Optimizing Magnetic Properties of Ce-containing Nd-Fe-B-based Magnets through 2-Powder Method

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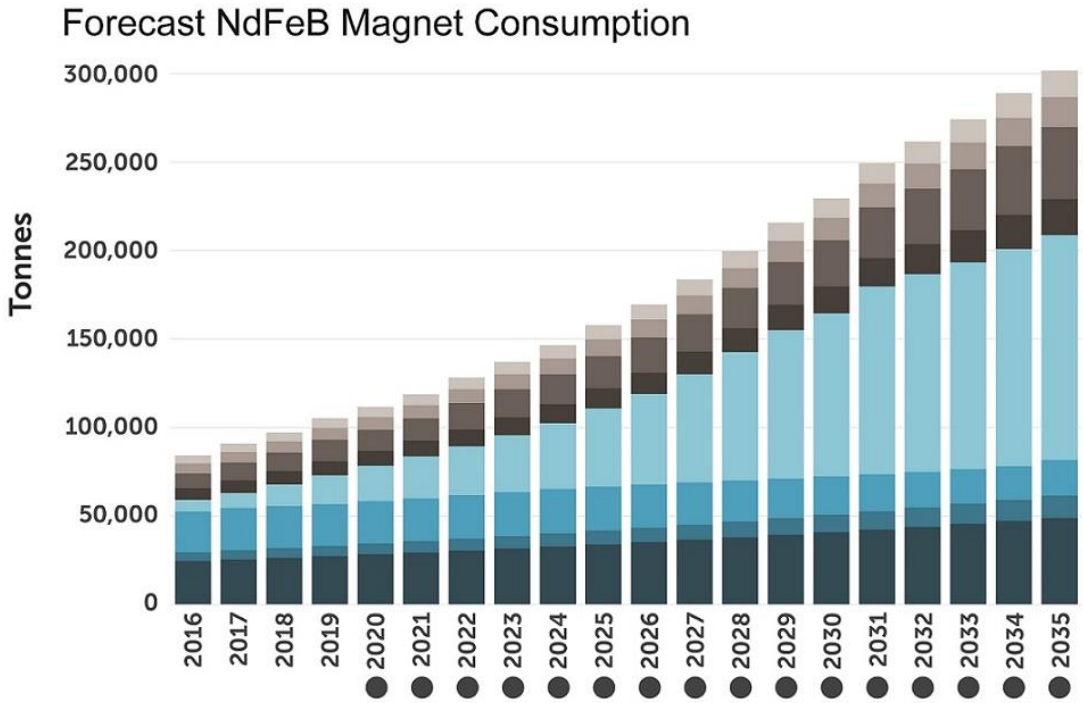
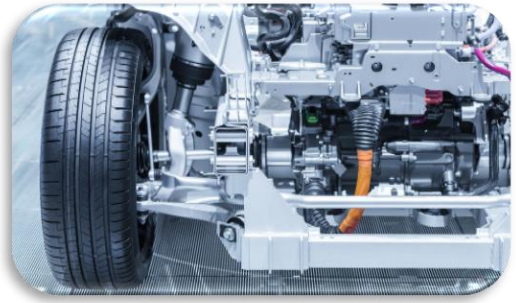
- **Motivation: Substituting Nd by Ce in Nd-Fe-B-based sintered magnets**
  - Supply and demand of REEs
  - Challenges of Ce-containing magnets
- **Application of the 2-powder method in Ce-containing Nd-Fe-B-based magnets**
  - Fundamentals
  - Results
- **Summary and outlook**

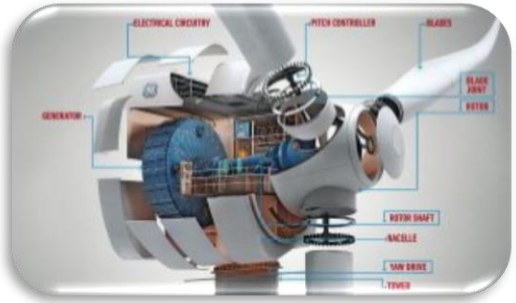
Substituting Nd by Ce
in Nd-Fe-B-based sintered magnets

Supply and demand of REEs

Applications and rapidly increasing demands



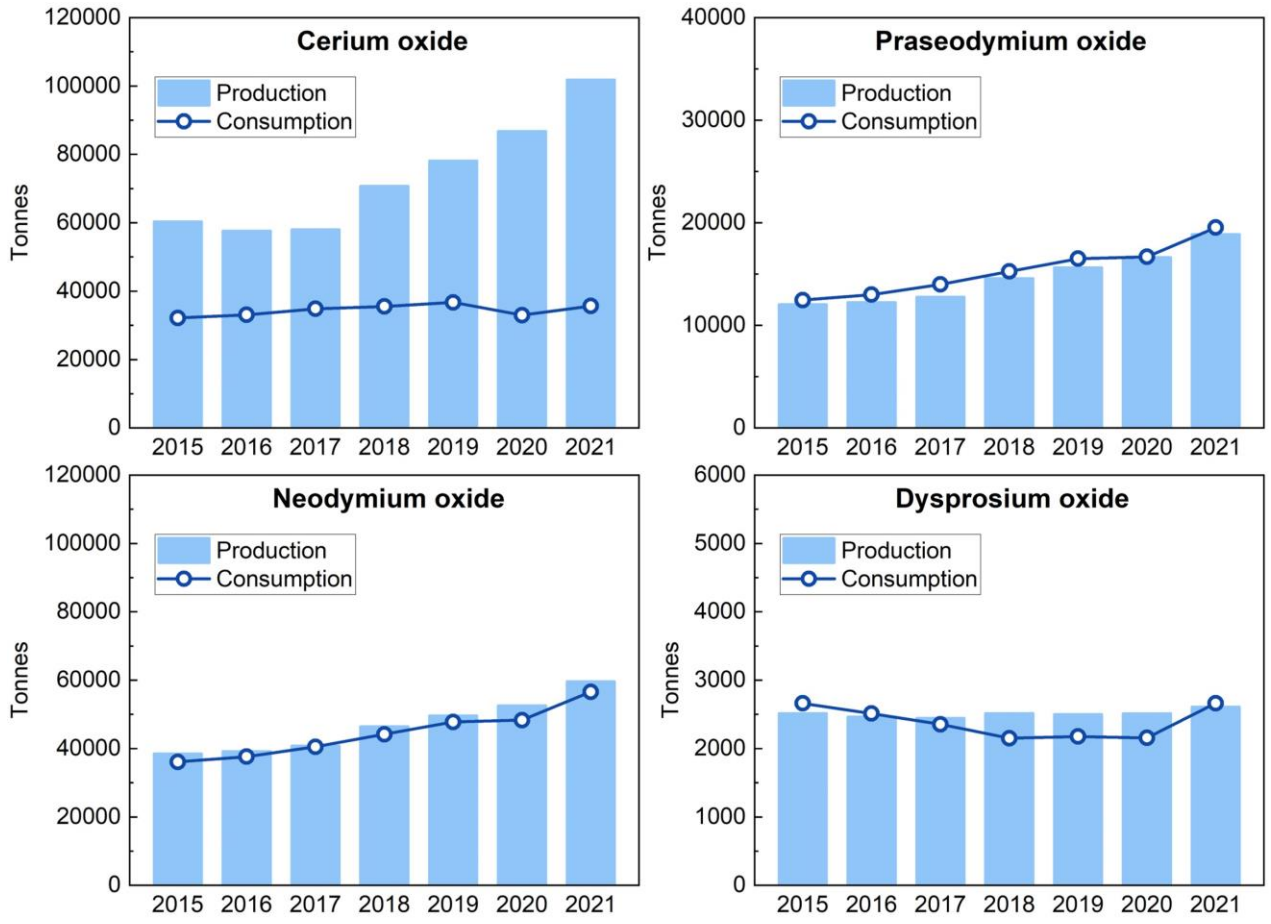




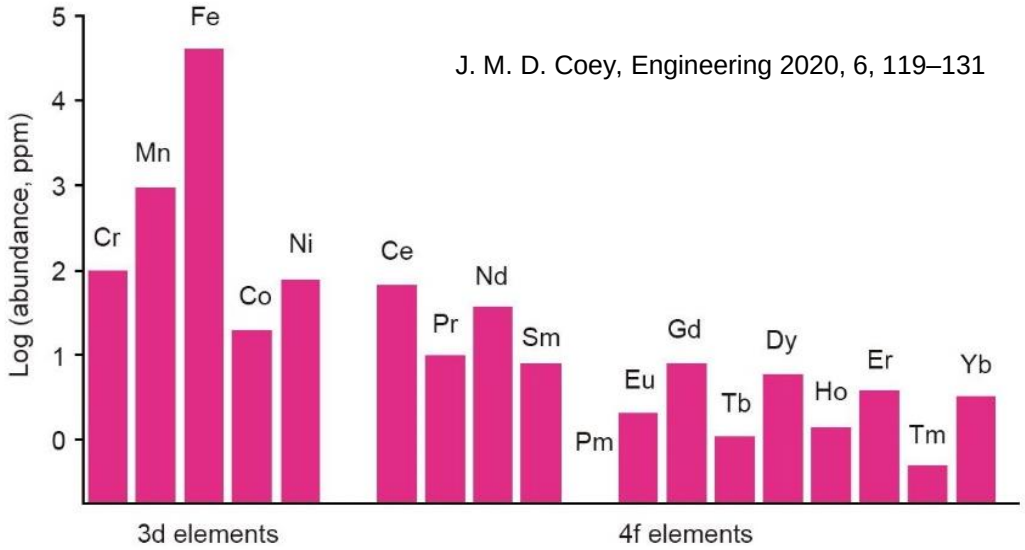
Roskill Rare-Earth Report 2020.

https://mpcomagnetics.com/blog/inverter-air-conditioner-a-new-point-of-growth-for-permanent-magnet-materials/
https://www.aemagnets.com/ndfeb-magnets/
https://knaufautomotive.com/de/wie-sieht-die-zukunft-der-hevs-hybrid-elektrofahrzeuge-aus/
https://tymagnets.com/typical-magnetic-properties-of-wind-turbine-magnets/

Supply and demand of REEs



Redrawn from Adamas Intelligence Rare Earth Magnet Market Outlook to 2035



J. M. D. Coey, Engineering 2020, 6, 119–131

Considering:

- Natural abundance
- Supply-demand balance

→Integration of Ce into Nd-Fe-B-based magnets

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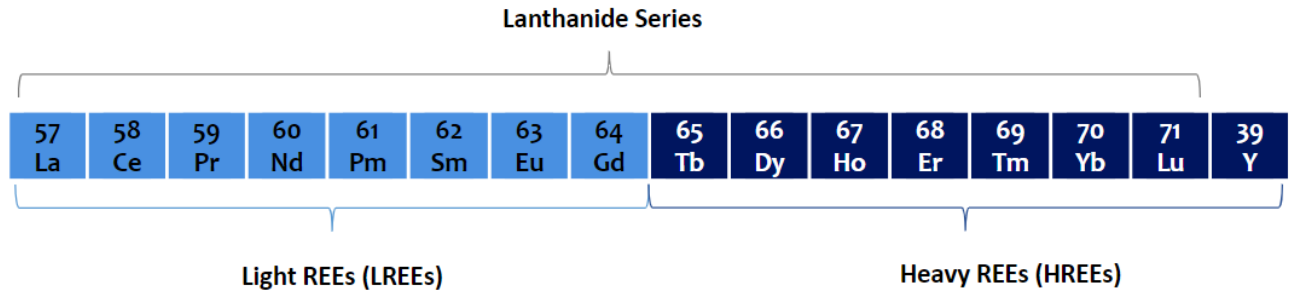
Challenges of Ce-containing magnets



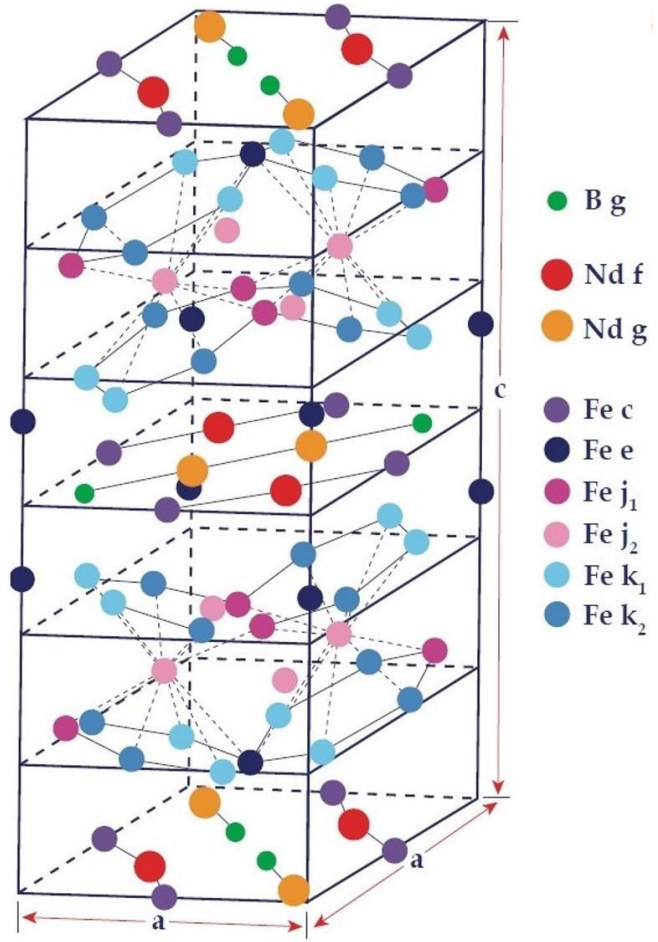
Challenges for Ce substitution:

- Inferior intrinsic properties

(T=25 °C)	$\mu_0 M_s$ [T]	$\mu_0 H_a$ [kA/m]	T_C [°C]	Lattice constant a [Å]	Lattice constant c [Å]
$Nd_2Fe_{14}B$	1.60	5809	312	8.80	12.20
$Ce_2Fe_{14}B$	1.17	2069	151	8.76	12.11

- Deteriorated microstructure due to secondary phases

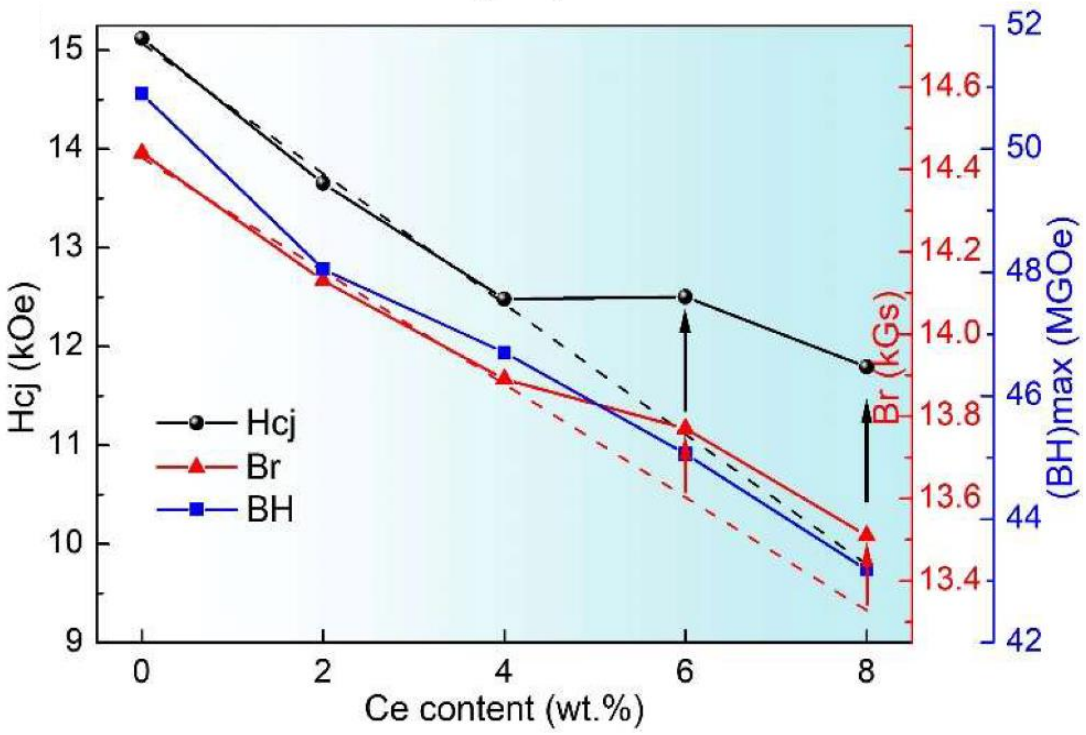
  ex: $REFe_2$ (harmful when RE contains Nd or Pr), RE_2Fe_{17}



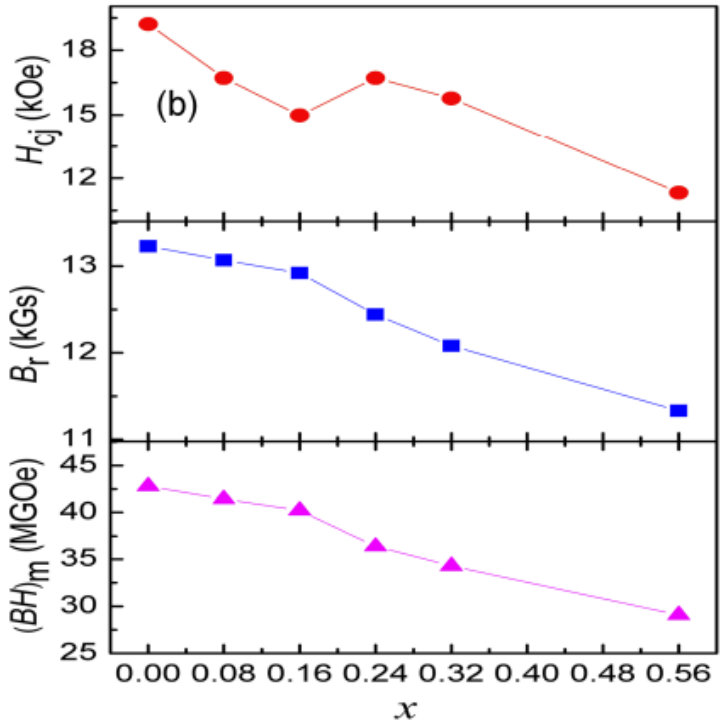
Adamas Intelligence Rare Earth Magnet Market Outlook to 2035
J. F. Herbst, Reviews of Modern Physics 1991, 63, 819–898

Challenges of Ce-containing magnets

$Di_{30.3-x}Ce_xFe_{bal}M_{1.4}B_{0.92}$



$(Di_{1-x}Ce_x)_{27.5}Dy_3M_{0.2}Fe_{bal}B_1$



Di: Nd+Pr

Increased amount of Ce substitution

→ Severe decline in magnetic performances.

G.M. Li et. al., Acta Materialia 2023
C. Yan, et al., IEEE Transactions on Magnetics 2014

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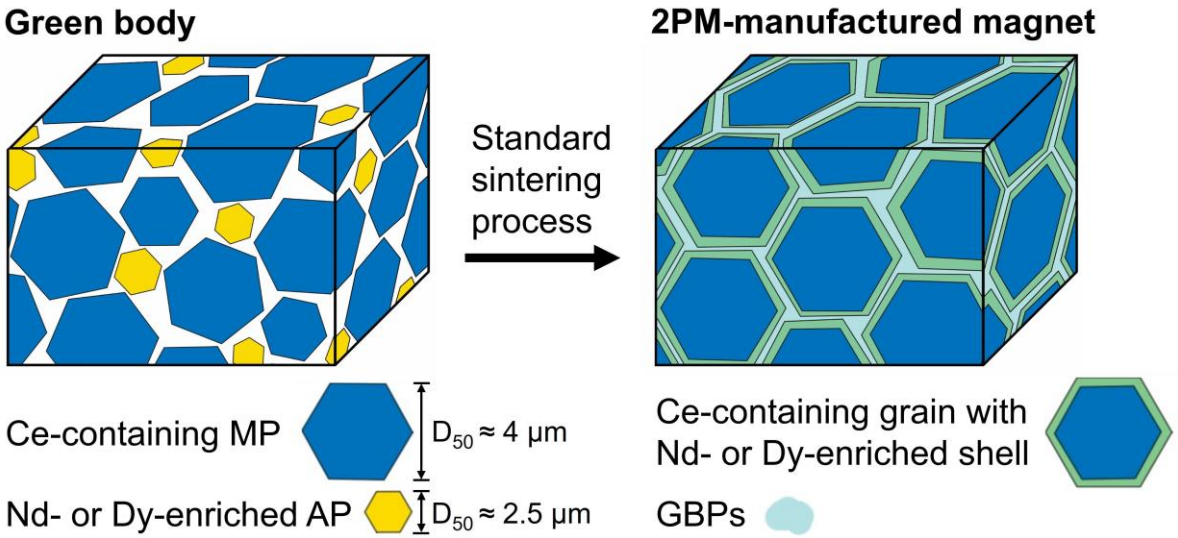
Application of the 2-powder method in Ce-containing Nd-Fe-B-based magnets

Fundamentals: 2-powder method



	Composition	Particle size [µm]
MP	$(Nd_{15.1}Pr_{5.1}Ce_{10})_{30.2}Fe_{bal.}TM_{0.32}B_{0.91}$	3.9
AP_1	$Nd_{30.2}Fe_{bal.}Co_{1.9}TM_{0.32}B_{0.91}$	2.4
AP_2	$(Nd_{15.1}Pr_{5.1}Dy_{10})_{30.2}Fe_{bal.}Co_{1.9}TM_{0.32}B_{0.91}$	2.6

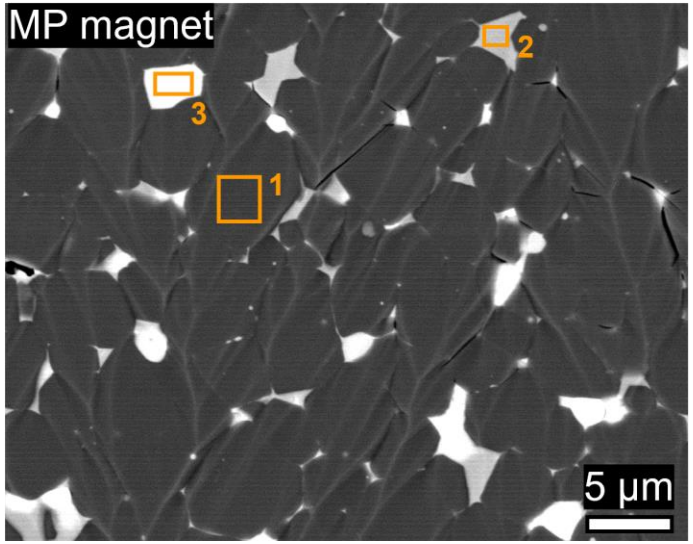
Size ratio MP:AP = 1.6:1

Mixing weight ratio MP:AP = 7:3

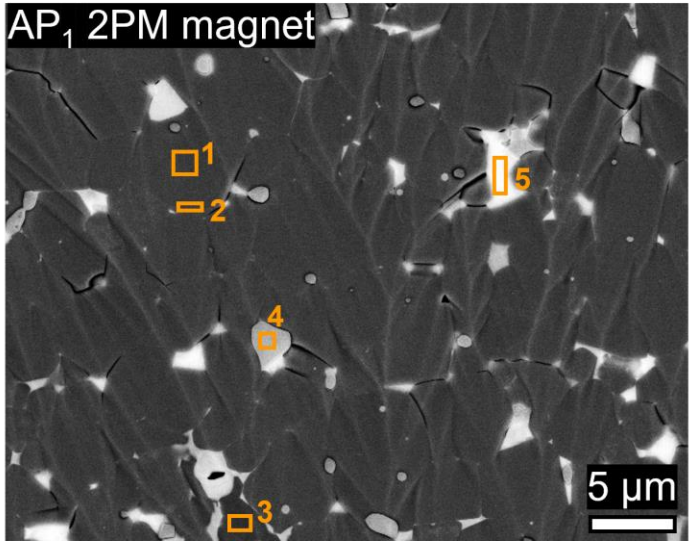
- Uniform core-shell structure
- No size and shape restriction
- No additional treatment required

Aim: to maintain sufficient magnetic properties while substituting certain amount of more critical Nd by Ce.

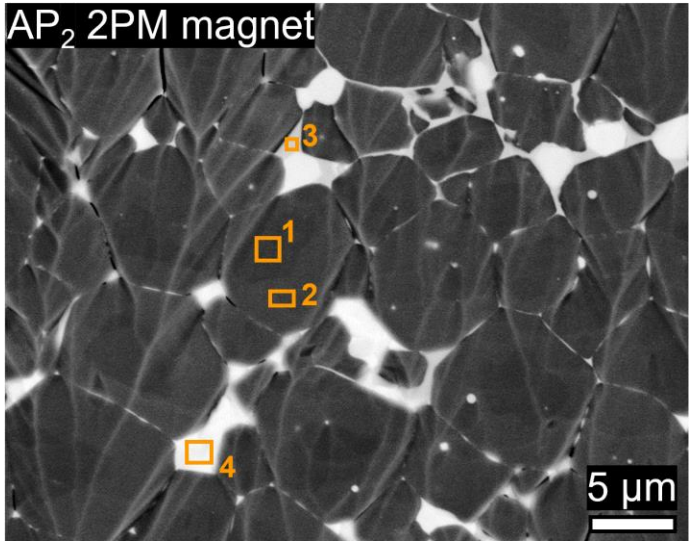
Results: microstructures



1	$(Ce,Nd)_2Fe_{14}B$
2	$(Ce,Nd)Fe_2$
3	(Ce,Nd)-rich phase



1	Nd-lean $(Ce,Nd)_2Fe_{14}B$
2	Nd-rich $(Ce,Nd)_2Fe_{14}B$
3	$(Ce,Nd)_{1-\varepsilon}Fe_4B_4$
4	$(Ce,Nd)Fe_2$
5	(Ce,Nd)-rich phase



1	Dy-lean $(Ce,Nd)_2Fe_{14}B$
2	Dy-rich $(Ce,Nd)_2Fe_{14}B$
3	$(Ce,Nd)Fe_2$
4	(Ce,Nd)-rich phase

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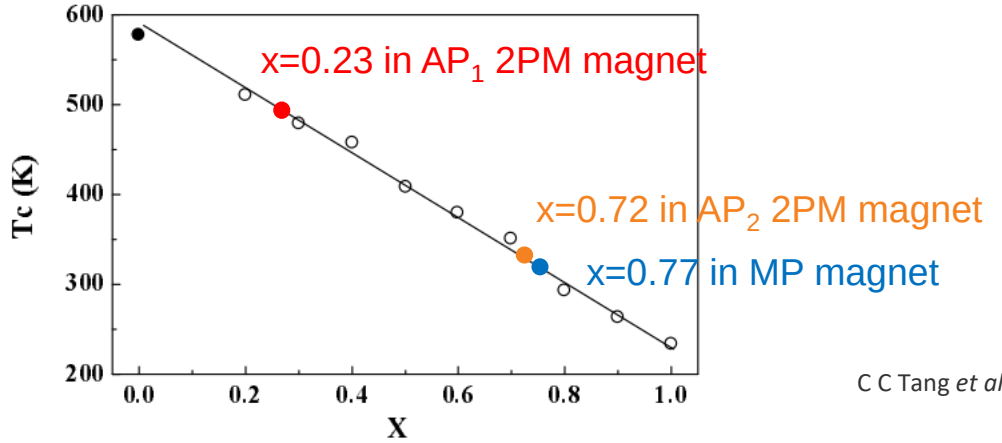
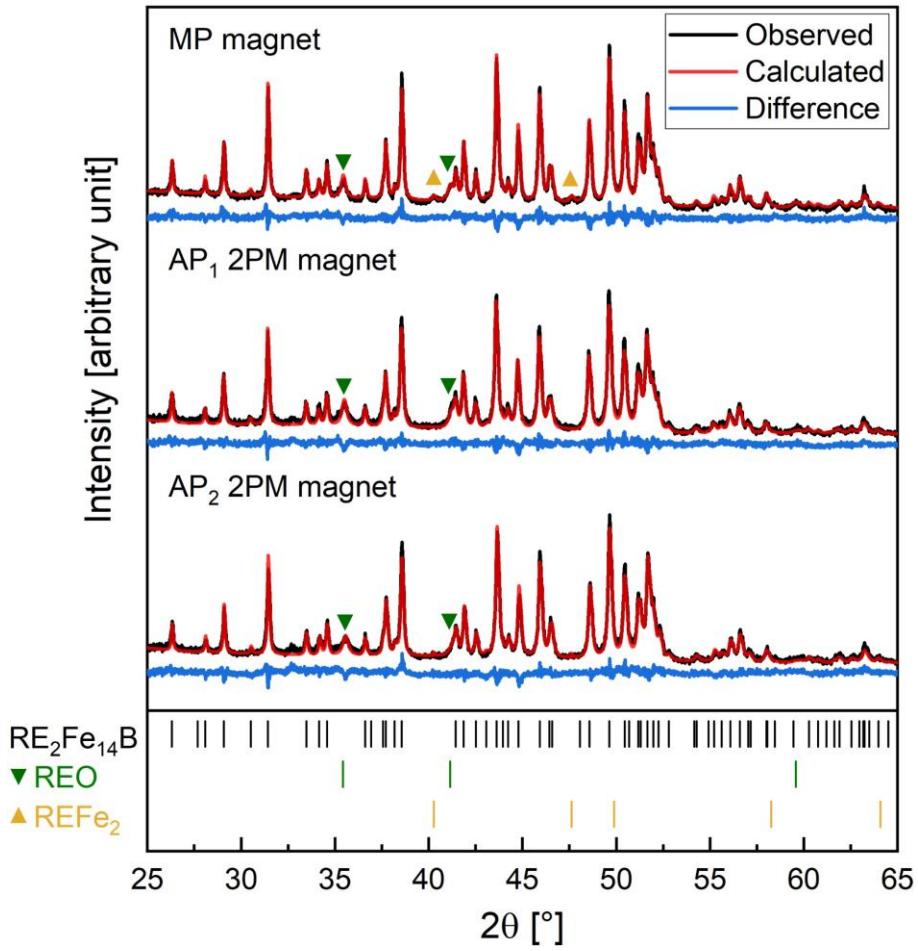
Results: $REFe_2$ analysis

	EDX [wt.%]				$(Nd,Pr)_{1-x}Ce_xFe_2$	XRD
	Nd	Pr	Ce	Fe	x	$REFe_2$ content
MP magnet	9.3	3.5	43.5	43.7	0.77	0.74 %
AP_1 2PM magnet	34.0	7.2	12.0	44.7	0.23	0.20 %
AP_2 2PM magnet	12.1	3.5	40.2	44.3	0.72	0.07 %

$Nd_{1-x}Ce_xFe_2$



C C Tang *et al* 1998 *J. Phys. D: Appl. Phys.* **31** 2426



→ $REFe_2$ phases in all magnets are soft ferromagnetic at RT.

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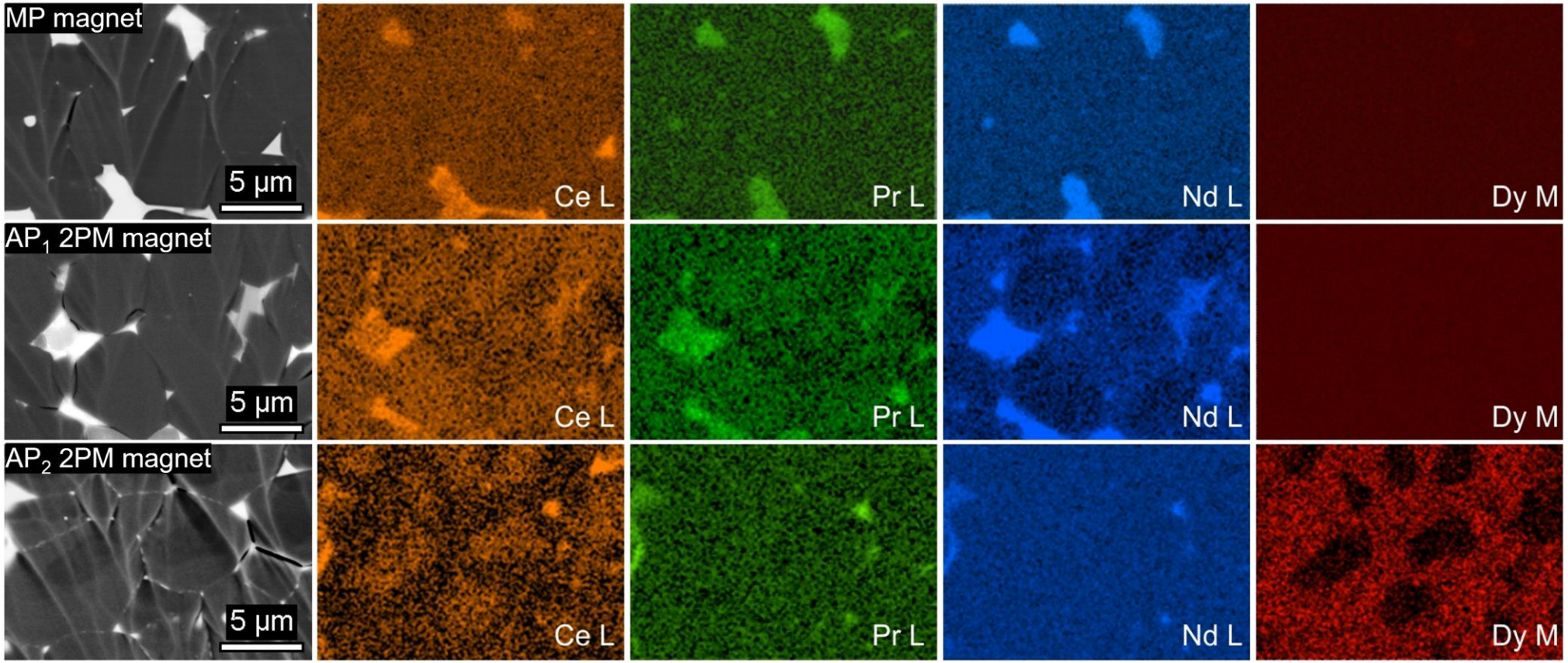
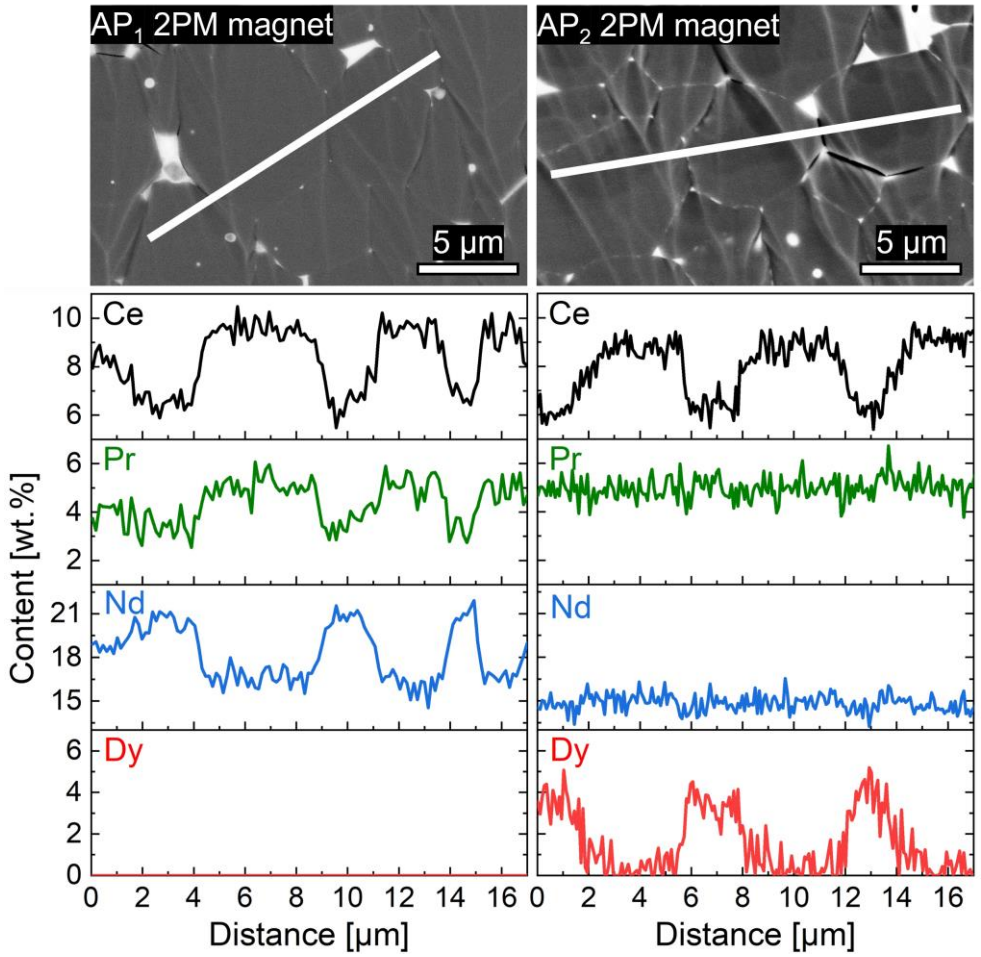
Results: element distribution



Core-shell structure formed in 2PM magnets.

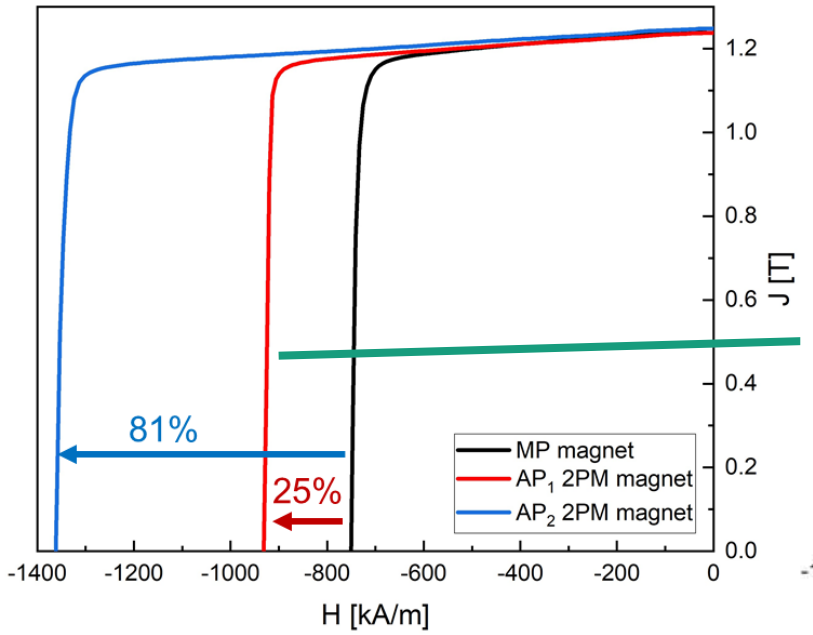
Results: element distribution

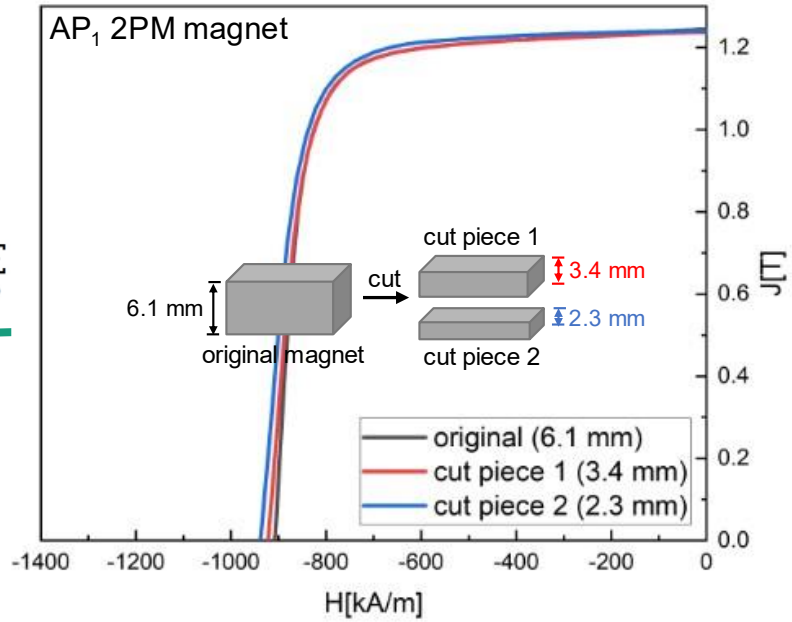


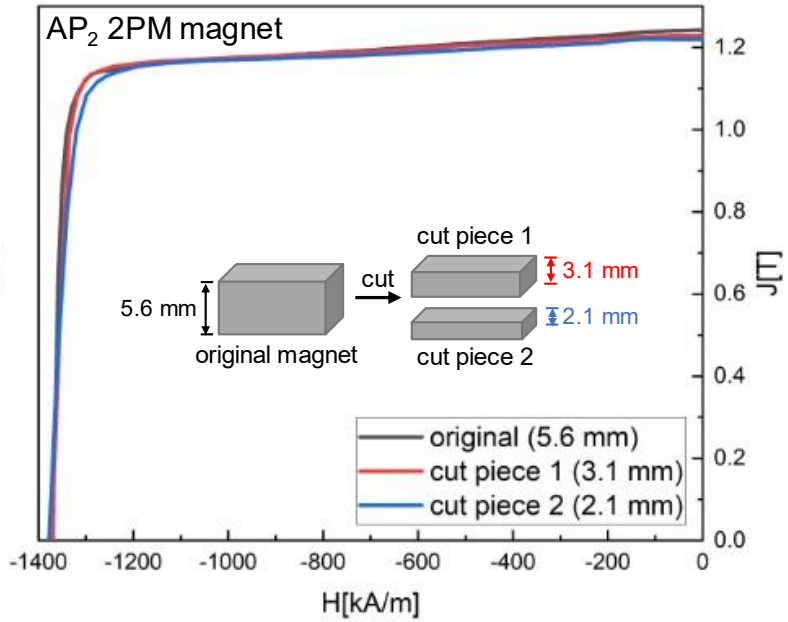
	Composition
MP	$Nd_{15.1}Pr_{5.1}Ce_{10}Fe_{bal.}TM_{0.32}B_{0.91}$
AP_1	$Nd_{30.2}Fe_{bal.}Co_{1.9}TM_{0.32}B_{0.91}$
AP_2	$Nd_{15.1}Pr_{5.1}Dy_{10}Fe_{bal.}Co_{1.9}TM_{0.32}B_{0.91}$

- RE concentrations in core region are based on those in MP.
- RE concentrations in shell region are determined mainly by AP:
  - AP_1 2PM magnet: Nd is enriched
  - AP_2 2PM magnet: Dy is enriched.

Results: magnetic properties







	Nd [wt.%]	Ce [wt.%]	Dy [wt.%]	Price [USD/kg]
MP magnet	20.2	10	0	15.78
AP_1 2PM magnet	23.2	7	0	17.96
AP_2 2PM magnet	20.2	7	3	25.39
Conventional Nd-Fe-B magnet	30.2	0	0	23.05

-22%

JL MAG Rare-Eart Co Europe B.V., Sustainable Design for Recycling, 2020.

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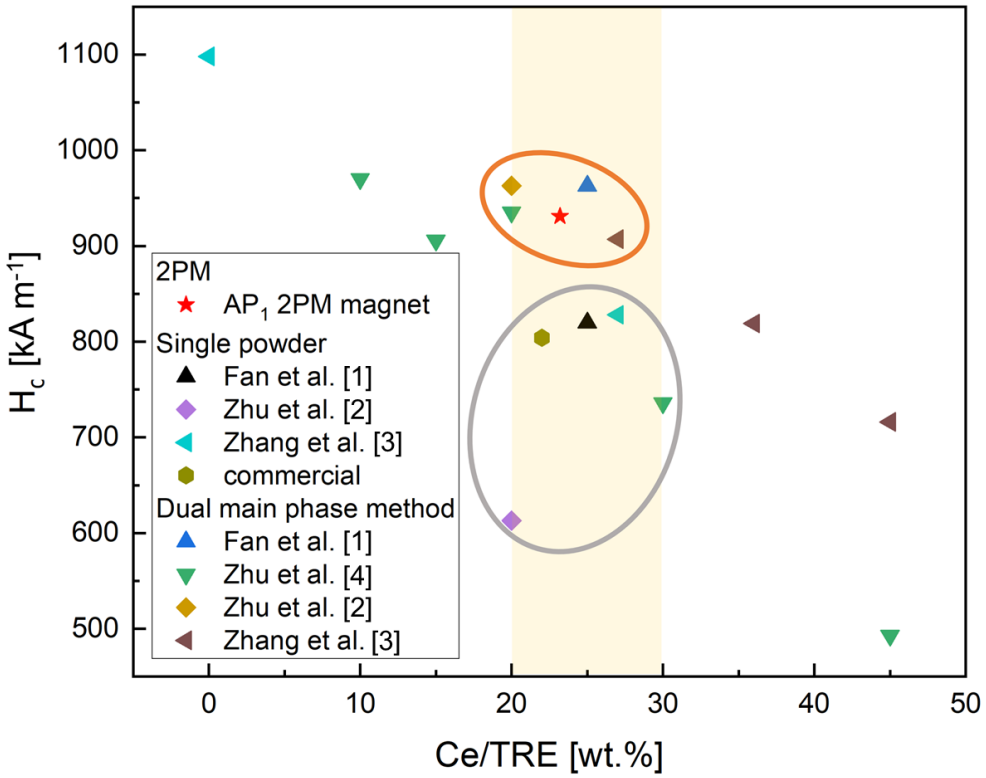
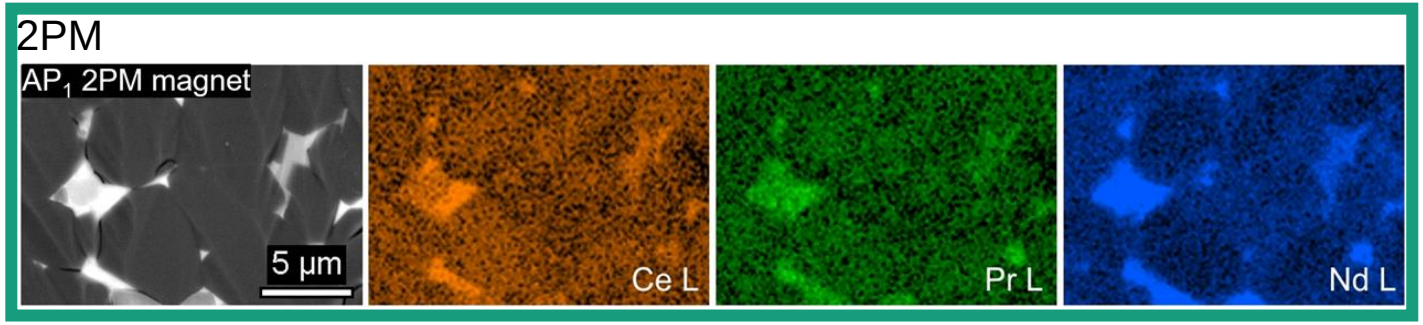
Evaluation of 2PM

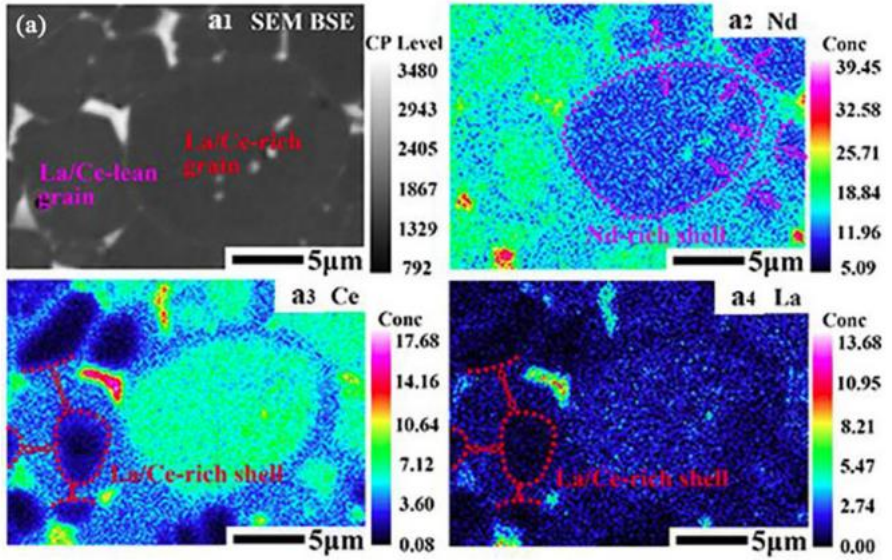


The effectiveness of the 2PM in enhancing coercivity is competitive with the dual main phase method.



v.s.

Dual main phase method



with conceptually higher potential!

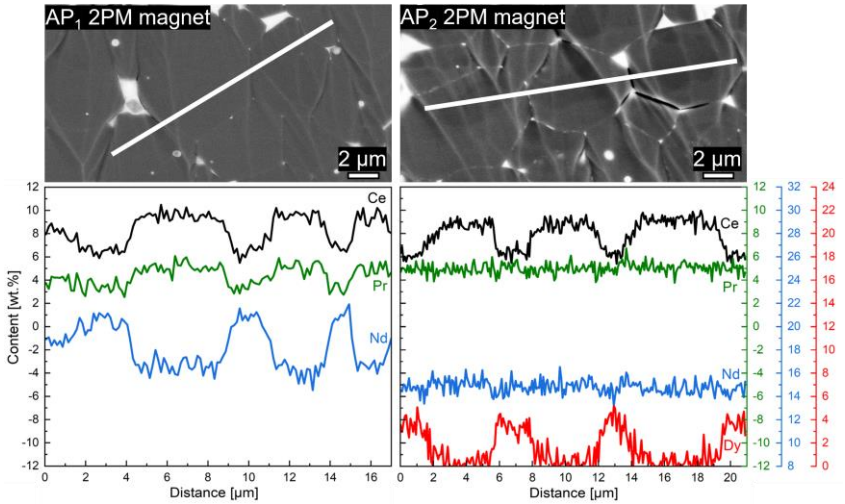
[1] X. Fan *et al*, *J. Magn. Magn. Mater.*, **2016**, 419, 394–399
[2] M. Zhu *et al*, IEEE Trans. Magn. **2015**, 51, 11 1–4.
[3] Y. Zhang *et al*, Acta Materialia, **2017**, 128 22–30.
[4] M. Zhu *et al*, IEEE Trans. Magn., **2014**, 50, 1 1–4.

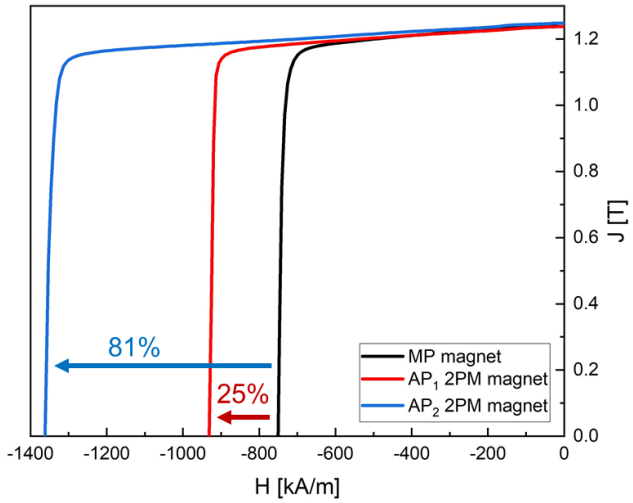
Wei Li *et al*, *J. Magn. Magn. Mater*, **2019**, 476, 302–3

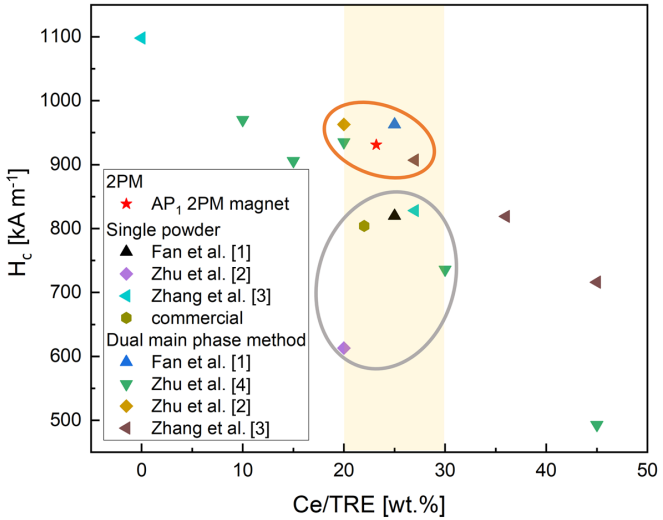
Summary and outlook

Summary:

- 2PM can effectively improve coercivity in Ce-containing magnets by forming core-shell structures.
- Nd and Dy preferentially enriched in grain shells shows the control of the 2PM over RE distribution in core-shell structures.







Detailed results have been submitted to Advanced Engineering Materials.

Outlook:

- Ongoing research optimizes the particle size ratio between MP and AP, anticipating further coercivity improvement.
- The efficiency of 2PM will be evaluated in magnets with different sizes compared to other methods (ex, GBDP).

Thank you for your attention!

Contact

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