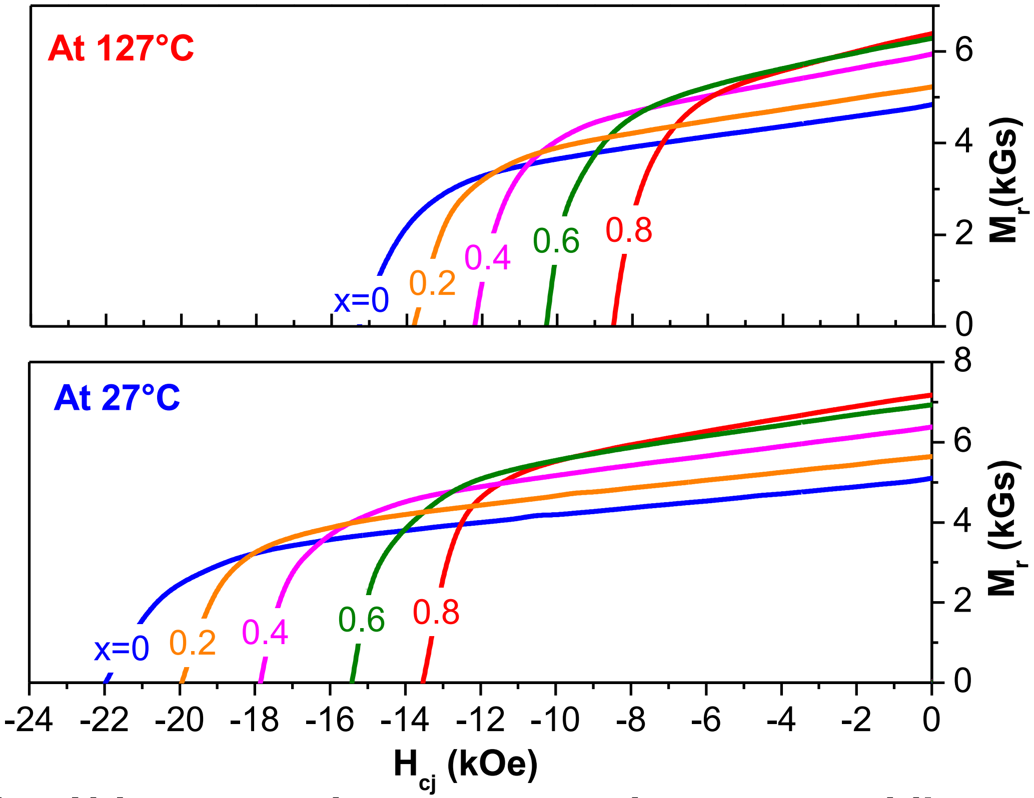
Demagnetization Curves

Annealed $[Nd_x(YDy)_{0.5(1-x)}]_{2.2}Fe_{14}B$ ribbons with different Nd contents



- **With increasing Nd content, the remanence increases, while coercivity decreases.**
- **The demagnetization curves exhibit good squareness at both 27 and 127°C.**

Effect of Nd-Substitution

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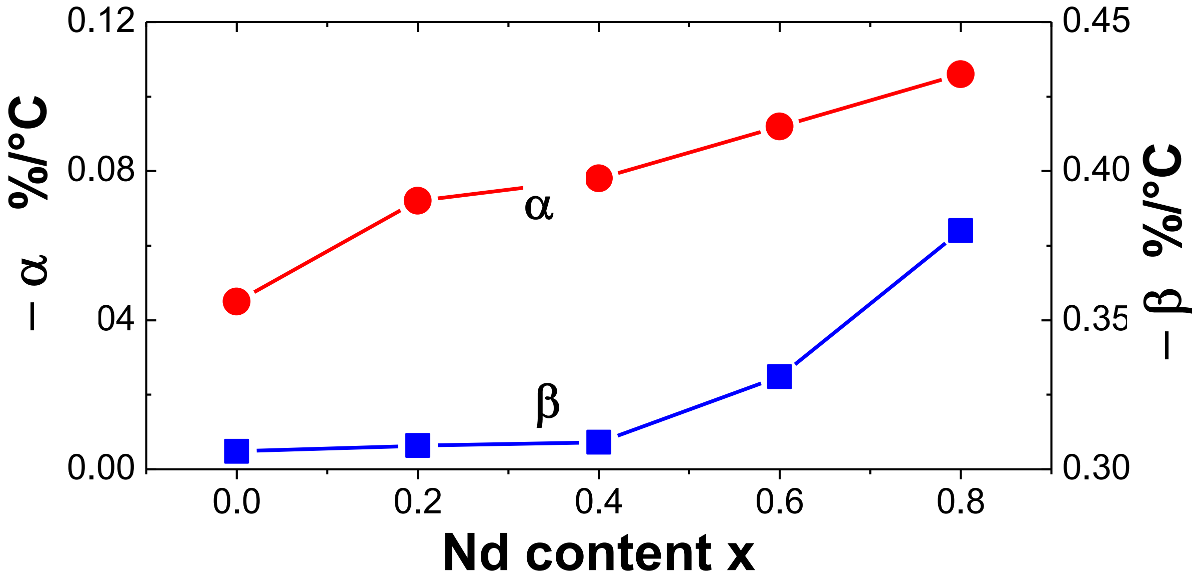
Thermal Stability From 27 to 127°C

Annealed $[Nd_x(YDy)_{0.5(1-x)}]_{2.2}Fe_{14}B$ ribbons with different Nd contents



- **α monotonically increases from -0.045 to -0.106 %/°C with increasing x from 0 to 0.8, while β has an essentially constant value of -0.3 %/°C when x is below 0.4.**
- **The thermal magnetic properties in a wide range of Nd substitution are much better than those of Nd-based ribbons.**

Effect of Nd-Substitution

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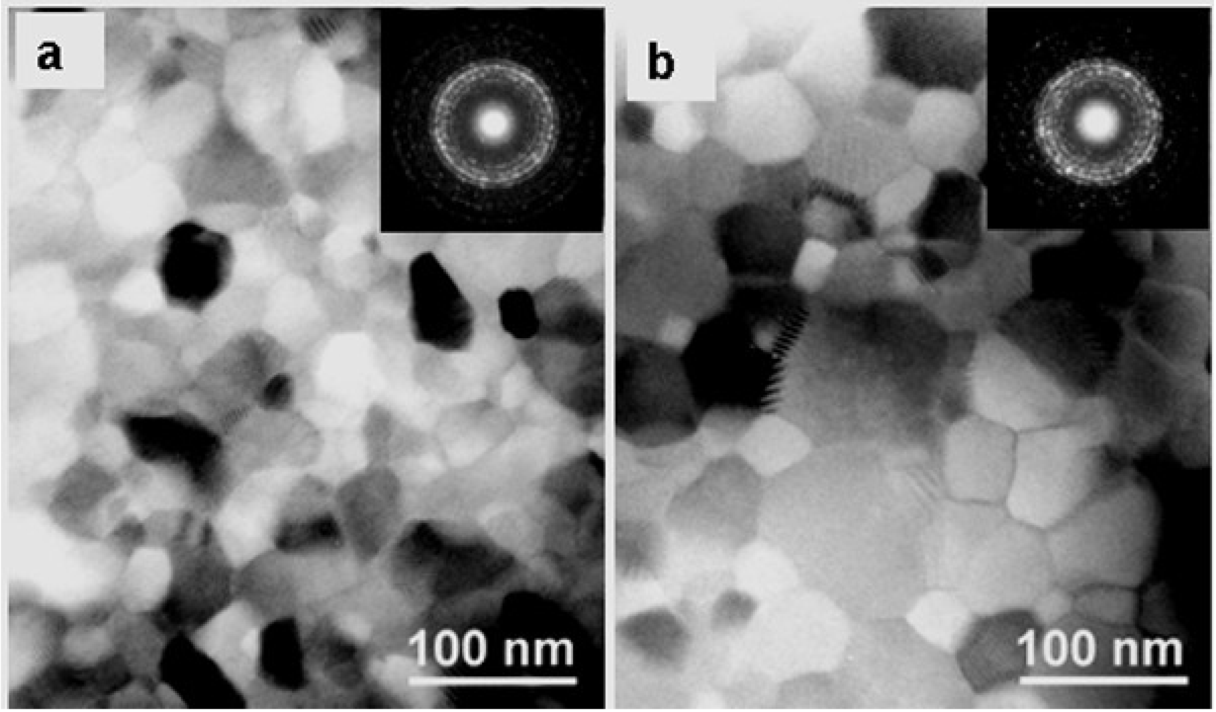
TEM Images

Annealed $[Nd_x(YDy)_{0.5(1-x)}]_{2.2}Fe_{14}B$ ribbons with x=0.2 (a) and 0.8 (b)



- **The sample with less Nd content (Fig. a) has a more uniform distribution of grains.**
- **The average size of grains is 40 and 50 nm for the samples with x=0.2 and 0.8, respectively.**

Effect of Co-Substitution

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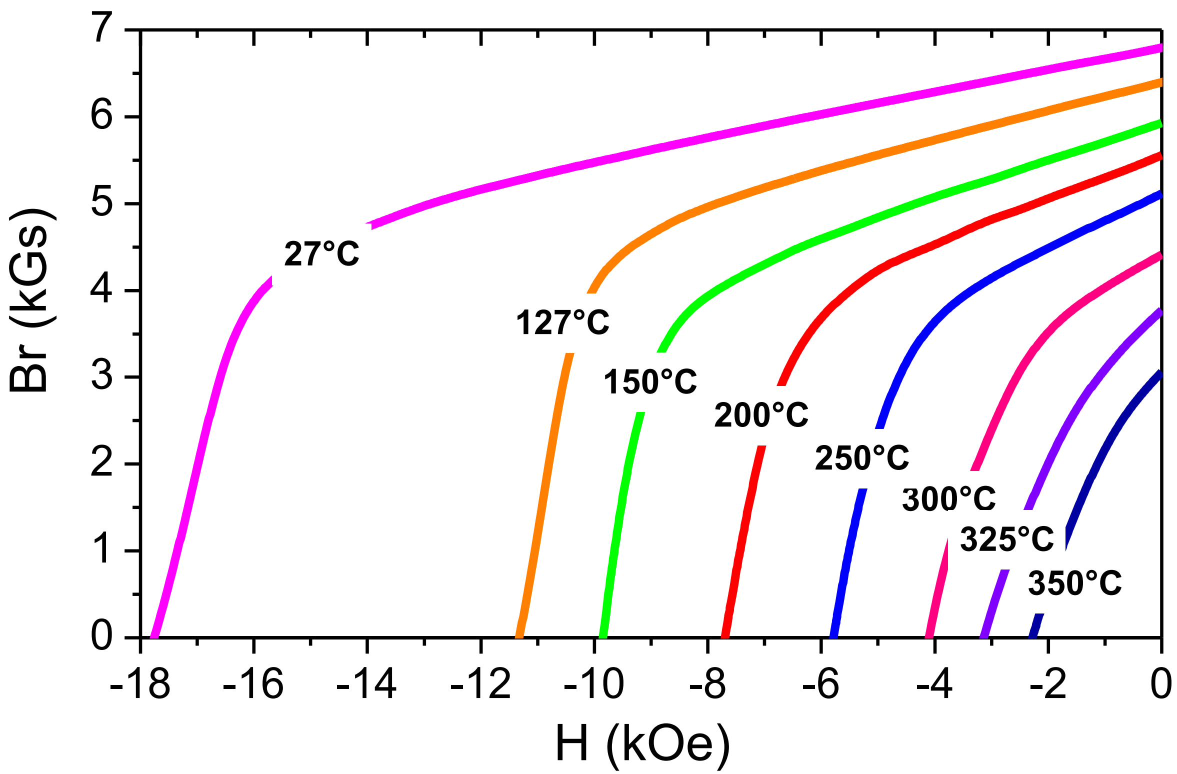
Demagnetized Curves

Annealed $[Nd_x(YDy)_{0.5(1-x)}]_{2.2}Co_{1.5}Fe_{12.5}B$ ribbons annealed at 750°C for 15 min.



- **The demagnetization curves exhibit good squareness at high temperature, even at 300°C.**

Effect of Co-Substitution

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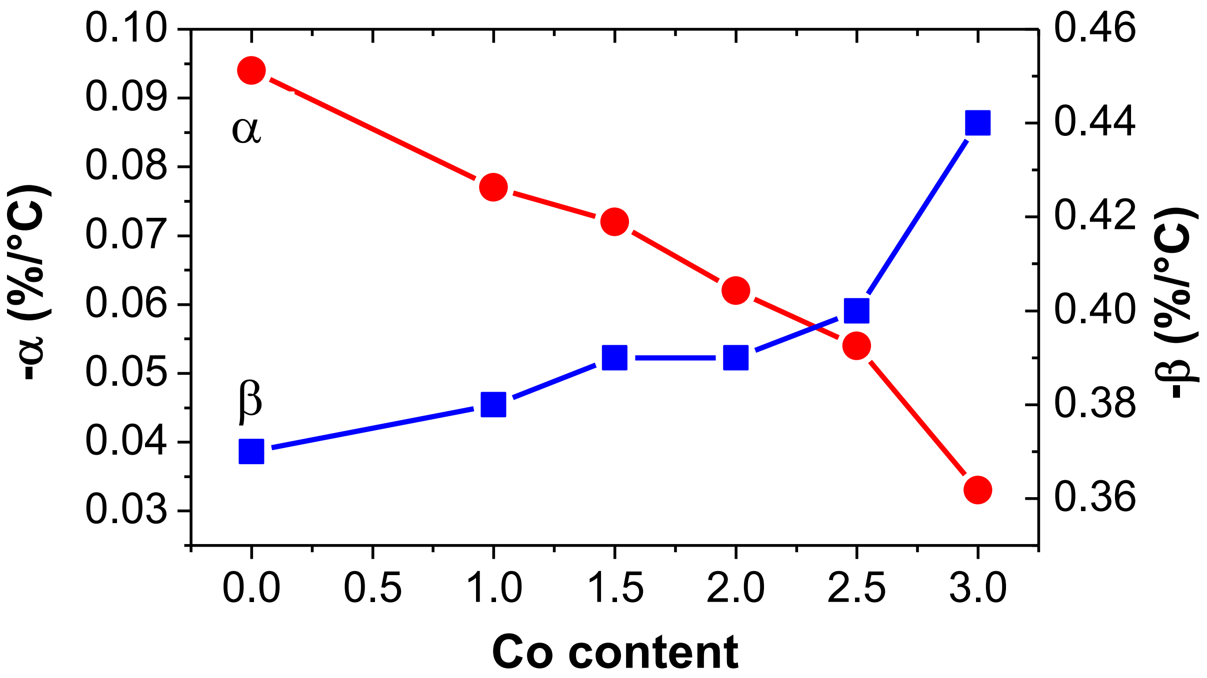
α and β as a Function of Co Content

Annealed $[Nd_{0.5}(YDy)_{0.25}]_{2.2}Co_yFe_{14-y}B$ ribbons annealed at 750°C for 15 min.



- **With increasing Co content ,** α decreases, while β increases.

Effect of Co-Substitution

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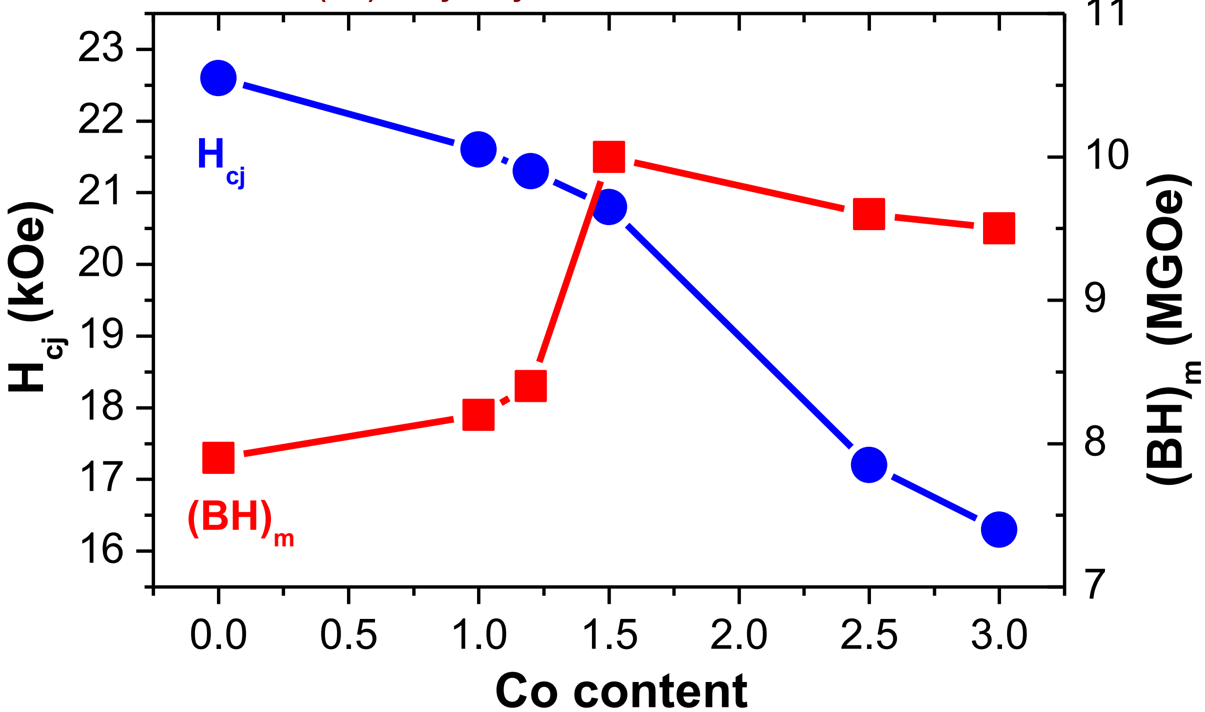
H_{cj} and $(BH)_m$ as a Function of Co Content

Annealed $[Nd_x(YDy)_{0.5(1-x)}]_{2.2-y}Co_yFe_{12.5}B$ ribbons annealed at 750°C for 15 min.



- **With increasing Co content ,** H_{cj} slightly decreases. $(BH)_m$ firstly increases and reaches its maximum value, and then slowly decreases.

Comparison

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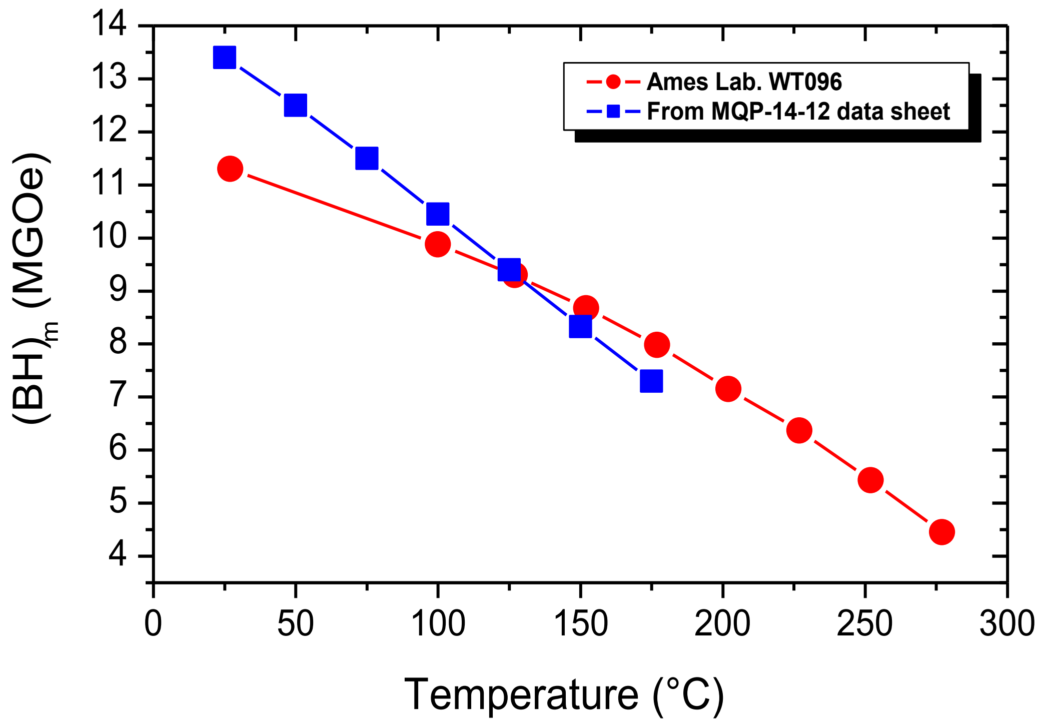
$(BH)_m$ as a Function of Temperature



- **The studied sample exhibits a better temperature dependence of $(BH)_{max}$.**

Alloy SUMMARY

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- YDy-based $[Nd_x(YDy)_{0.5(1-x)}]_{2.2}Fe_{14-y}Co_yB$
  - compensate the loss of M_s and H_{cj} due to heating
  - simultaneously yield smaller temperature coefficient of B_r and H_{cj}.
- The desired properties and thermal stability can be optimized by a judicious mixture of Nd-Y-Dy.
- The YDy-based $R_2Fe_{14}B$ magnets are very promising for high temperature performance.

WT-096 Ames Alloy Composition Converted into 100 kg of Particulate (MQP-11HTP) by Magnequench International

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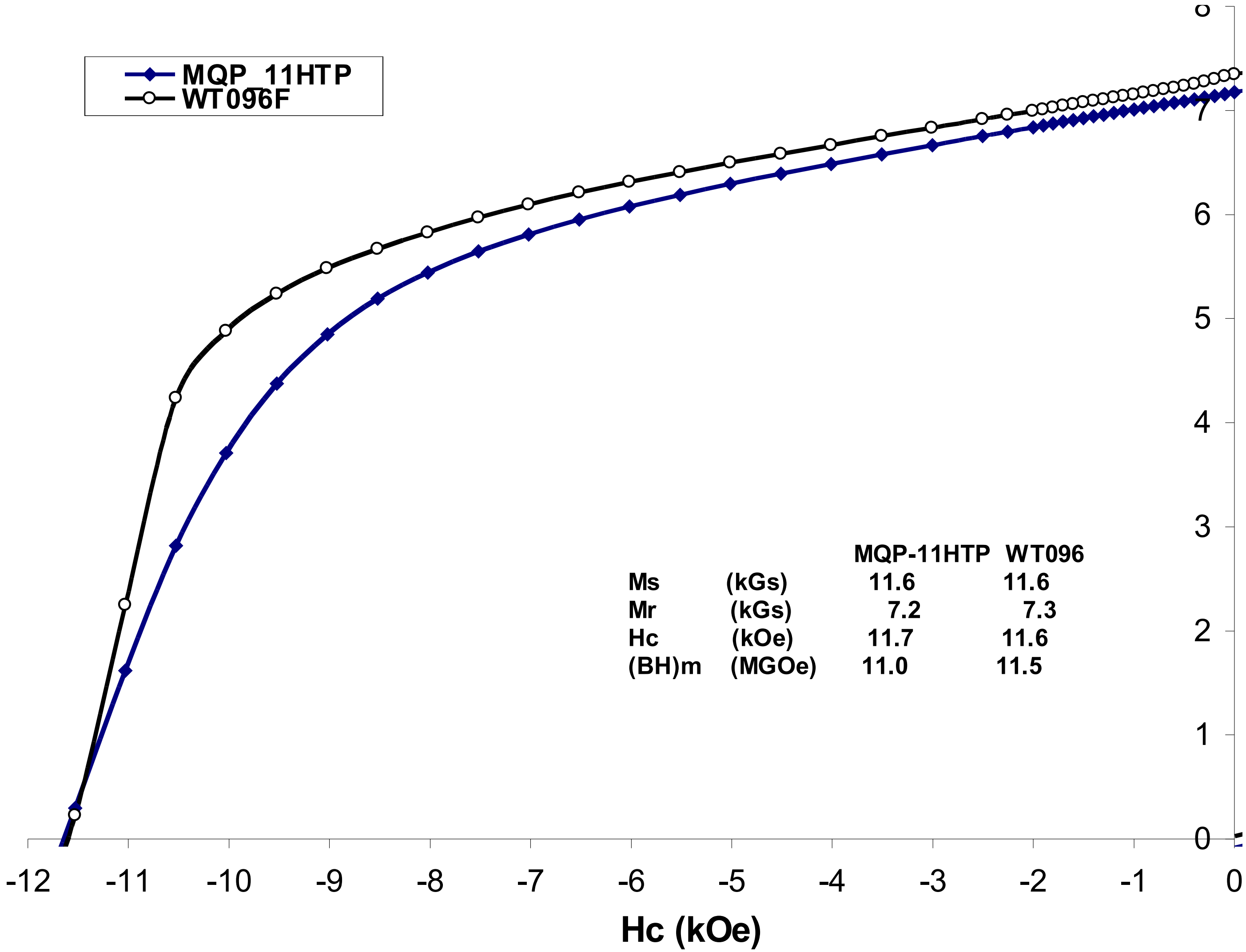
Comparison of Composition and Magnetization of WT-096 and MQP-11HTP



Estimated alloy performance

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