

Nanocrystalline Alloy Ribbons and Their Applications

PROTERIAL

Prof. Dr. Motoki Ohta

Global Research and Innovative Technology Center

(Professorship from Shimane University)



Motoki Ohta

Affiliation

- Senior Researcher: PROTERIAL (Hitachi Metals)
- Professor: Shimane University Next Generation Tatara Co-creation Center

Background

- Academic degree: PhD. 2002 Tohoku University (Sendai Japan)
“Spin Fluctuation and Thermal Expansion Anomaly in $Y_6(Mn_{1-x}Fe_x)_{23}$ Compounds and Amorphous Alloys”
- Work History:
 - 2002-05: Assistant Professor @ Tohoku University:
 - Magnetics of solid-state metals
 - Thermal expansion & Spin fluctuation (itinerant feature of spins)
 - 2005-now: Researcher @ Hitachi Metals (2013-15 Metglas):
 - Development of rapid quenched soft magnetic materials such as nanocrystalline & amorphous ribbons
 - 2019-now: Professorship from Shimane University:
 - Project Leader of the commercialization of amorphous motor
 - Processing and characterization of Fe-based amorphous ribbon

My Lifework Research (relation with todays presentation)

- Basically R&D person
- Materials development, Soft magnetic properties
- High Fe content nanocrystalline soft magnetic material (total citations: 979 google scholar)
 - Most cited: APL 91 (2007) 062517. (citations: 152)
- Pursuit of the origin of nanocrystallization and magnetic anisotropy in FINEMET®

- About PROTERIAL (Former Hitachi Metals)
- Ideal Soft Magnetic Materials (SMMs) and
 - Fe-based nanocrystalline alloy FINEMET®
- SMMs in medium frequencies
 - Development of High Fe content nanocrystalline alloys High B_s nanocrystalline alloy (Hi- B_s nano)
- Applications of Hi- B_s nano
- Remaining issues

We were Hitachi Metals... Now we are PROTERIL

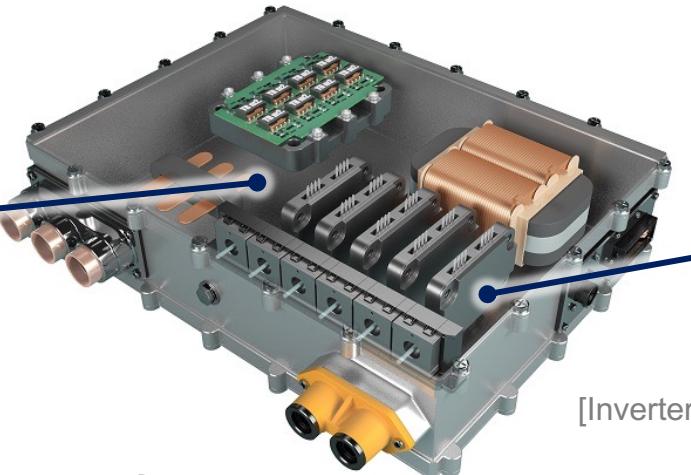
Date of Establishment	April 10, 1956
Capital	310 million yen <small>(as of March 31, 2023)</small>
Representative	Sean M. Stack - Representative Director, Chairman, President and CEO
Number of Employees	Proterial, Ltd., Non-consolidated: 5,754 <small>(as of end of March 2023)</small> Proterial Group, Consolidated: 26,496 <small>(as of end of March 2023)</small>
Revenues	Proterial Group, Consolidated: 1,118.9 billion yen <small>(FY2022)</small>
Number of Consolidated Subsidiaries	Japan 23, Overseas 38, Total 61 <small>(as of end of March 2023)</small>

Our Advanced Soft Magnetic and Ceramic Materials Contribute to Energy Conservation and ICT innovations

We offer a long list of specialty materials and components; Metglas® amorphous metals, FINEMET® nanocrystalline materials and high-performance soft ferrites and ceramics.



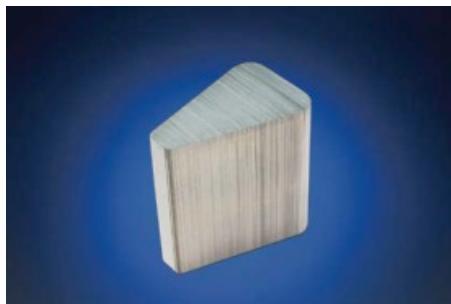
Nanocrystalline materials FINEMET®
(Ribbon, Core, Coil)



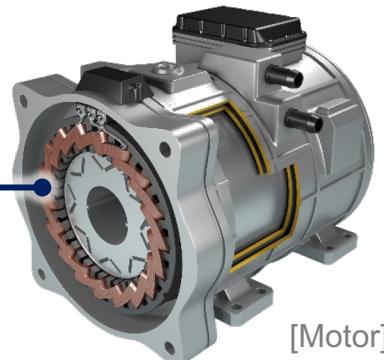
[Inverter]



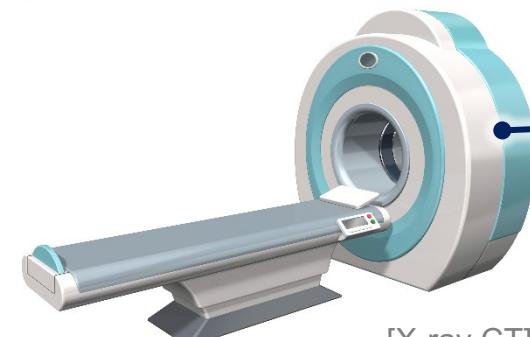
Insulating substrate Si_3N_4



Amorphous Magnetic Materials
for Motors



[Motor]



[X-ray CT]



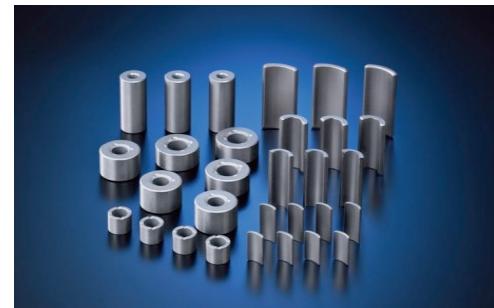
Ceramic Scintillator

NEOMAX® brand, key material for industries

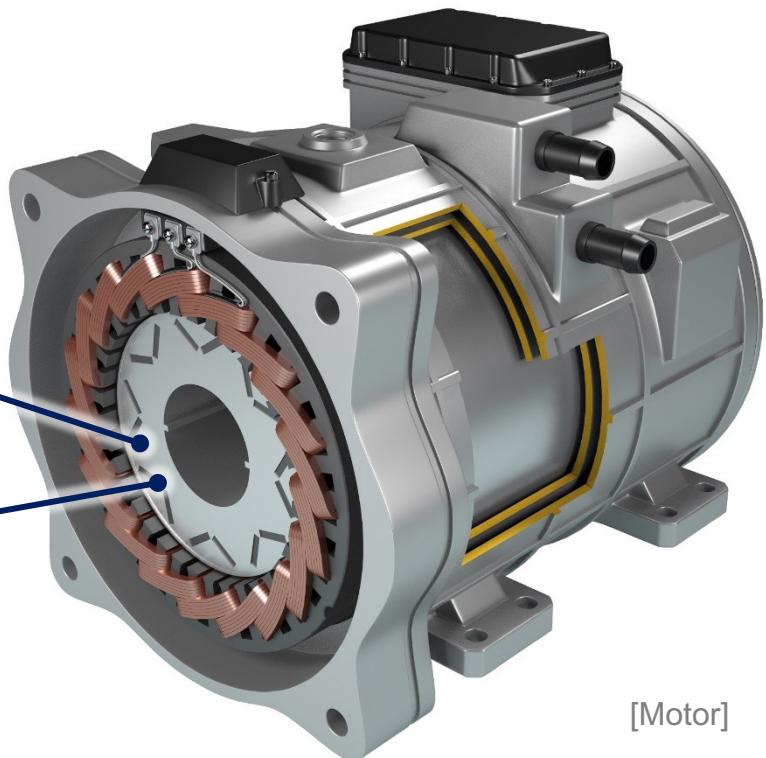
We boast an extensive magnet range, which includes NEOMAX® rare earth magnets and ferrite magnets, and provide our products across a wide range of fields, encompassing automobiles, electronics and home appliances. As pioneers in the field of magnetic materials, we take on the challenge of new materials and new production technologies, meeting our customers' diverse needs and contributing to the creation of a more energy-efficient society.



Neodymium Magnets NEOMAX®

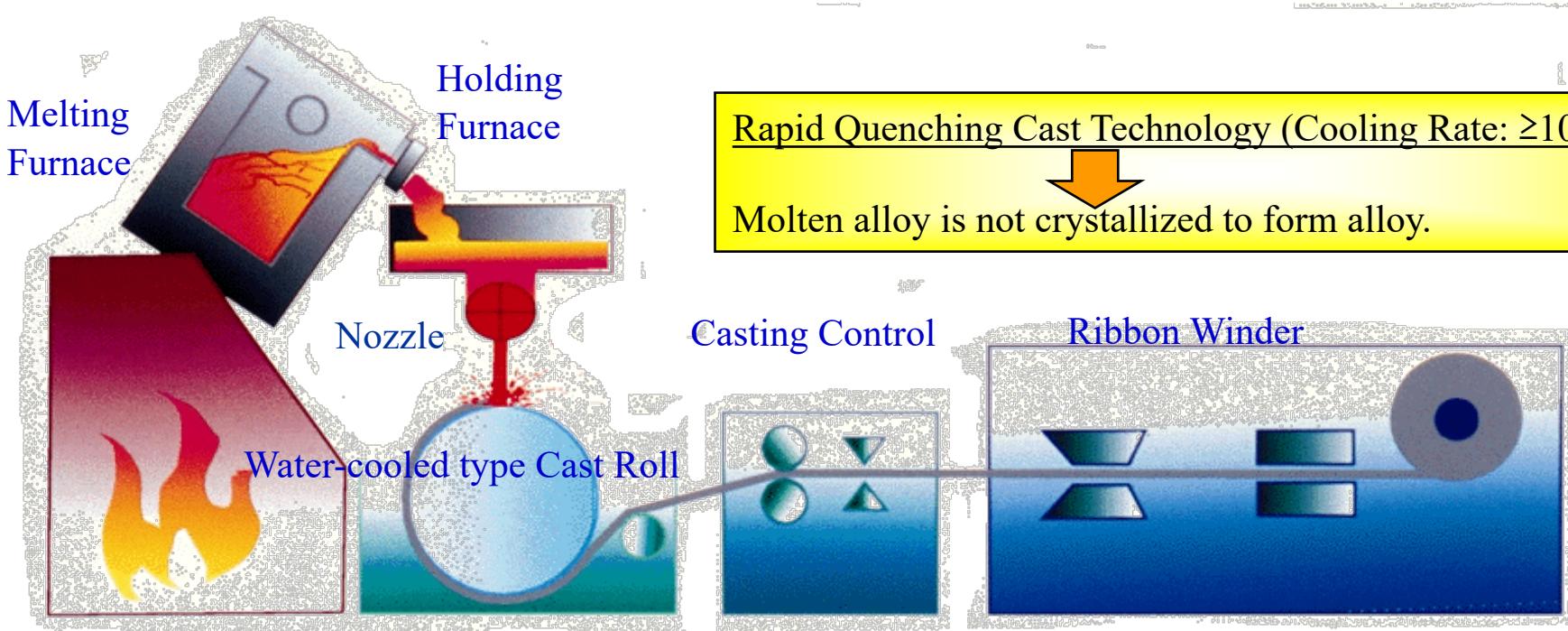


Ferrite Magnets NMF™

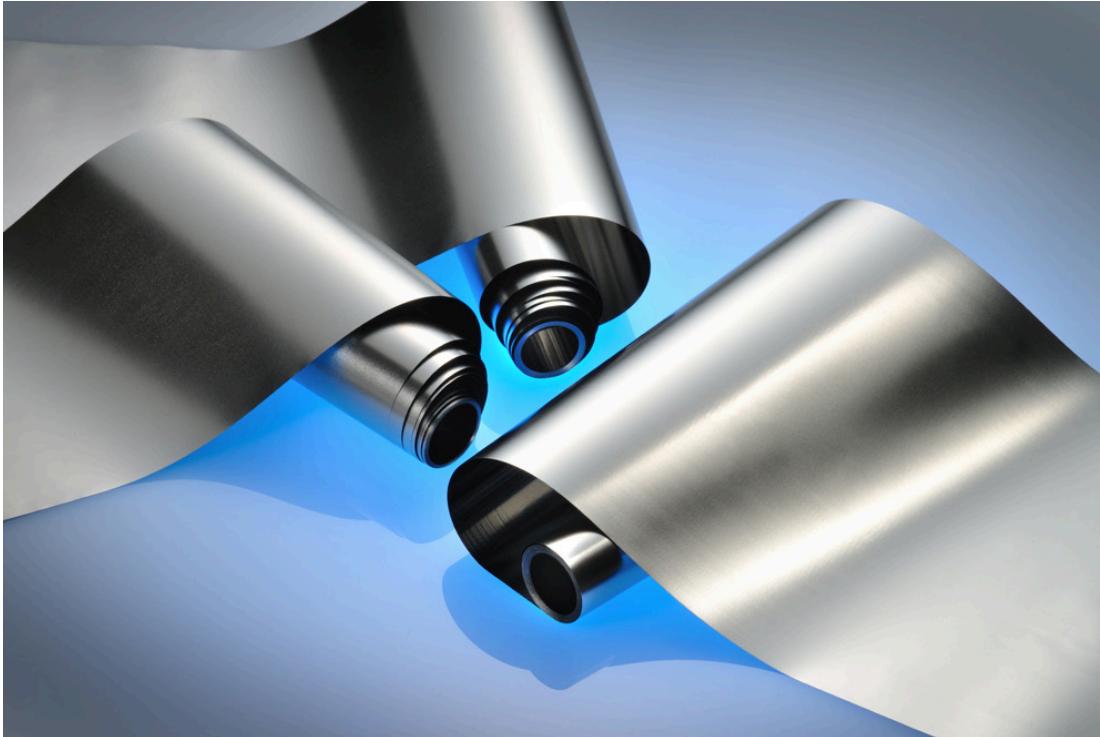


[Motor]

Alloy Name	Constituent Elements	Thickness	Grain Size	Induction	Core Loss
Grain Oriented Si Steel	Fe, Si	230 μm	$\sim 10 \text{ mm}$	◎	△
Fe-based Amorphous	Fe, Si, B	25 μm	—	○	○
Nano-Crystalline Alloy	Fe, Si, B, Cu, Nb	18 μm	$\sim 10 \text{ nm}$	△	◎



Our main product for Rapid Quenching business



Amorphous Alloy for Transformer "Metglas® 2605HB1M"



Amorphous Transformer*

* Photo Credit: Hitachi Industrial Equipment System Co., Ltd.

Major Bases (amorphous & nano)

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■ North America

Proterial America, Ltd.
Diehl Tool Steel, Inc.
Waupaca Foundry, Inc.
Ward Manufacturing, LLC

Metglas, Inc.

Proterial Cable America,
Inc.

~~HC Queretaro, S.A. de C.V.~~



Metglas®, Inc.
Conway, South Carolina

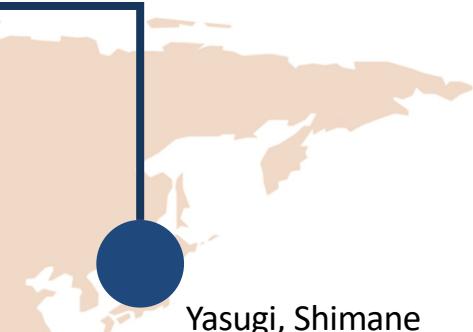


PROTERIAL HP

■ Japan

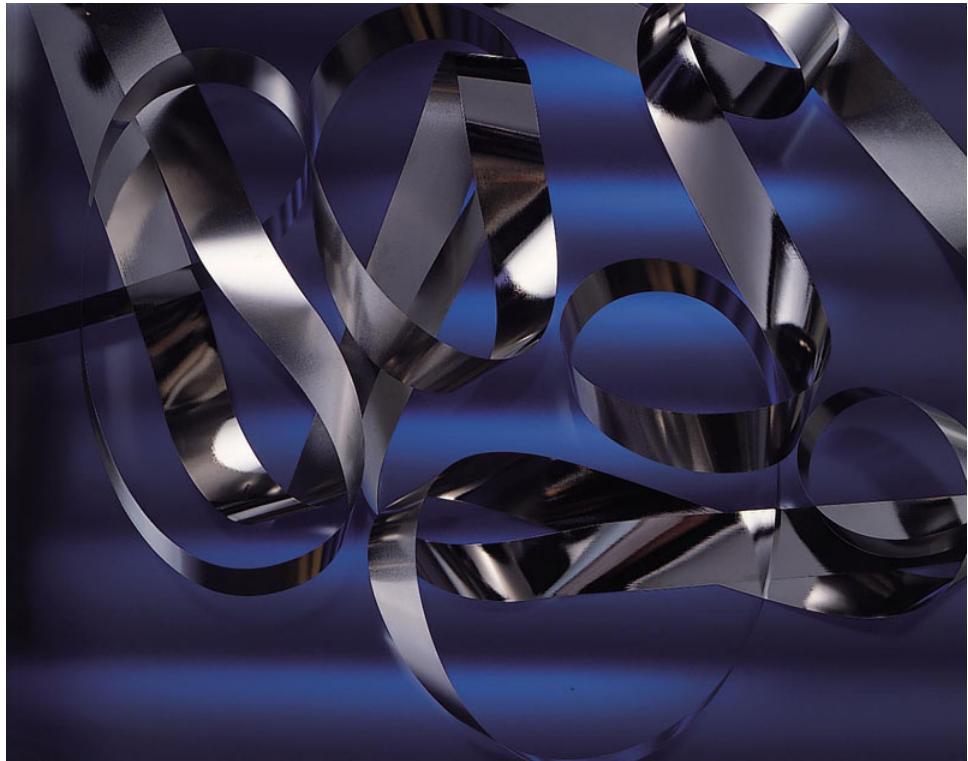
Metglas Yasugi Works

Applied Components Dept.
Proterial Ferrite Electronics, Ltd.



Japan



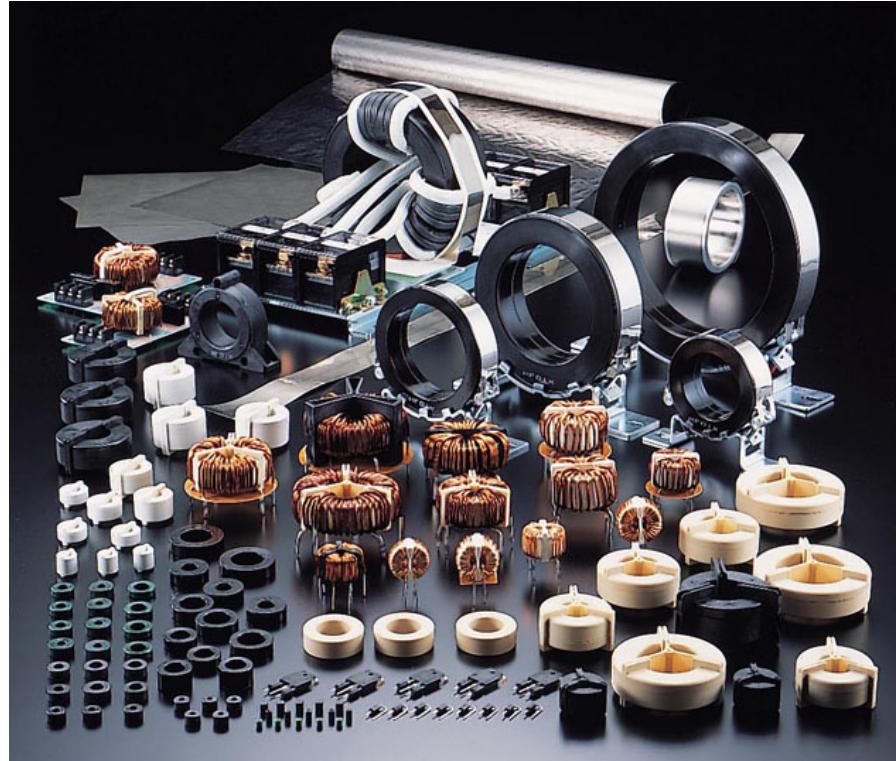


Nano-Crystalline Soft Magnetic Material “FINEMET®”

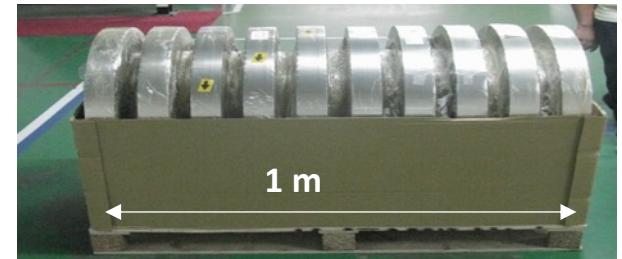
Production capacity Amo & Nano total ... 1 0 0 kt/year (US&JP)

Item Amorphous alloy ... width 142-213 mm, Thickness 0.025 mm

Nanocrystalline alloy... W 50-85 mm, T 0.014-0.018 mm



Application products using “FINEMET®”



1 spool = 100kg (17km)

- Ideal Soft Magnetic Materials (SMMs) and
 - Fe-based nanocrystalline alloy FINEMET®

Material-derived factors

Intrinsic factors (Structure, Concertation)

$\left\{ \begin{array}{l} K: \text{Mag-Cry anisotropy} \\ \lambda: \text{Magnetostriction} \\ \rho: \text{Resistivity} \\ E: \text{Young's modulus} \\ B_s (M_s): \text{Induction} \end{array} \right.$

$\mu: \text{Permeability}$

$$\mu_i \propto \frac{B_s^2}{K + \alpha \lambda_s \sigma}$$

$\mu_i: \text{Initial permeability}$

$\alpha: \text{coefficient}$

Extrinsic factors

$\left\{ \begin{array}{l} H: \text{Magnetic field} \\ wdh: \text{Size, dimension (volume, cross section)} \\ \sigma: \text{Stress, Strain} \end{array} \right.$

Ideal SMMs \rightarrow zero $K +$ zero λ

Fe-Ni (Permalloy) Fe-Al-Si (Sendust)
 Mn-Zn ferrite, Ni-Zn ferrite
 Co-based amorphous alloy

Relatively low B_s such as max 1 T or so
 Motivation of developing
 Fe-based nanocrystalline alloy, the FINEMET®

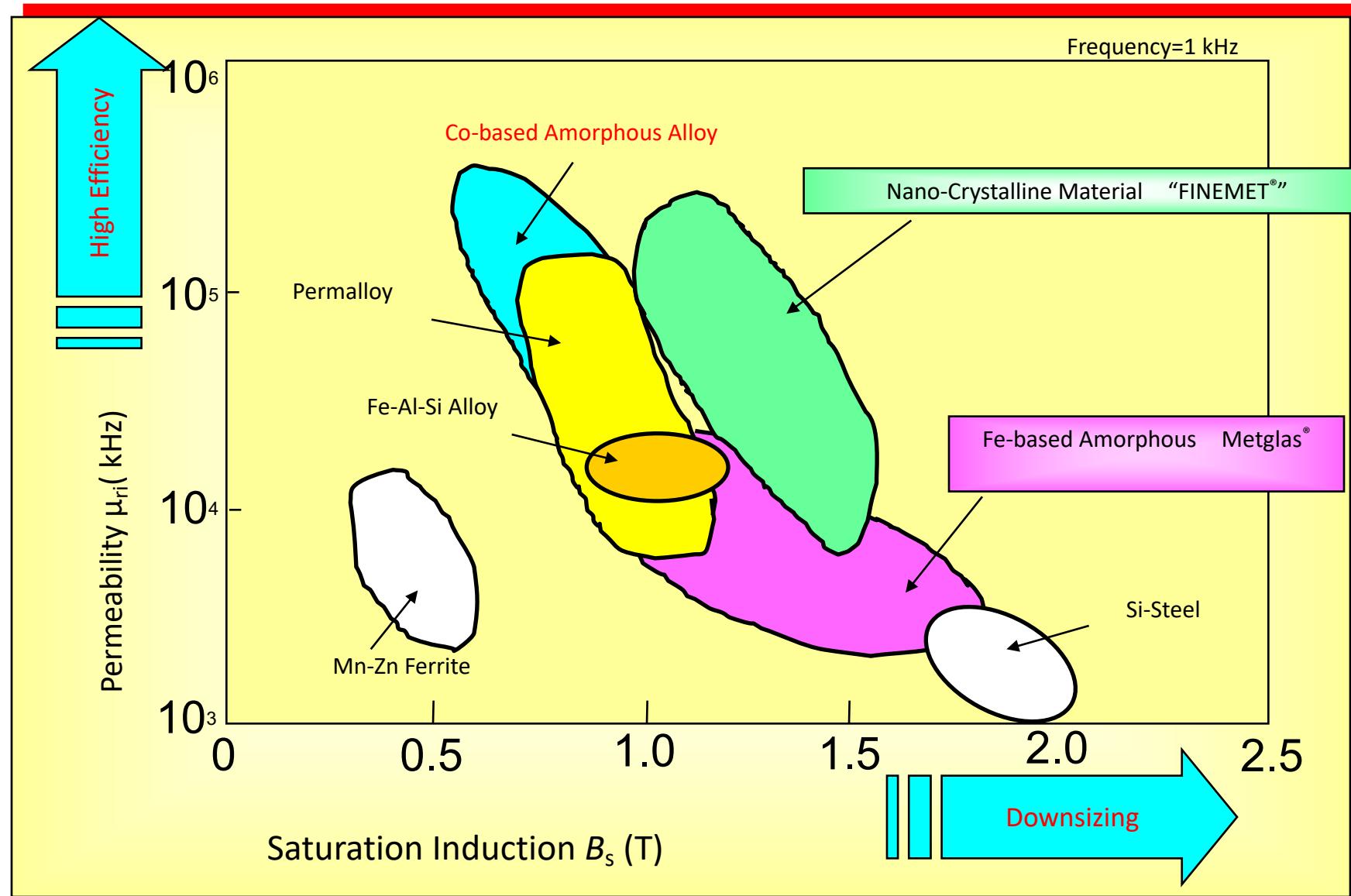
Tips

non ideal soft magnetic materials are widely used if it is compatible with the usage.

Like amorphous ribbon in transformers which has High λ

However, λ is limiting its usage.

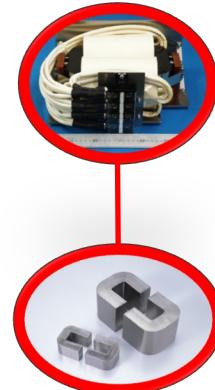
Controlling extrinsic factor to cancel the anti-factors



Main applications using FINEMET®

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xEV

Transformer for high frequency



Cut core

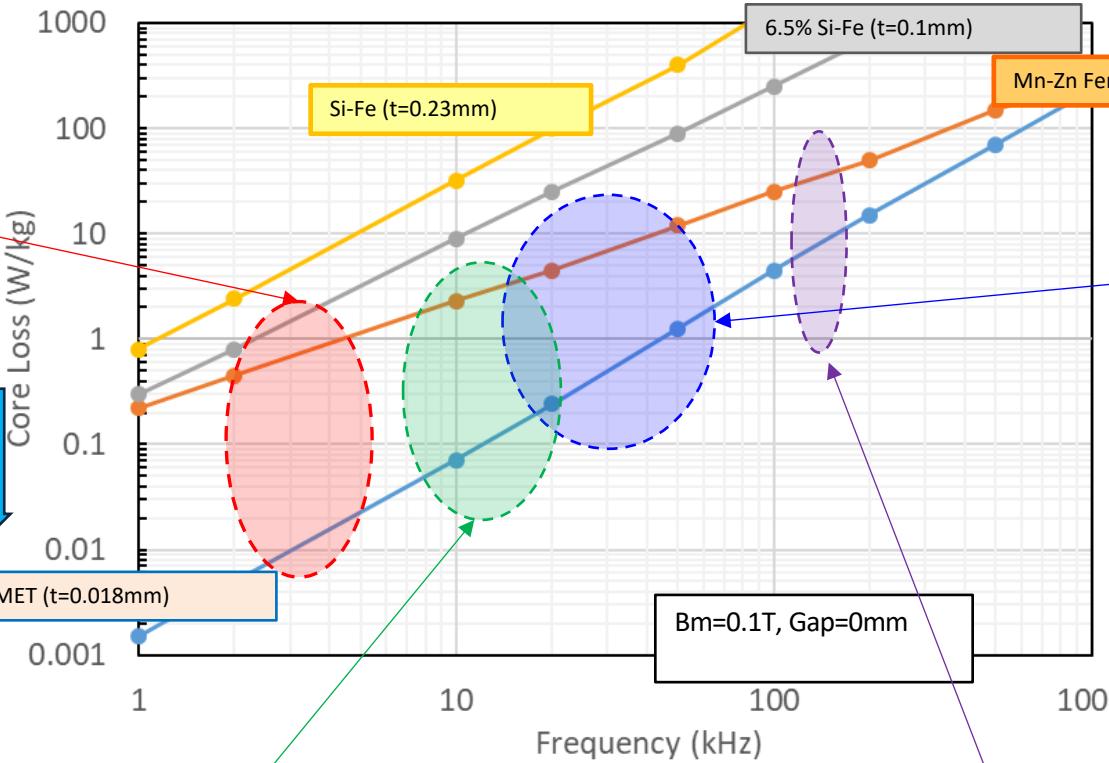
High efficiency



Wind and solar power



Train



Wound core

Reduction in size and weight



Shield sheet

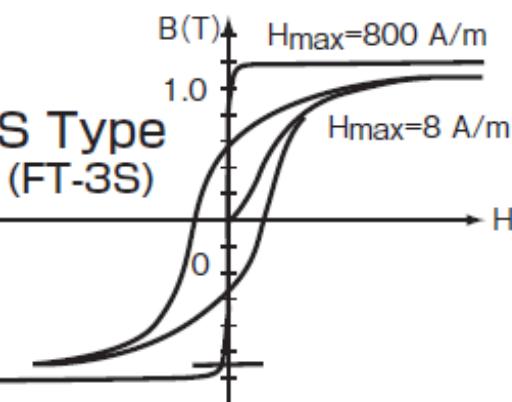
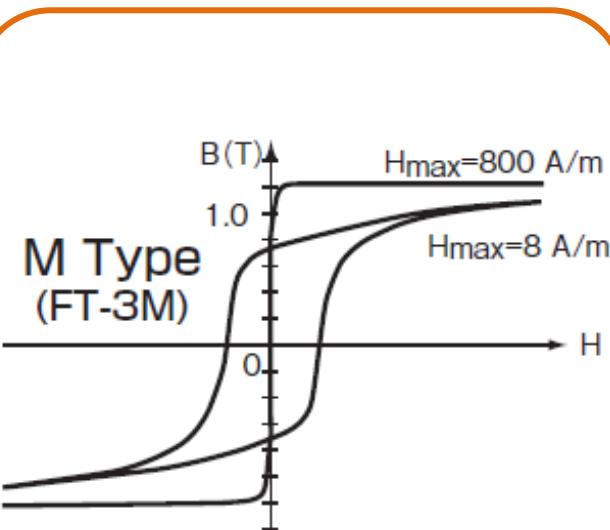
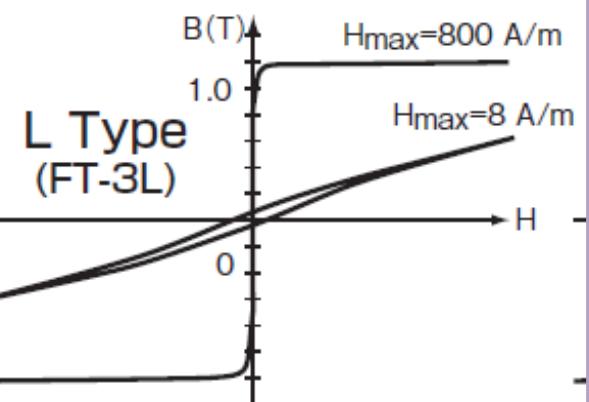
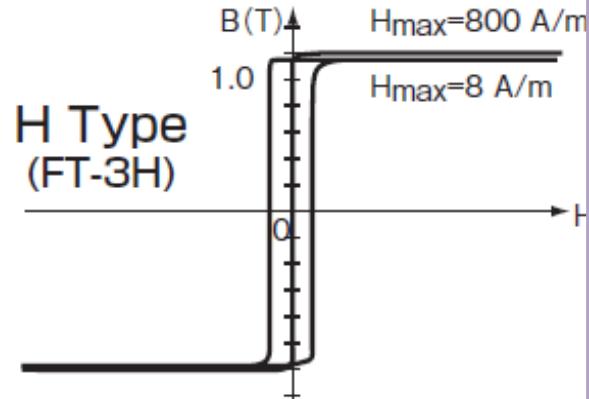


Mobile phone



Noise filter for OBC,
Inverter, etc.

Examples of DC B-H curve



By controlling shape of *B-H* loop



Variety of Flavors

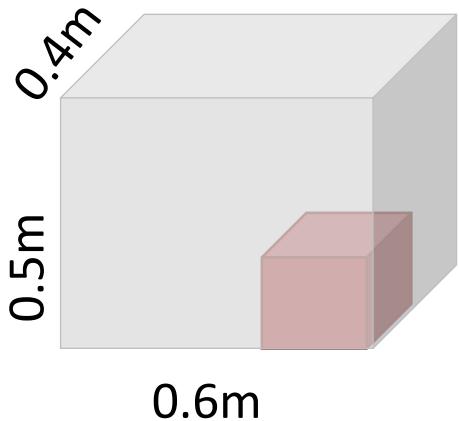


Can be used for many purpose

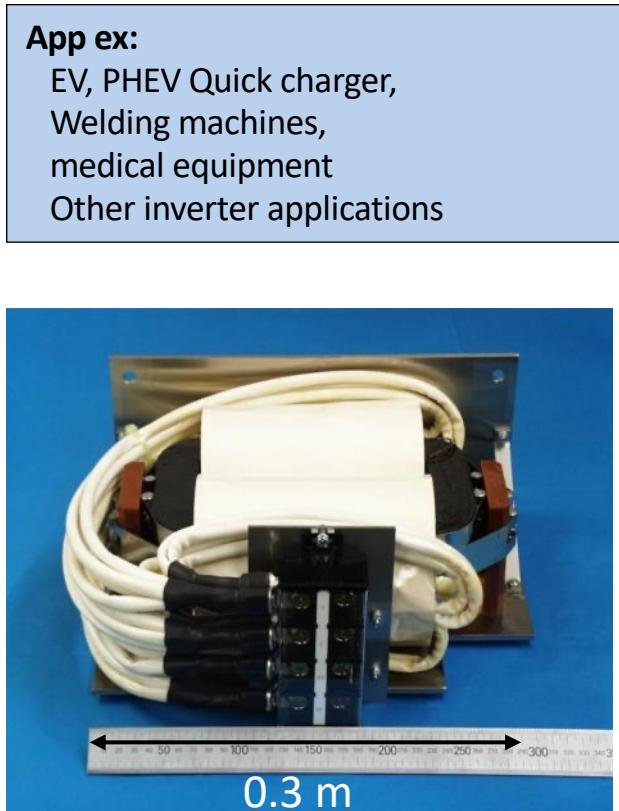
Example for PE ~High frequency transformers~

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- Transformer suitable for high-power, high-frequency SW circuits



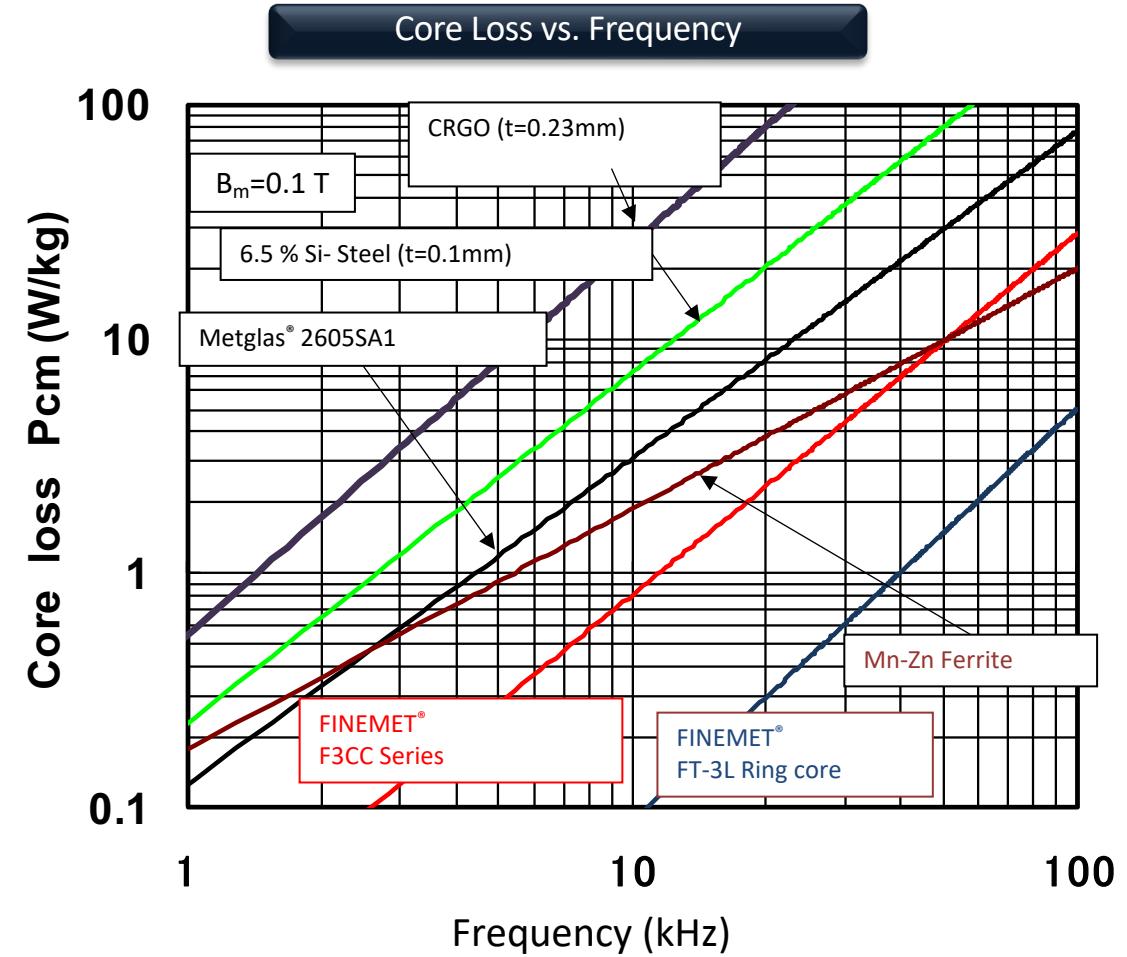
Size comparison vs 40 kVA commercial freq. trans.
Volume 約 1/20
Weight 約 1/30



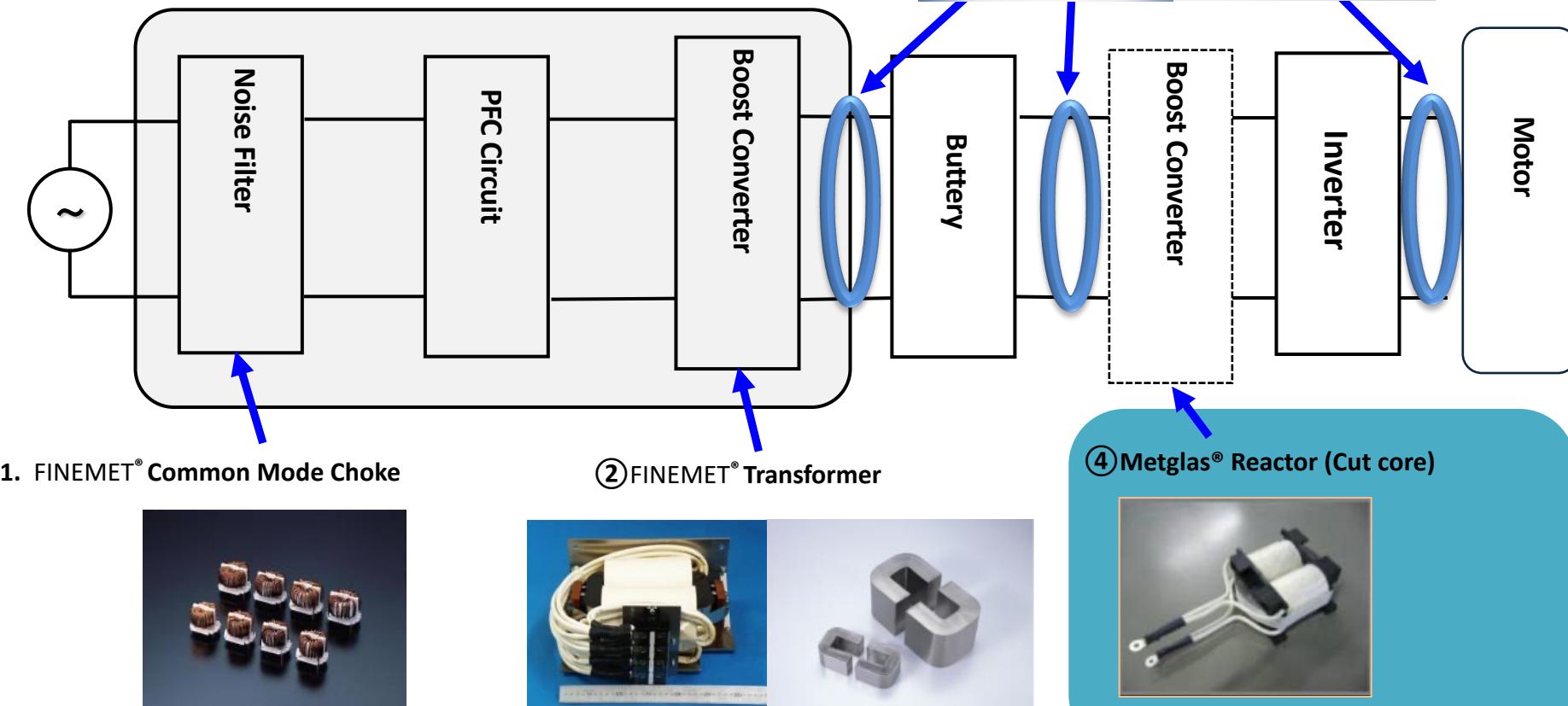
App ex:

EV, PHEV Quick charger,
Welding machines,
medical equipment
Other inverter applications

40 kVA 10 kHz High Frequency Transformer



- Automotive charging circuit / Quick Charger



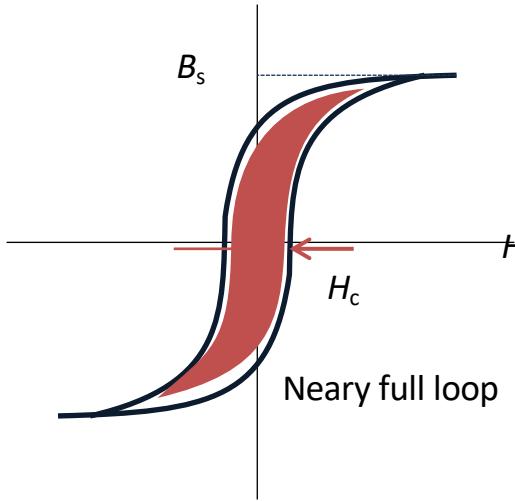
Applications requires power density

- SMMs in medium frequencies

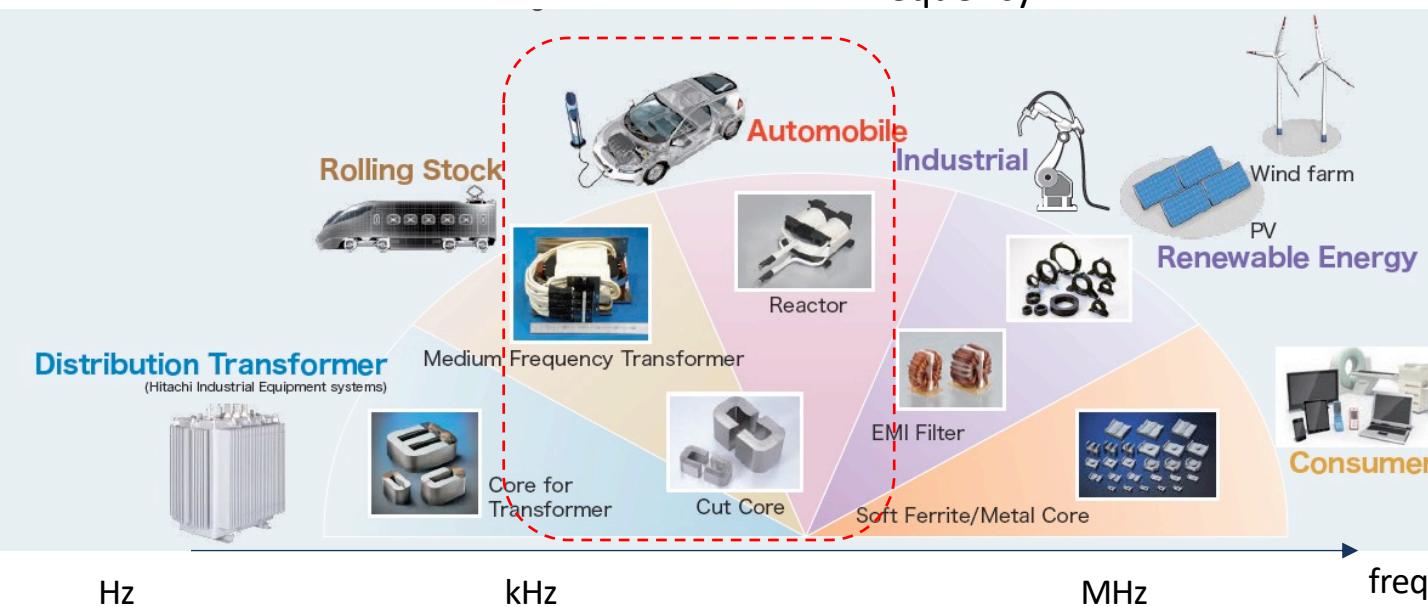
- Development of High Fe content nanocrystalline alloys High B_s nanocrystalline alloy (Hi- B_s nano)

Applications which requires higher B_s

Choose materials with a good balance of high B_s and low losses to obtain high power density at the expense of the best low-loss performance



- Applications that use B - H loops throughout
- Medium frequency (sub kHz – tens kHz)
- Output will be determined not only by the B_s , but also by frequency.
- Higher the frequency, higher the core loss i. e it creates heat.
- If the coefficient of core loss is low, it is easier to pull out power by increasing driving frequency.



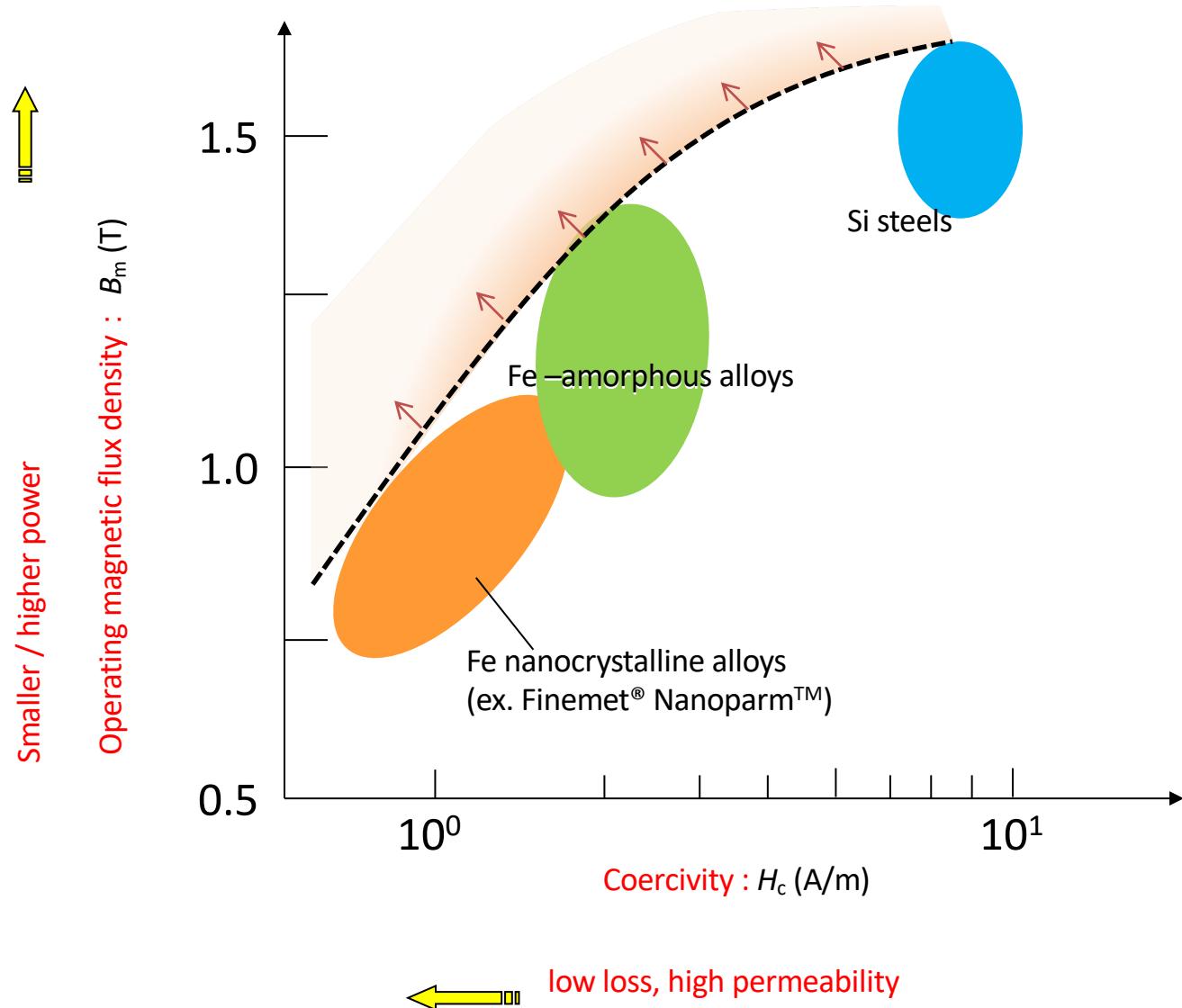
Reactors



Motors

Metallic SMMs on B_m vs. H_c map

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B_m : determined by Saturation magnetic flux density B_s & iron loss

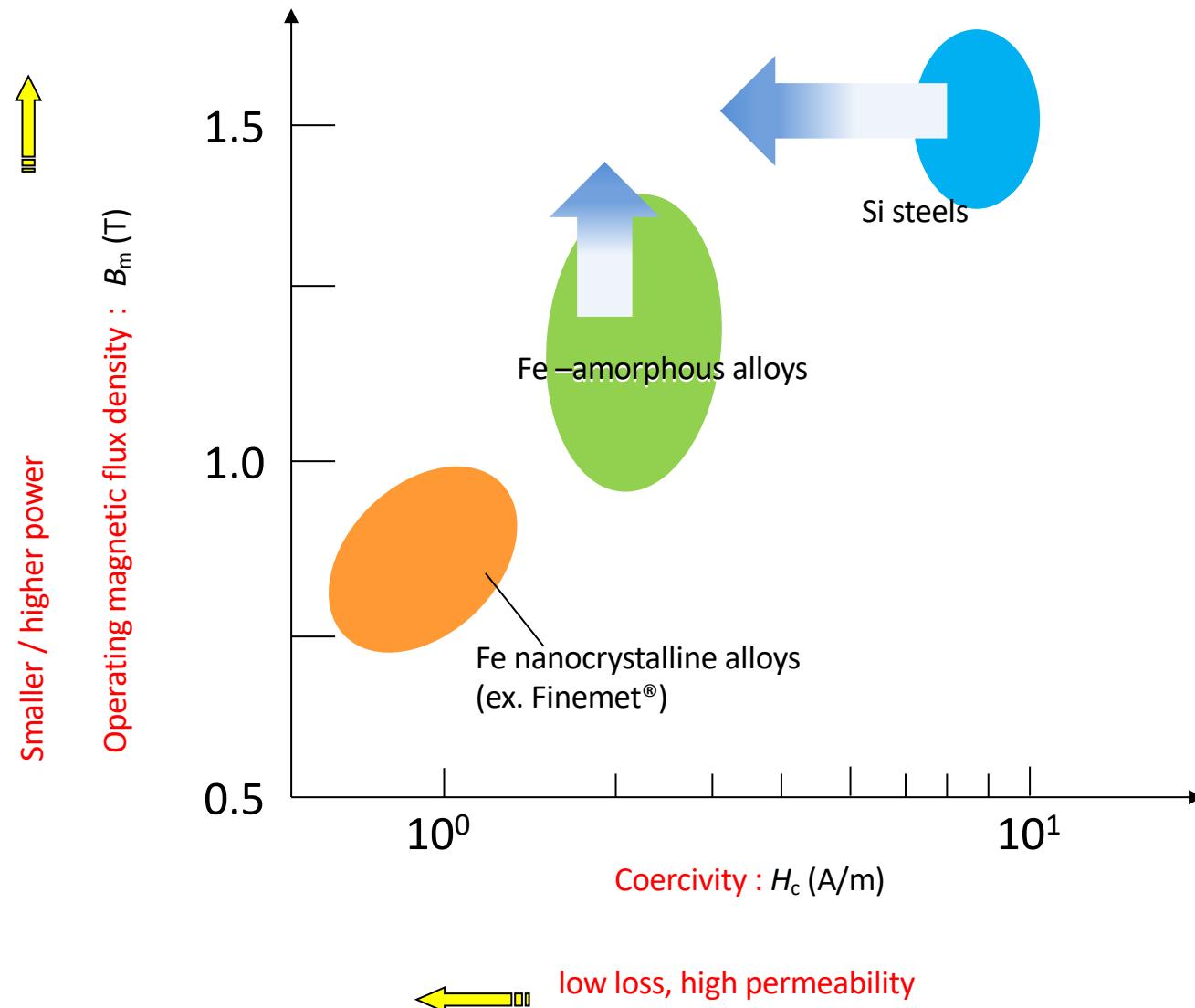
B_m vs. H_c Tradeoff

Direction

high B_m
low H_c

Soft magnetic materials on the B_m vs. H_c map

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Two approaches

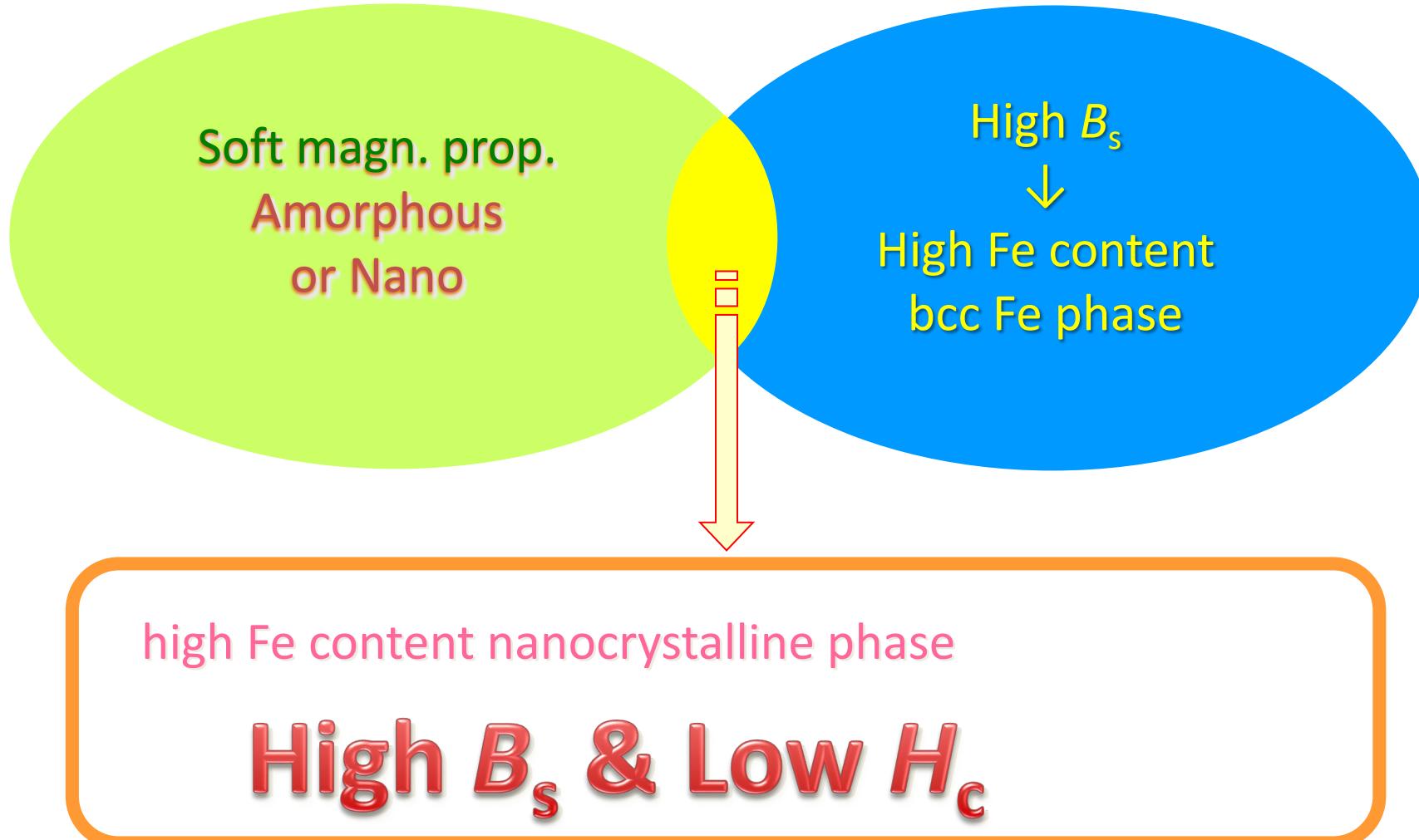
Lower H_c in crystalline system?

or

Higher B_s in
nano/random systems?

- ✓ Fe crystal has higher B_s
- ✓ random structure exhibits good SMM

High B_s Nanocrystalline alloy



Composition of FINEMET® alloy



Y. Yoshizawa, et. al.: *Mater. Sci. Eng.*, A181/A182 (1994)
871-875.

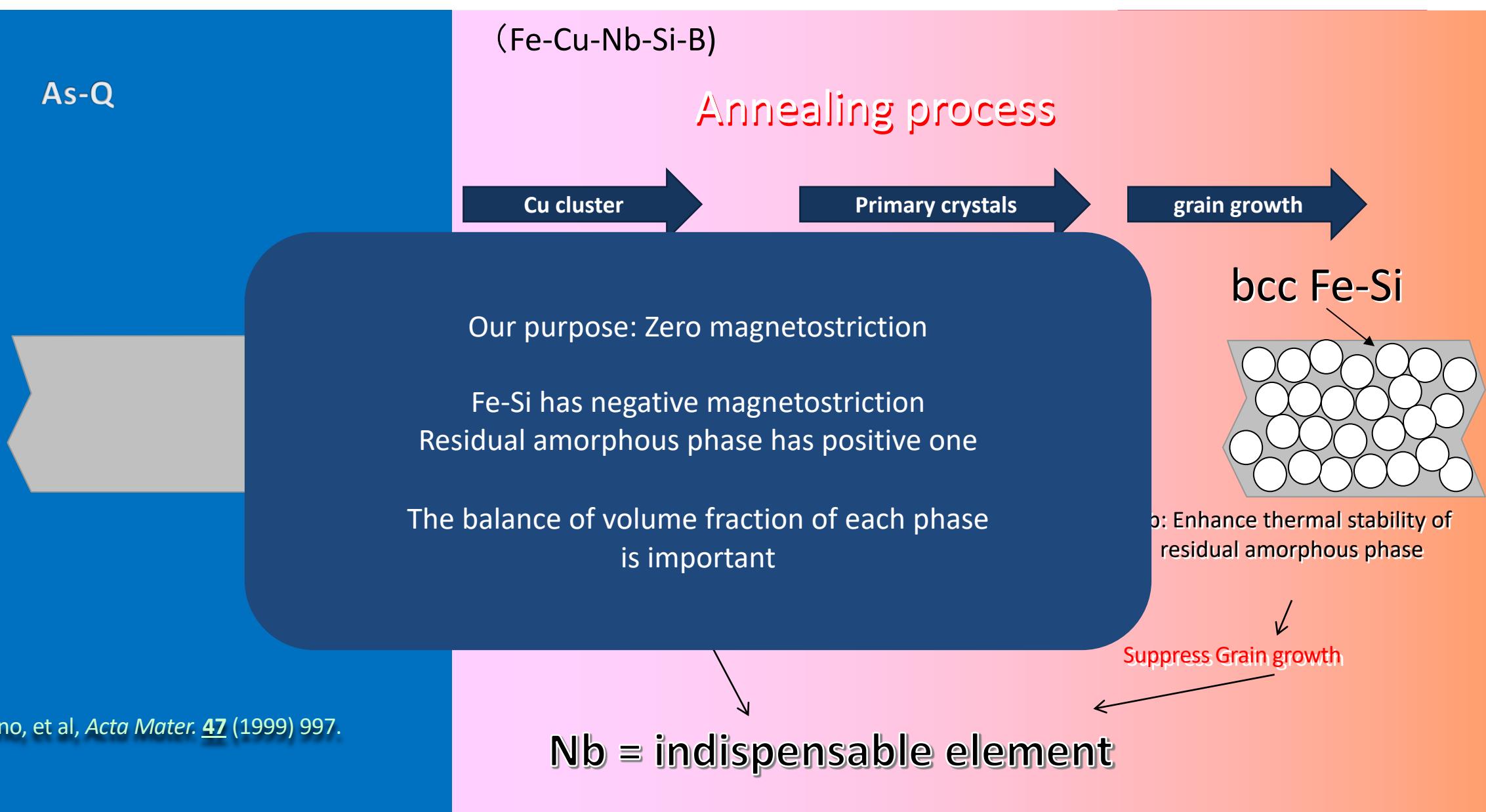
Low Fe, relatively high Nb \Rightarrow Low B_s

Fe: source of magnetic moments

Nb: high number density of seeds & suppresses grain growth

Annealing process of FINEMET®

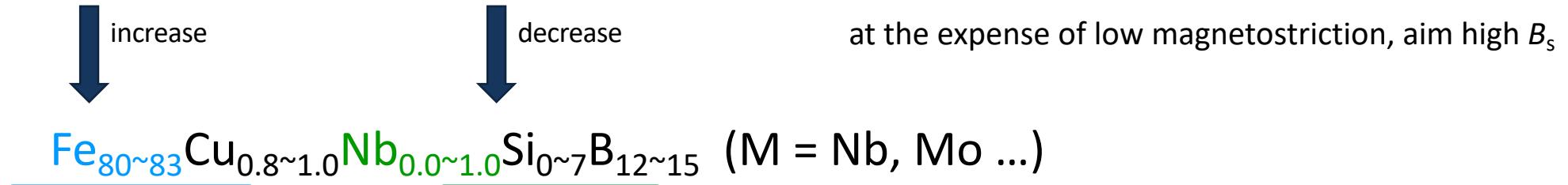
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Composition of FINEMET® alloy



(at.%)

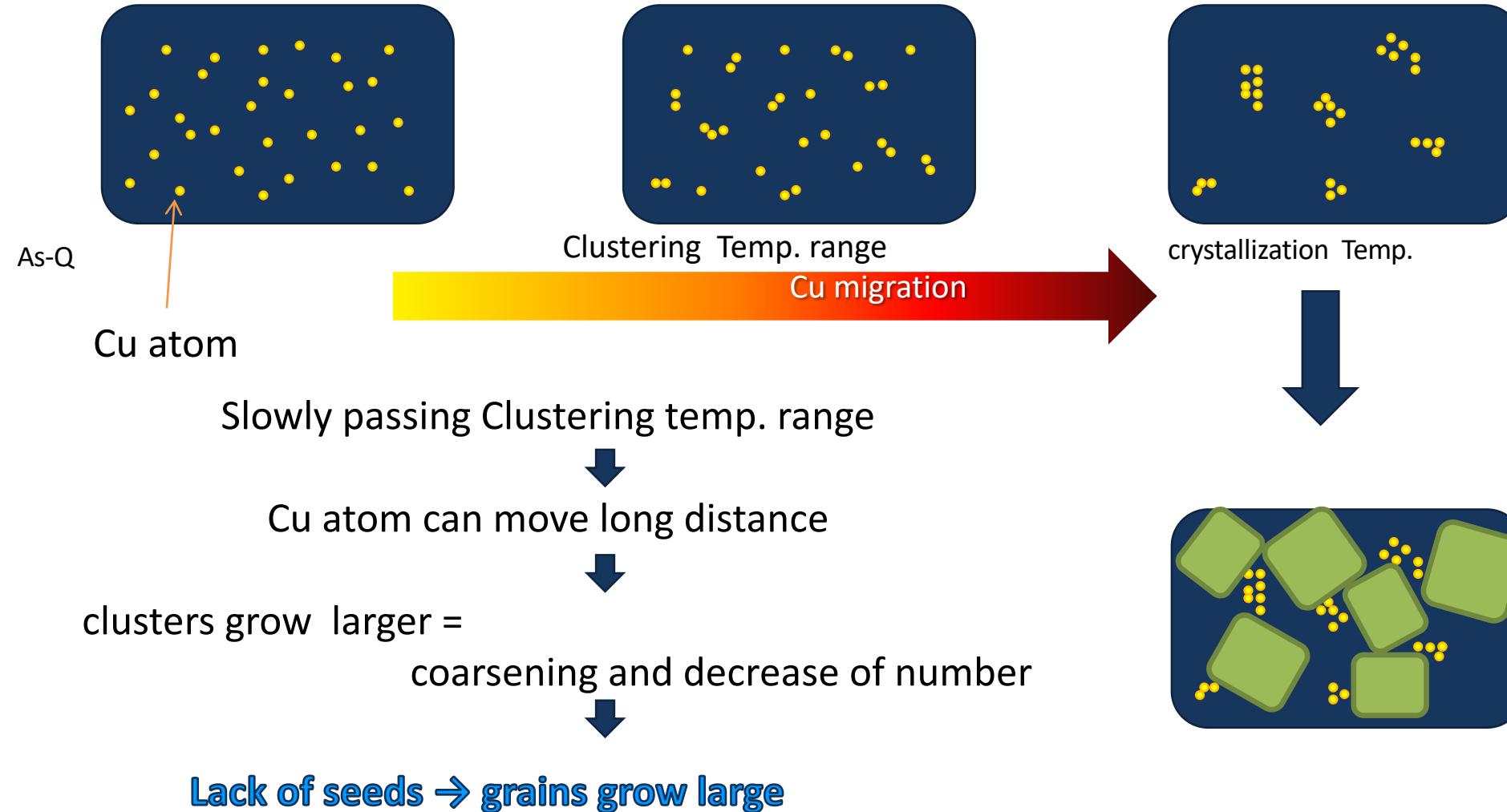


Roles of Nb elements
→ substituted by Quick Anneal

(flash anneal)

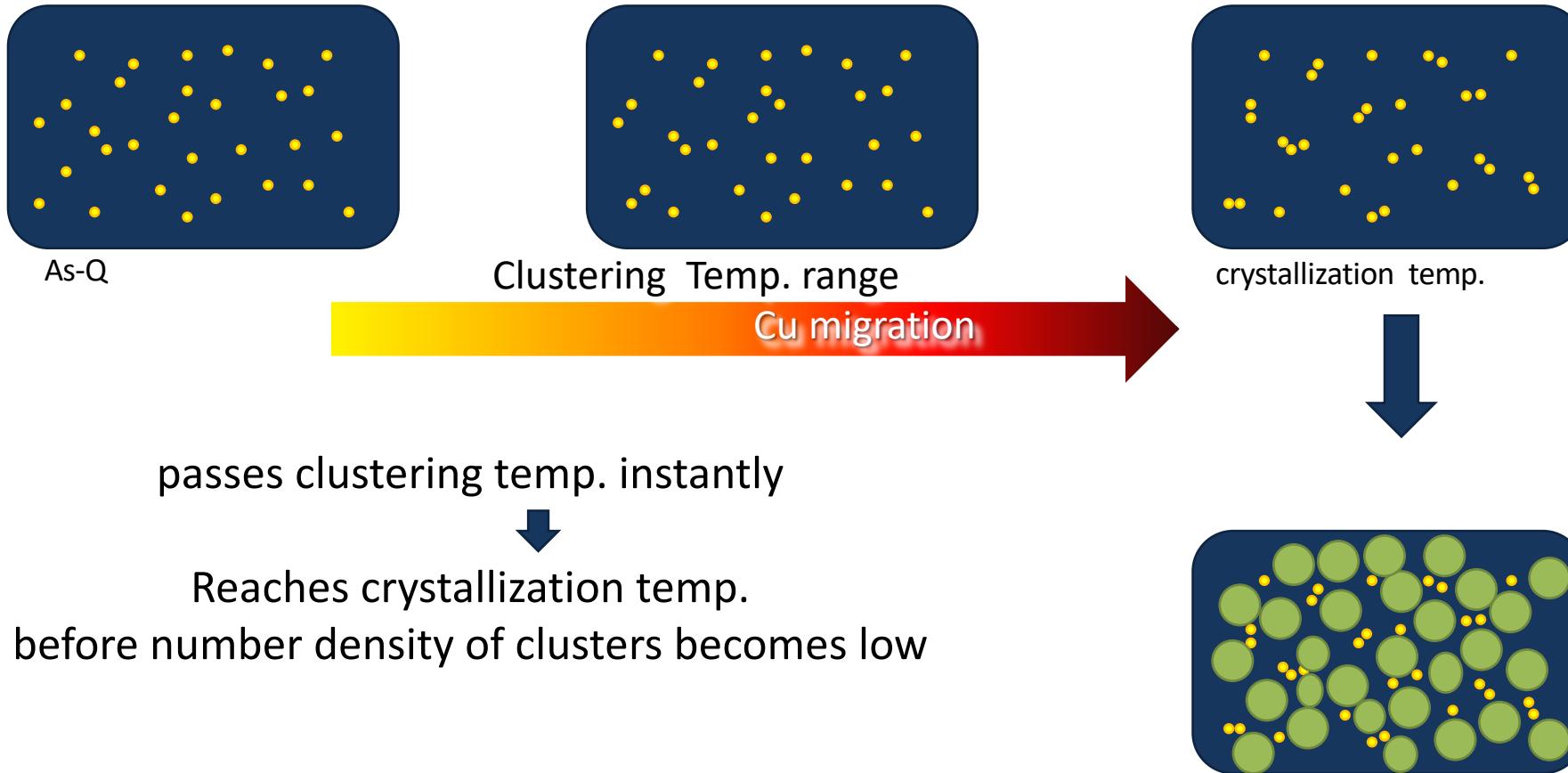
Approach 2. Rob migration time of Cu atoms

Cu clustering in Normal Annealing in new composition PROTERIAL



Cu clustering in Quick Annealing

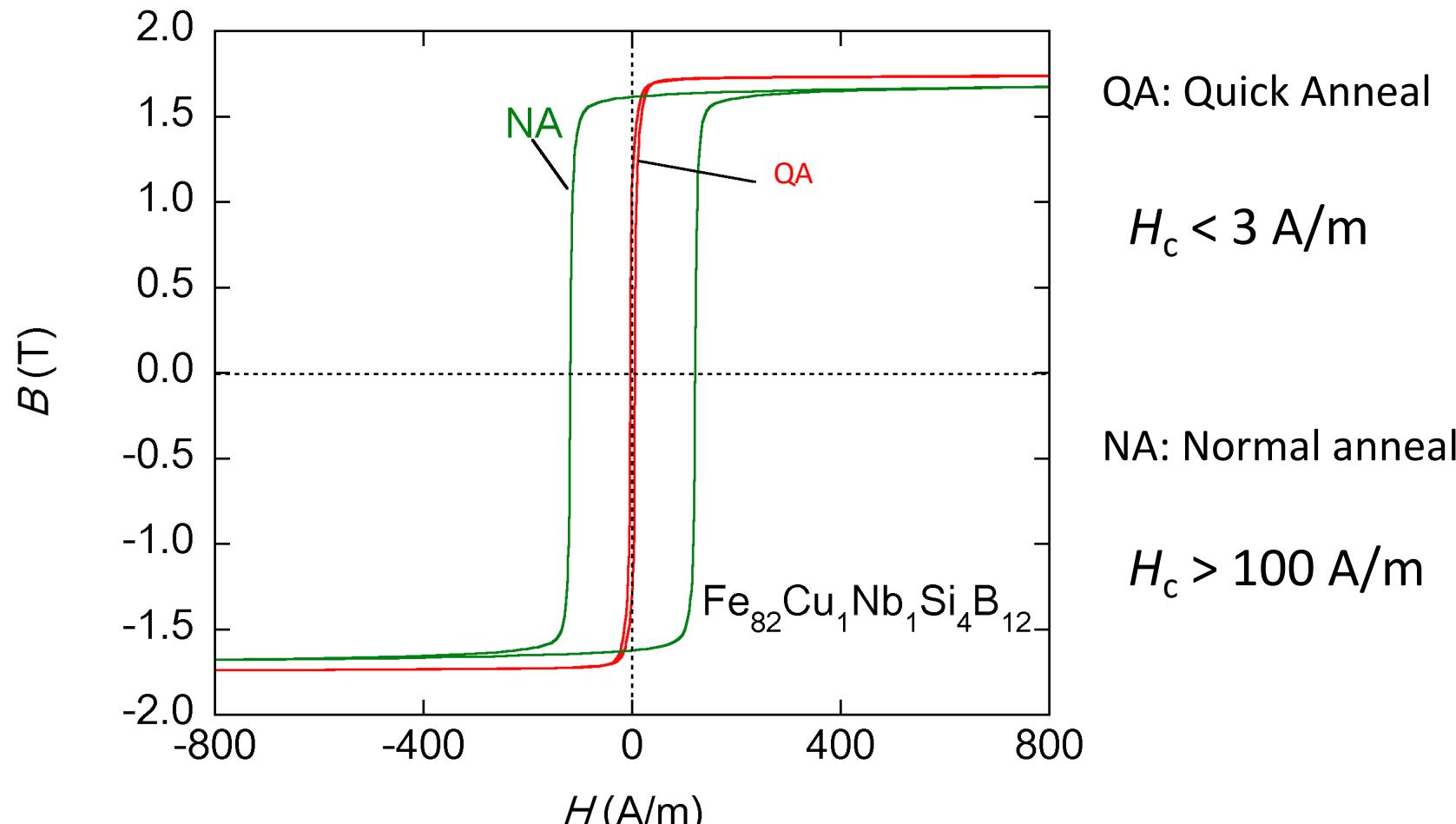
PROTERIAL



High number density of seeds remains → fine nanocrystalline phase

B-H loops of NA and QA ribbons

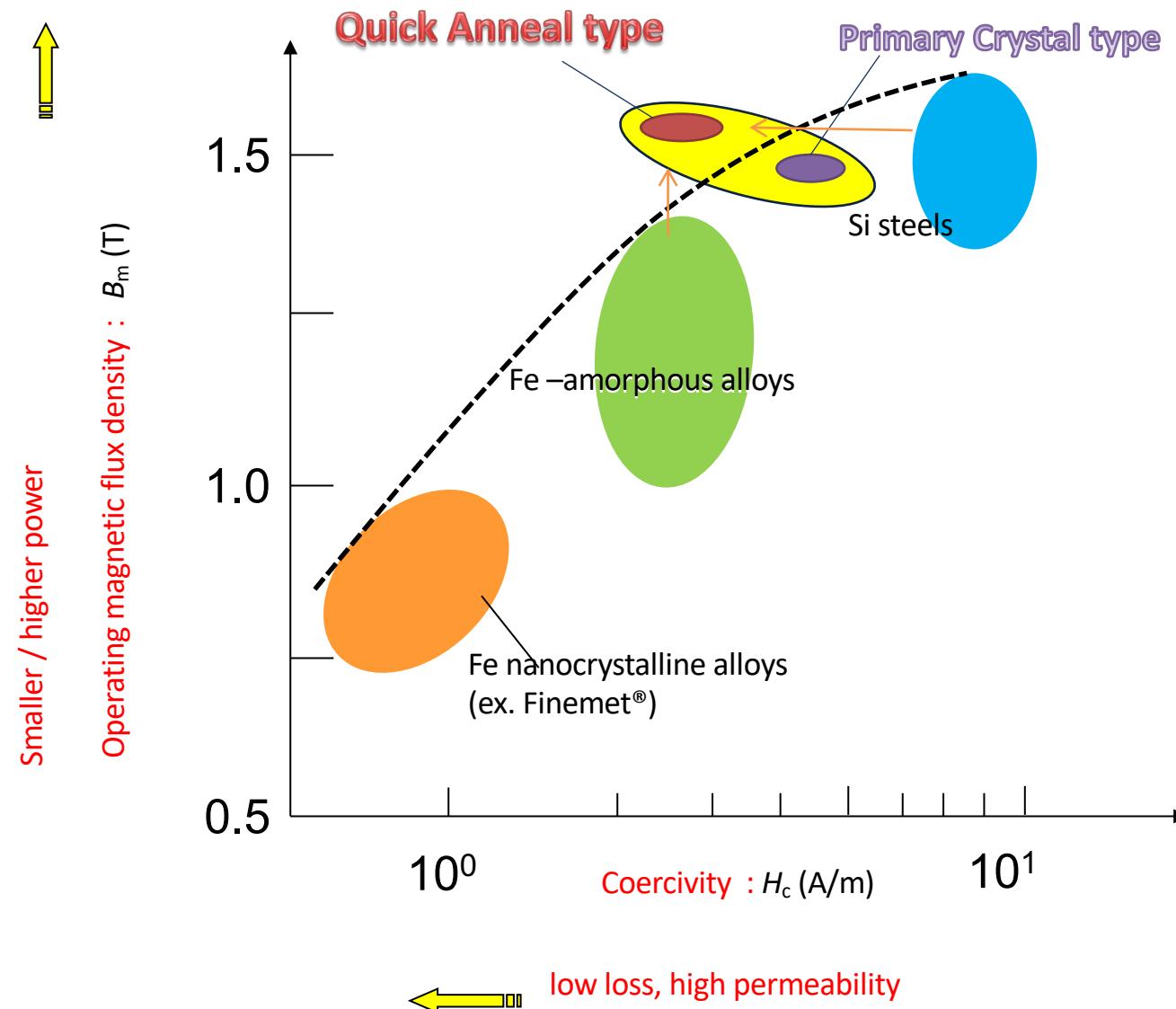
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Low Nb, but high B_s & low H_c

Position of developed high B_s nano alloys

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Loss is 1/3 of Si-steels

$B_s \cdot B_m$ are 10% higher than Fe-AM

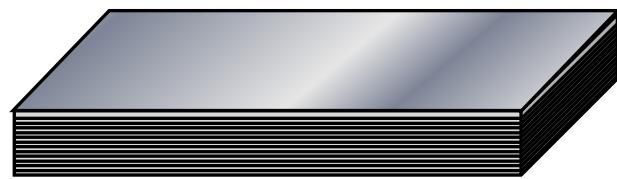
Quick annealing type may be suitable for industrial products

If we can solve the processing issues

- Applications of Hi- B_s nano
 - Block core for a reactor
 - Motors

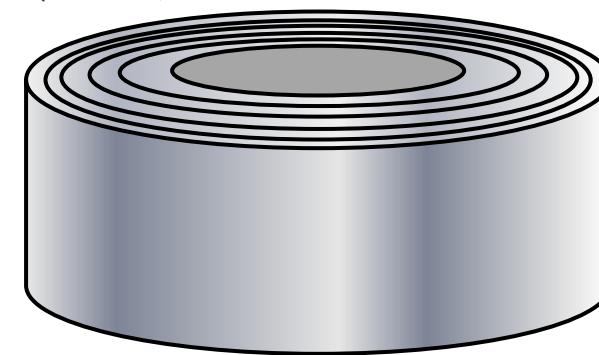
We want to search application field for this material.

Block core
(laminated)



thickness of
lamination

Toroidal core



wound ribbon

Affects annealing

We cannot apply quick anneal
to cores

Quick anneal first
then form the core



Easy to implement and easy to adapt to various applications

http://kuretake-denko.co.jp/pages/core_shurui/TOR.html

Soft magnetic properties block cores

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continuous Quick (flash) anneal



spool

laminate single strips



mold (impregnation)



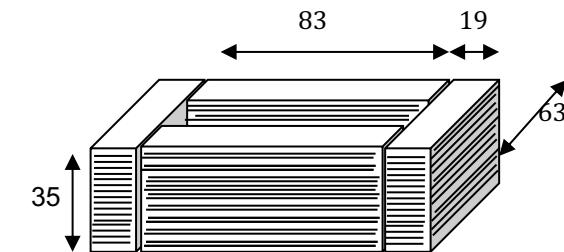
cutting/Grinding/Etching



Block



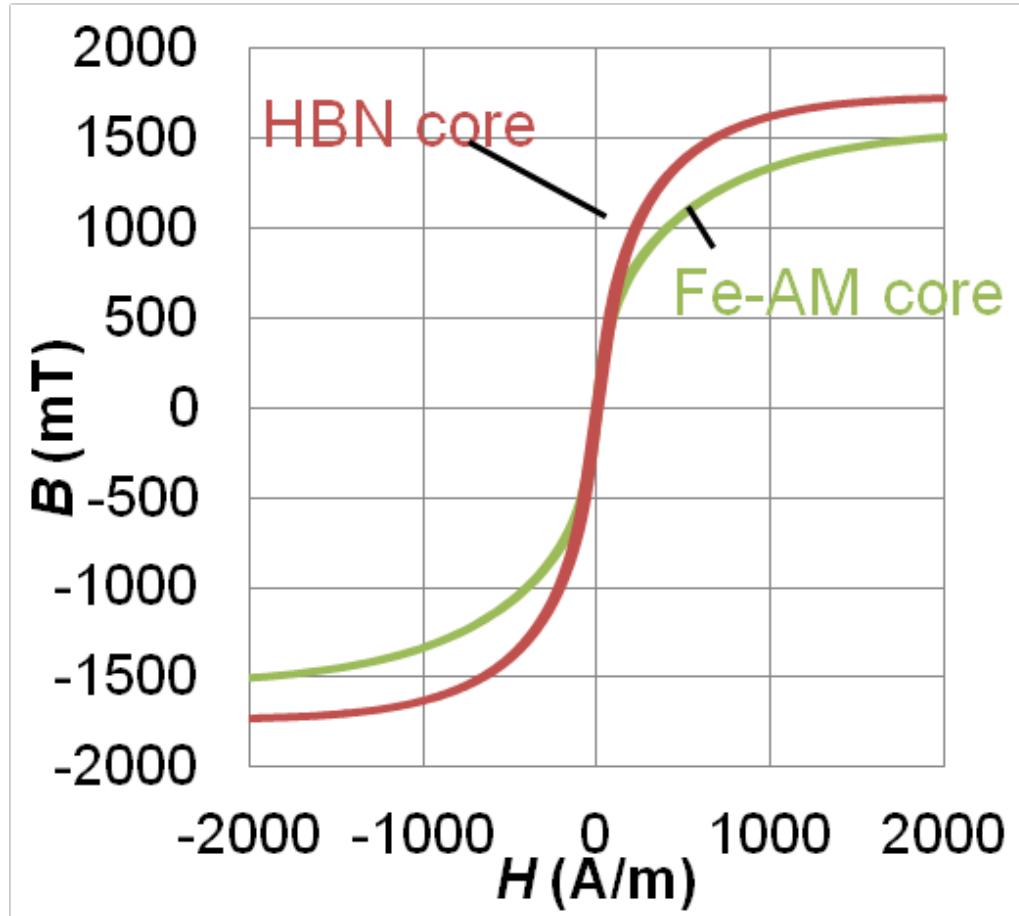
Form a circuit by 4 blocks



HBN core

Soft magnetic properties block cores

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Hi- B_s nano core shows high B_{2000}

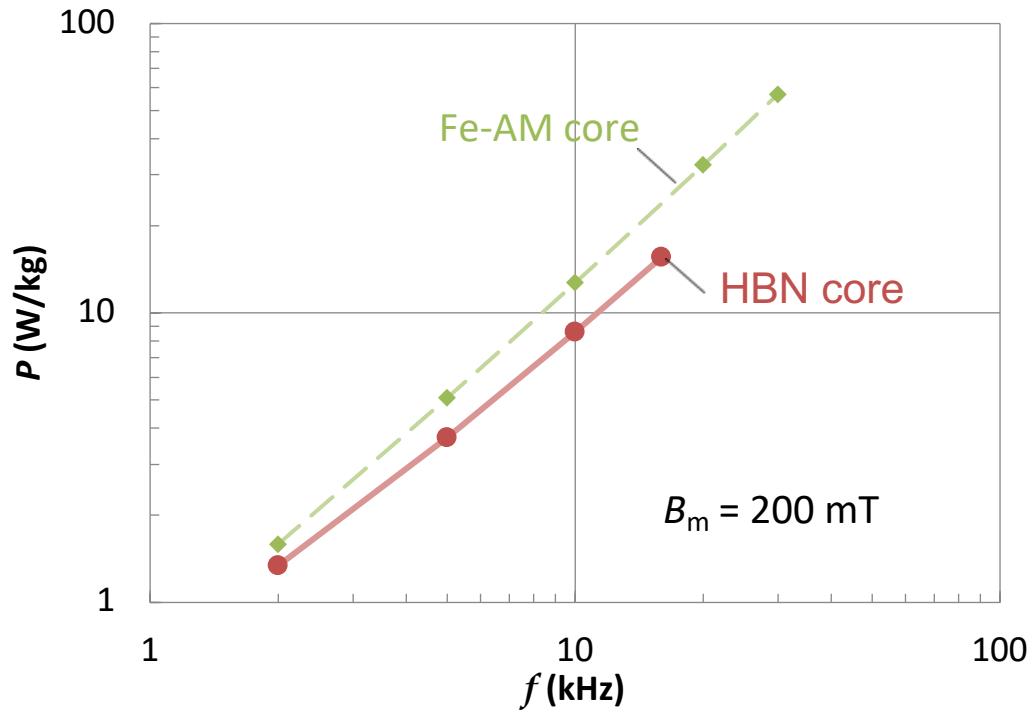
	B_{2k} (T)	B_s (T)	B_{2k}/B_s	λ_s (10^{-6})
HBN	1.73	1.75	99%	14
Fe-AM	1.50	1.57	96%	27

Better saturation behavior in HBN.

Hi- B_s nano can handle 10~15% larger DC superposition current

Soft magnetic properties block cores

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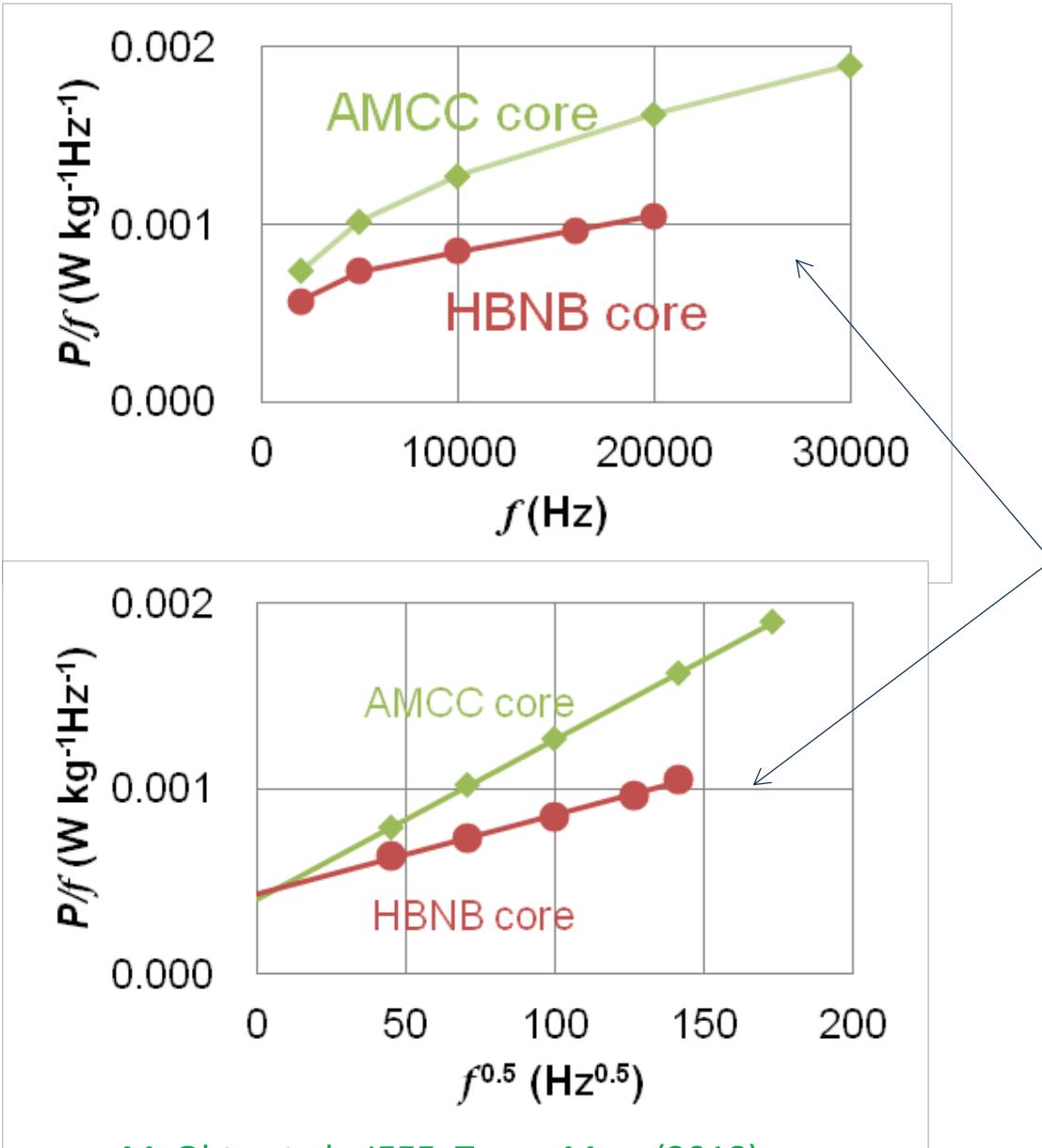


2/3 of core loss of Fe-AM

Amorphous core is recognized as a sufficiently low-loss material

loss separation of block cores

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$$P_{\text{total}} = P_h + P_e + P_{\text{ex}}$$

$$P_h \propto f^1$$

$$P_e \propto f^2$$

$$P_{\text{ex}} \propto f^{1.5}$$

$$P = af + cf^2 + bf^{1.5}$$

conventional plot: liner =
eddy current

$$P/f = a + cf + bf^{0.5}$$

c : negligibly small

Contribution of excess eddy current loss is dominant in medium f

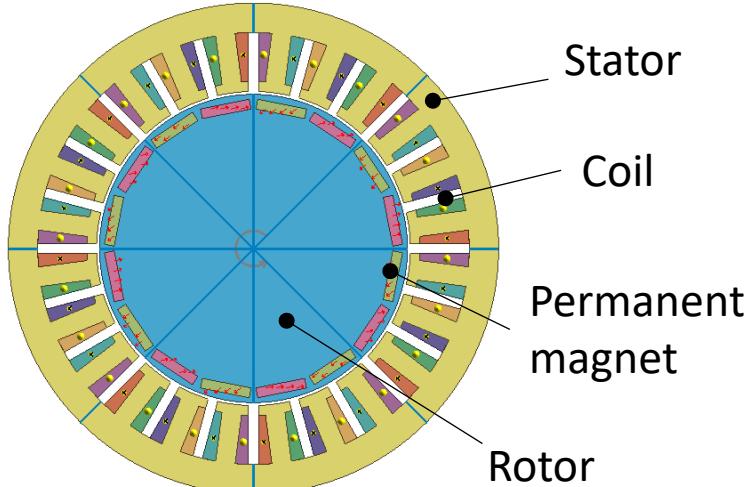
b is strongly depending on pinning of domain wall

High B_s nano can be used in higher frequency

Comparison of core materials in Φ50mm motor

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SPEC



Cross section

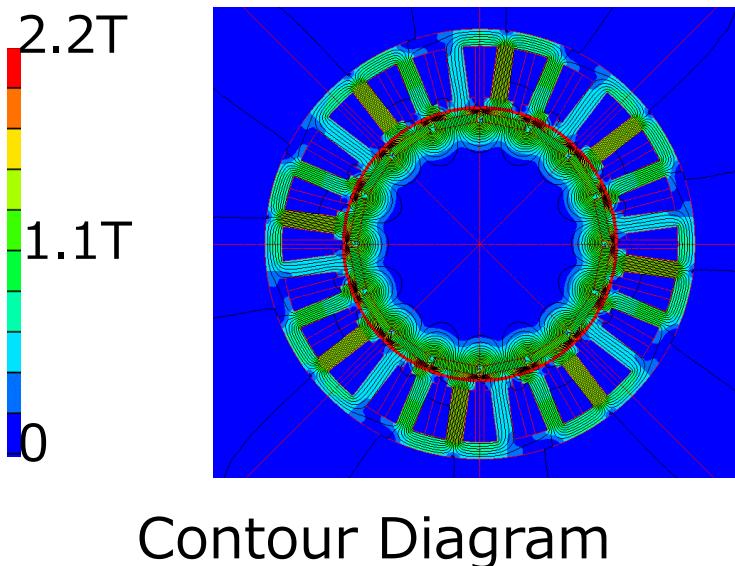


Motor

item	value
Stator	Φ50 mm
Rotor	Φ31.4 mm
Gap	0.3 mm
Thickness	50 mm
Stator core Material	Amorphous (HB1M: PROERIAL)* Hi B_s Nano (PROTERIAL) Si-steel (35H300: Nippon Steel)
Output	30 W (at 1000rpm) 300 W (at 10000rpm)
Voltage	Max. 200V
Current	Max. 3A

*result from Shimane Univ

- Amorphous, High B_s Nano:
@10000rpm(1333Hz) 85% lower core loss than Si-steel core
- Similar torque



Analysis (@3.2 A)

RPM	Core material	Torq (Nm)	Coil loss (W)	Core loss (W)	Total loss (W)
1000 min ⁻¹ (133Hz)	Amorphous*	1.03	3.06	0.147	3.207
	Hi Bs Nano	1.03	3.06	0.137	3.197
	Si-steel	1.02	3.06	1.175	4.235
10000 min ⁻¹ (1333Hz)	Amorphous*	1.03	3.06	2.917	5.977
	Hi Bs Nano	1.03	3.06	3.308	6.368
	Si-steel	1.02	3.06	39.82	42.88

*result from Shimane Univ

Core
1/8
Total
25% ↓

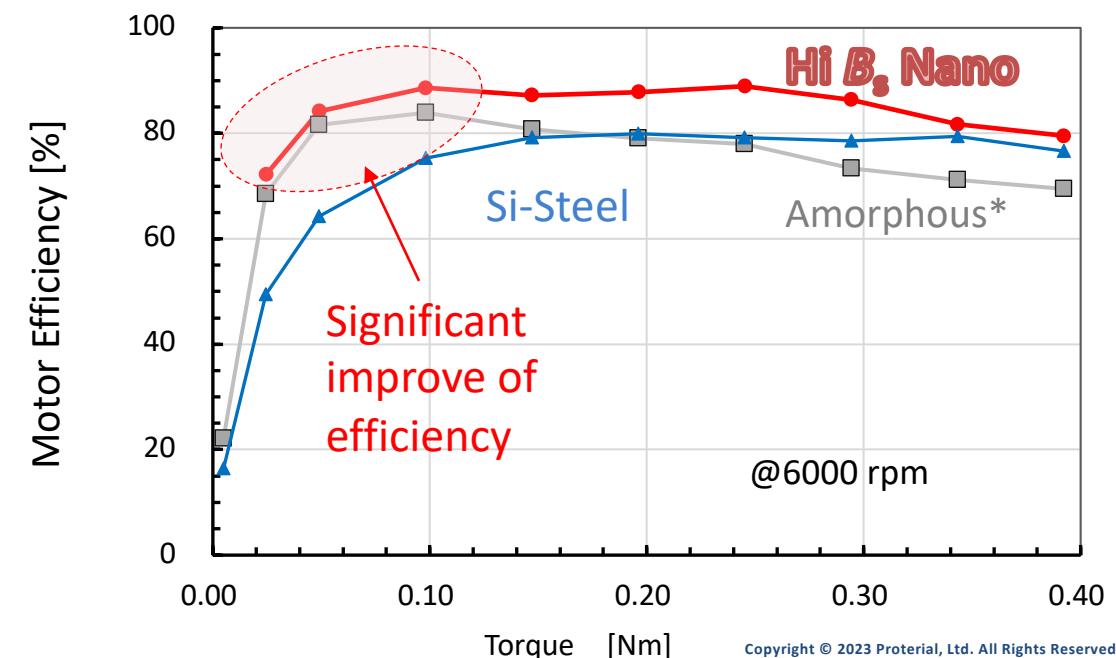
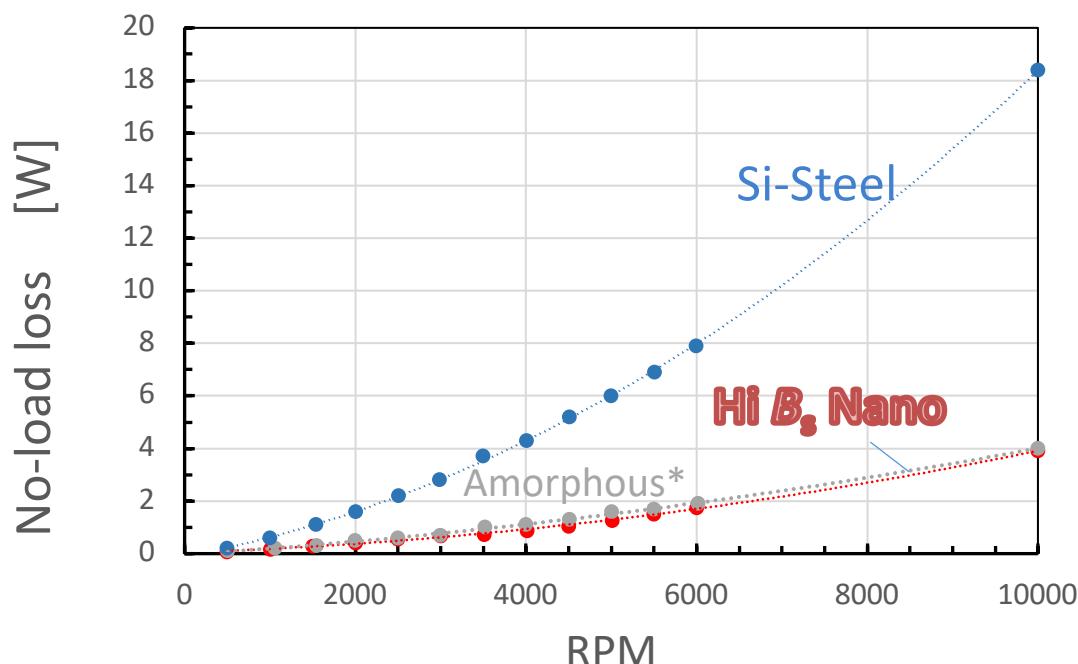
Core
1/14
Total
85% ↓

Very meaningful difference can be expected!

- No-load loss: equivalent to Amorphous and Hi- B_s nano teeth
- In the light-load: efficiency of Amo/Hi- B_s nano... **significant improvement**
- In the high-load: the proportion of coil loss increases, so the difference with Si-steel core decreases, and eventually the efficiency is reversed



There is an optimal design point for utilization

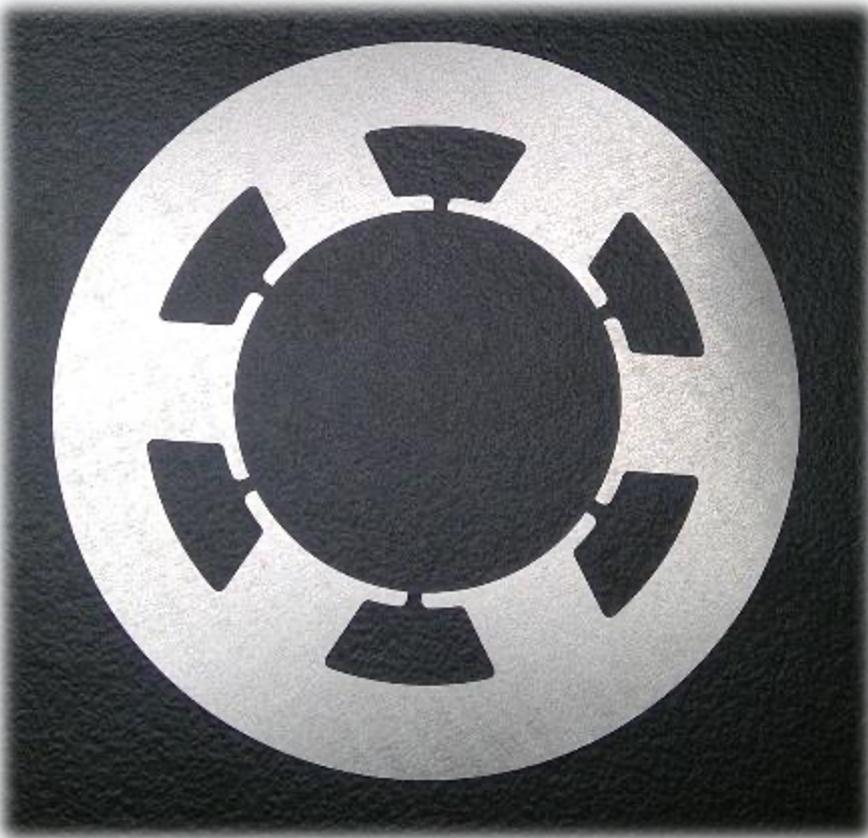


Issues of amorphous ribbon production

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*nanocrystalline ribbons are also casted as amorphous phase

Punched (stamped) amorphous ribbon as a stator shape



No problem in shearing process



Shearing is easy!

Go simpler shape!

Thin & hard ... requires more processes than thick & soft materials

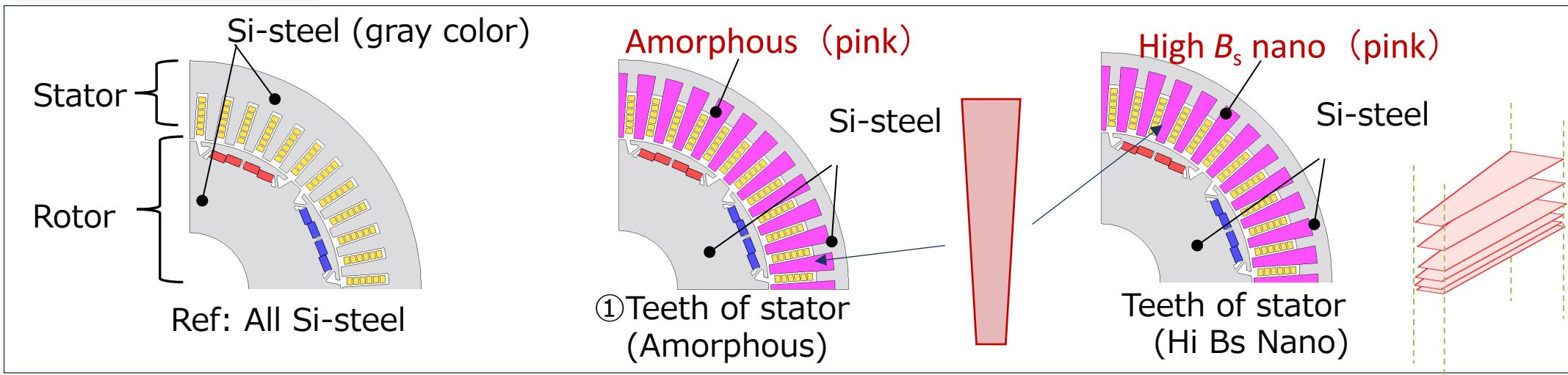
But don't forget that "thin" will lead to low eddy current loss in high freq.

Now we are trying to keep the number of strokes down in punching process

SPEC



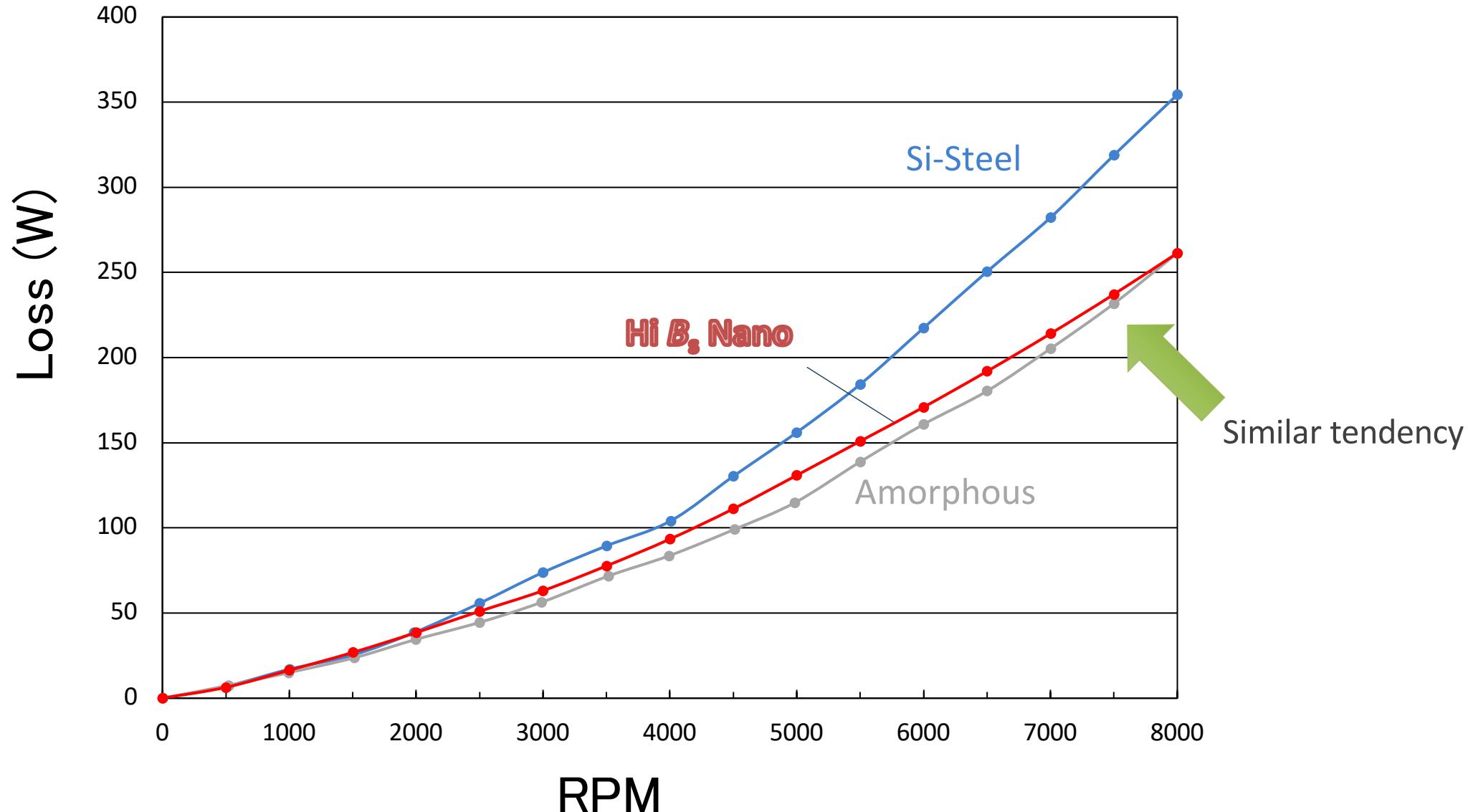
Contents	IPM Motor
Power	22kW(6000 rpm, 35 N·m) Max : 66kW(7000 rpm, 90 N·m)
Torque	90 N·m
RPM	20000r/min
Size	Φ215×50mm (1.8L)
Weight	13.6kg
Efficiency	96.0% (Calculated value)



The models, Cross section of 1/4 of Motor

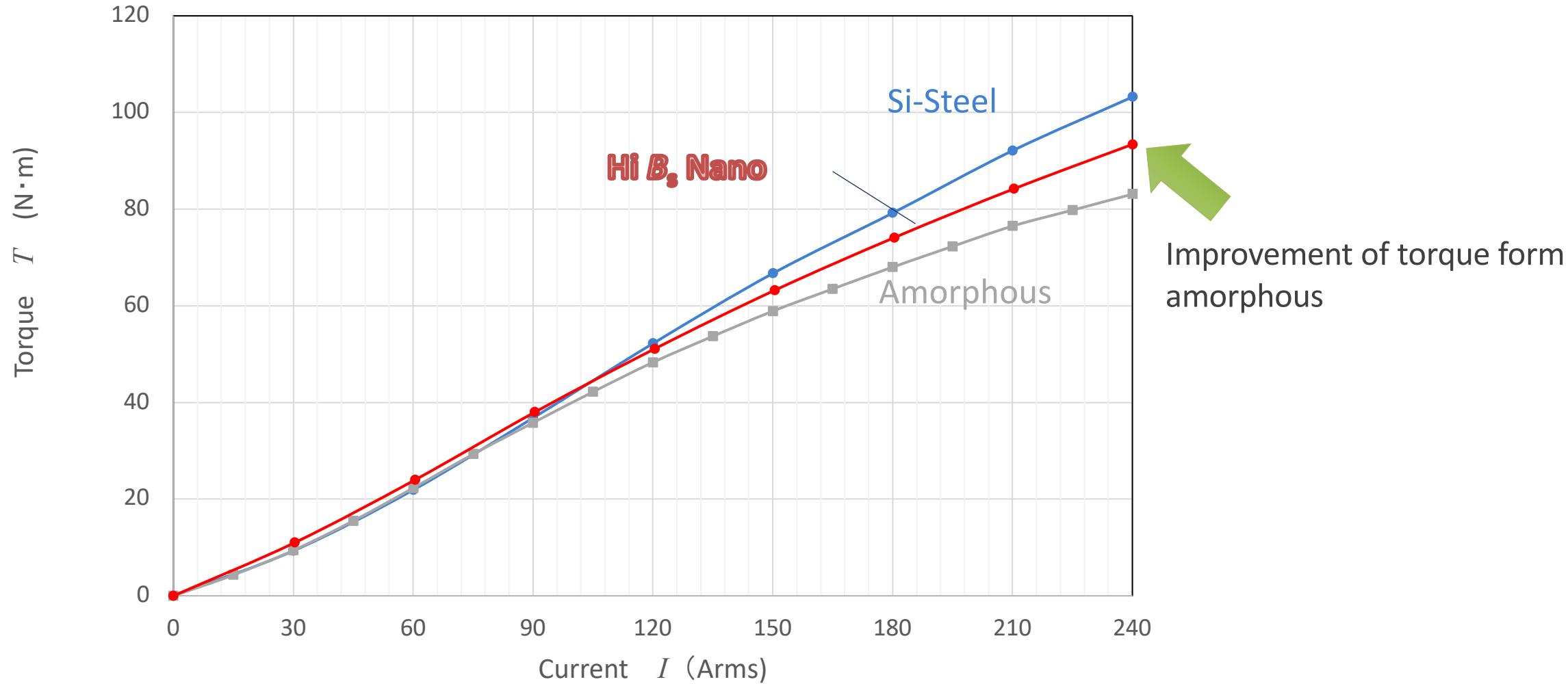
This simple shape can be prepared by shearing

■ No-load loss



Current vs. Torque

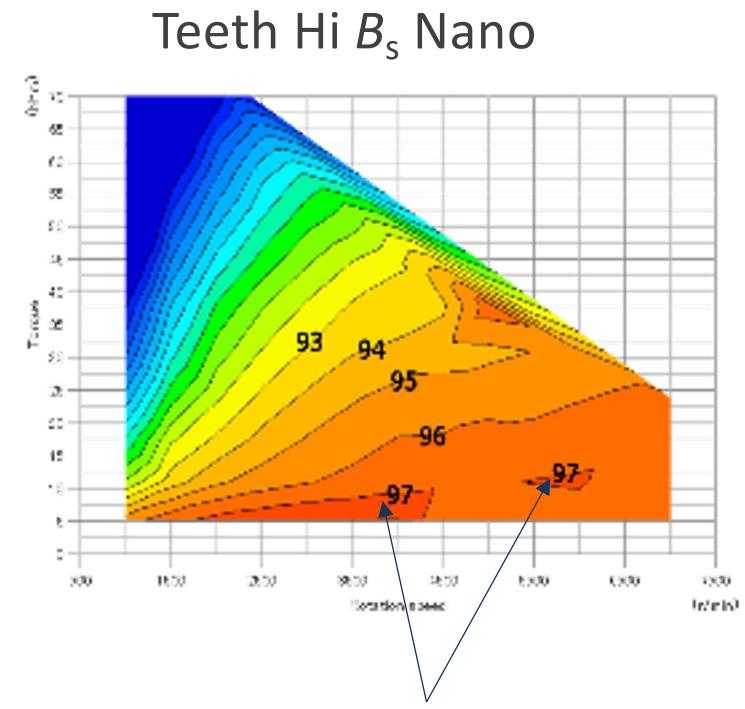
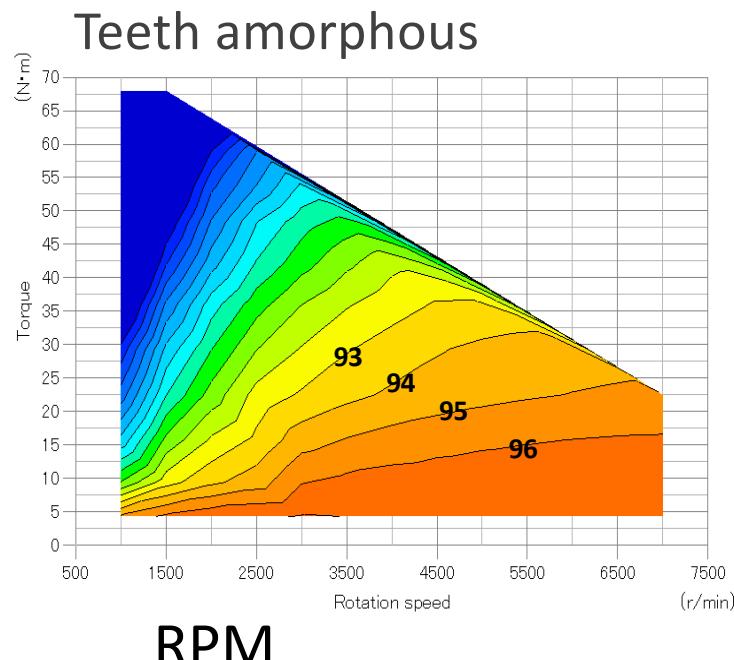
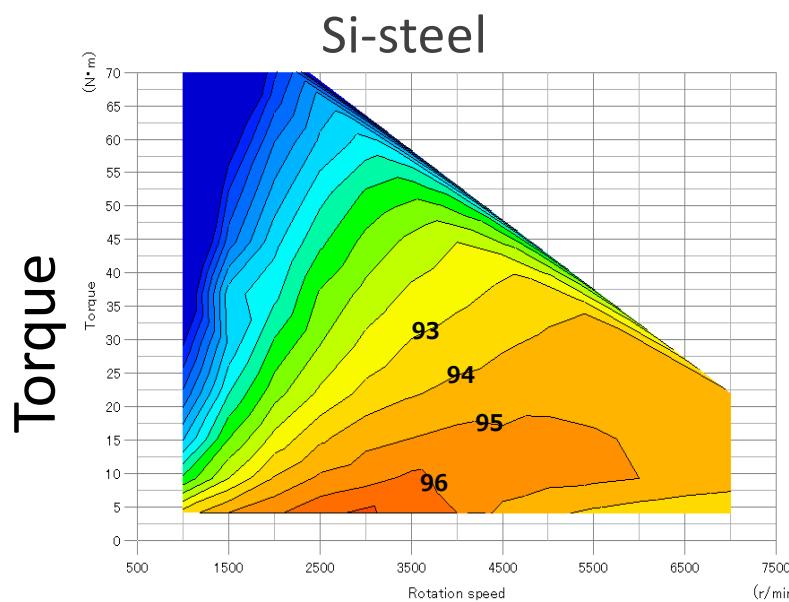
PROTERIAL



*The result could be expected

Efficiency map (tested result)

PROTERIAL



Highest efficiency

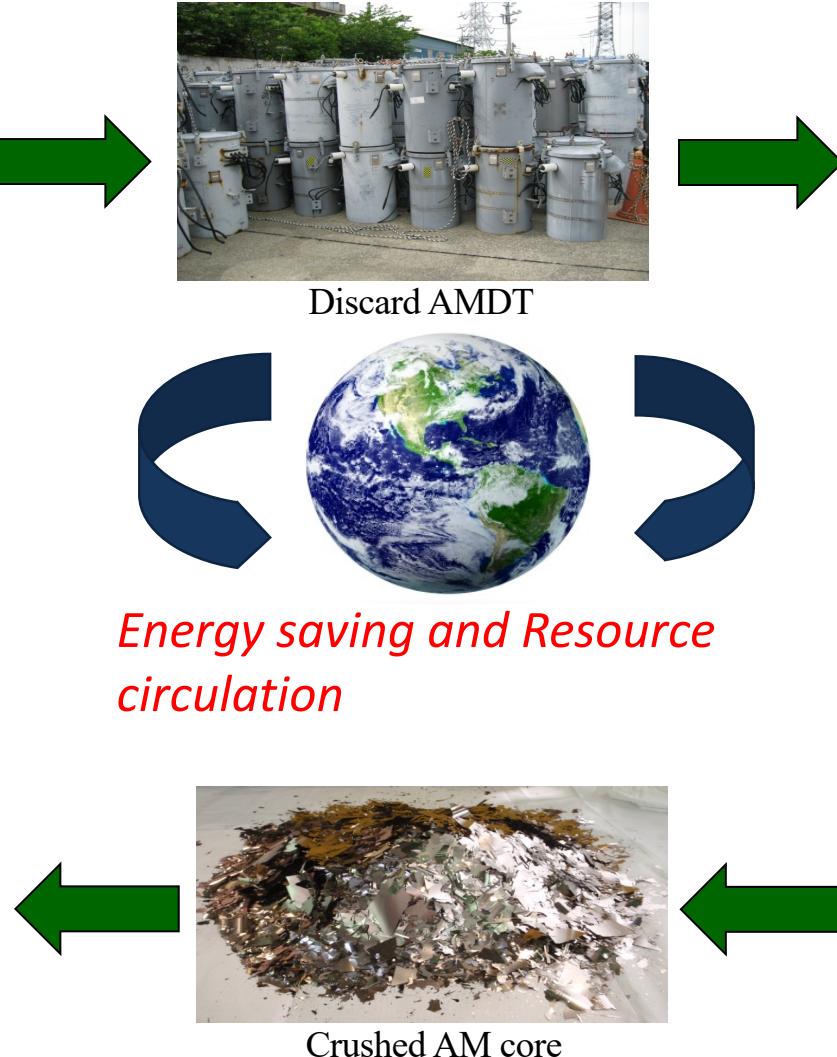
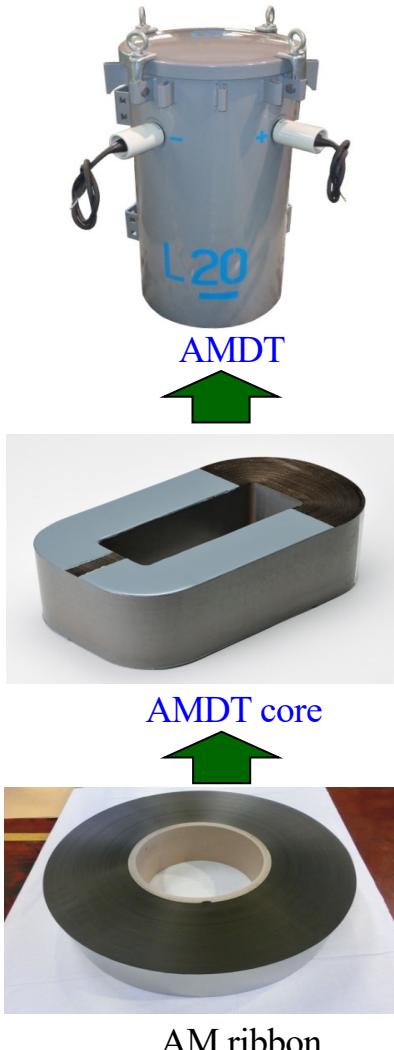
Higher efficiency in wide condition

• Si-steel < Amorphous (teeth) < High B_s nano (teeth)

* ... So far, the high B_s nano is the best

- Remaining issues
 - Recycling
 - Punching processing

Recycle of Amorphous Transformer



Recycle process
Capacity : 50 MT/mo
(April, 2013~)



Retrieve AM core from AMDT



Crush and Screen



Wash and Dry

Challenges specific to Hi B_s nano

New machining process or Consider the usage

Material	Assumed production process and challenges	Countermeasure
<ul style="list-style-type: none"> ▪ Brittleness with crystallization ▪ Shrinkage with crystallization 	<p>Anneal ribbon</p> <p><i>Material</i></p> <p><i>Machining</i></p> <ul style="list-style-type: none"> ▪ Simpler Shape is easier 	<ul style="list-style-type: none"> ▪ Shearing method ex : Teeth core
<ul style="list-style-type: none"> ▪ High heating rate anneal 	<p>Shaping</p> <p><i>Material</i></p> <p><i>Machining</i></p> <ul style="list-style-type: none"> ▪ In-plane variation of contraction ▪ Handling issue 	<ul style="list-style-type: none"> ▪ Processing methods other than stamping → developing
		<ul style="list-style-type: none"> • Shrinkage evaluation & distortion reduction • New heat treatment method • New piece adhesion method

In present speak, the magnetic properties and their applications of **the nanocrystalline alloy ribbons** were introduced. Developed materials can be one of the best candidate for next generation **power electronics materials** from **several kHz to MHz**.

- FINEMET® is designed having zero K and zero λ with high B_s owing to its nanocrystalline structure.
- In high B_s nanocrystalline alloy, owing to high Fe content nanocrystalline structure, **high B_s** and **low core loss** can be realized simultaneously.