Nanocrystalline Alloy Ribbons and Their Applications

PROTERIAL

Prof. Dr. Motoki Ohta

Global Research and Innovative Technology Center

(Professorship from Shimane University)

About Me

PROTERIAL

Motoki Ohta

Affiliation
- Senior Researcher: PROTERAL (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®

Contents

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- 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

Corporate Summary

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We were Hitachi Metals… Now we are PROTERIL

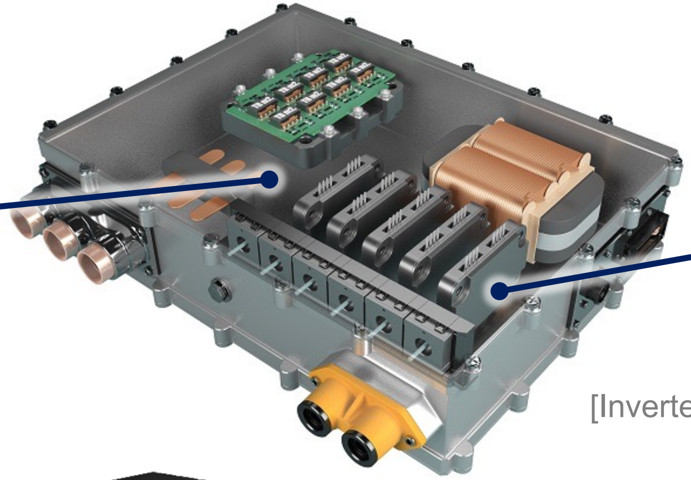
Date of Establishment	April 10, 1956
Capital	310 million yen （as of March 31, 2023）
Representative	Sean M. Stack - Representative Director, Chairman, President and CEO
Number of Employees	Proterial, Ltd., Non-consolidated: 5,754 （as of end of March 2023） Proterial Group, Consolidated: 26,496 （as of end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

Power Electronics Materials Business Unit

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

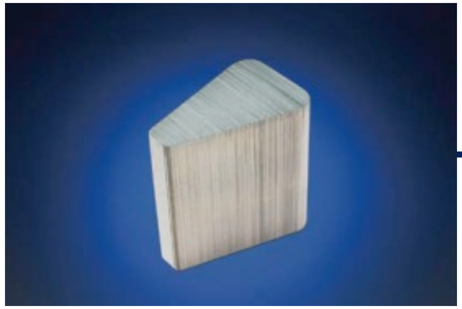
We offer a long list of specialty materials and components; Metglas® amorphous metals, FINEMET® nanocrystalline materials and high-performance soft ferrites and ceramics.

Nanocrystalline materials FINEMET®
(Ribbon, Core、Coil)

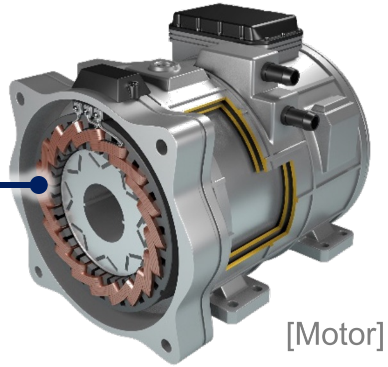


[Inverter]

Insulating substrate Si_3N_4



Amorphous Magnetic Materials
for Motors



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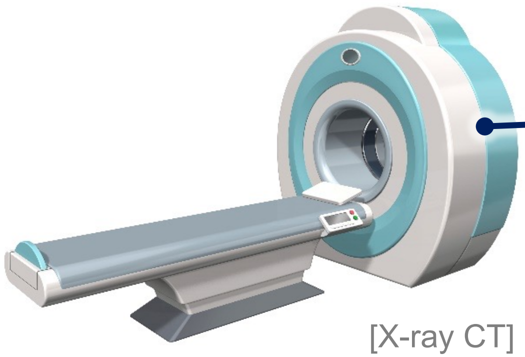
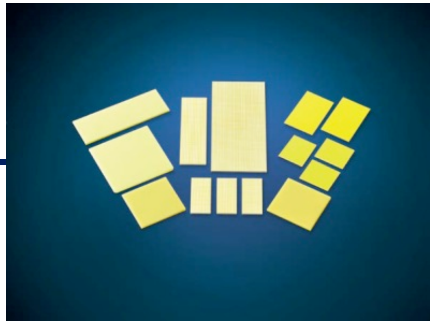


[X-ray CT]



Ceramic Scintillator

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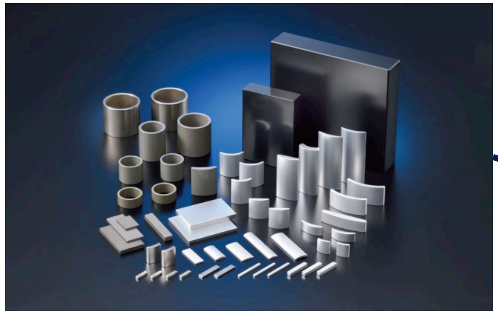
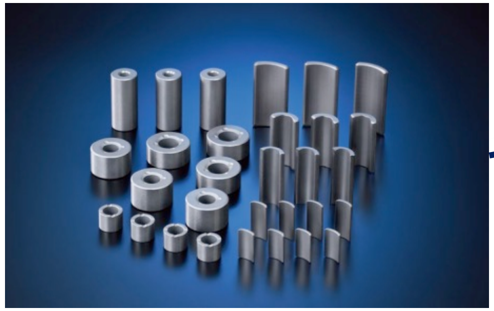
NEOMAX® brand, key material for industries

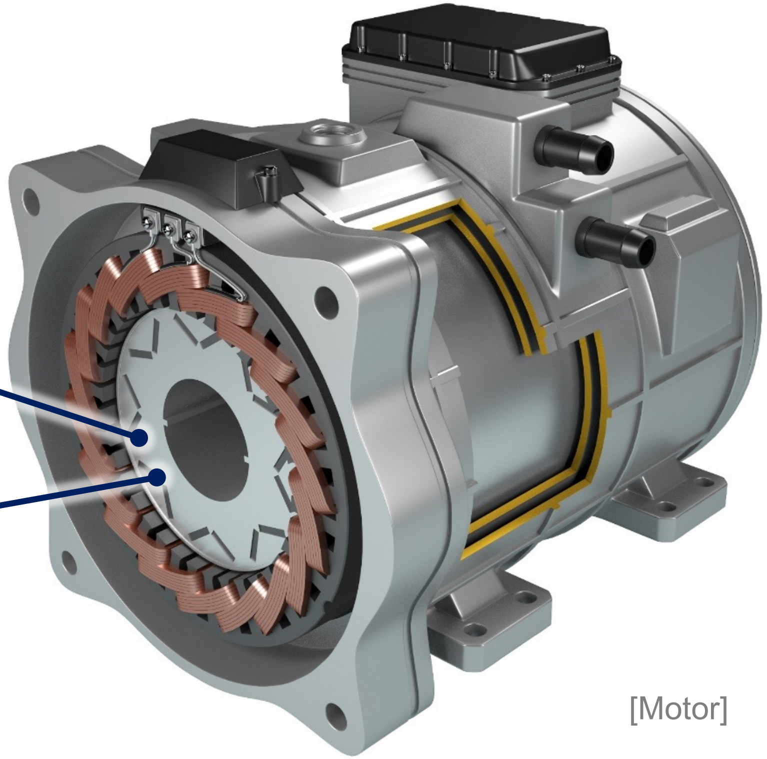
We boast an extensive magnet range, which includes NEOMAX® rare earth magnets and ferrite magnets, and provide our products across a wide range of fields, encompassing automobiles, electronics and home appliances. As pioneers in the field of magnetic materials, we take on the challenge of new materials 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]

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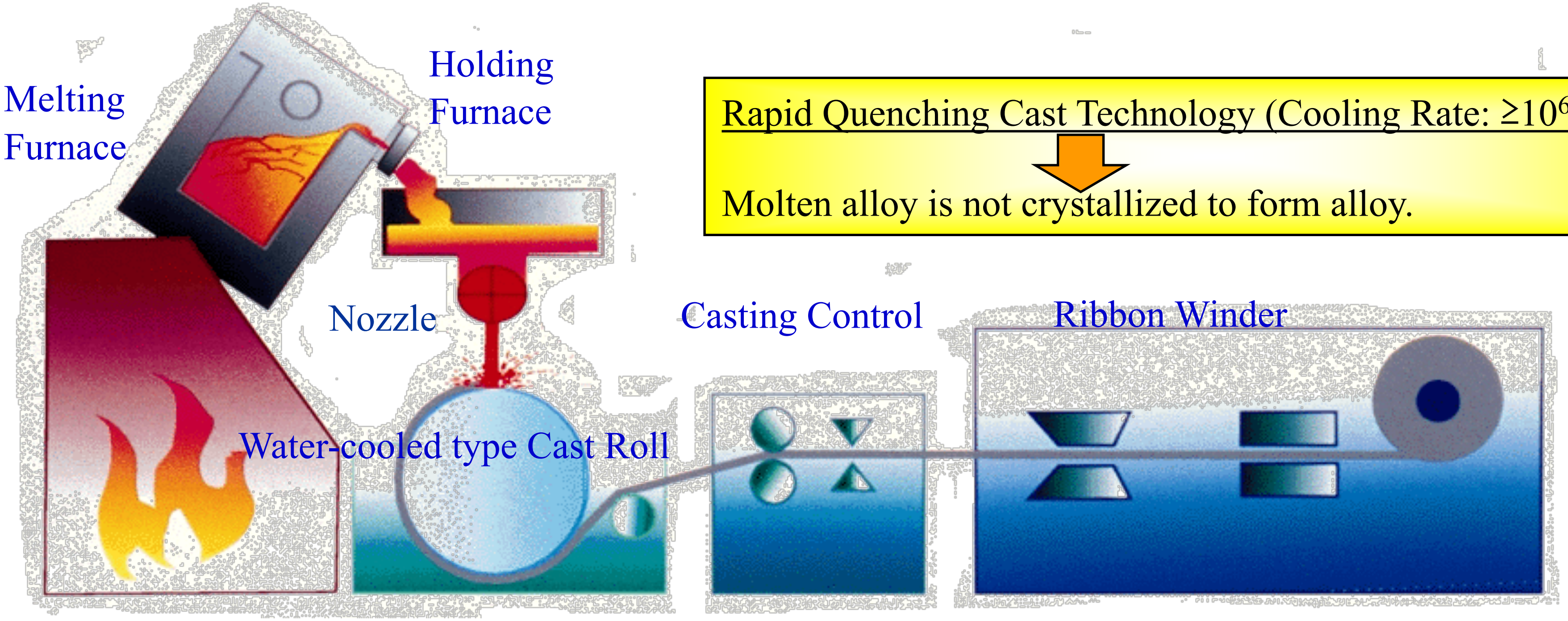
Alloy Name	Constituent Elements	Thickness	Grain Size	Induction	Core Loss
Grain Oriented Si Steel	Fe, Si	230 µm	～10 mm	◎	△
Fe-based Amorphous	Fe, Si, B	25 µm	—	○	○
Nano-Crystalline Alloy	Fe, Si, B, Cu, Nb	18 µm	～10 nm	△	◎



Rapid Quenching Cast Technology (Cooling Rate: ≥10^6°C/s)

Molten alloy is not crystallized to form alloy.

Key Technology
Continuous
Rapid Quenching Cast

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Amorphous Alloys for Transformers

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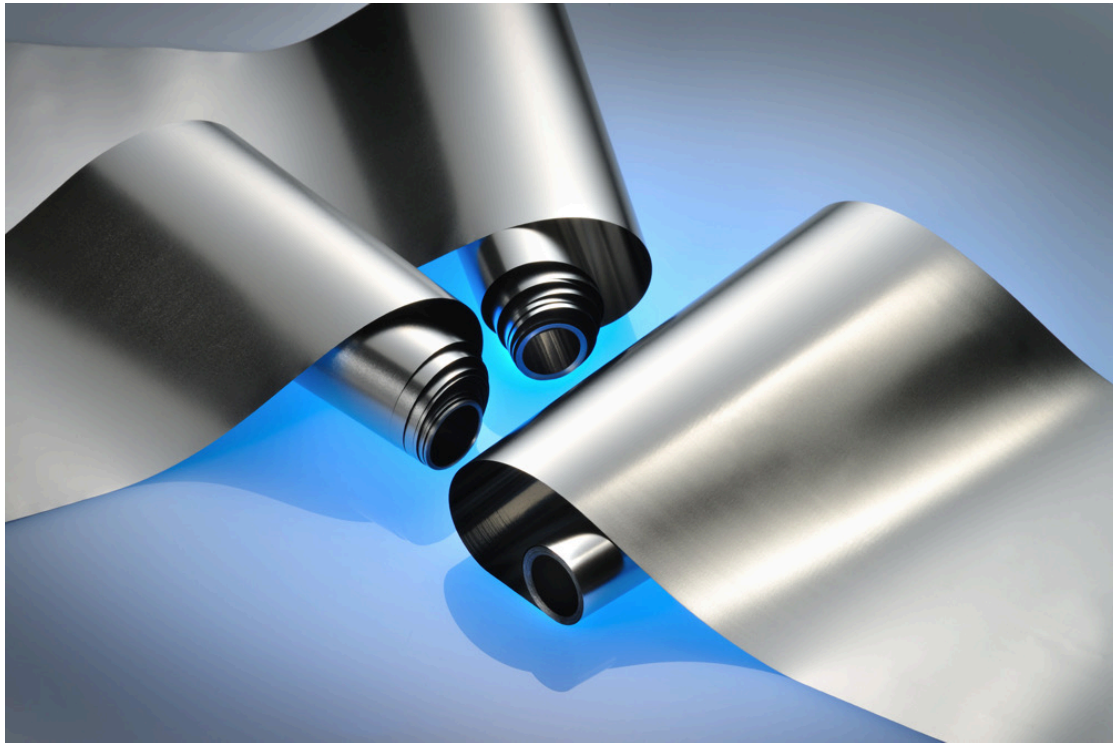
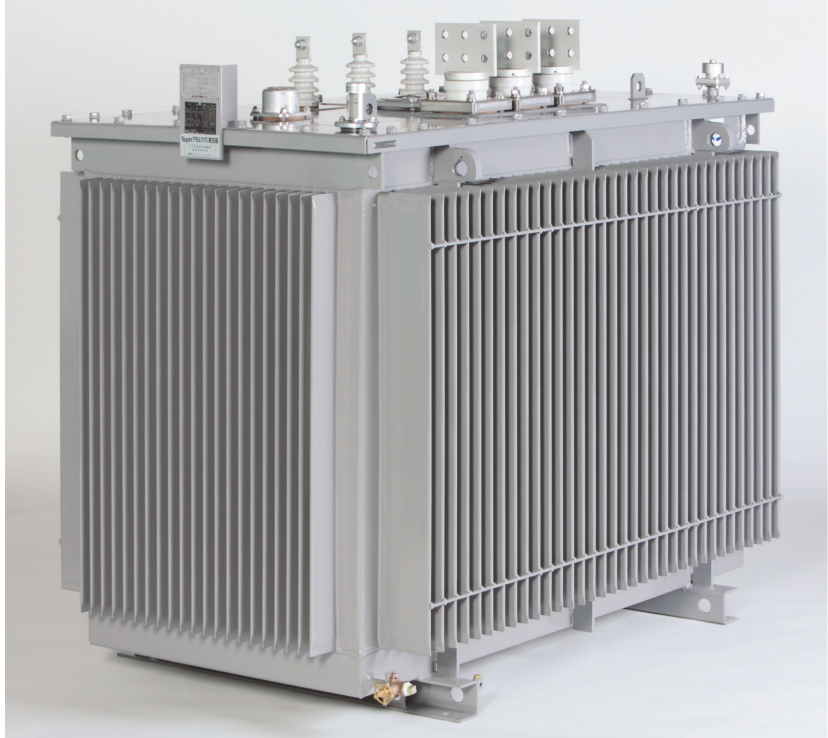
Our main product for Rapid Quenching business



Amorphous Alloy for Transformer “Metglas® 2605HB1M”



Amorphous Transformer*

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

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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.

■Japan

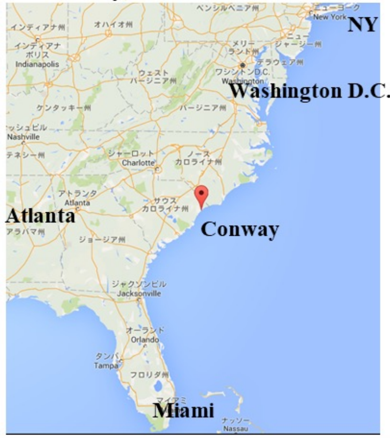
Metglas Yasugi Works

Applied Components Dept.
Proterial Ferrite Electronics, Ltd.

Yasugi, Shimane

USA

Metglas®, Inc.
Conway, South Carolina



Japan

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Products of Amorphous Alloy & “FINEMET®”

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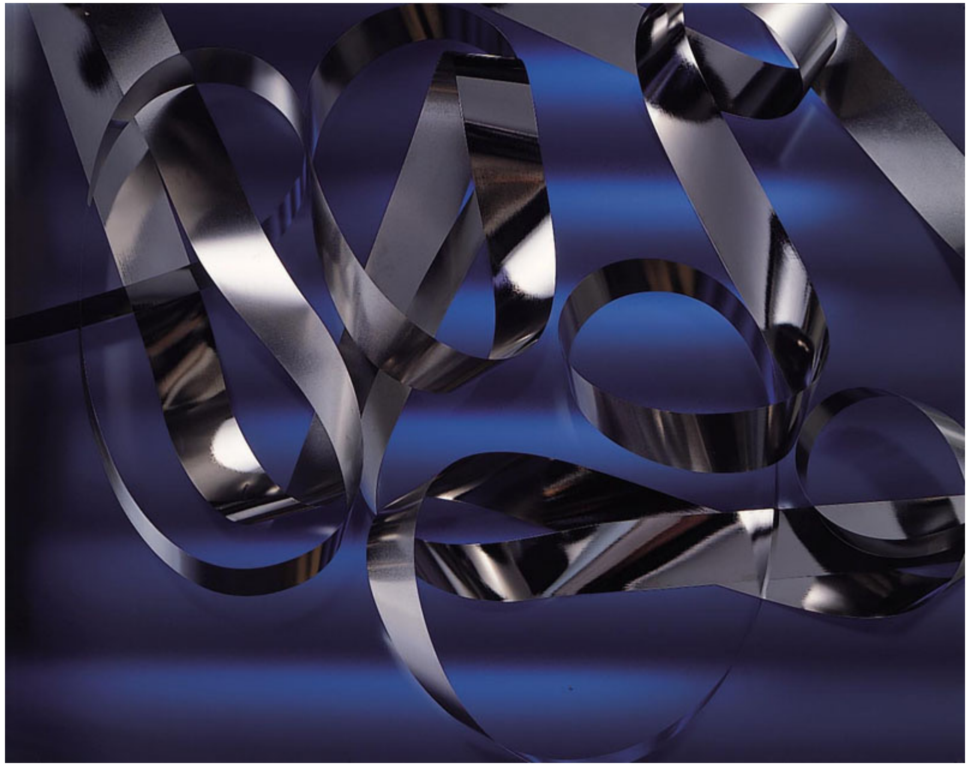
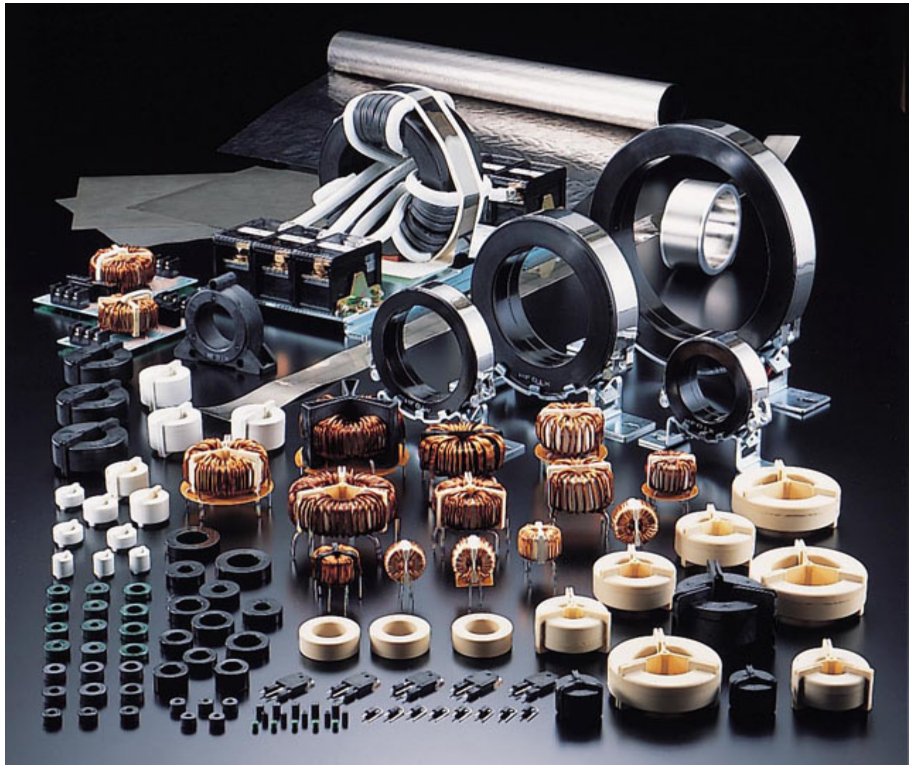


Nano-Crystalline Soft Magnetic Material “FINEMET®”



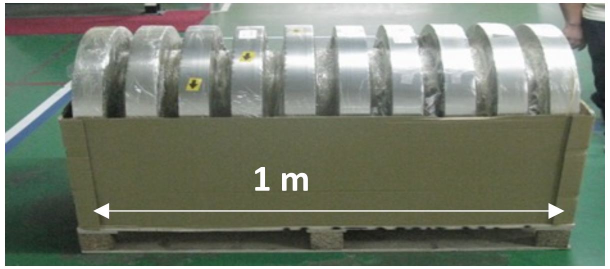
Application products using “FINEMET®”

Production capacity Amo & Nano total … １００kt/year (US&JP)

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

Nanocristillne alloy… W 50-85 mm, T 0.014-0.018 mm

1 spool = 100kg (17km)



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

Ideal SMMs

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Material-derived factors

μ: Permeability

Intrinsic factors (Structure, Concertation)

- K: Mag-Cry anisotropy
- λ: Magnetostriction
- ρ: Resistivity
- E: Young's modulus
- B_s (M_s): Induction

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

μ_i: Initial permeability

α: coefficient

Extrinsic factors

- H: Magn field
- wdh: Size, dimension (volume, cross section)
- σ: Stress, Strain

Ideal SMMs→ 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

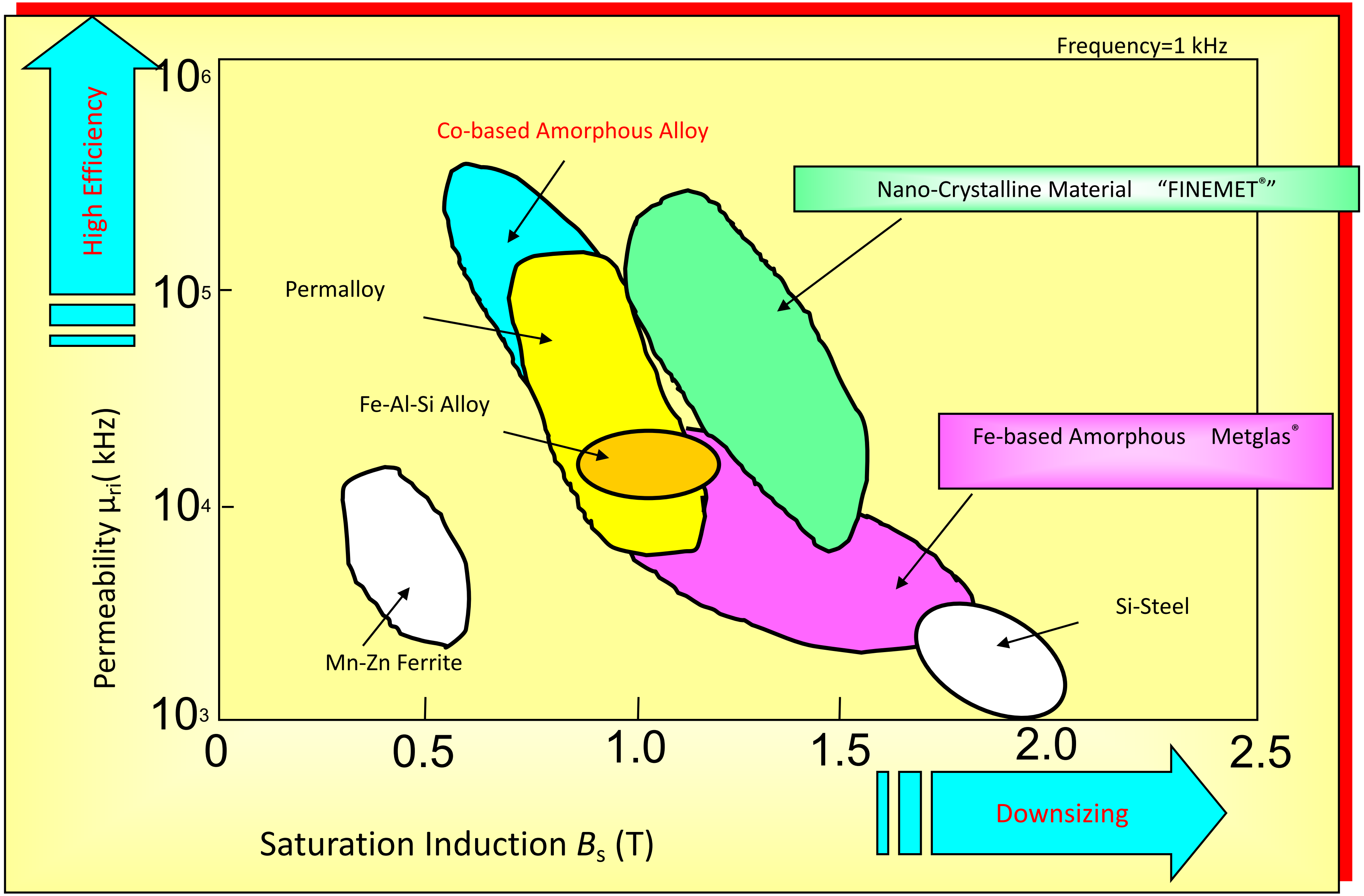
non ideal soft magnetic materials are widely used if it is compatible with the usage.

→ Like amorphous ribbon in transformers which has High λ

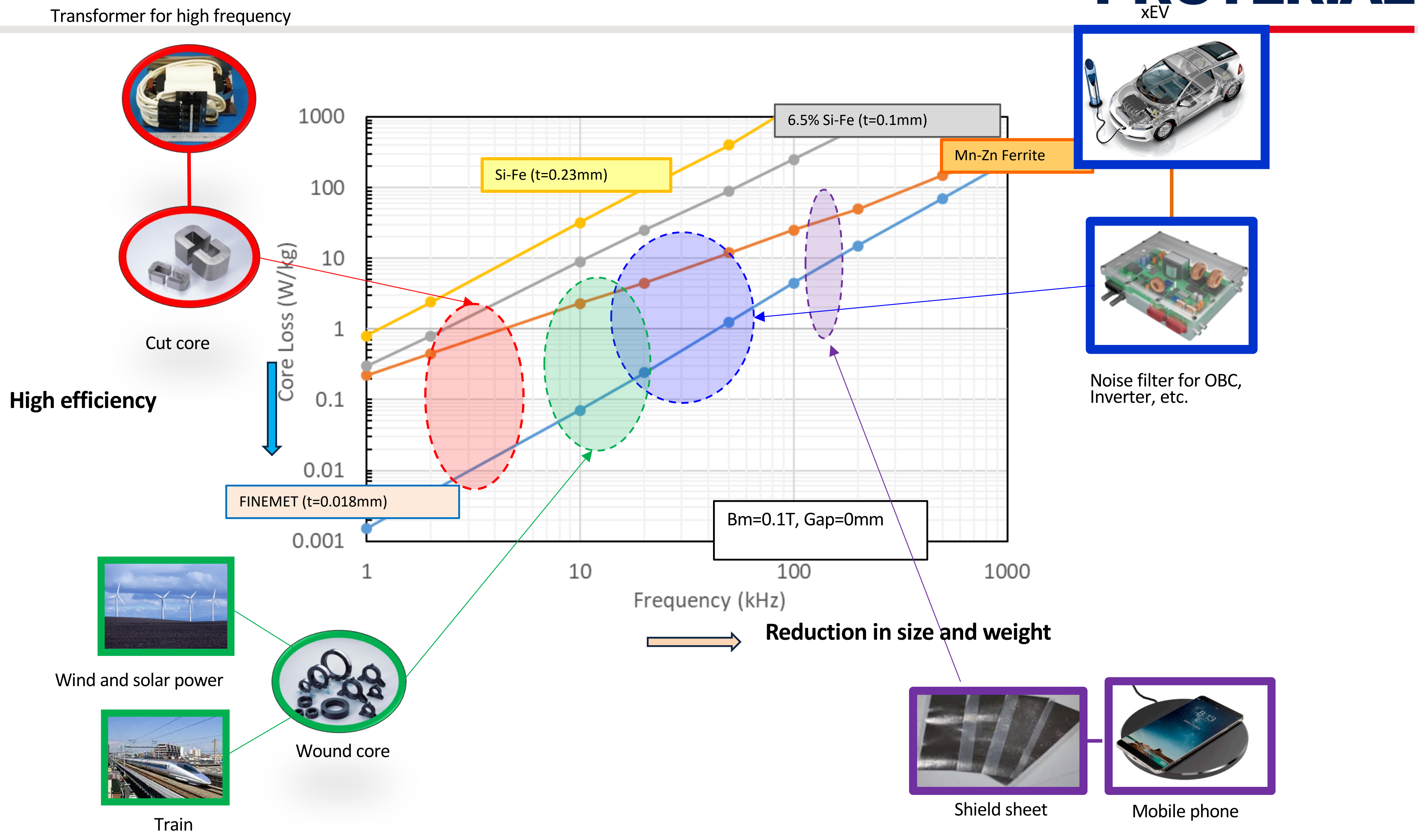
However, λ is limiting its usage.

Controlling extrinsic factor to cancel the anti-factors

Magnetic Properties Comparison of Various Materials



Main applications using FINEMET®



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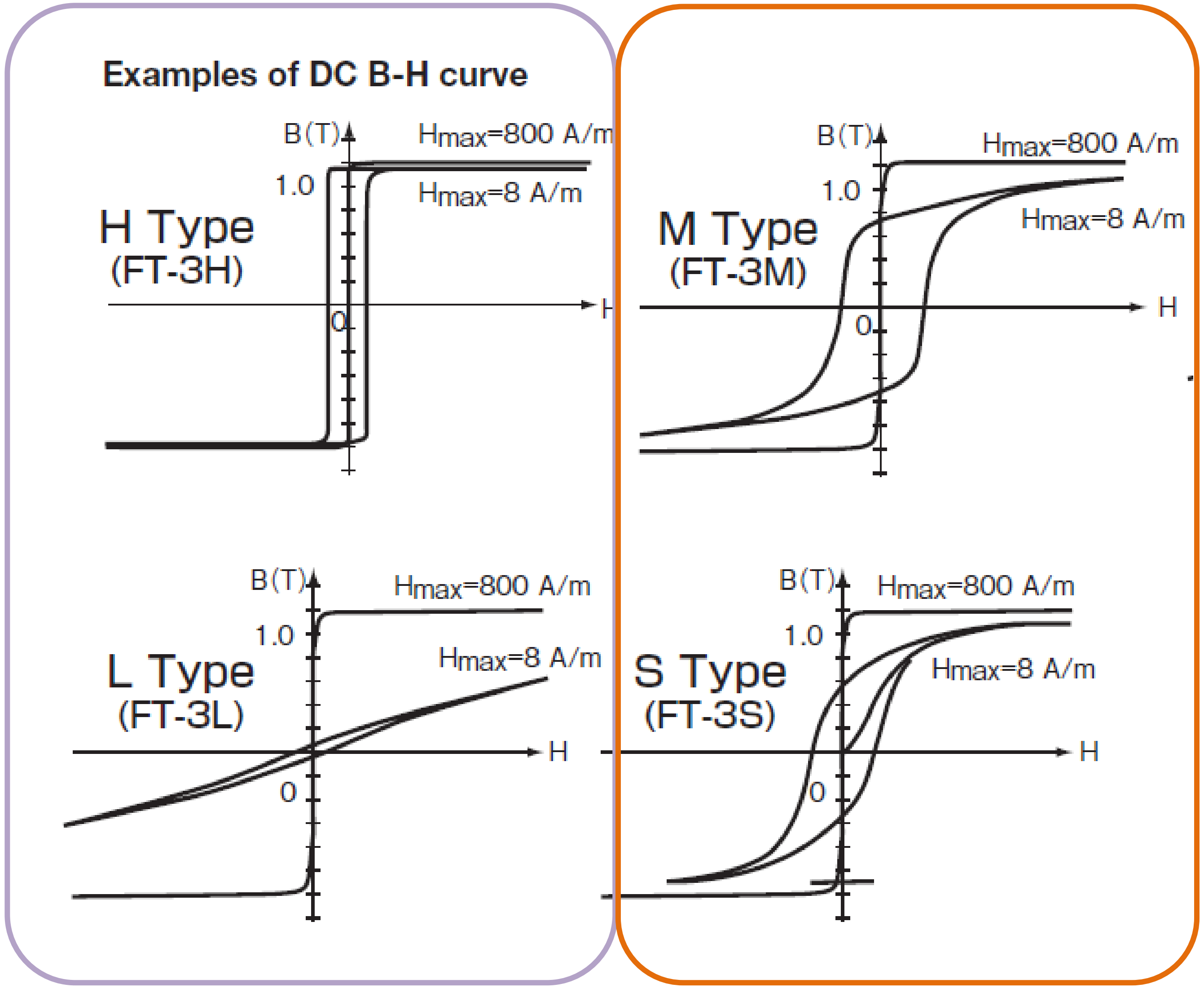
B-H loop Options



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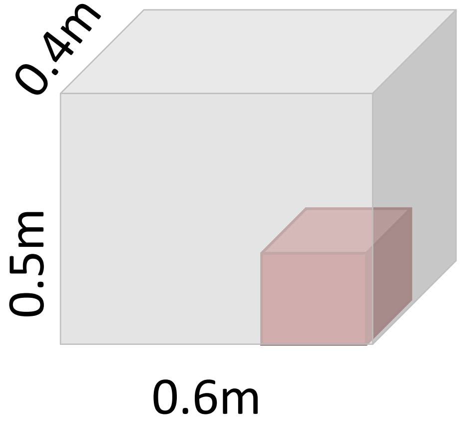
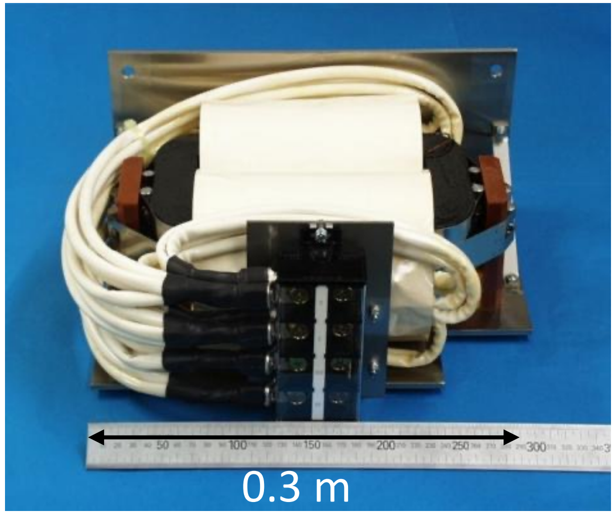
- **Transformer suitable for high-power, high-frequency SW circuits**

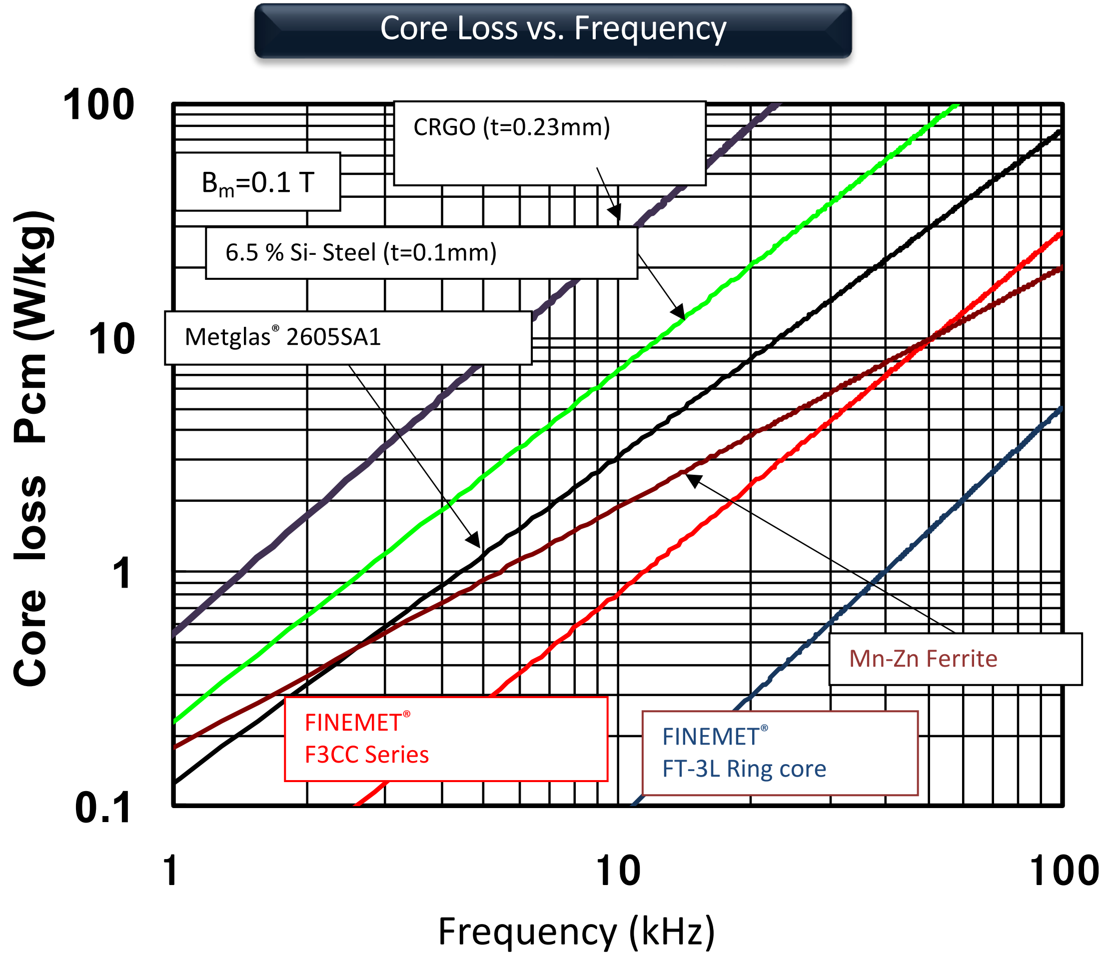
App ex:
EV, PHEV Quick charger,
Welding machines,
medical equipment
Other inverter applications



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



40 kVA 10 kHz High Frequency Transformer



FINEMET & Metglas in EV&PHEV

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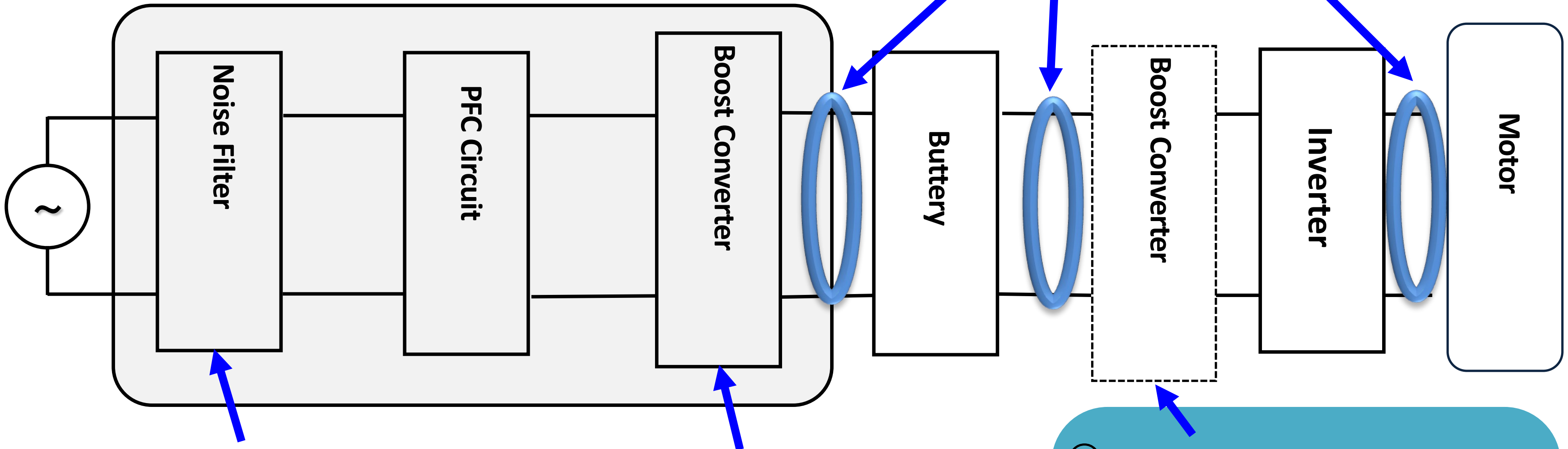
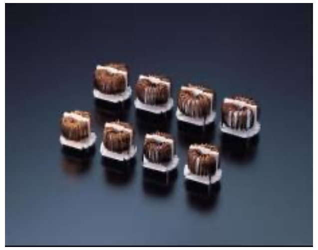
- Automotive charging circuit / Quick Charger

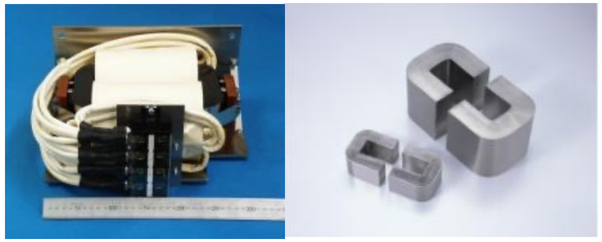
2. FINEMET® **Common Mode Choke**



1. FINEMET® **Common Mode Choke**



②FINEMET® **Transformer**



④**Metglas® Reactor (Cut core)**

Applications requires power density

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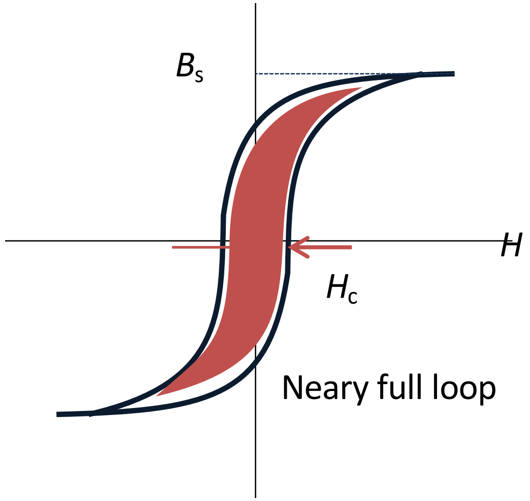
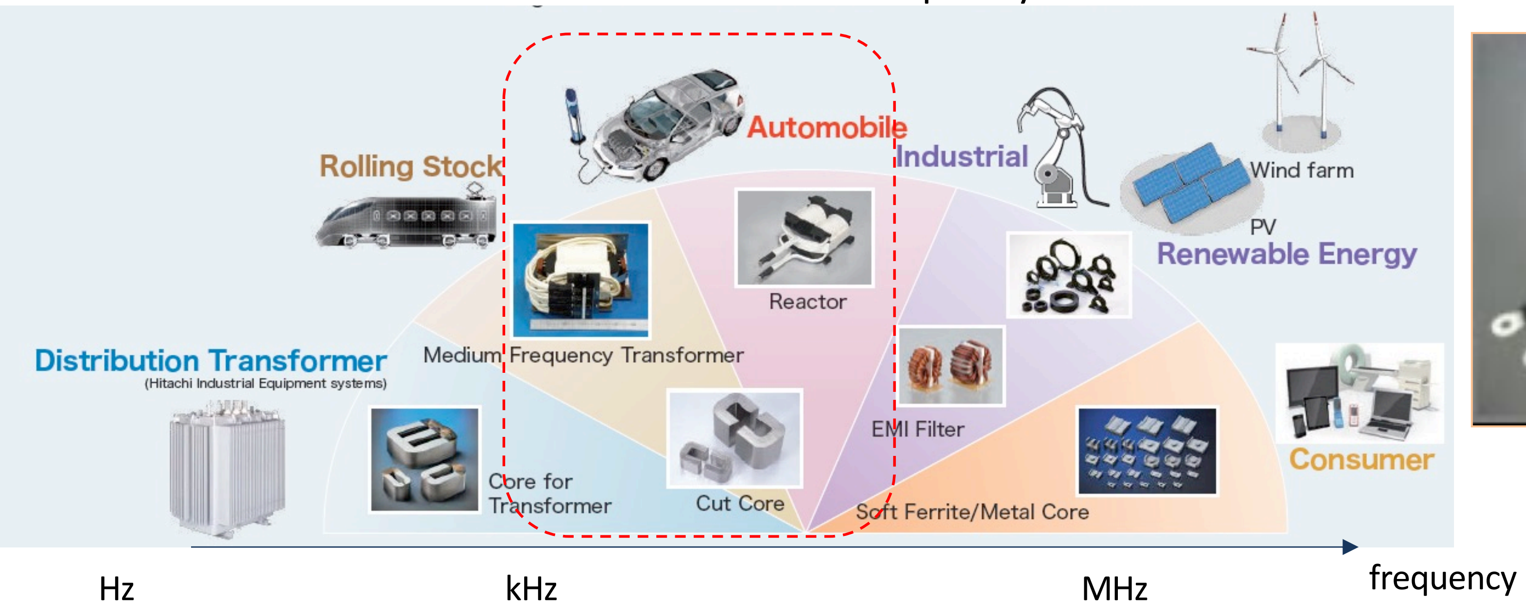
- **SMMs in medium frequencies**
  - Development of High Fe content nanocrystalline alloys High B_s nanocrystalline alloy (Hi-B_s nano)

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

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Metallic SMMs on B_m vs. H_c map

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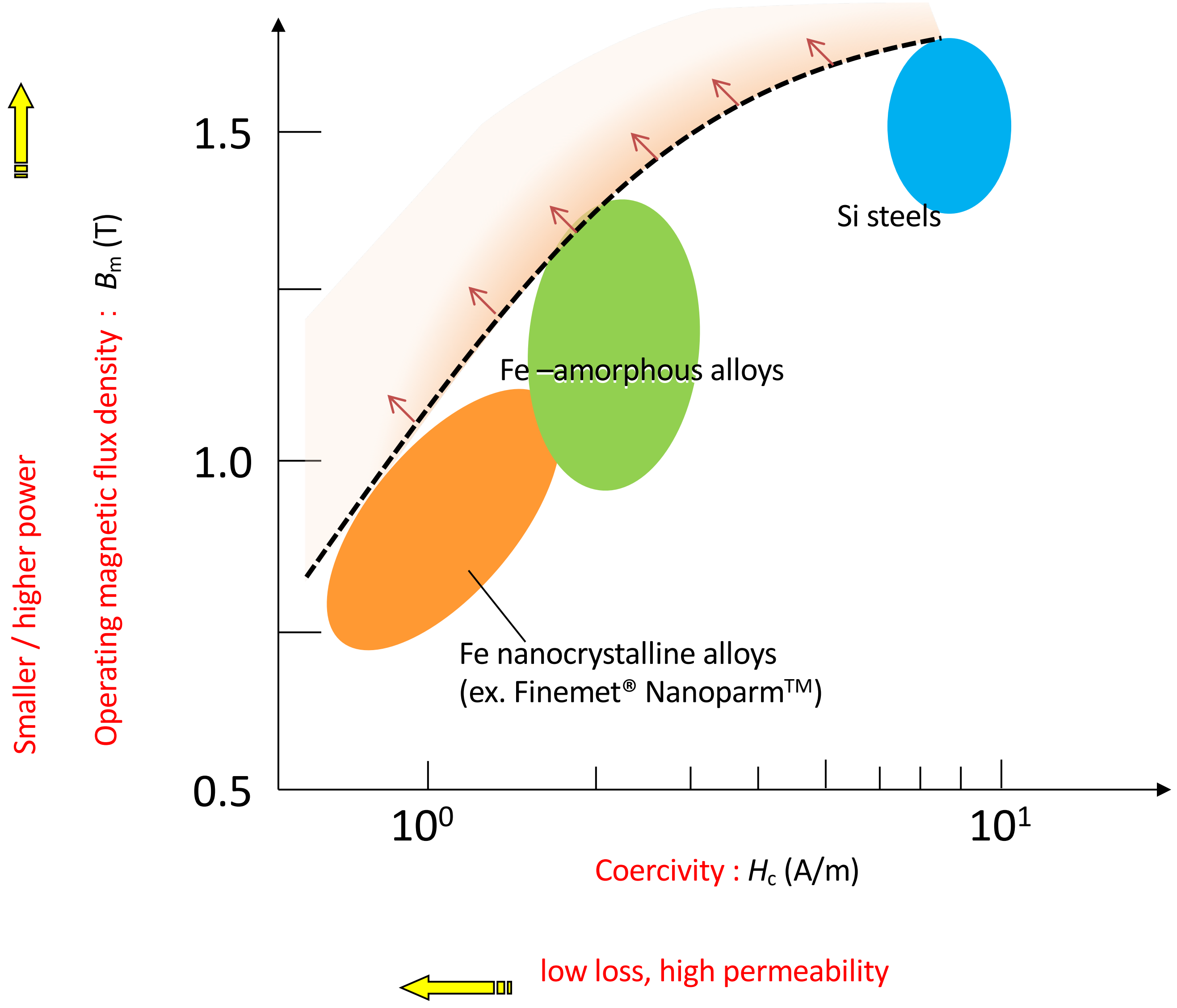


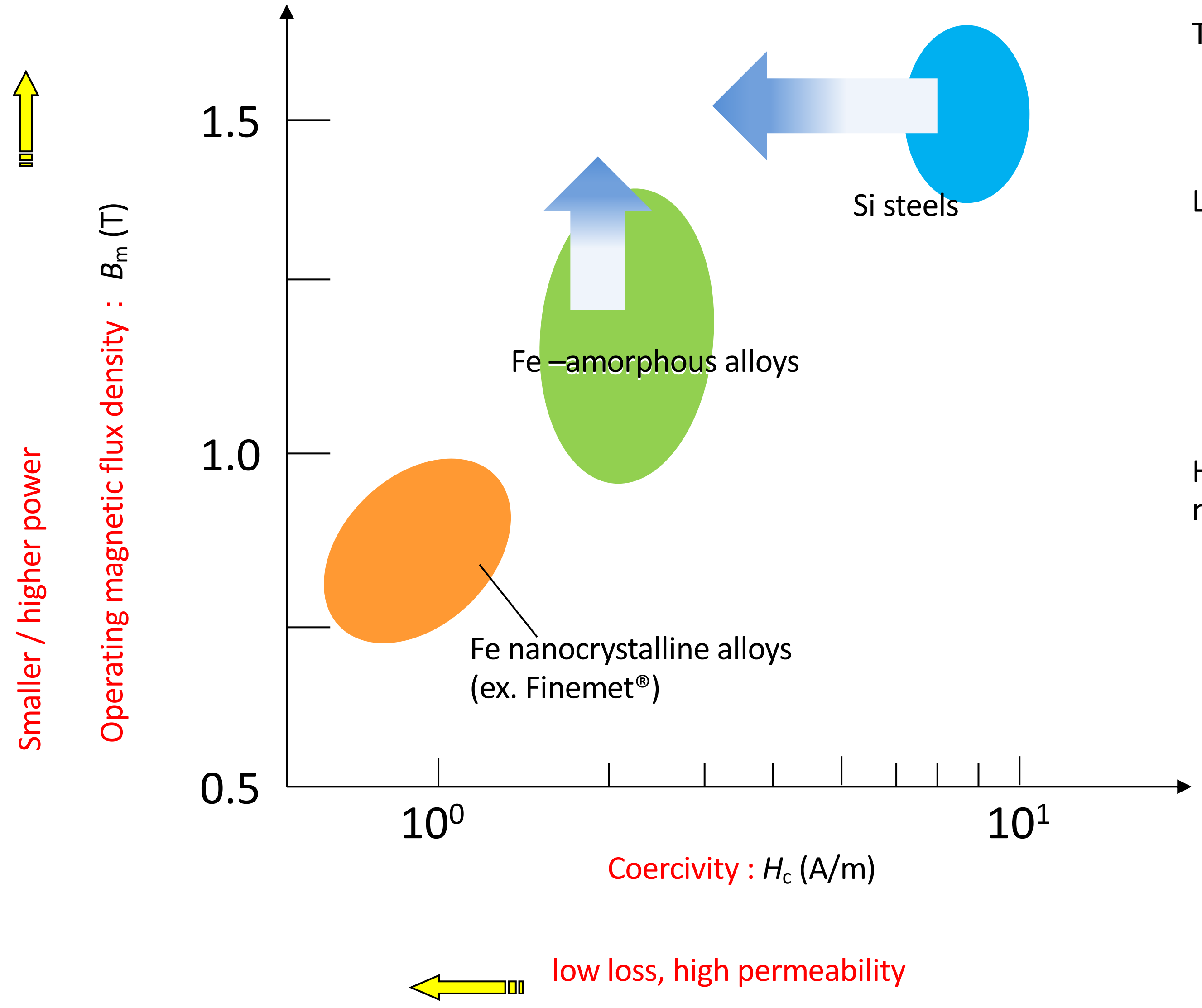
B_m: determined by Saturation magnetic flux density B_s
& iron loss

B_m vs. H_c Tradeoff

Direction

high B_m
low H_c

Soft magnetic materials on the B_m *vs.* H_c map



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

Concept of Materials Development

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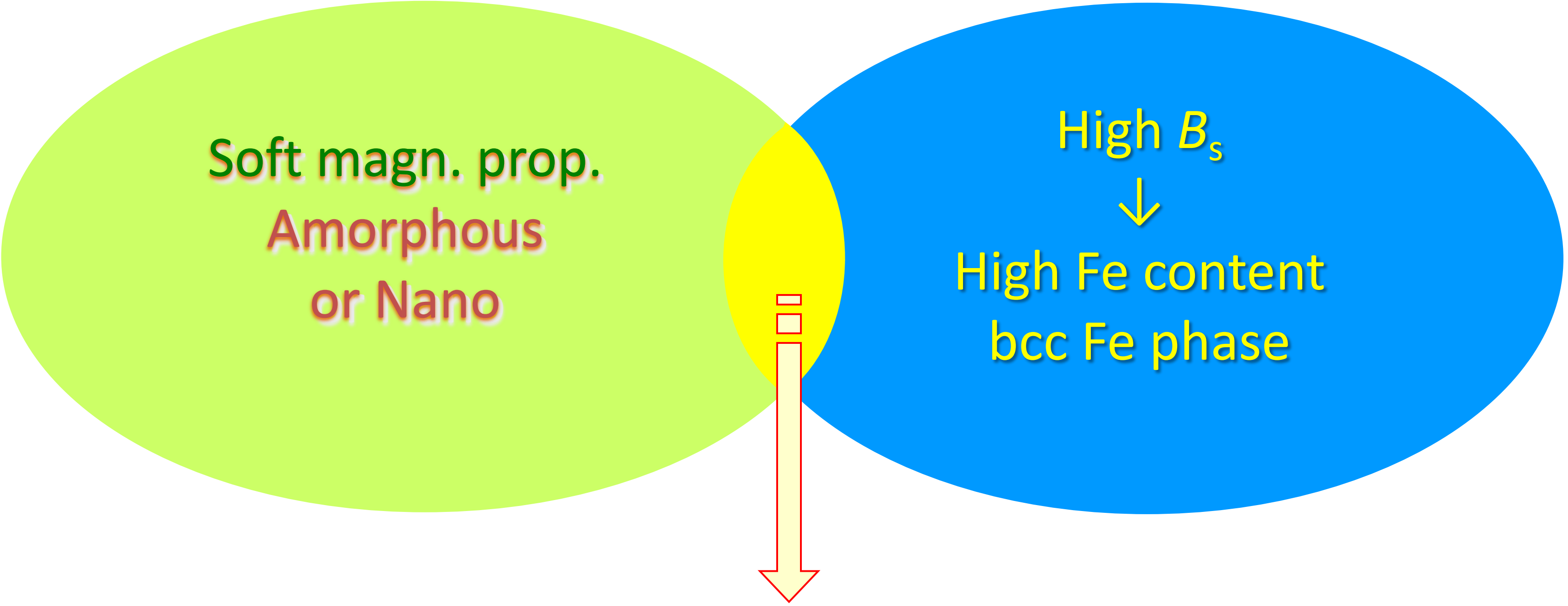
High B_s Nanocrystalline alloy



high Fe content nanocrystalline phase

High B_s & Low H_c

Characters of FINEMET® composition

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Composition of FINEMET® alloy

$$Fe_{73\sim75}Cu_{0.8\sim1.0}Nb_{2.6\sim3.0}Si_{13\sim16}B_{6\sim9}$$

(at.%)

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

Low Fe, relatively high Nb ⇒ 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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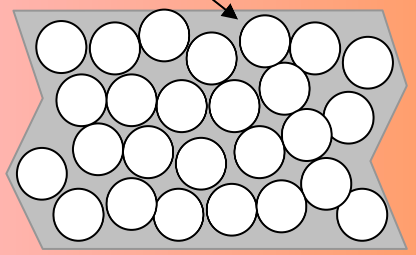
（Fe-Cu-Nb-Si-B)

As-Q

Annealing process

Cu cluster → Primary crystals → grain growth

bcc Fe-Si



: Enhance thermal stability of
residual amorphous phase

Suppress Grain growth

Our purpose: Zero magnetostriction

Fe-Si has negative magnetostriction
Residual amorphous phase has positive one

The balance of volume fraction of each phase
is important

K. Hono, et al, *Acta Mater.* **47** (1999) 997.

Nb = indispensable element

Adopting Quick Anneal

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Composition of FINEMET® alloy

$Fe_{73\sim75}Cu_{0.8\sim1.0}Nb_{2.6\sim3.0}Si_{13\sim16}B_{6\sim9}$ (at.%)

↓ increase ↓ decrease

at the expense of low magnetostriction, aim high B_s

$Fe_{80\sim83}Cu_{0.8\sim1.0}Nb_{0.0\sim1.0}Si_{0\sim7}B_{12\sim15}$ (M = Nb, Mo ...)

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

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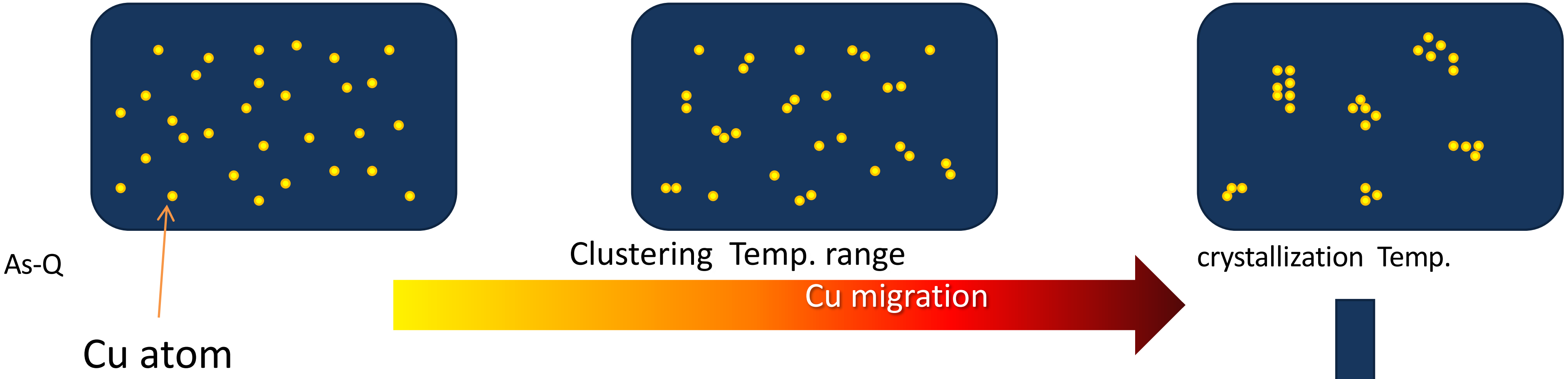

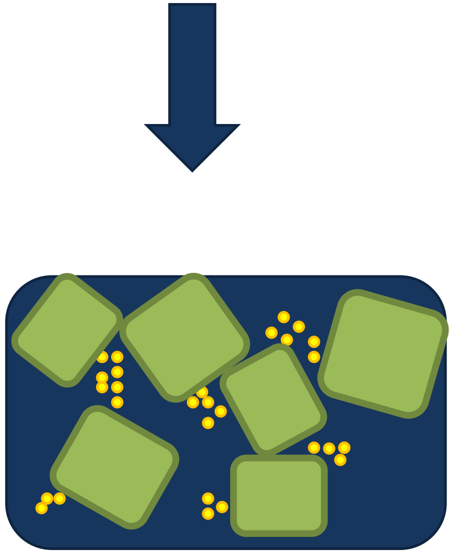

Slowly passing Clustering temp. range

Cu atom can move long distance

clusters grow larger =
coarsening and decrease of number

Lack of seeds → grains grow large

Cu clustering in Quick Annealing

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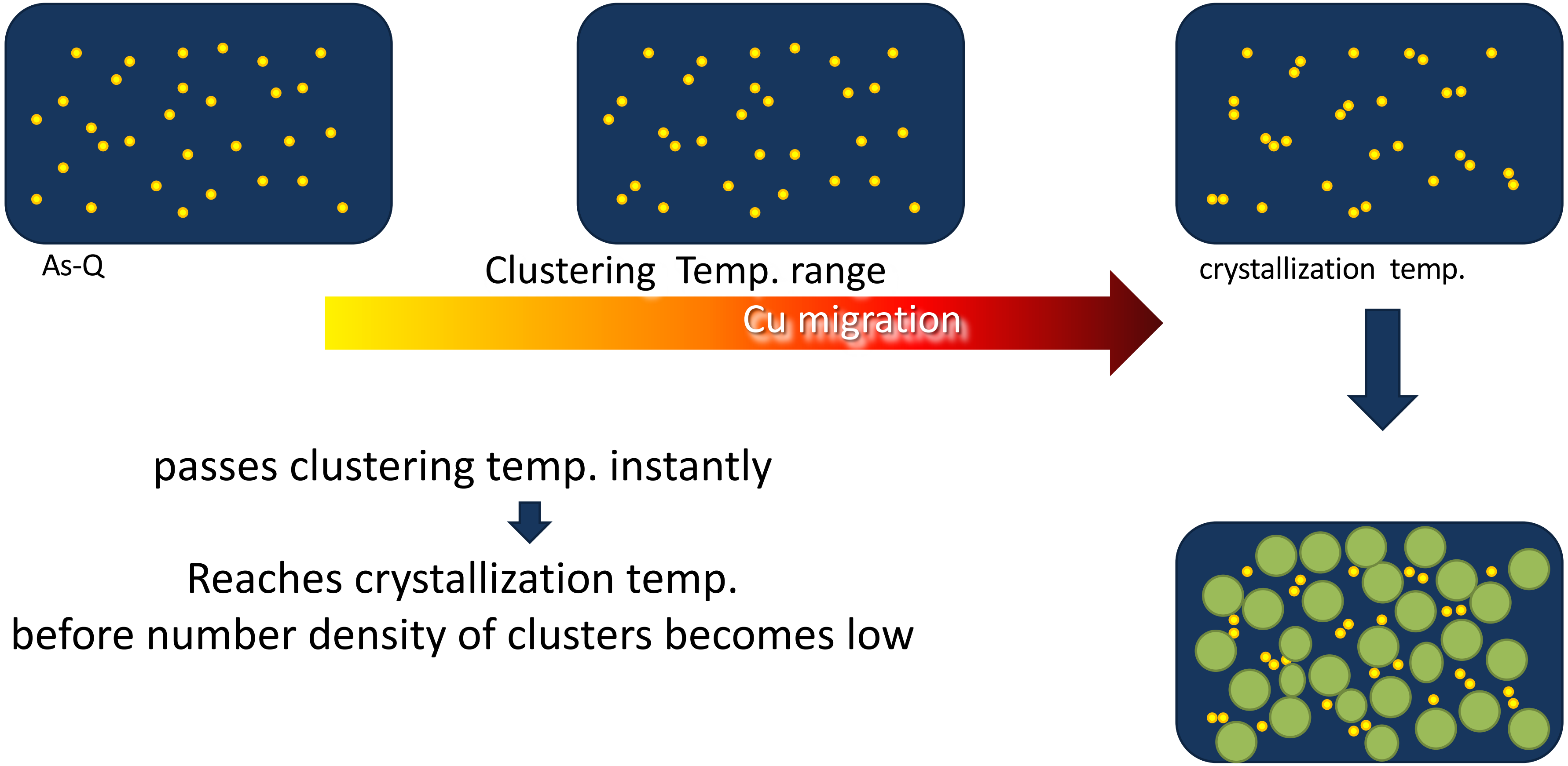

High number density of seeds remains → fine nanocrystalline phase

B-H loops of NA and QA ribbons

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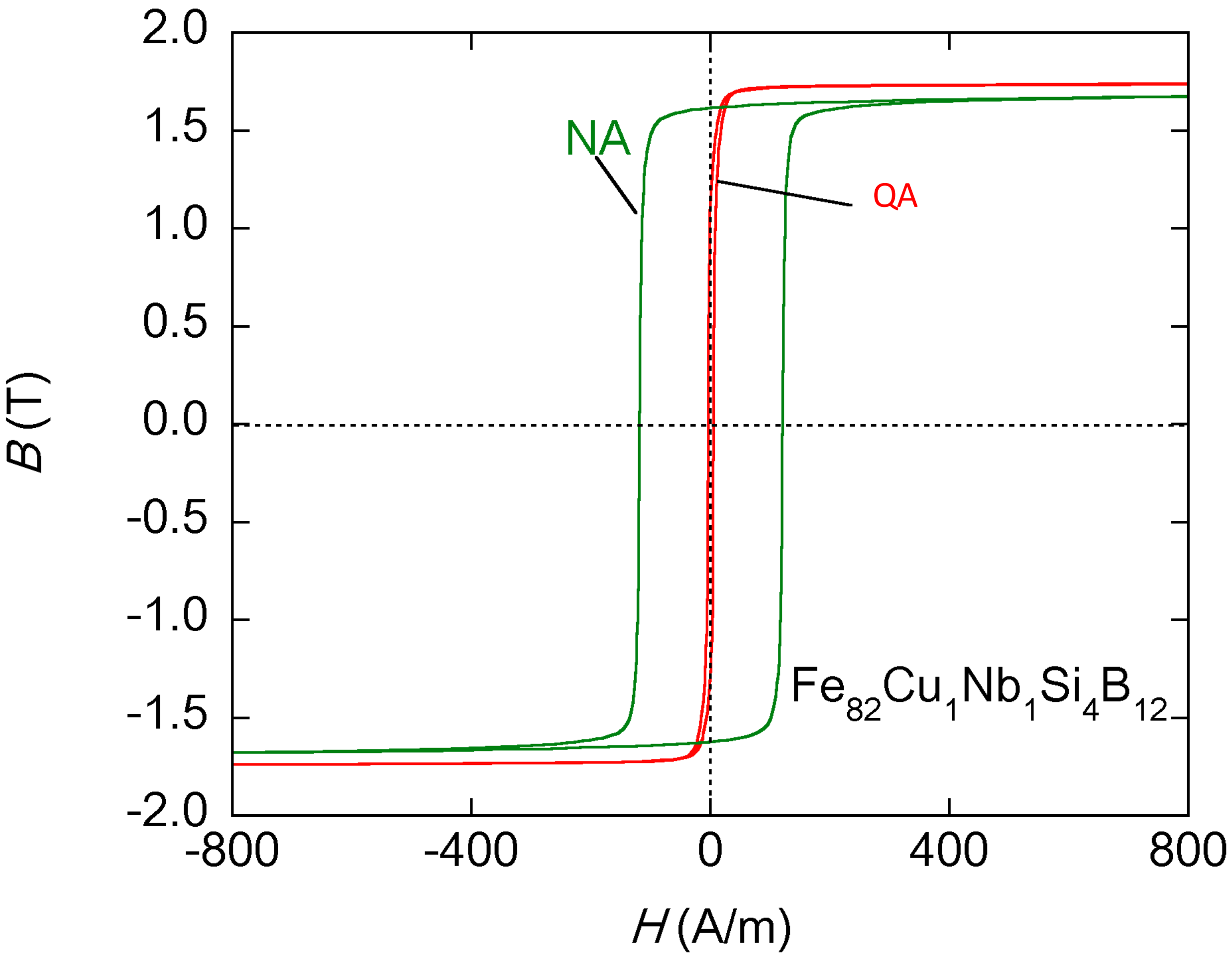

QA: Quick Anneal

$H_c < 3$ A/m

NA: Normal anneal

$H_c > 100$ A/m

Low Nb, but high B_s & low H_c

M. Ohta, Y. Yoshizawa, JMMM 321 (2009) 2220–2224.

Position of developed high B_s nano alloys

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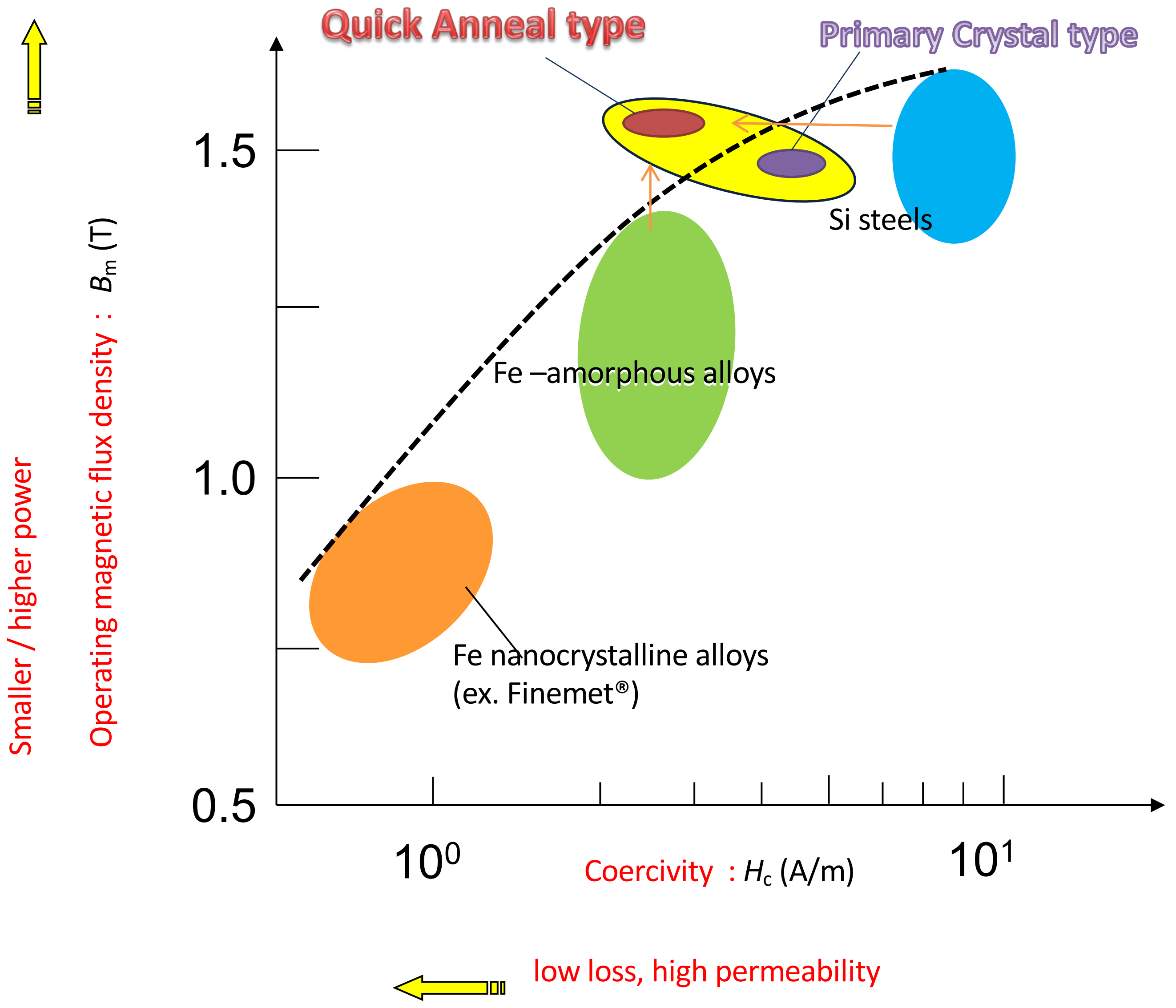

Loss is 1/3 of Si-steels

B_s · B_m are 10% higher than Fe-AM

Quick annealing type may be suitable for industrial products

If we can solve the processing issues

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

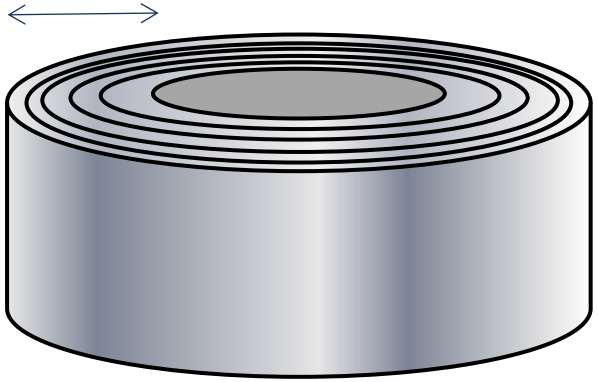
Core types

We want to search application field for this material.

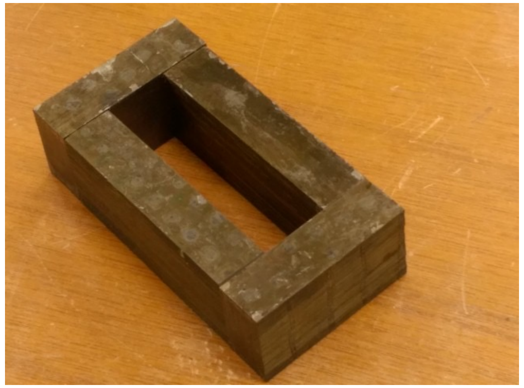
Block core
(laminated)

thickness of
lamination

Toroidal core



wound ribbon



Affects annealing

We cannot apply quick anneal to cores

Quick anneal first then form the core

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

Easy to implement and easy to adapt to various applications

Soft magnetic properties block cores

continuous Quick (flash) anneal

spool

laminate single strips

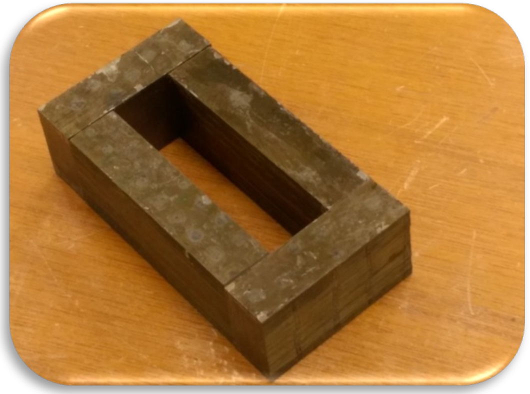
mold (impregnation)

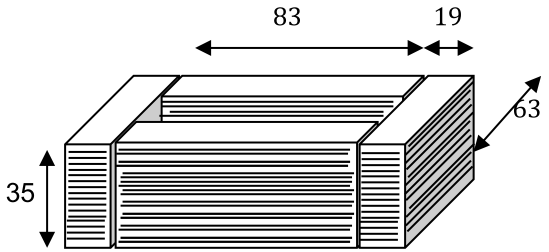
cutting/Grinding/Etching

Block

Form a circuit by 4 blocks

M. Ohta et al.: *IEEE. Trans. Mag.* (2018).





HBN core

Soft magnetic properties block cores

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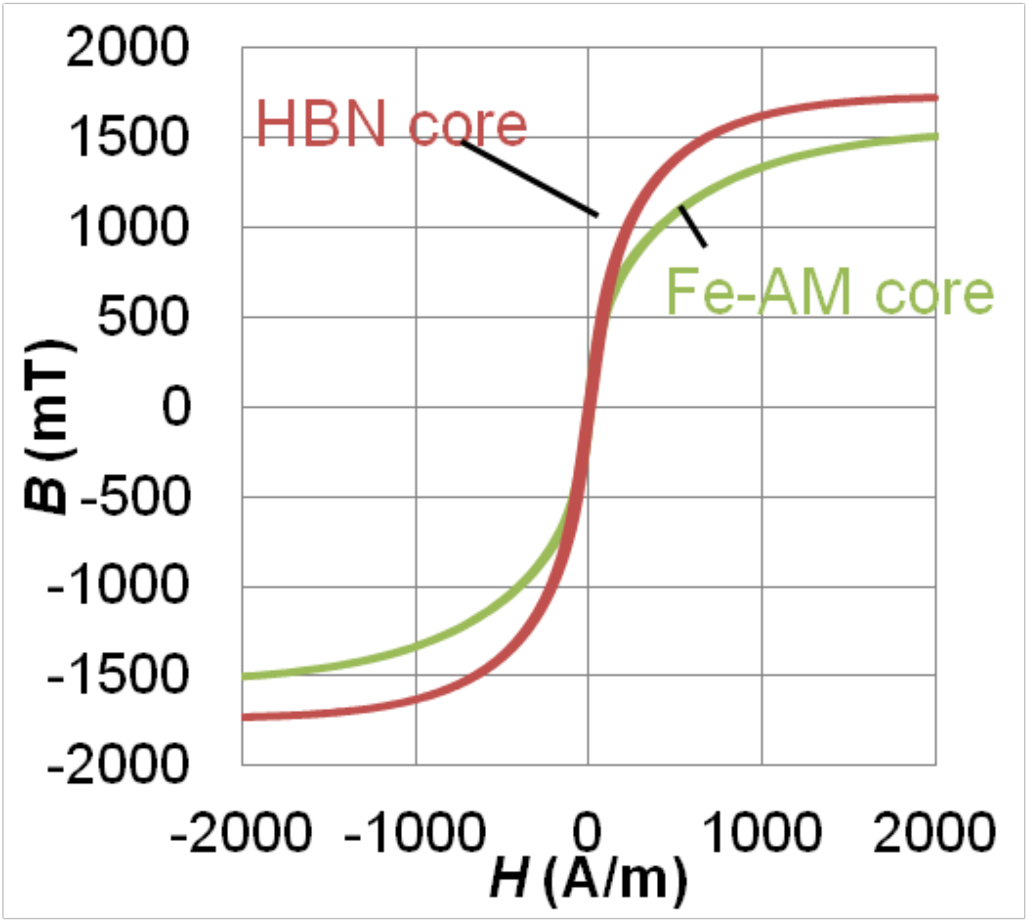

Hi-B_s nano core shows high B_{2000}

	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

M. Ohta et al.: *IEEE. Trans. Mag.* (2018).

Soft magnetic properties block cores

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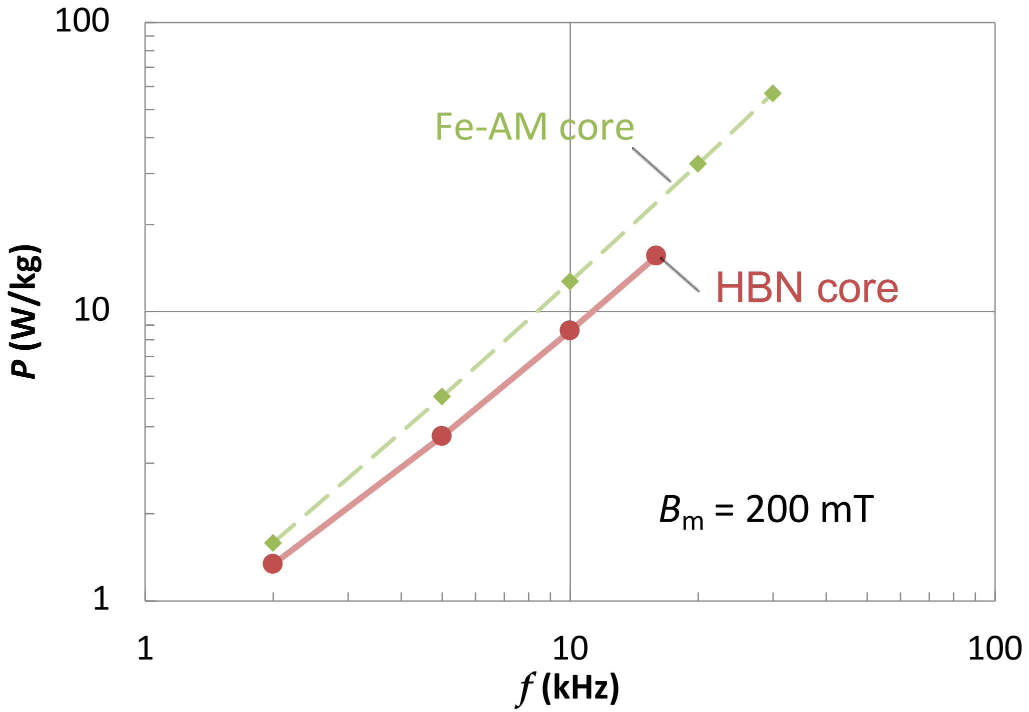

2/3 of core loss of Fe-AM

Amorphous core is recognized as a sufficiently low-loss material

	HBN core	Fe-AM core
$P_{2/10k}$ (W/kg)	8.5	12.7
$P_{1/20k}$ (W/kg)	5.4	7.7

M. Ohta et al.: *IEEE. Trans. Mag.* (2018).

loss separation of block cores

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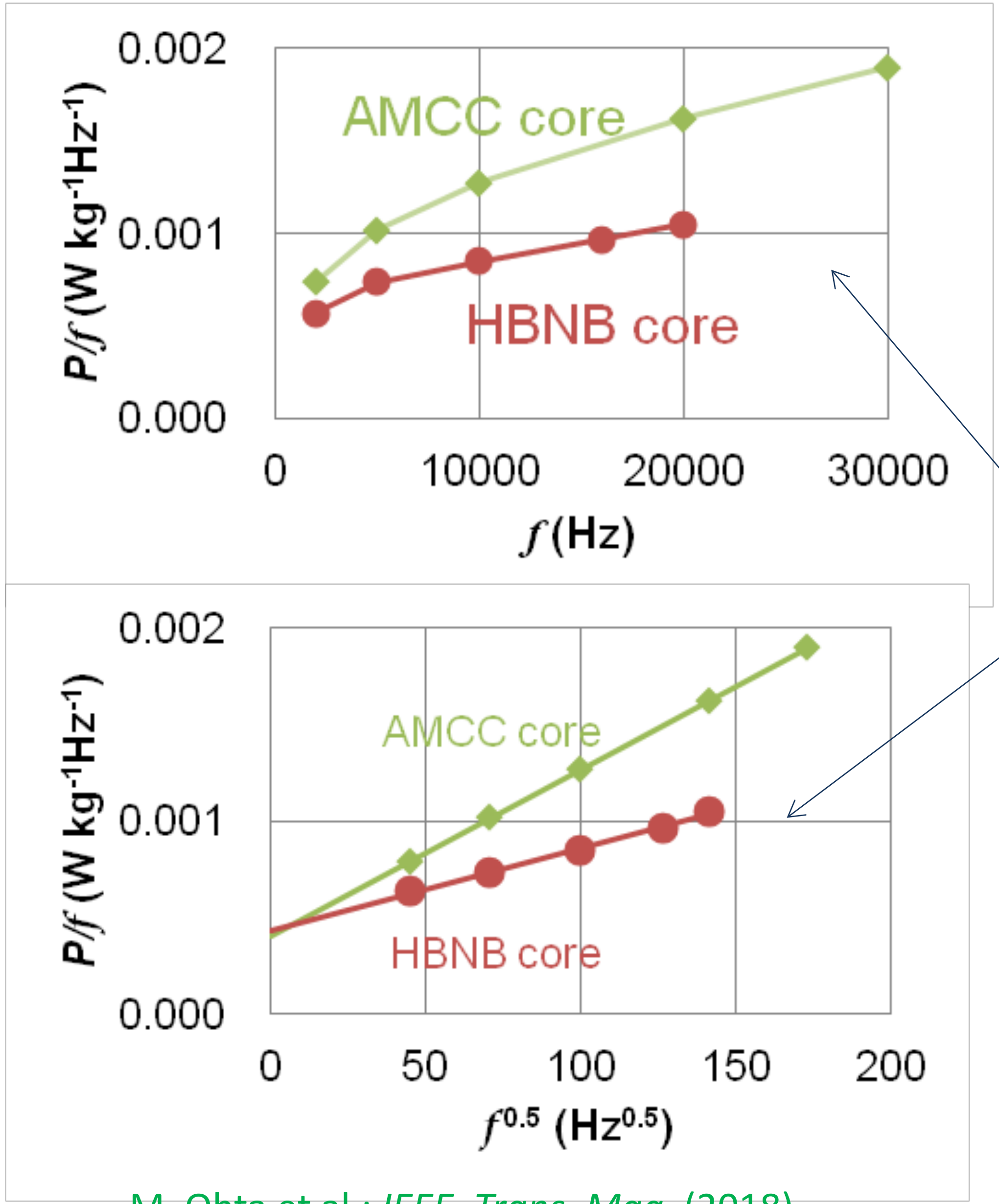


M. Ohta et al.: *IEEE. Trans. Mag.* (2018).

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

$P_h \propto f^{1}$ $P_e \propto f^{2}$ $P_{ex} \propto f^{1.5}$

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

conventional plot: liner = eddy current

$P/f = a + cf + bf^{0.5}$ c : negligibly small

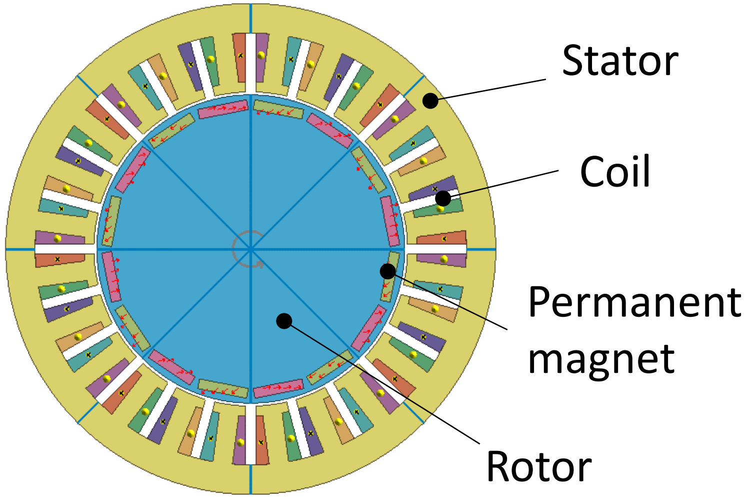
Contribution of excess eddy current loss is dominant in medium *f*

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

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

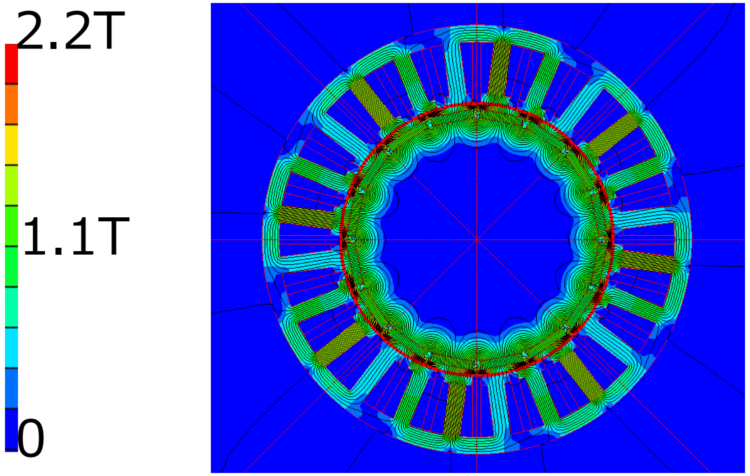
Result from Simulation

PROTERIAL

- Amorphous, High B_s Nano:

  @10000rpm(1333Hz) 85% lower core loss than Si-steel core

- Similar torque



Contour Diagram

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

Core 1/8 Total 25%↓

Core 1/14 Total 85%↓

*result from Shimane Univ

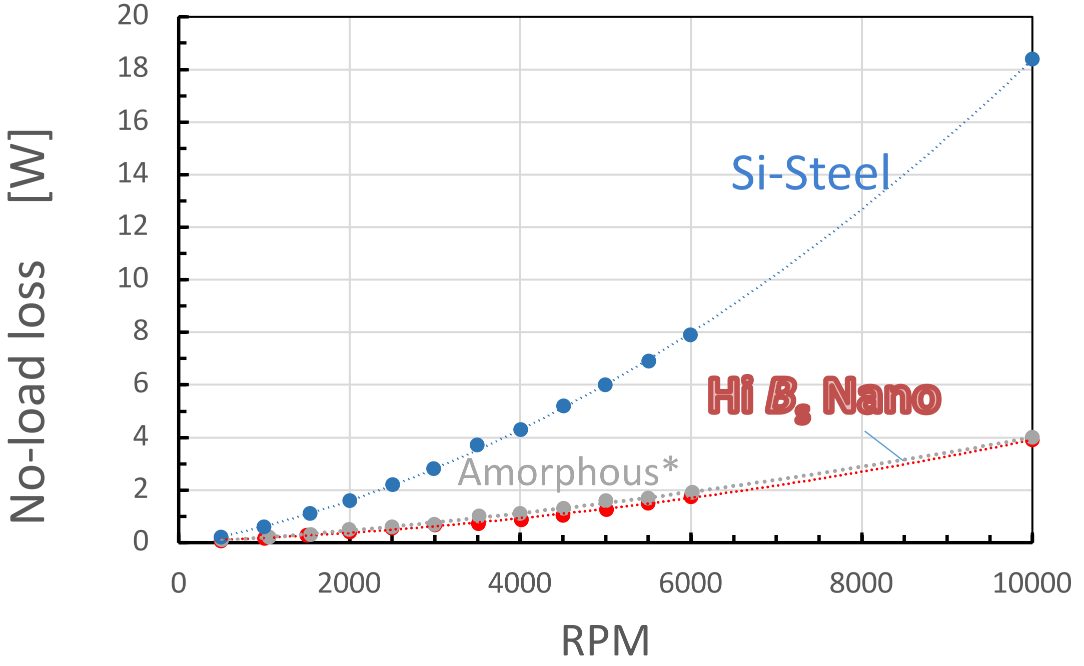
Very meaningful difference can be expected!

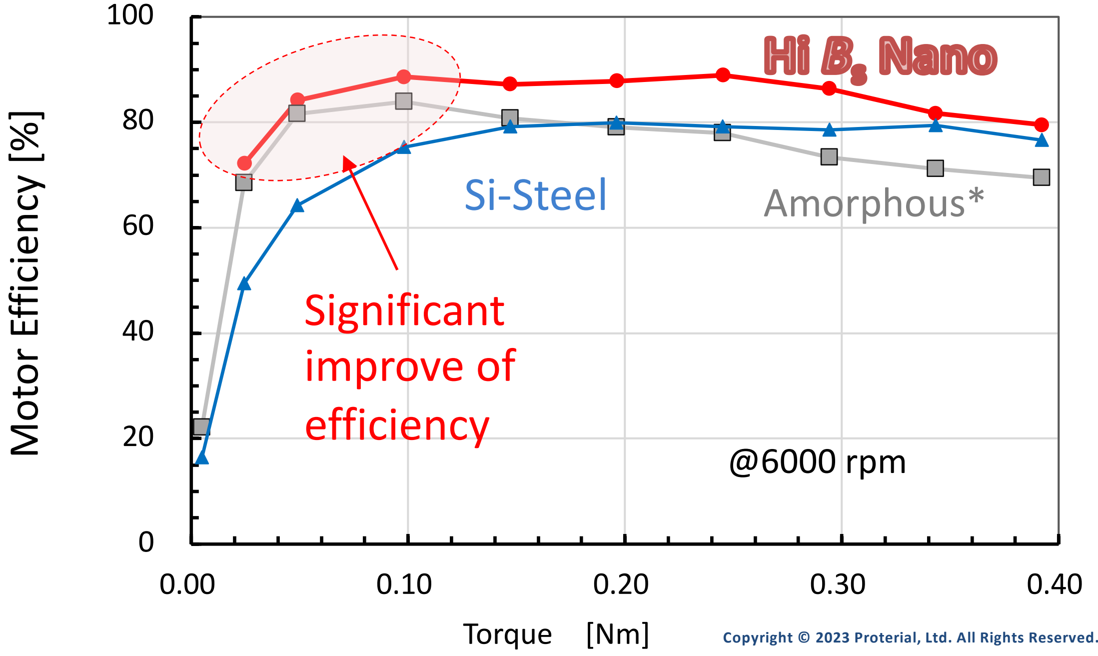
Actual Measurement Results

PROTERIAL

- ➢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



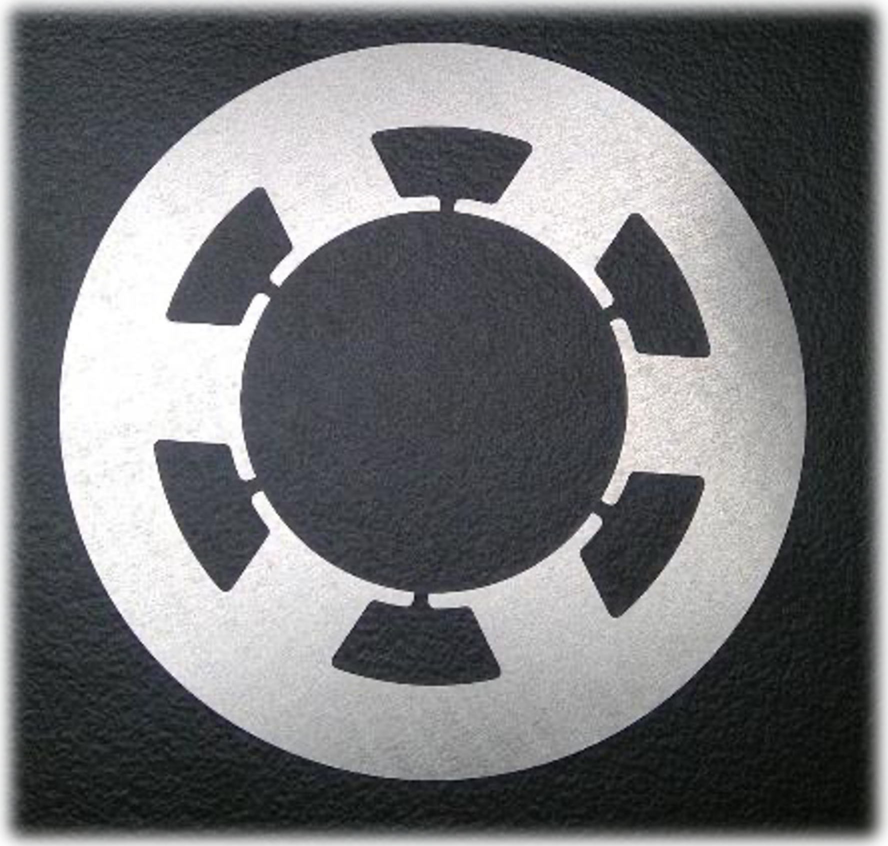


Issues of amorphous ribbon production

PROTERIAL

*nanocrystalline ribbons are also casted as amorphous phase

Punched (stamped) amorphous ribbon as a stator shape



Otherwise

No problem in shearing process

Shearing is easy!

Go simpler shape!

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

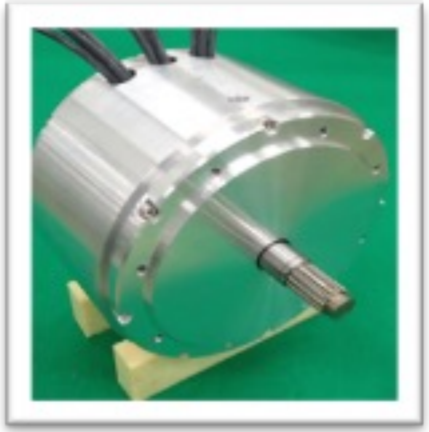
But don't forget that "thin" will lead to low eddy current loss in high freq.

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

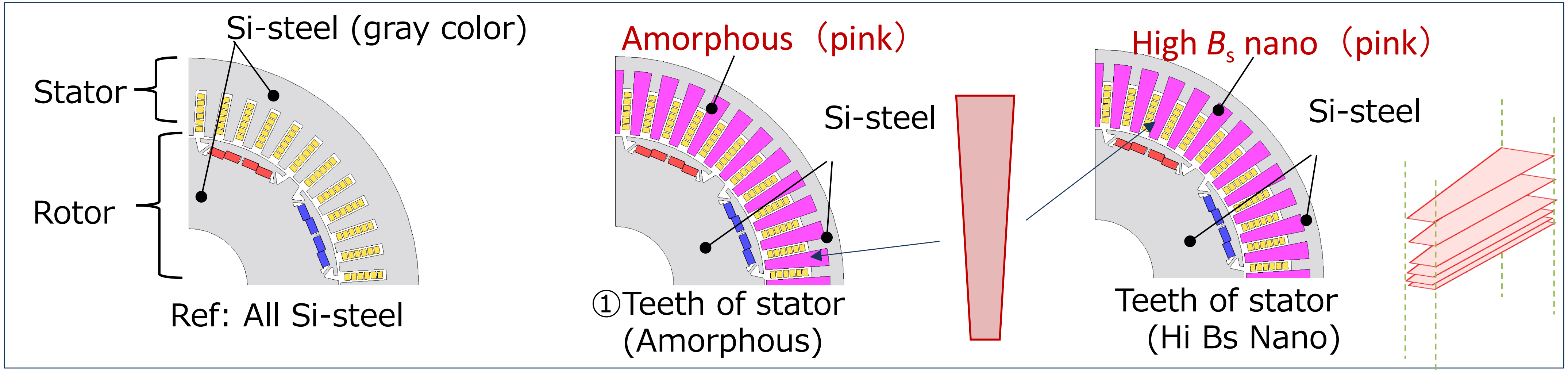
Radial Gap Motor

PROTERIAL

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 ¼ of Motor

This simple shape can be prepared by shearing

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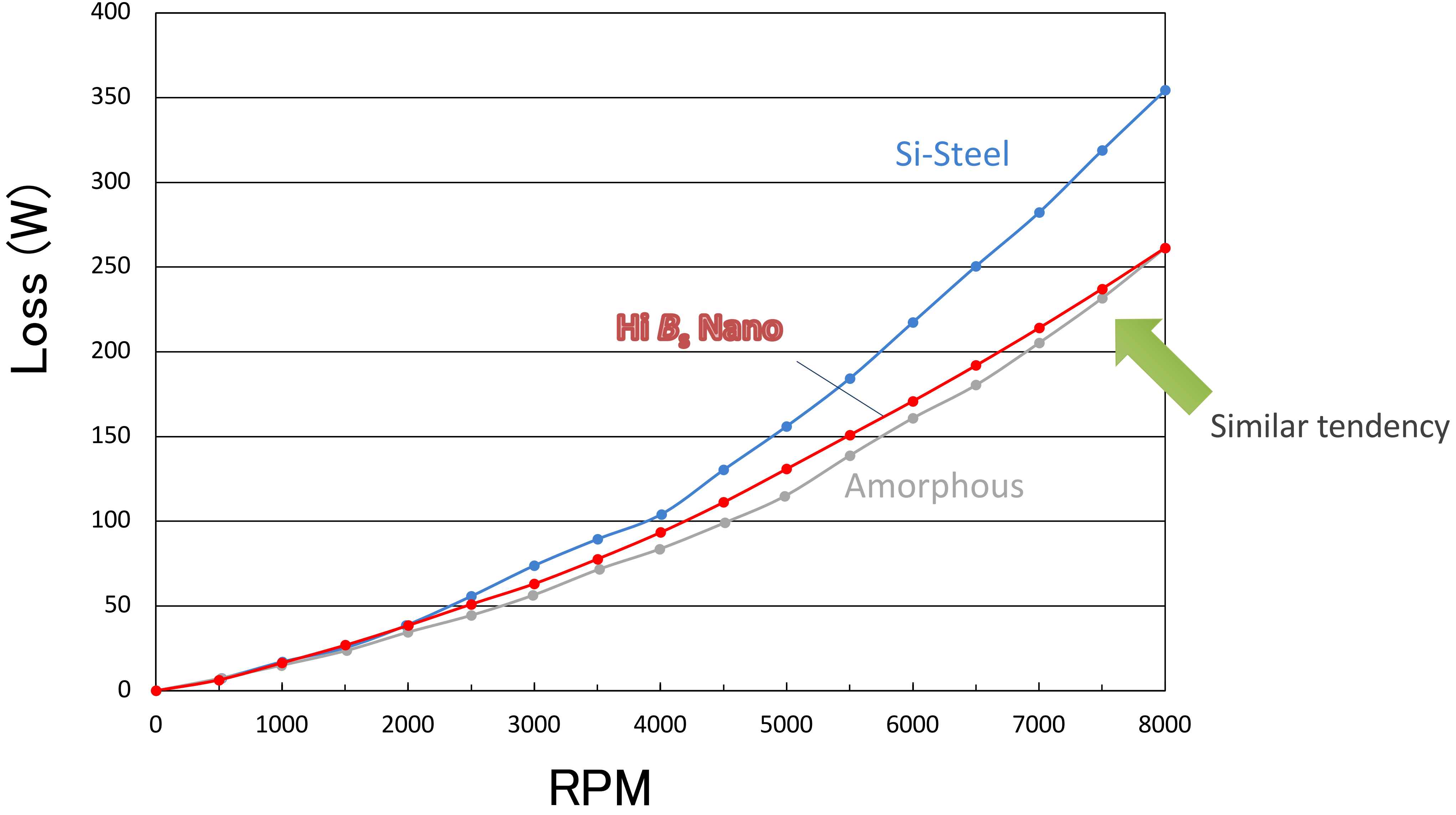
■ No-load loss

PROTERIAL



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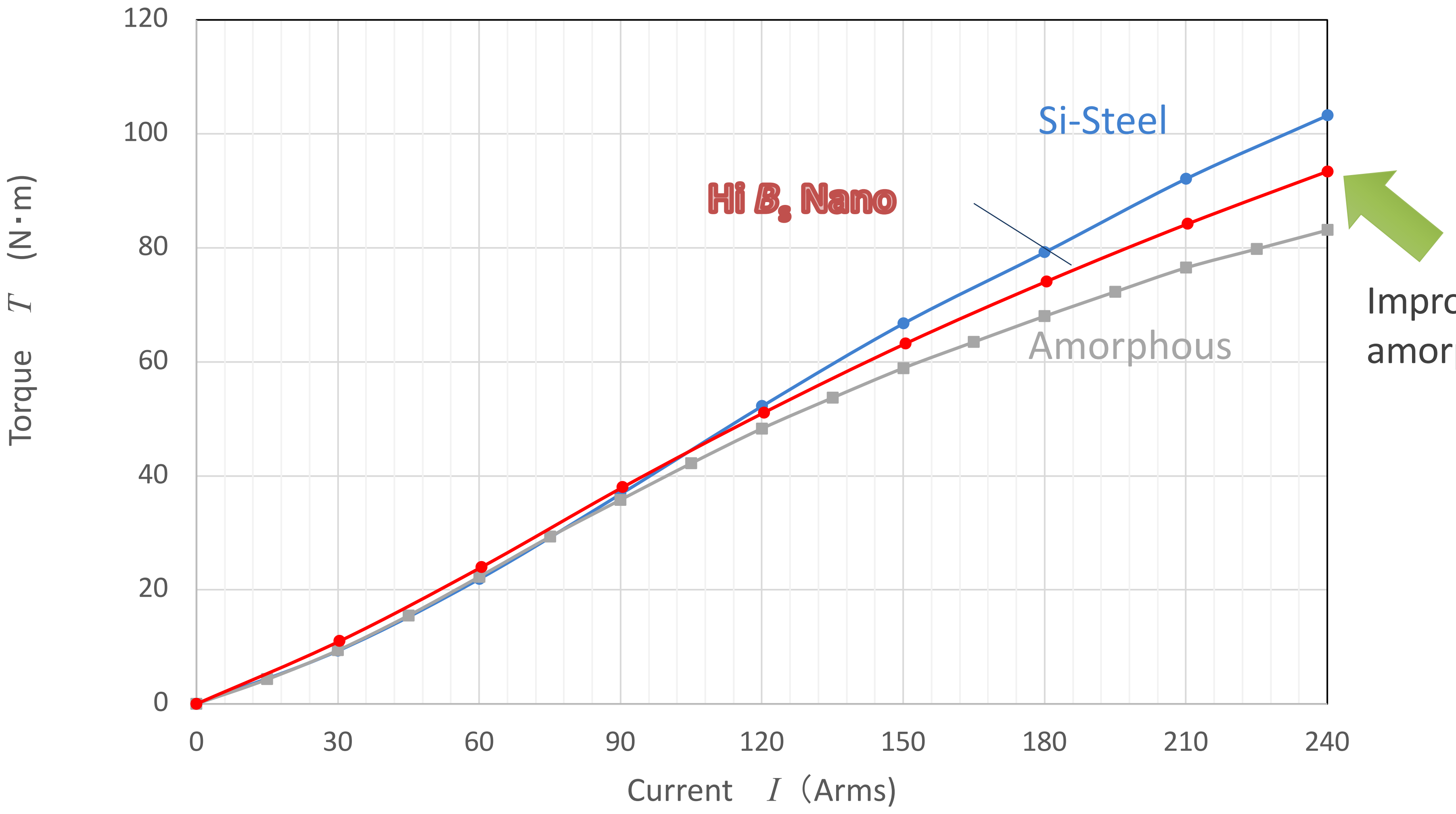
Current vs. Torque

PROTERIAL



Improvement of torque form amorphous

*The result could be expected

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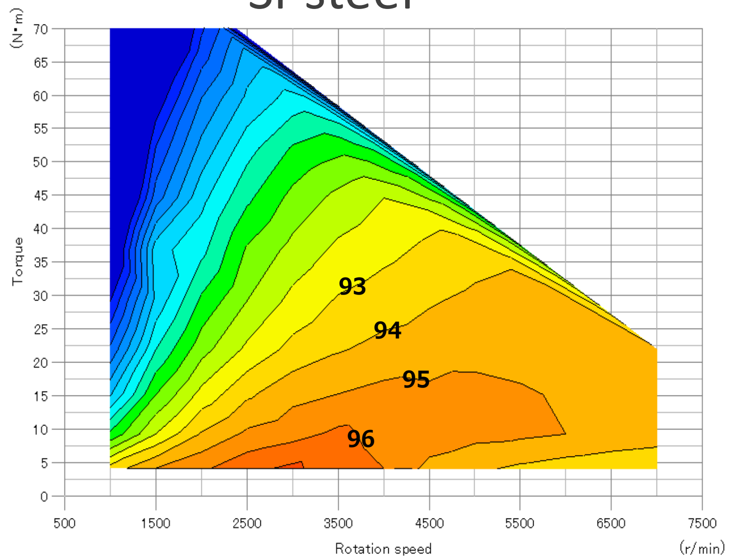
Efficiency map (tested result)

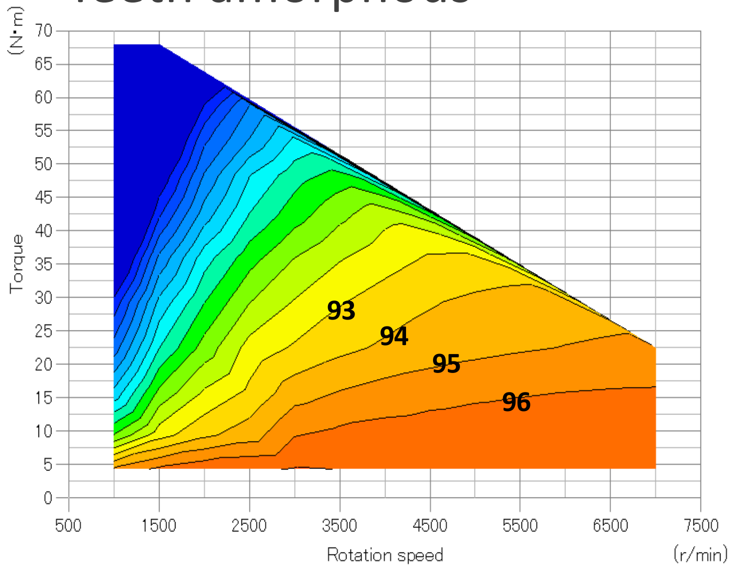
PROTERIAL

Torque

Si-steel

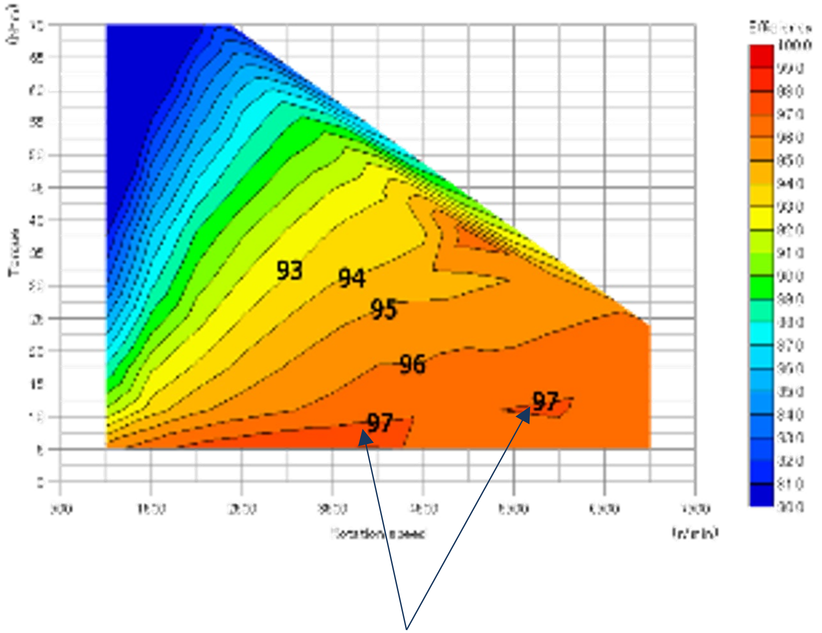


Teeth amorphous



RPM

Teeth Hi B_s Nano



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

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PROTERIAL

- **Remaining issues**
    - Recycling
    - Punching processing

Recycle Flow of AMT (2013～)

Recycle of Amorphous Transformer

Challenges for practical application

PROTERIAL

Challenges specific to Hi B_s nano ▶ New machining process or Consider the usage

Material	Assumed production process and challenges	Countermeasure
▪ Brittleness with crystallization ▪ Shrinkage with crystallization	Anneal ribbon *Material*: ↓ Lamination ↓ Shaping *Machining*: ↓ Shaping ↓ Lamination ▪ Simpler Shape is easier	▪ Shearing method ex：Teeth core ▪ Processing methods other than stamping ⇒developing
▪ High heating rate anneal	Shaping *Material* / *Machining* ↓ Parts anneal ↓ Lamination ▪ In-plane variation of contraction ▪ Handling issue	• Shrinkage evaluation & distortion reduction • New heat treatment method • New piece adhesion method

Conclusion

PROTERIAL

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.

