2025/6/27 15:00-15:50
軟磁性材料研究会(第28回) 日本ボンド磁石協会

超低損失軟磁性材料開発のための新規アプローチ

岡本 聡

東北大学 多元物質科学研究所

Funding

MEXT DXMag DXMT NEDO

Research Groups and Collaborators

MONASH University K. Suzuki

TOKIN A. Urata, H. Oikawa, M. Ikeda

Material Developments

Loss Analysis
Experiment, Theory, Simulation

Our group
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NIMS
G. Ravi, H.Sepehri-Amin, T. Ohkubo

Characterization

Loss Measurements and Modeling

AIST S. Tamaru, T. Ogasawara

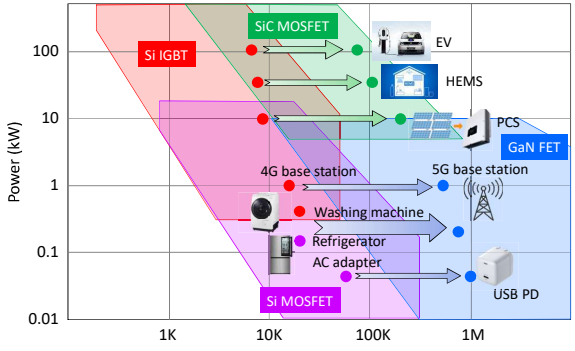
Y. Sato

Magnetic Device Laboratory Ltd. Y. Uehara

Today's Contents

1. Introduction
2. Recent Approaches of Amorphous and Nanocrystalline Alloys
3. Our Recent Approaches for Nanocrystalline Alloys
   - 3.1. Very Low Crystallinity NC Alloy Ribbon [Nature Comm, Under review]
   - 3.2. Hot-Pressed NC Alloy Powder [Acta Mater 294 (2025) 121159]

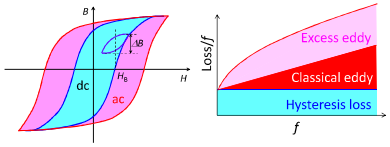
Soft Magnetic Materials in Advanced Power Electronics



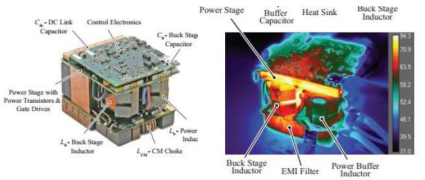
Next generation power semiconductors SiC, GaN

Toward high frequency switching

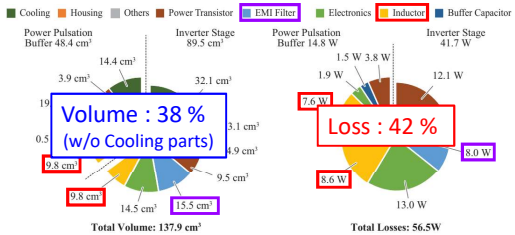
⇨ Significant iron loss in magnetic passive devices



■ Google Little Box Challenge (GLBC)

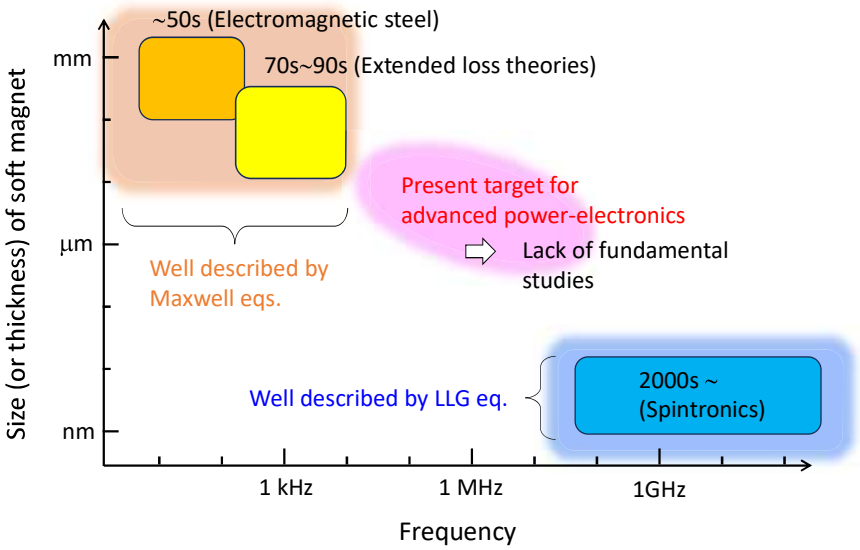


[Neumayr, CPSS Trans. Power Electro. Appl. 5, 251 (2020)]

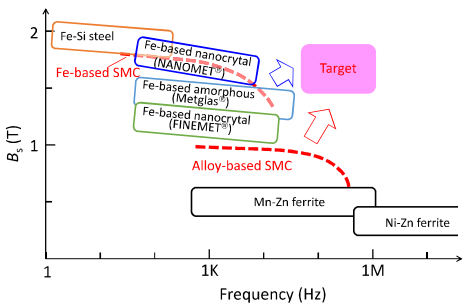


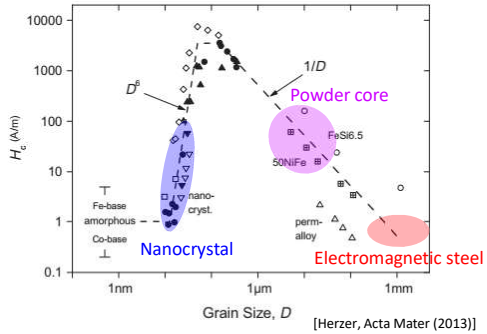
Magnetic passive devices

Size and Frequency Regions of Soft Magnetic Studies



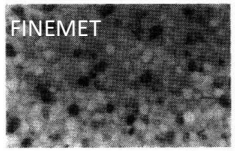
High $\mu_0 M_s$ Nanocrystalline Alloys





[Herzer, Acta Mater (2013)]

Nanocrystalline alloys



[Yoshizawa, JAP (1988)]

Well dispersed α-Fe nano-crystalline grains with amorphous matrix

- FINEMET ($Fe_{73.5}Nb_3Si_{13.5}B_9Cu_1$) : 1.24T [Yoshizawa, JAP (1988)]
- NANOPERM ($Fe_{90}Zr_7B_3$) : 1.63T [Suzuki, JAP (1996)]
- $Fe_{82.7}Si_2B_{14}Cu_{1.3}$: 1.85T [Ohta, JJAP (2007)]
- $Fe_{84.8}Si_1B_{10}P_3Cu_{1.2}$: 1.82T [Urata, IEEE Mag (2011)]
- HiB-NANOPERM ($Fe_{87}B_{13}$) : 1.92T [Zang, Scripta Mater (2017)]

Problems of recent high $\mu_0 M_s$ NC alloys

⇧

Our new approaches

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1. Introduction
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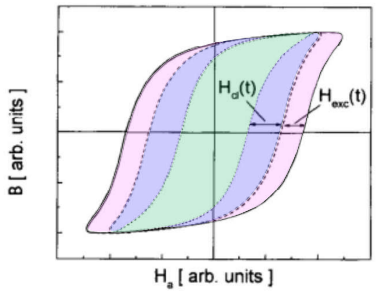
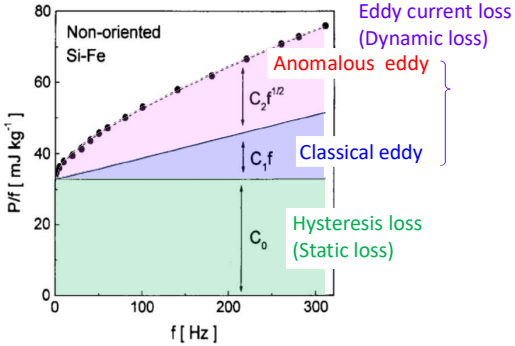
[Acta Mater 294 (2025) 121159]

Classical Intuitive Understanding of Iron Loss





Steinmetz eq. $P = kf^{\alpha}B_m^{\beta}$ ⇨ W [J/m³] = W_{hys} + W_{cl} + W_{an}

[Steinmetz (1892)]

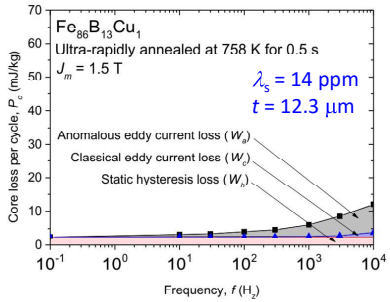
W_{hys} : constant

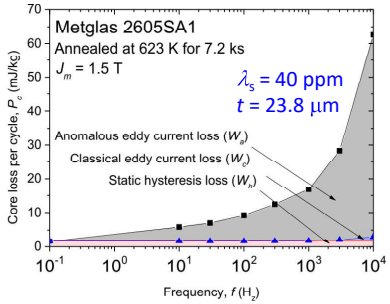
$W_{cl} = \frac{\pi^2}{6}\sigma d^2 B_m{}^2 f$ from Maxwell eqs. for uniform flux change

$W_{an} = 8\sqrt{\sigma G S V_0} B_m{}^2 f^{0.5}$ from statistic theory for domain wall motion

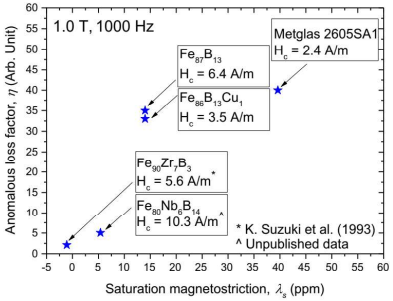
[Bertotti (1985)]

Anomalous Eddy Current Loss?





[Parsons, JMMM 476, 142 (2019)]



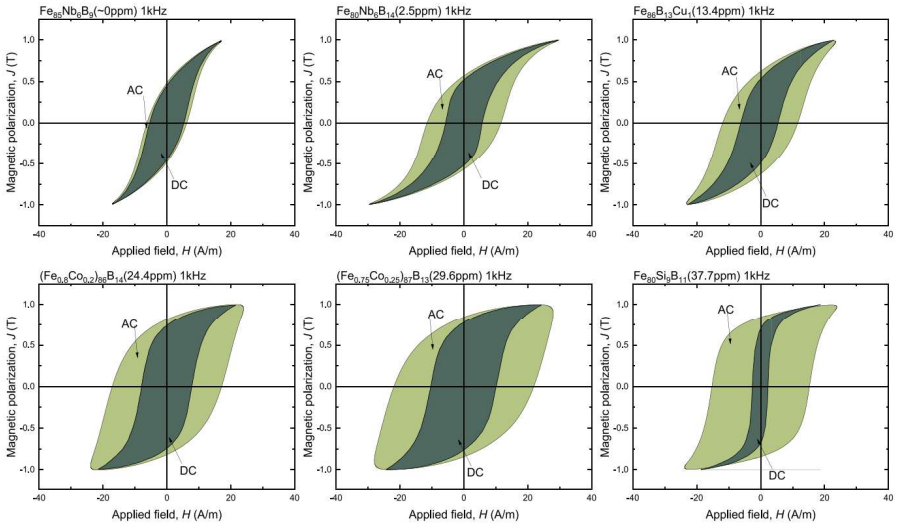
- It is hard to explain W_{exc} by eddy current origin.
- W_{exc} has strong relation with λ

⇨ Possibility of λ origin loss

* This is not static effect such as inverse λ effect but the dynamic effect.

"Anomalous eddy current loss" is misleading term. Excess loss is better.

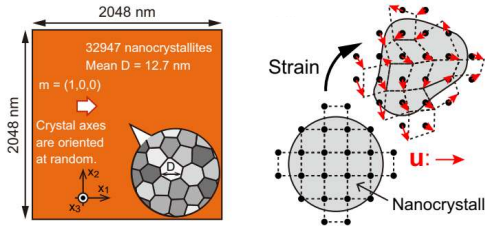
AC and DC *B-H* Curves of Different λ_s Ribbons

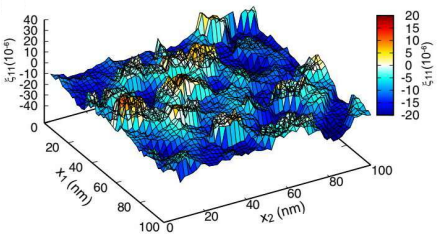


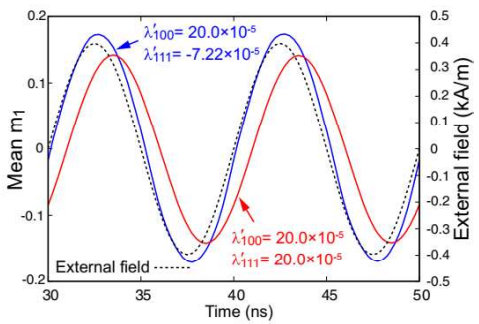
[Huang, JMMM 592, 171810 (2024)]

- P_{hys} and DC coercivity have less relation with λ_s.
- AC loss becomes larger for larger λ_s.

Magnetostriction Origin Excess Loss







Magnetostriction cause phase lag through friction of lattice deformation.

[Tsukahara, NPG Asia 476, 142 (2019)]

Formulation of Magnetostriction Origin Excess Loss

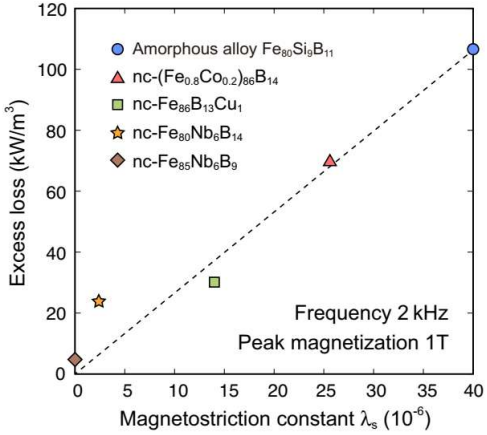
[Tsukahara, NPG Asia Meter. 16, 19 (2024)]

$$P_{dw}/f \sim 8\sqrt{\beta_{dw} V_{dw} S \kappa_{dw}^3 (M_{max} f)}^{1/2}$$

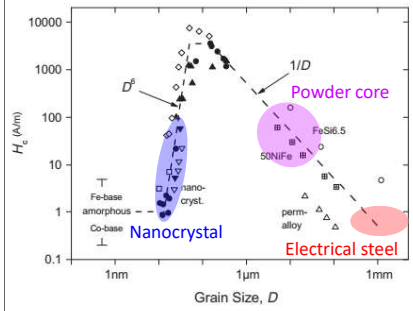
$$\beta_{dw} \propto \alpha + \lambda_s D$$

α : Gilbert damping
D : Viscosity of elasticity

Same power law of eddy current origin P_{exc}



Nancrystalline Alloys

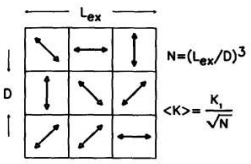


Random anisotropy model

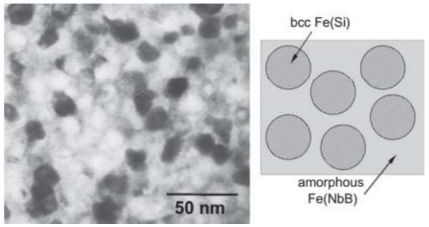
Exchange coupled averaging

$K_{av} \approx (K^4/A_{ex}^3)D^6$

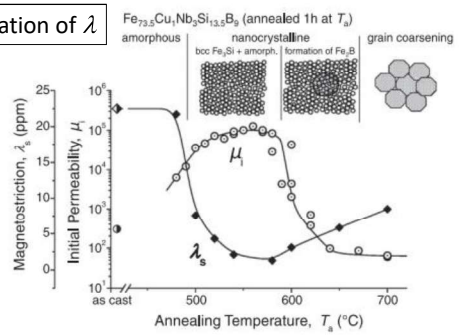
[Herzer, IEEE Trans Mag 26, 1397 (1990)]



Cancellation of λ



[Herzer, Acta Mater (2013)]



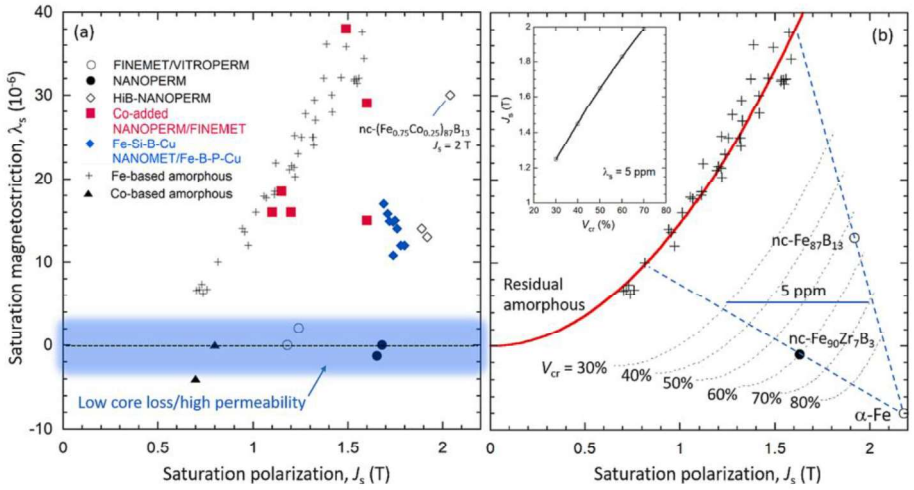
$\lambda_s \approx x_{cr}\lambda_s^{Fe(Si)} + (1 - x_{cr})\lambda_s^{am}$

Negative Positive

Crystallinity of 50 % has been best.

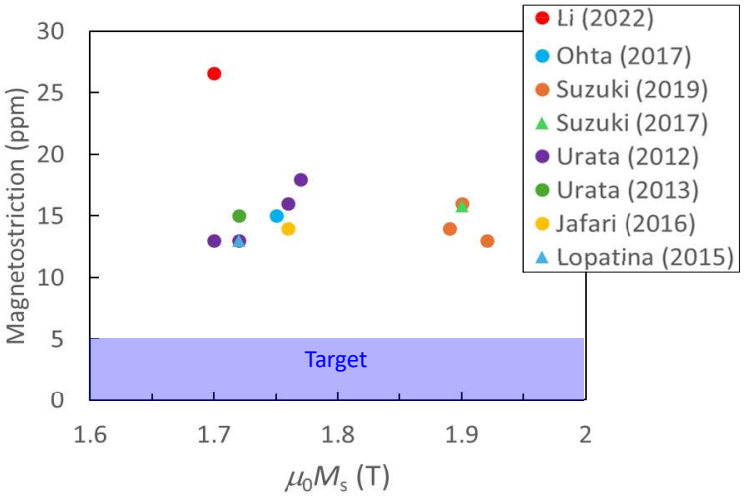
Material Design Prospect for High-M_s NC-Ribbons

MONASH University
Prof. Suzuki Gr.



[Suzuki, JMMM (2024)]

Recent High-M_s nc-Ribbons

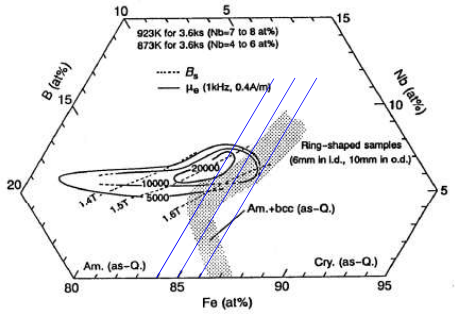


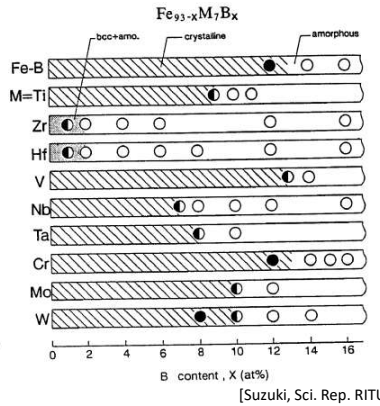
Recent High-M_s nc-Ribbons

FINEMET	$Fe_{73.5}Nb_3Si_{16.5}B_6Cu_1$
NANOPERM	$Fe_{80-91}(Nb, Zr, Hf)_{5-7}B_{2-14}$
Hitachi Metal Alloy	$Fe_{80-83}Si_{2-5}Mo_{0-0.2}B_{13-15}Cu_{1-1.5}$
NANOMET	$Fe_{83-85}Si_{0-6}P_{3-9}B_{5-11}Cu_{0.7-1.2}$
HiB-NANOPERM	$Fe_{86-87}B_{13-14}Cu_{0-1.5}$

- 3~6 elements
- Almost upper limit of Fe content
- How to reduce the element which reduces M_s?

Fe-Nd-B Ternary Alloy





[Suzuki, Sci. Rep. RITU (1994)]

Problems of Soft Magnetic Materials for AI

Material space Extremely huge and complex

- Various alloy categories
  - ✓ Crystalline (Fe, Fe-Co, Fe-Si, Fe-Si-Al, Fe-Ni)
  - ✓ Amorphous (Fe-based, Co-based)
  - ✓ Nanocrystalline
  - ✓ High entropy alloy (HEA)
  - ✓ Ferrite
- Complex multi elements
- Various forms
  - ✓ Ribbon
  - ✓ Powder
  - ✓ Bulk

Multi Objectives Soft magnetic properties are categorized to two group.

B_s, T_c, K_u, λ_s, H_c, μ, P_{cv}

Intrinsic physical parameters of material

Technical parameters

How to get data? Experiment, DFT cal

Experiments, Simulation, Empirical model

Complex Descriptors

✓ Composition

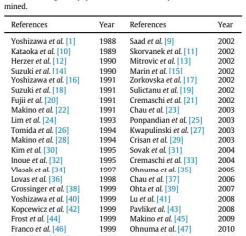
✓ Microstructure
✓ Temperature
✓ Time (frequency)
✓ Amplitude

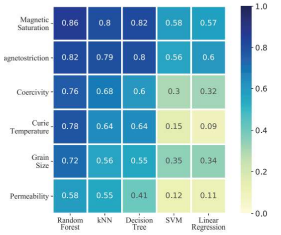
✓ Composition
✓ Fabrication condition
✓ Annealing
✓ ...
✓ ...

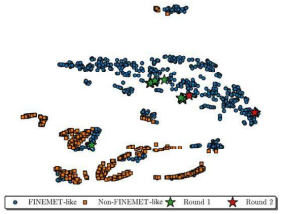
✓ ...
✓ ...
✓ ...
✓ ...

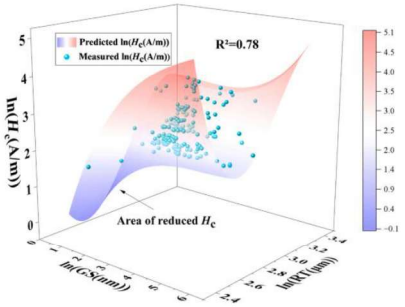
Data Science Approaches for Soft Magnetic Materials

Nanocrystal









$Fe_{85.5}B_{11}P_{1.5}Cu_{0.5}Nb_{1.5}$
$\mu_0 M_s$ = 1.76 T, H_c = 5.15 A/m, ΔT_x = 168 K

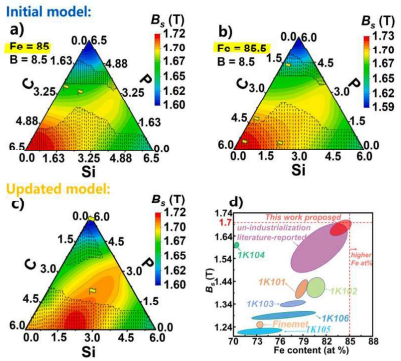
[Sun, J Alloy Comp (2025)]

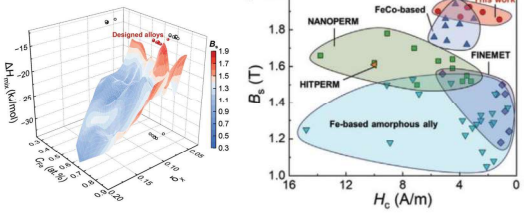
FINEMET like new alloys
$Fe_{77.1}Si_{8.5}Cu_{0.4}Nb_{3.1}Ta_{0.6}B_{7.3}P_{0.3}Zr_{2.8}$
$Fe_{76.3}Si_{12}Cu_{0.3}Nb_{3.1}Mo_{0.2}Nb_{2.2}B_9$

[Wang, Acta Mater (2020)]

Data Science Approaches for Soft Magnetic Materials

Fe-based Amorphous





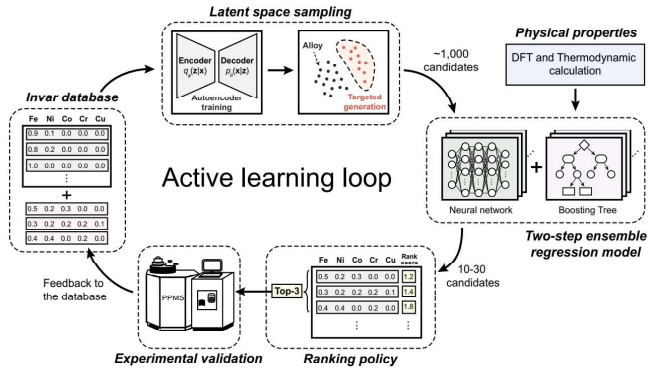
am-$(Fe_{82}Co_{18})_{85.5}Ni_{1.5}B_9P_3C_1$
$\mu_0 M_s$ = 1.92 T

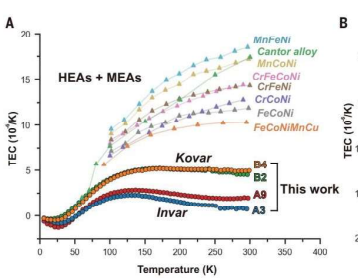
[Yang, Adv Mater (2025)]

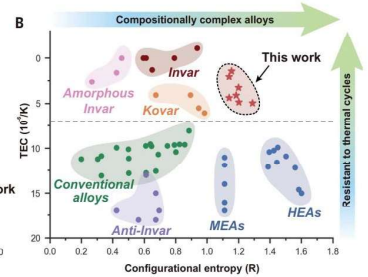
am-$Fe_{85.5}Si_2B_{8.5}P_2C_2$
$\mu_0 M_s$ = 1.68 T

[Tang, J Alloy Comp (2025)]

Advanced Active Learning for High-Entropy Alloys

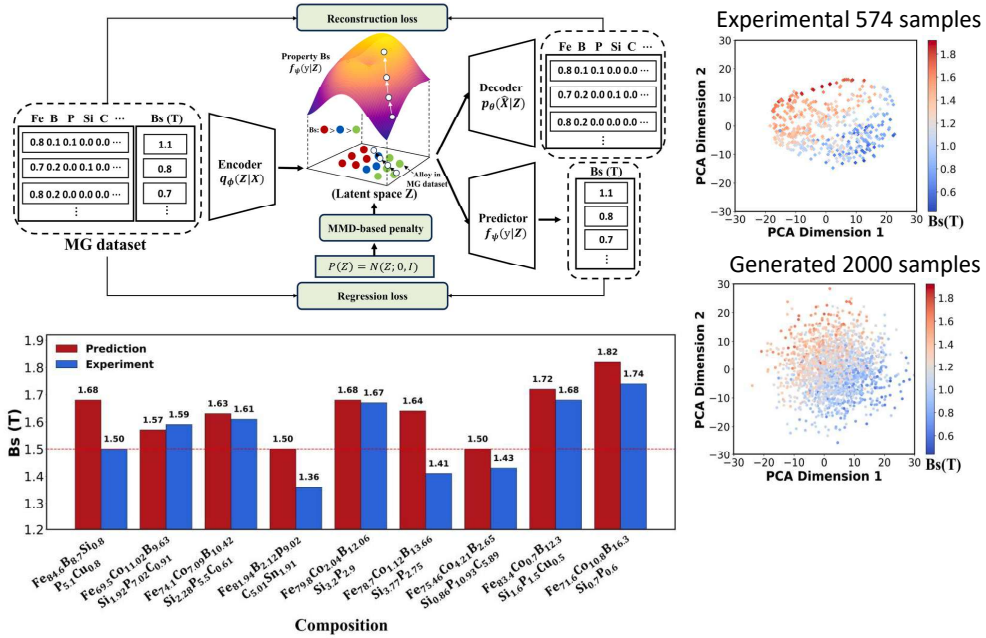






[Rao, Science (2022)]

Generative AI for Soft Magnetic Material Search



[Li, J Alloy Comp (2025)]

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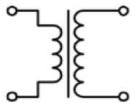
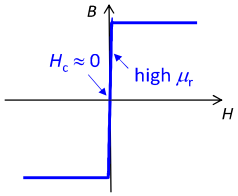
Magnetic Devices in Power-Electronics

Application

Transformer



Required *B-H* curve

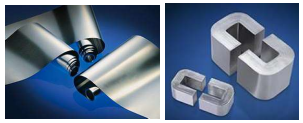


Requirements

High $\mu_0 M_s$ and low P_{cv}

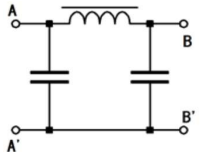
+

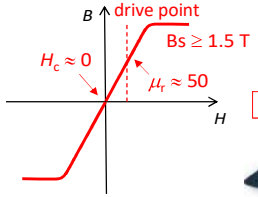
- High μ_r
- Good squareness



Ribbon wound core

Inductor



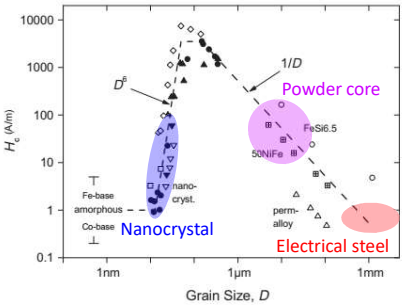


+

- Low or moderate μ_r
- Good linearity

Powder core

Nancrystalline Alloys

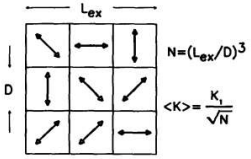


Random anisotropy model

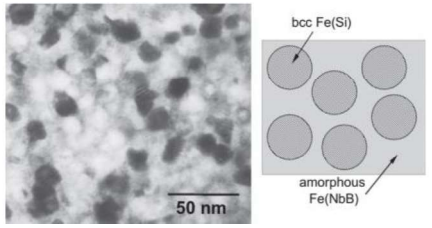
Exchange coupled averaging

$K_{av} \approx (K^4/A_{ex}^3)D^6$

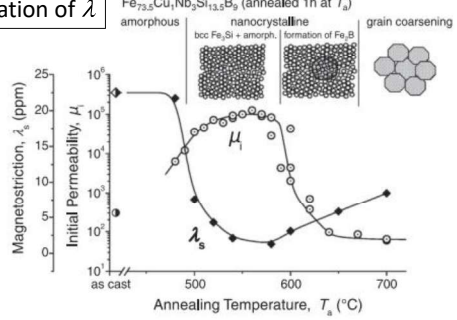
[Herzer, IEEE Trans Mag 26, 1397 (1990)]



Cancellation of λ



[Herzer, Acta Mater (2013)]



Crystallinity of 50 % has been best.

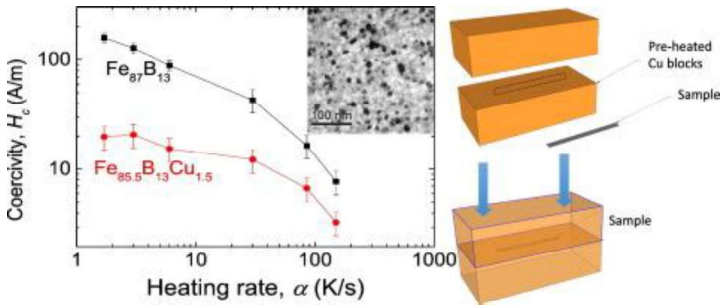
$\lambda_s \approx x_{cr}\lambda_s^{Fe(Si)} + (1 - x_{cr})\lambda_s^{am}$

Negative Positive

Problems of Recent High $\mu_0 M_s$ Nanocrystalline Alloys

- $Fe_{82.7}Si_2B_{14}Cu_{1.3}$: 1.85T [Ohta, JJAP (2007)]
- $Fe_{84.8}Si_1B_{10}P_3Cu_{1.2}$: 1.82T [Urata, IEEE Mag (2011)]
- HiB-NANOPERM ($Fe_{87}B_{13}$) : 1.92T [Zang, Scripta Mater (2017)]

- Requirement of rapid thermal annealing
- Very high mechanical hardness and brittleness

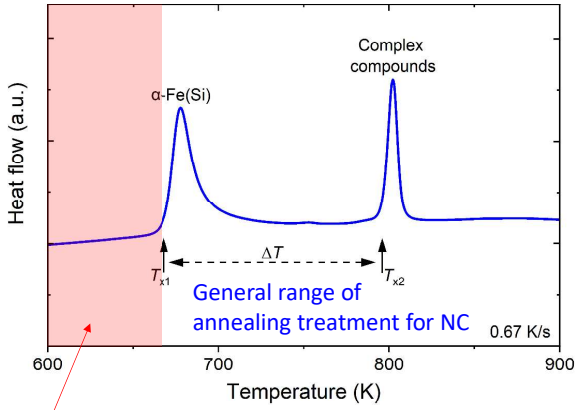


[Zang and Suzuki, Scrpta Mater. (2017)]

By introducing a rapid thermal annealing, new NC alloys have been developed.

DSC Curve

$Fe_{84.8}Si_{0.5}B_{9.4}P_{3.4}Cu_{0.8}C_{1.1}$ amorphous precursor ribbon



Heat treatment range < T_{x1} in this study

Low Core Loss Found for Annealing at Lower T_a

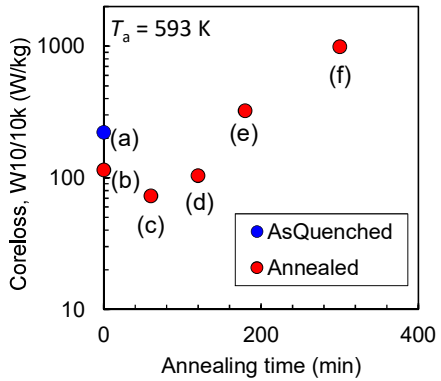
Hiramoto (Former Affiliation TMI)

Annealing condition

Annealing at 593 K
Heating rate 20 K/min

- About 100 K lower than T_{x1}
- Not rapid heating rate

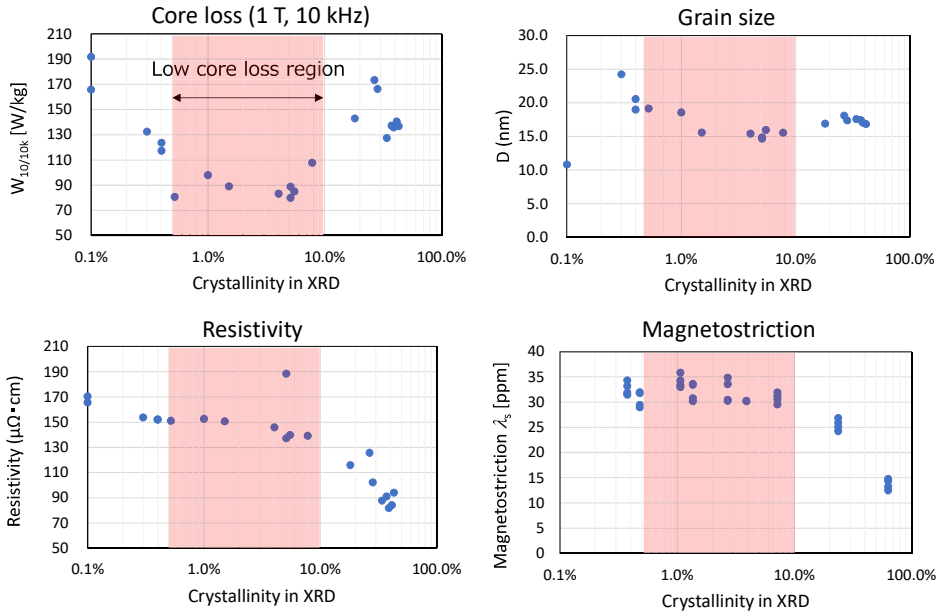
Very low core loss condition was found



	Annealing time	W10/10k (W/kg)	Coercivity (A/m)	Crystallinity	Grain size (nm)	M_s (emu/g)
(a)	AsQ	222	4.5	NA	NA	169.2
(b)	0min	115	3.8	NA	NA	169.6
(c)	60min	73	6.6	6.6%	15.2	169.3
(d)	120min	104	12.6	9.2%	17.4	170.6
(e)	180min	324	97.4	12.4%	21.0	172.0
(f)	300min	994	250	21.5%	25.6	177.2

Crystallinity Dependent Properties

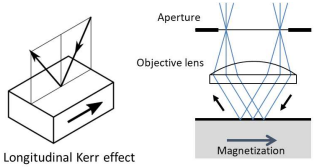
Hiramoto (Former Affiliation TMI)



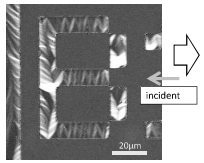
- Low core loss region keeps almost same properties of precursor amorphous

Time-Resolved Vector MOKE Microscopy

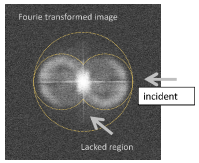
Conventional μ-MOKE



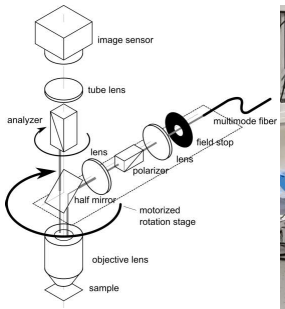
MOKE image

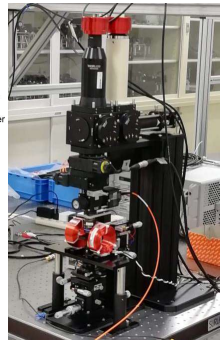


FFT

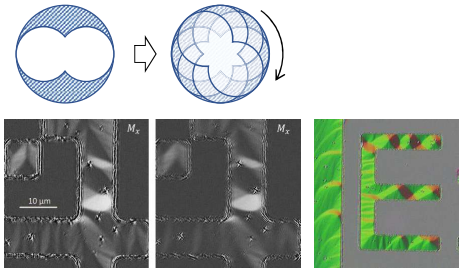


Newly developed Vector μ-MOKE





Conventional This method

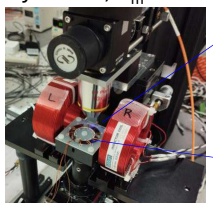


High resolution and vector magnetization

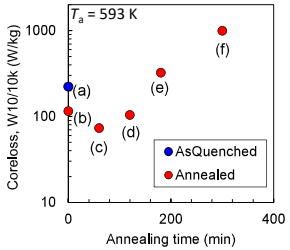
T. Ogasawara, Jpn. J. Appl. Phys. 56, 108002 (2017).

Time-Resolved Vector MOKE

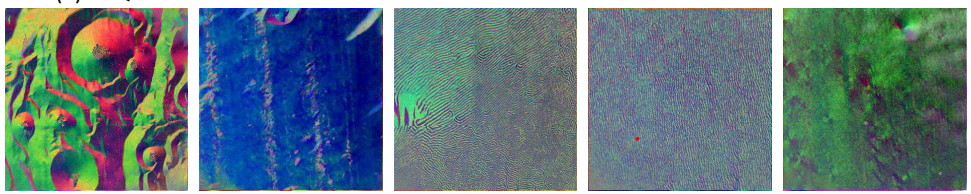
f = 1kHz, B_m ~ 1T



OD30-ID20 mm



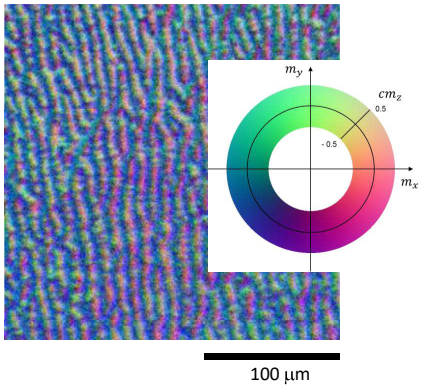
(a) AsQ (b) 0 min (c) 60 min (d) 120 min (e) 180 min

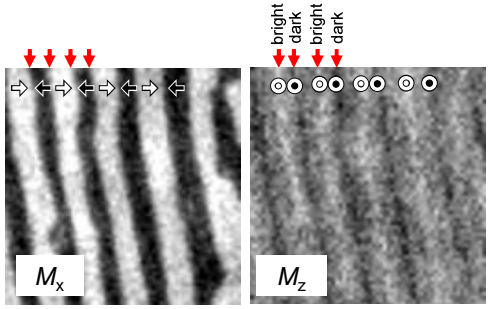


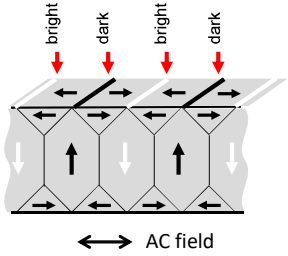
- Reduction of core loss in (b) is stress relaxation from AsQ.
- Fine stripe domain structures are found in (c), (d), (e), ant its width becomes finer for longer annealing time.
- Domain walls move little, indicating magnetization rotation becomes dominant.

Details of Stripe Domain

Annealed at 593K for 60 min

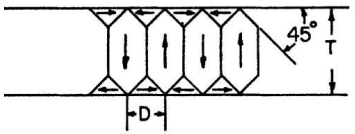






- Perpendicularly magnetized stripe domain structure.
- Perpendicular magnetization corresponds to hard-axis driving, resulting in magnetization rotation.

Analysis Based on Stripe Domain Theory



[C. Kittel, Phys. Rev. 70, 965 (1946)]

By assuming Bloch wall, energy per area E_w is given as,

$$E_w = \gamma_w\left[2\sqrt{2} + (T-D)/D\right] + K_u D/2$$

where T thickness, D domain width, γ_w wall energy, K_u anisotropy energy.
Then, from the energy minimum condition,

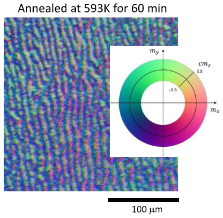
$$D = \sqrt{2\gamma_w T/K_u}$$

Using $\gamma_w = 4\sqrt{AK_u}$, where A exchange stiffness constant, $\boxed{K_u = 64T^2A/D^4}$

When the origin of K_u is magnetorstriction λ_s and stress σ, $\boxed{K_u = \frac{3}{2}\lambda_s\sigma}$

The wall thickness $l_w = \pi\sqrt{A/K_u} = \pi D^2/8T$ for $l_w << T, D$

T = 25 μm, D ~ 3 μm ⇨ l_w = 140 nm, K_u = 2.5 kJ/m^3, σ = 5.5 × 10^7 N/m^2



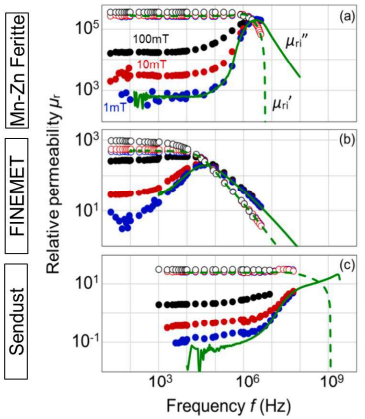
- Large positive λ_s is important factor.

Broadband Iron Loss Analyses Based on Magnetization Process

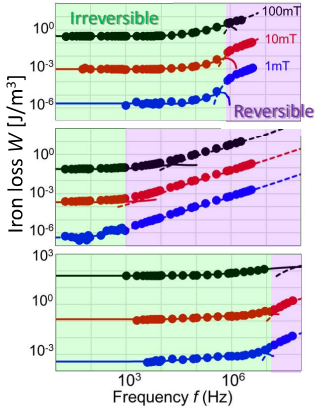
Loss analysis based on magnetization process proposed by Fiorillo Gr.

[Beatrice, JMMM 429, 129 (2017)]

B_m dependent μ_r spectra



Broadband core loss and
Analysis based on magnetization process

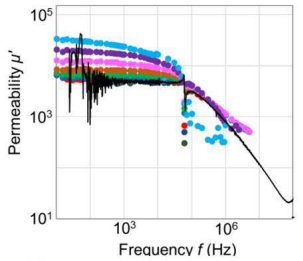


[Ono, SO, JMMM 603 (2024) 172222]

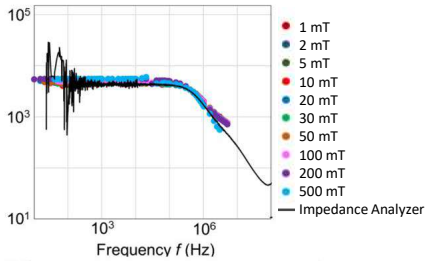
- Universally applicable for various materials.
- Low and high frequency regions are irreversible and reversible processes, respectively.

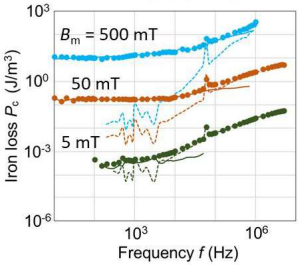
Broadband Iron Loss and Loss Analysis

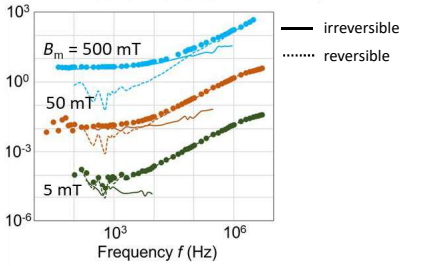
Well nanocrystallized



Annealed at 593K for 60 min







- μ_r of low core loss sample is insensitive to B_m.
- Irreversible core loss component significantly decreased.

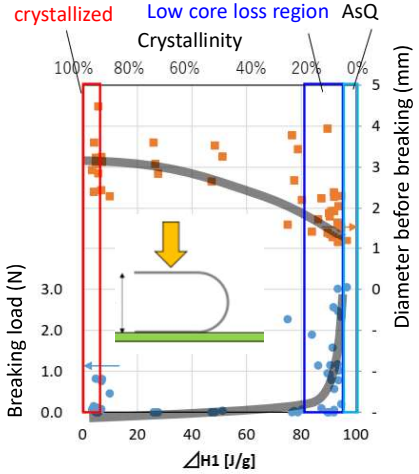
⇨ Corresponding to very low excess loss

Bending Test and Wound Core Prototyping

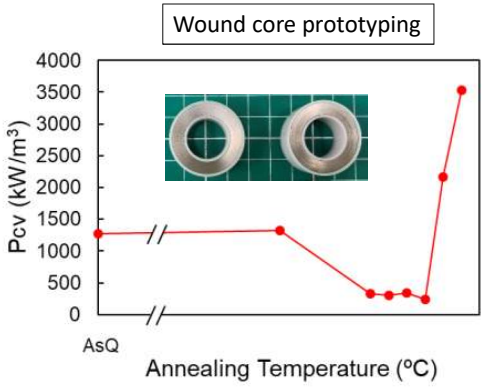
Our finding low core loss ribbon keeps almost amorphous state.

⇨ Suppression of brittleness is highly expected.

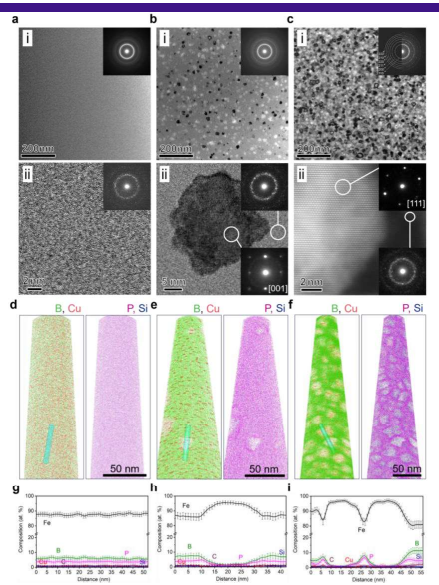
Bending test

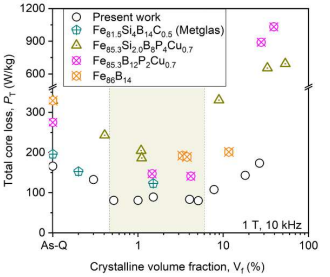


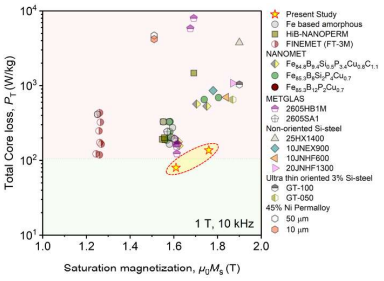
Wound core prototyping



Microstructures and Comparison with Other Materials



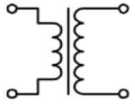




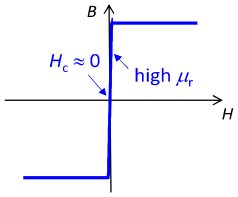
Magnetic Devices in Power-Electronics

Application

Transformer



Required *B*-*H* curve

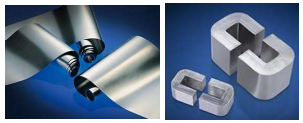


Requirements

High $\mu_0 M_s$ and low P_{cv}

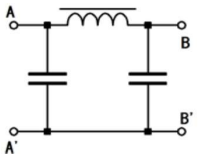
+

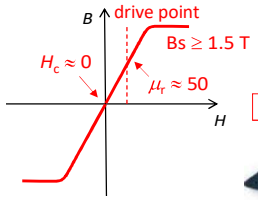
- High μ_r
- Good squareness



Ribbon wound core

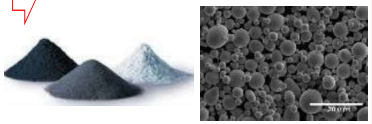
Inductor





+

- Low or moderate μ_r
- Good linearity

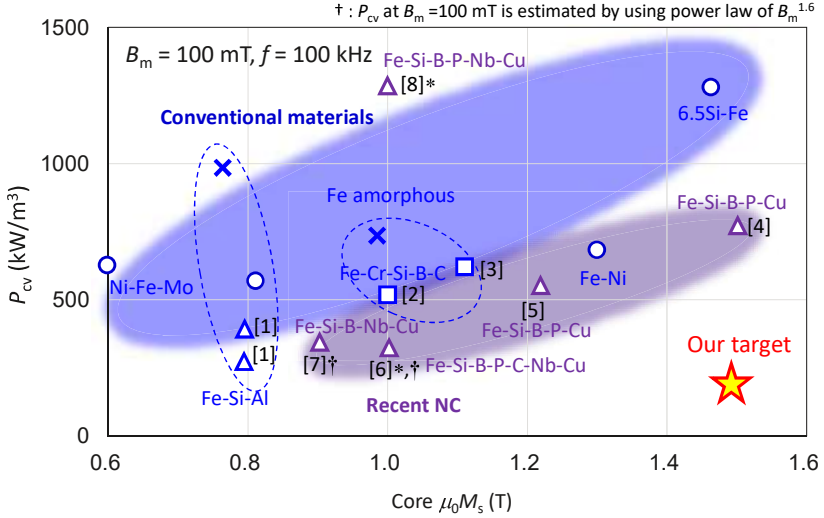


Powder core

Trend of P_{cv} and $\mu_0 M_s$ of Powder Cores

∗ : core $\mu_0 M_s$ is estimated by assuming packing density of 0.7

† : P_{cv} at B_m =100 mT is estimated by using power law of $B_m^{1.6}$



How to realize SENDUST (Fe-Si-Al) class low P_{cv} and Fe-Si class high $\mu_0 M_s$?

[1] Tsuruta, J. Jpn. Soc. Powder Powder Metal. (2016), [2] Yagi, JMSJ (2002), [3] Yagi, JMMM (2000), [4] Zhang, IEEE Trans. Magn. (2014), [5] Luan, AIP Adv. (2016), [6] Zhang, J. Mater. Sci. (2024), [7] Wang, JMMM (2024), [8] Lia, Intermetallics (2018).

Our Strategies

TOKIN Urata

[Acta Mater 294 (2025) 121159]

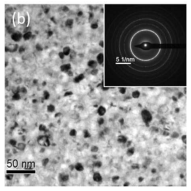
Low loss and high $\mu_0 M_s$ candidate materials

Recent high $\mu_0 M_s$ nanocrystalline alloys

2007 nc-Fe-Si-B-Cu (1.84 T), Ohta

2011 nc-Fe-Si-B-P-Cu (1.8 T), Urata

2017 nc-Fe-B (1.9 T), Suzuki

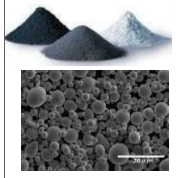


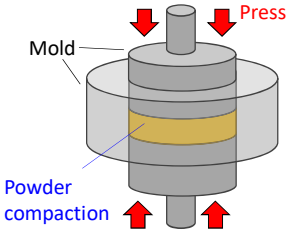
[Zang, Scripta Mater. 132, 68 (2017)]

Problems for powder core application

- Requirement of rapid thermal annealing
- Very high mechanical hardness and brittleness

Powder core fabrication for high packing density





- Conventional : Cold-press
- Press + : Spark plasma sintering (SPS)
- Press + : Hot-press

Powder of Amorphous Precursor Fe-B-P-Cu alloy

TOKIN Urata

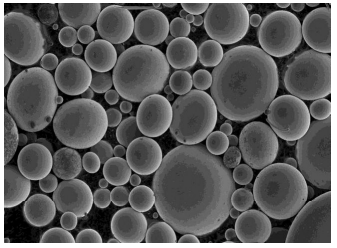
[Acta Mater 294 (2025) 121159]

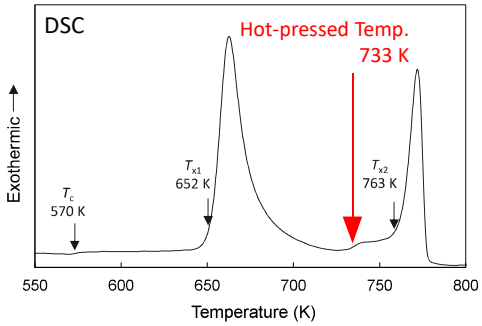
Water atomized powder of amorphous precursor Fe-B-P-Cu alloy

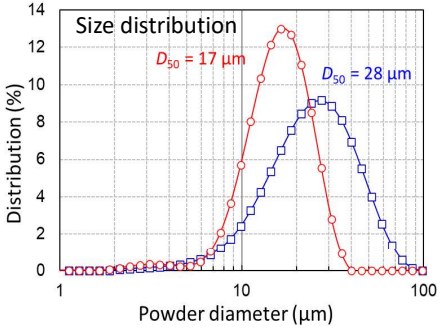
[Kuno, proc. IEEE Int. Magn. Conf. (2023), 10.1109/INTERMAG50591.2023.10265097.]

SEM

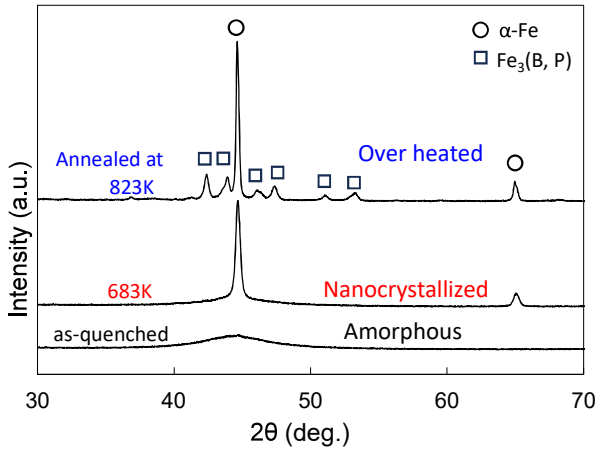
D_{50} = 28 μm





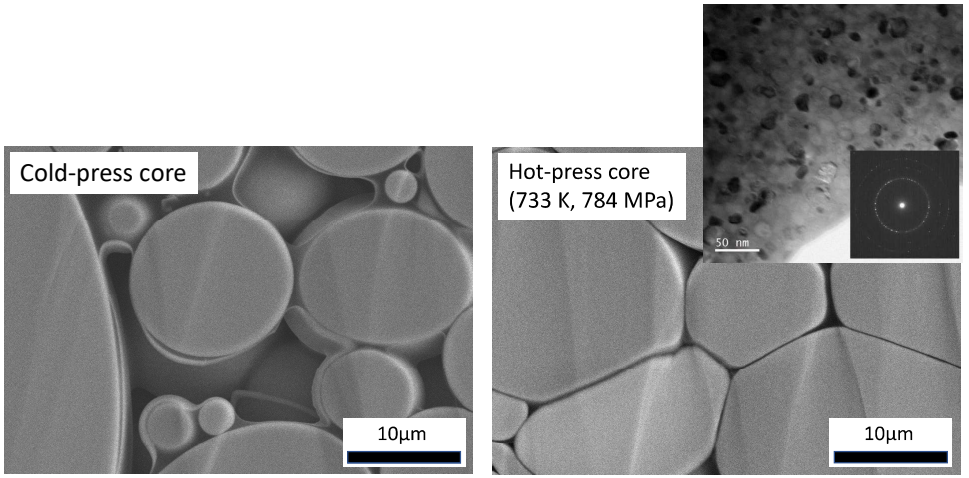


Powder Annealing and Static Magnetic Properties



Annealing Temp.	AsQ	683 K	823 K
H_c (A/m)	101	31	1793
$\mu_0 M_s$ (T)	1.62	1.74	1.79

Microstructure of Cold- and Hot-Press Cores

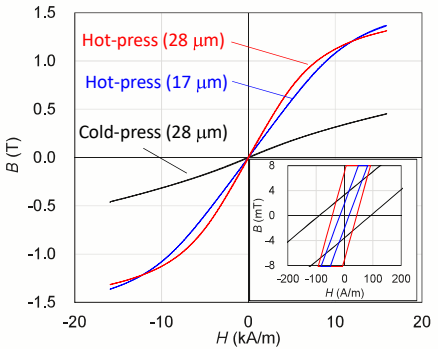


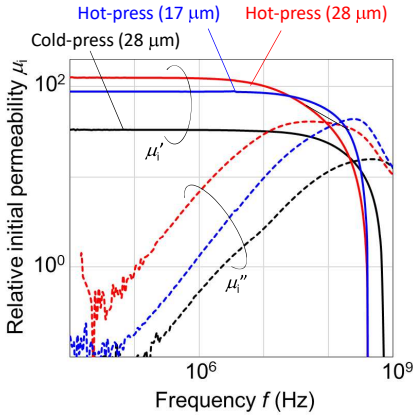
Packing density 70 %

Packing density 89 %

- Powder keeps its original spherical shape.
- Plastic deformation and nanocrystallization concurrently occurred during hot-press process.

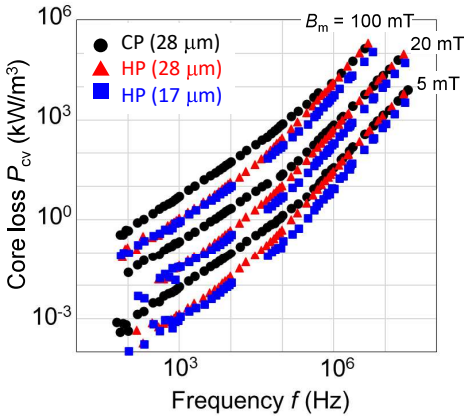
Magnetic Properties of Cold- and Hot-Press Cores

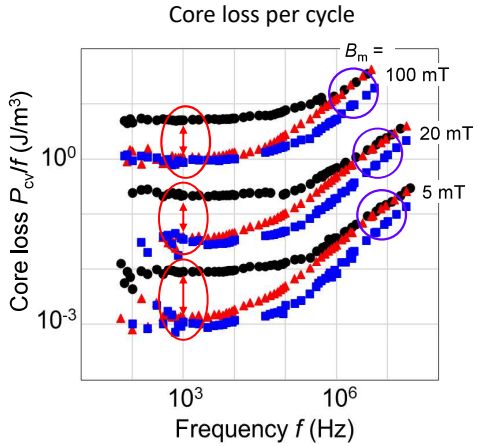




Cores	Cold-press (28 μm)	Hot-press (28 μm)	Hot-press (17 μm)
H_c (A/m)	91	43	16
$\mu_0 M_s$ (T)	1.28	1.55	1.54
μ_i' at f = 100 kHz	39	136	98

Core Loss of Cold- and Hot-Press Cores





- Low frequency region :
  HP(17μm) ≈ HP(28 μm) < CP (28 μm)
- High frequency region :
  HP (17 μm) < HP (28 μm) ≈ CP (28 μm)

Core Loss and Analysis based on Magnetization Process

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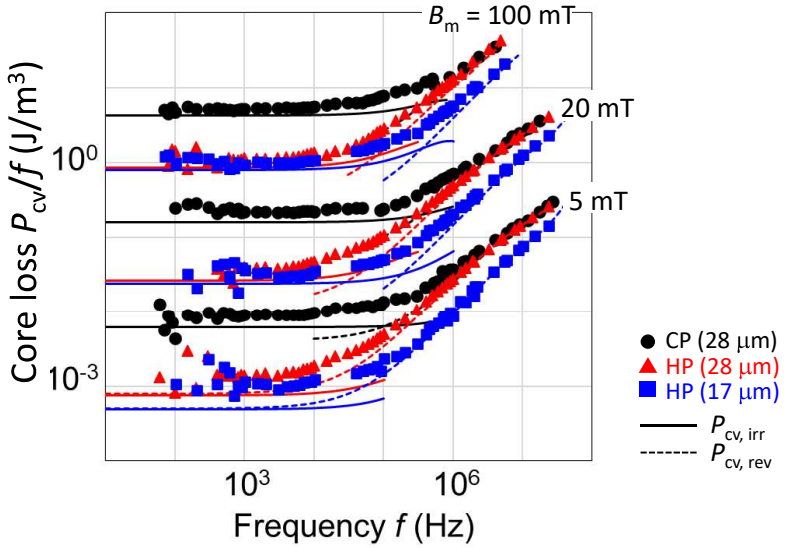
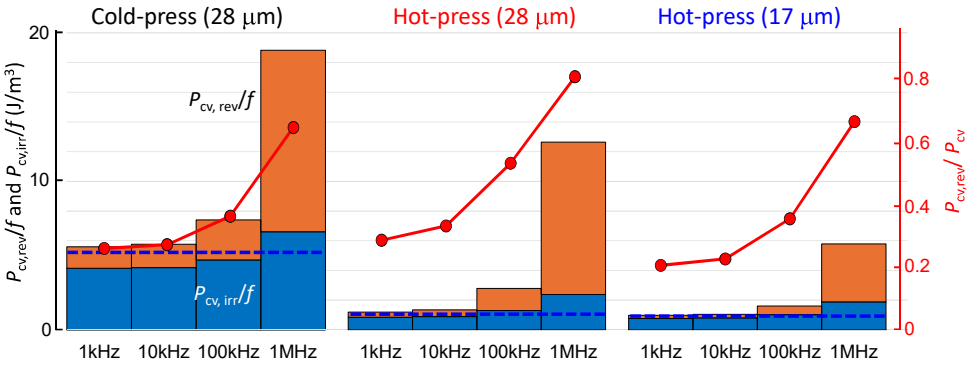


Frequency Dependencies of Loss Components



- Hot-press significantly reduces $P_{cv, irr}$ compared with cold-press.
- Hot-press (17 μm) exhibits smaller $P_{cv, rev}/P_{cv}$

Trend of P_{cv} and $\mu_0 M_s$ of Powder Cores

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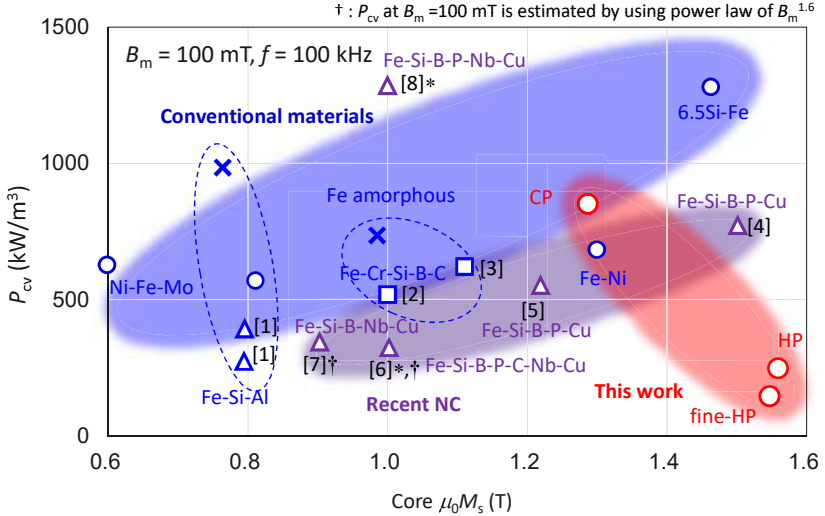
∗ : core $\mu_0 M_s$ is estimated by assuming packing density of 0.7

† : P_{cv} at B_m =100 mT is estimated by using power law of $B_m^{1.6}$



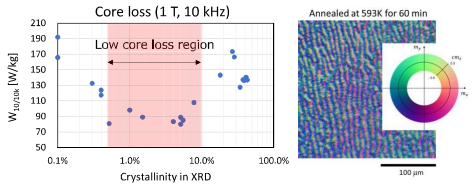
SENDUST (Fe-Si-Al) class low P_{cv} and Fe-Si class high $\mu_0 M_s$ are realized using Fe-B-P-Cu nanocrystalline alloy and hot-press process.

[1] Tsuruta, J. Jpn. Soc. Powder Powder Metal. (2016), [2] Yagi, JMSJ (2002), [3] Yagi, JMMM (2000), [4] Zhang, IEEE Trans. Magn. (2014), [5] Luan, AIP Adv. (2016), [6] Zhang, J. Mater. Sci. (2024), [7] Wang, JMMM (2024), [8] Lia, Intermetallics (2018).

Summary

We developed novel approaches of nanocrystalline Fe-Si-B-P-Cu alloys for next-generation powder-electronics applications.

Low-Crystallinity Ribbon



- Low core loss region was found for annealing at about 100 K lower than T_{x1} and conventional heating heating rate.
- Fine stripe domain with perpendicular magnetization is the origin of low core loss.
- Very low irreversible core loss component, suggesting magnetization rotation is dominant.
- Large λs and compressive stress cause PMA.

Hot-Pressed Powder Core

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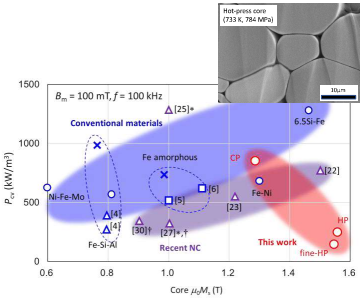

- High density powder core of high $\mu_0 M_s$ low P_{cv} can be obtained using hot-press process.
- Irreversible core loss component significantly decreased.
- Hot-press process enables SENDUST class low P_{cv} and Fe-Si class high M_s.

お知らせ

■ 日本磁気学会 シンポジウム (International session)

「軟磁性材料のグリーンエネルギー応用-モータとパワーエレクトロニクス-」
「Soft Magnetic Applications for Green Energy -Advanced Motors and Power Electronics-」

開催日 9月18日＠松山

■ バルク軟磁性シンポジウム (企画中)

「 (仮) 高周波磁気損失　その鍵を握る磁歪を掘り下げる」

開催日 11月10日(予定) ＠ 東北大

■ INNOPELシンポジウム

開催日 1月27-28日 ＠ 東京 (調整中)