Dec. 06 (Fri) Symposium on 'Current Research Trends in Magnetic Materials'

The development of Dy free MAGFINE and its applications to Motors

MAGFINE means NdFeB anisotropic bonded magnet produced by d-HDDR process

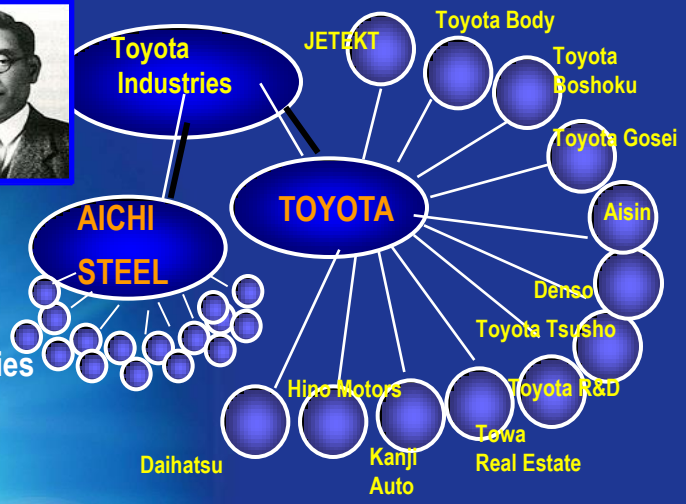
§1 Background
§2 Development for Magfine powder
§3 How to produce Magfine bonded magnet
§4 Motor applications of Magfine bonded magnet
§5 Future scope

Dec. 6th . 2013
Yoshinobu Honkura
Adviser of Aichi Steel Corp.
Vice President of Magnetic Society of Japan

AICHI STEEL

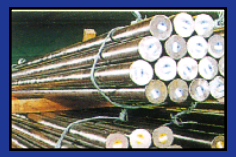
A TOYOTA Group Company
Established:1940
Location: Nagoya, Japan
Capital: 25 billion JPY
Employees: 4,406 (total Aichi Group)
Annual Sales : 227 billion JPY (2012)

TOYOTA Group 15 companies



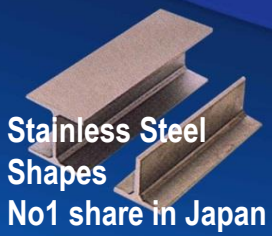
AICHI Group
18 subsidiary companies

Main Business



Specialty Steel
2nd largest in Japan

Forged Parts for Automotive industry
The world's most
from a single plant



Stainless Steel
Shapes
No1 share in Japan

-Next Core Business
-Sales 13billion yen in 2012
-Target : EV motor

Nd anisotropic Bonded Magnets
500ton/ year No.1 share in the world

Magnetic Sensors

Heatsink part for EV car
100% Share of TOYOTA

Dental Magnet Attachment
No1 share in the world

MAGFINE production process

NdFeB anisotropic bonded magnet

Compression molded magnet

compound

Ring magnet

Press fit to PH

Magnet Powder

resin

(BH)max : 43MGOe

Magnet powder
+ epoxy resin
thermo setting resign

(BH)max
18～23MGOe

Motor

Injection molded magnet

pellet

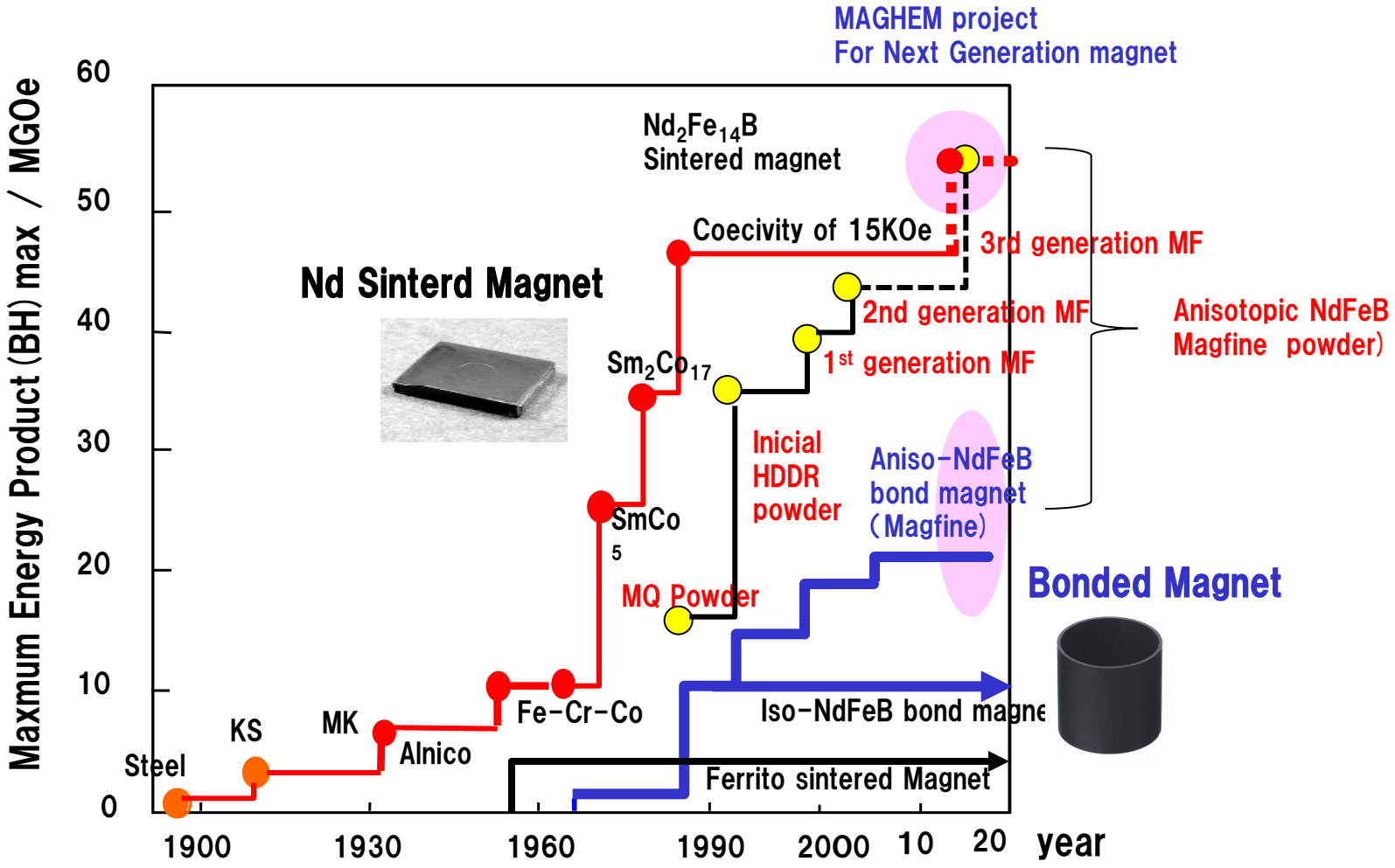
Direct injected to motor Rotor

Magnet powder
+ thermo plsticity resign

(BH)max10～17MGOe

The development of NdFeB anisotopic magnet powder

Bonded magnet with BH max of 20 and good formability must be desired for ideal motor design. MAGFINE powder was developed in 2000 and improved up to 43MGOe with the coecivity of 15KOe. This performance is almost same to Nd sintered magnet.



the Yamazaki Teiichi Prize in 2012

山崎貞一賞　The Yamazaki Teiichi prize given by
Foundation for promotion of Material Science and Technology of Japan,

Title
The development of
Dy free NdFeB anisotropic bonded magnet and its motor applications

The development of Dy free MAGFINE and its applications to Motors

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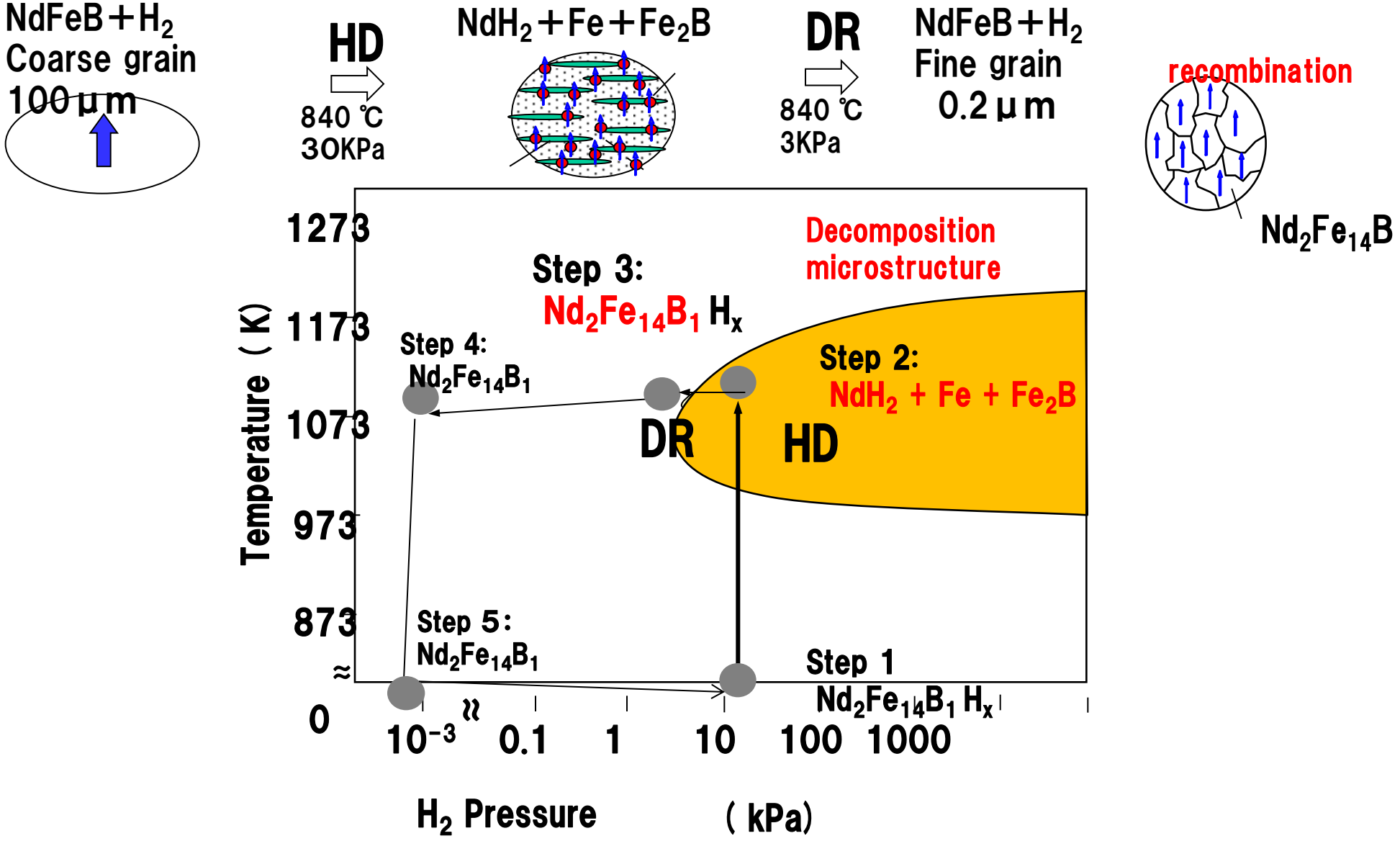
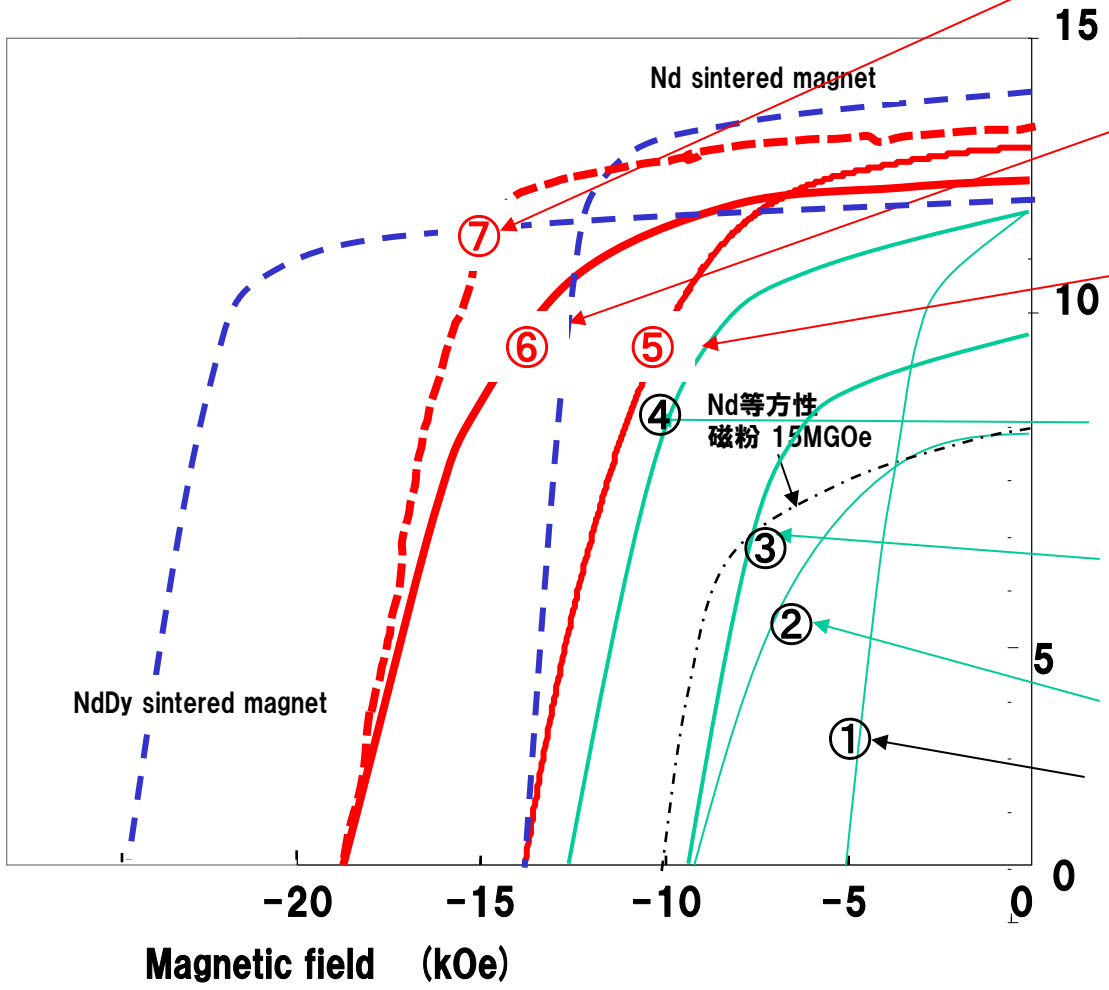
Phase diagram on HDDR-process

（Hydrogenation Desproportionation -Desorption Recombination）



History of the development of NdFeB anisotropic powder

First challenger was GM. GM successfully developed it n 1998 using die upset method but GM gave up the development in 1995 because of high cost.



⑦after 2015年 愛知製鋼
challege to improve anisotory
to 55MGoe

⑥2010年 Mr. Honkura(愛知製鋼)
Discover Dy-free by diffusin process
to 42MGoe

⑤2000年 Mr. Honkura(愛知製鋼)
Dicsover d-HDDR to 40MGOe

In 1996 deiscover d-HDDR

④1995年 Mr. Takeshita(三菱material)
Improve to 33MGOe by Ga,Zr addition

③1990年 Mr. Takeshita (三菱Material
Discover anisotropic HDDR by Co addition
17MGOe

②1989年 Mr. Takeshita (三菱Maerial)
discover isotropic HDDR

①1985年 Mr.Inoue(並木精密)
First discover HDDR phenomina not perfect

Previous research on HDDR phenomena

(Hydrogenation-Disproportionation Desorption Recombination)

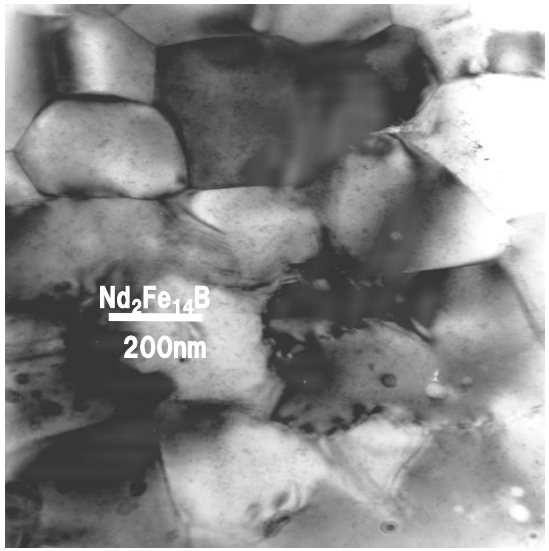
In 1992 Anisotropic powder of NdFeB alloy was found by Co addition
This is mysterious phenomena , because recrystallization structure is isotropic .

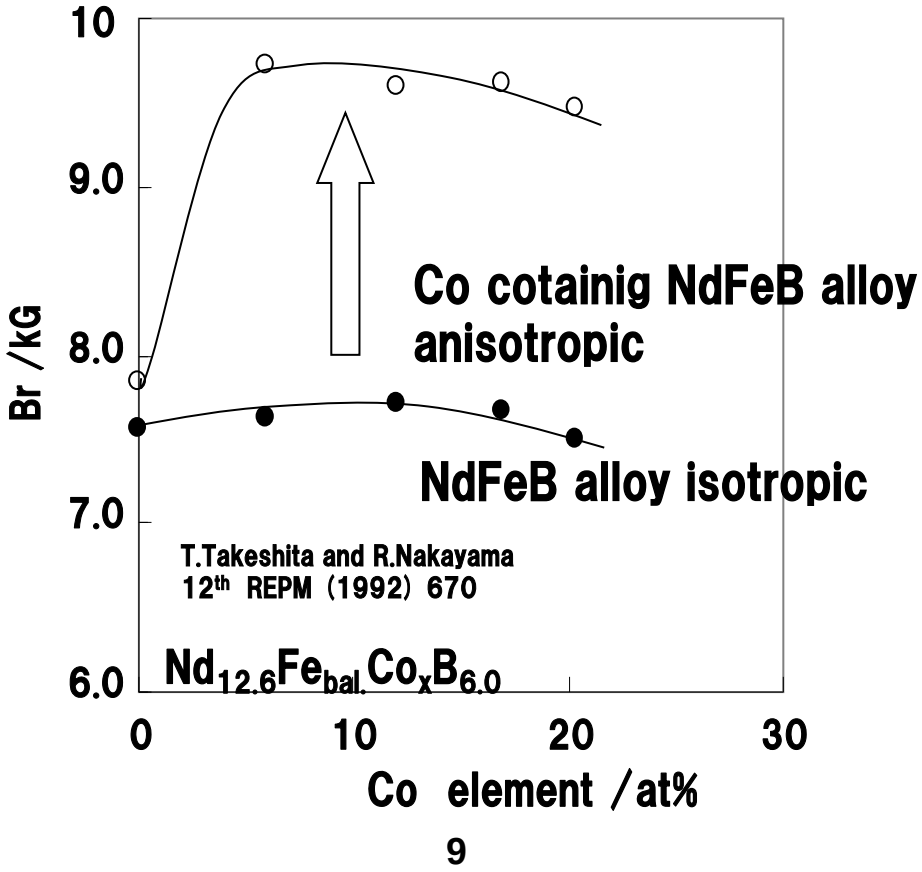
absorption

$Nd_2Fe_{14}B + H_2 \rightleftharpoons \alpha Fe + NdH_2 + Fe_2B$

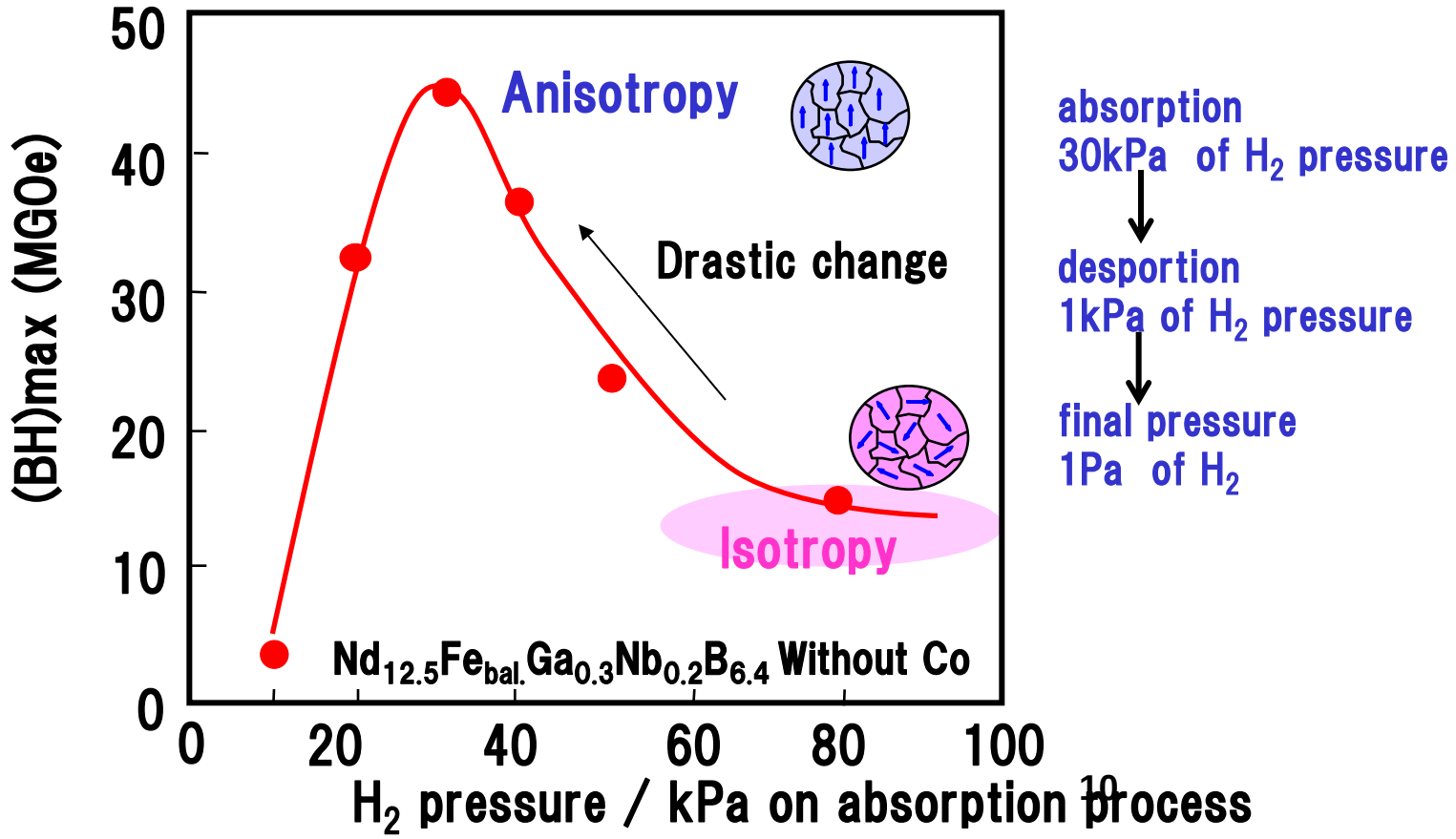
desorption

grain size of 0.2 μm from 100 μm

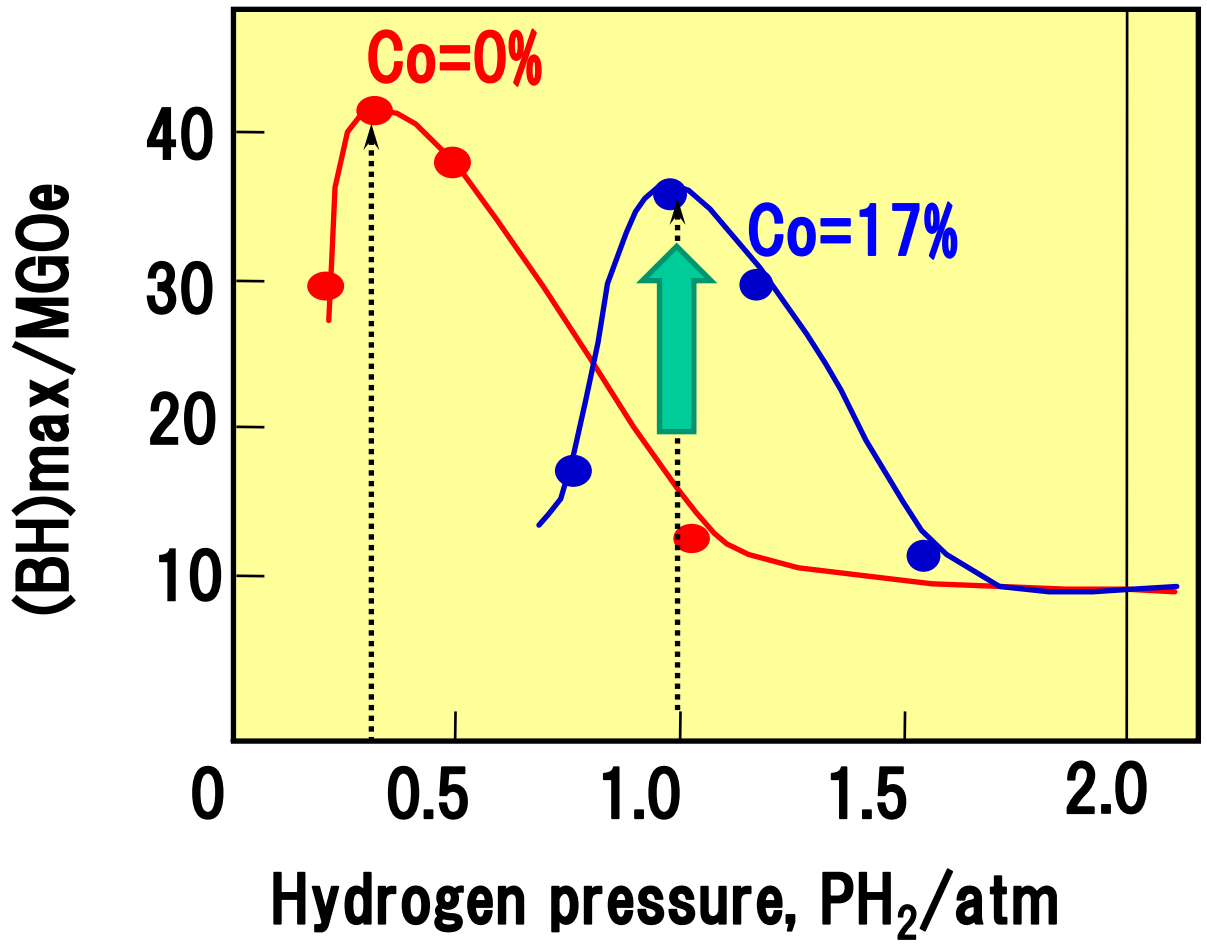




New phenomena in Co less NdFeB alloy discovered by Aichi Steel in 1996 named as d-HDDR process



Effect of Co element on anisotropy or isotropy

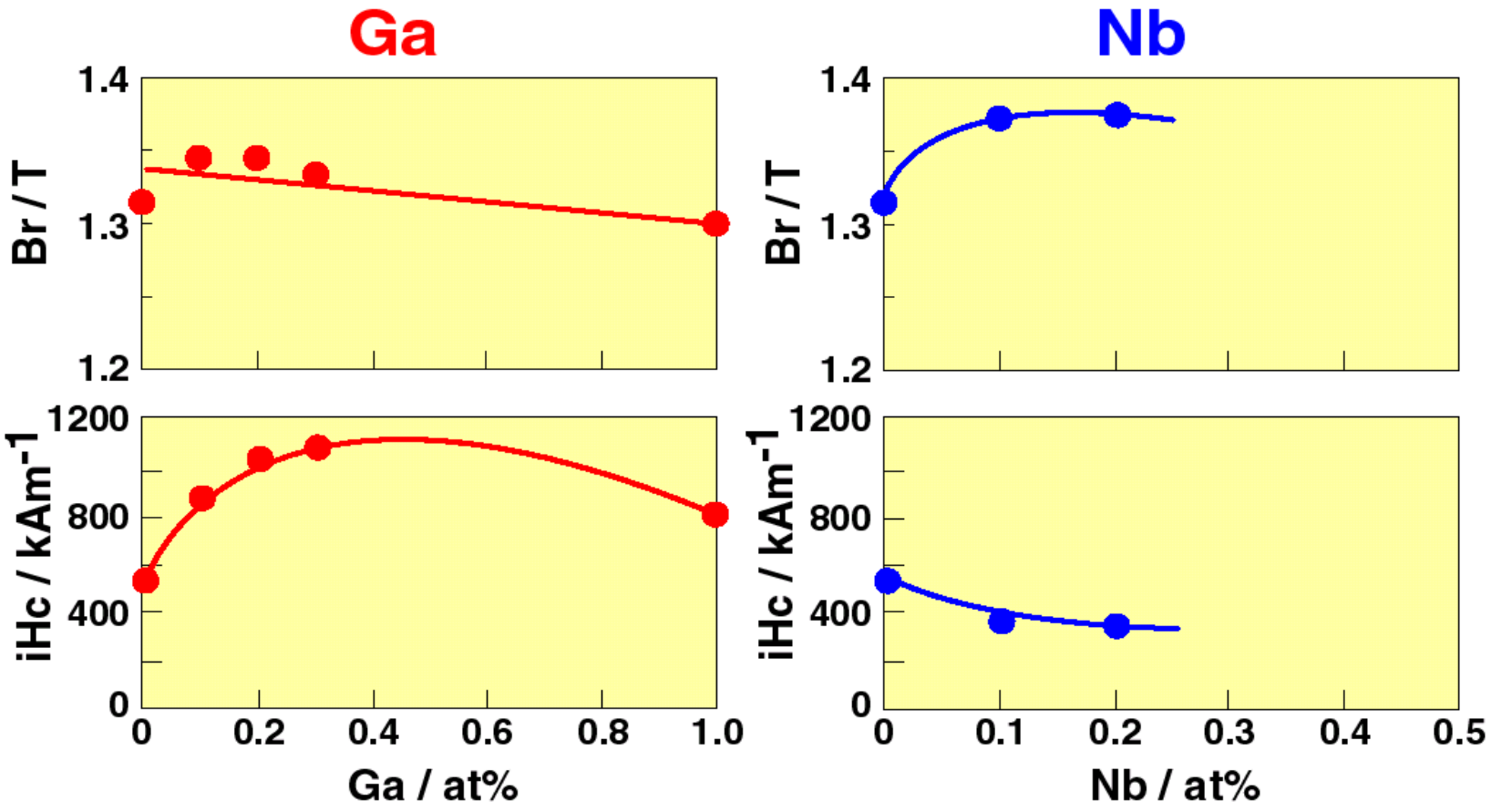


Effect of alloy elements to magnetic properies

18 Additive elements (Al,Si,Ti,V,Cr,Nb,Mn,Ni,Cu,Ga,) were tested.

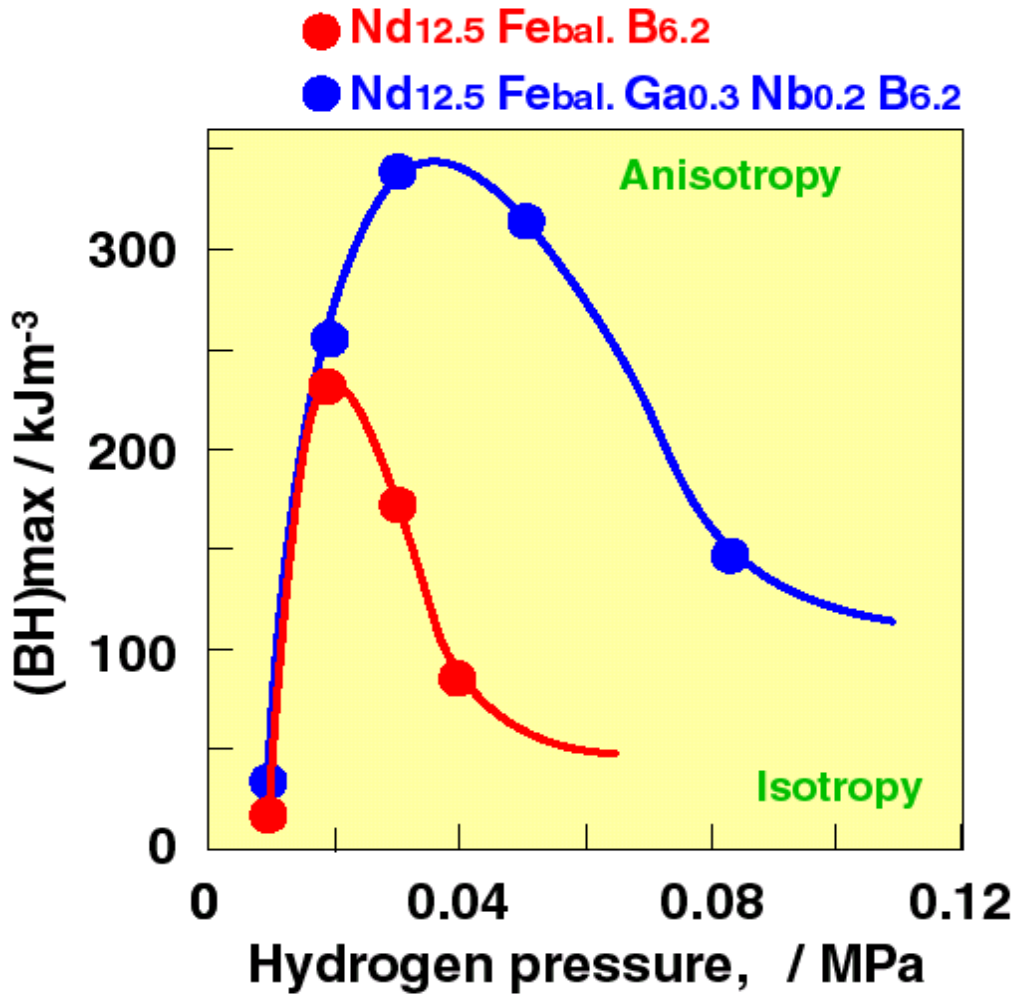
Ga can improve coecivity

Nb can improve Br , which means to improve anisotropy



Alloy design for MAGFINE powder

Alloy design :$Nd_{12.5}Fe_{bal.}Ga_{0.3}Nb_{0.2}B_{6.2}$



Properties of Co-free NdFeB magnet powder

Br	1.38T
iHc	1122kA/m
(BH)max	342kJ/m3

Hipothesis on the mechanism how to make anisotropy

Hypothesis in 1996

$NdFeB + H_2$ ⇨ $NdH_2 + Fe + Fe_2B$ ⇨ $NdFeB + H_2$

Coarse grain — Tetragonal, C: easy axis

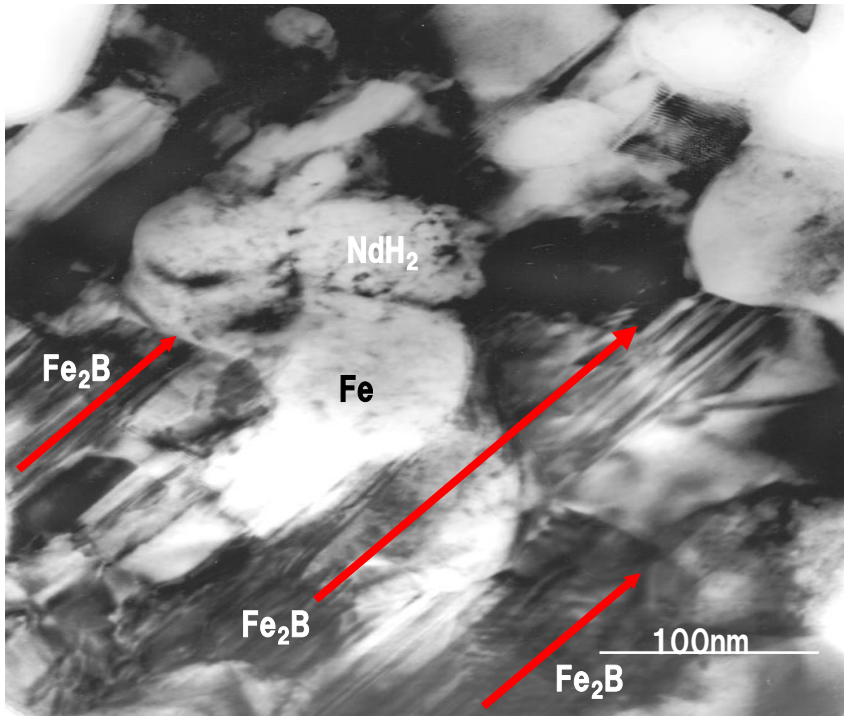
NdH_2: fcc, isotropic

Fe: bcc, isotropic

Fe_2B: Tetragonal, C: easy axis

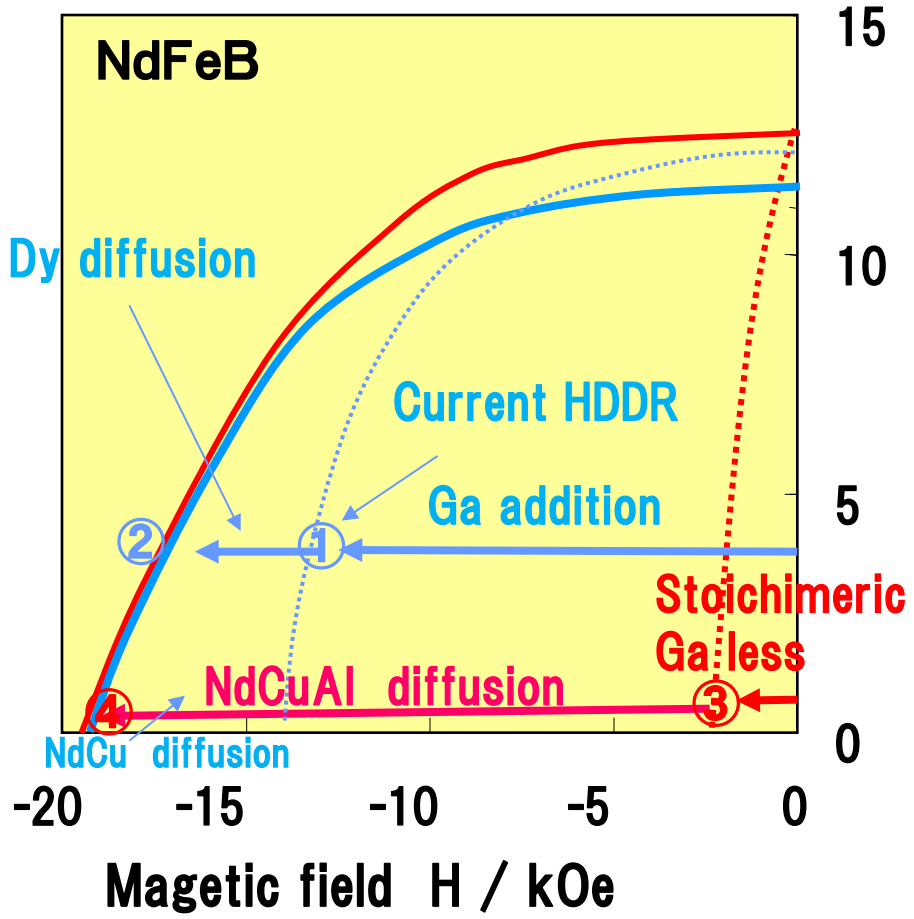
Fine grain — Tetragonal, C: easy axis

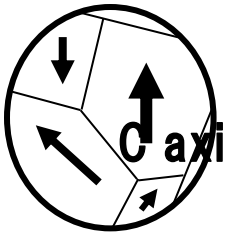
In 2004 we found good aliment of Fe2B phase by TEM observation and proposed this mechanism named as Texture memory effect.



Development for 2nd generation : Dy free Magfine powder

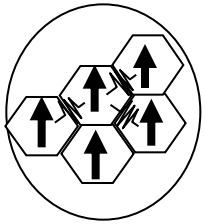
New idea for improving the Coecivity without Dy and Ga addition





$Nd_2Fe_{14}B_1$
stoichiometric
+Ga less
composition

d—HDDR process



Anisotropic + fine grain
with no boundary phase

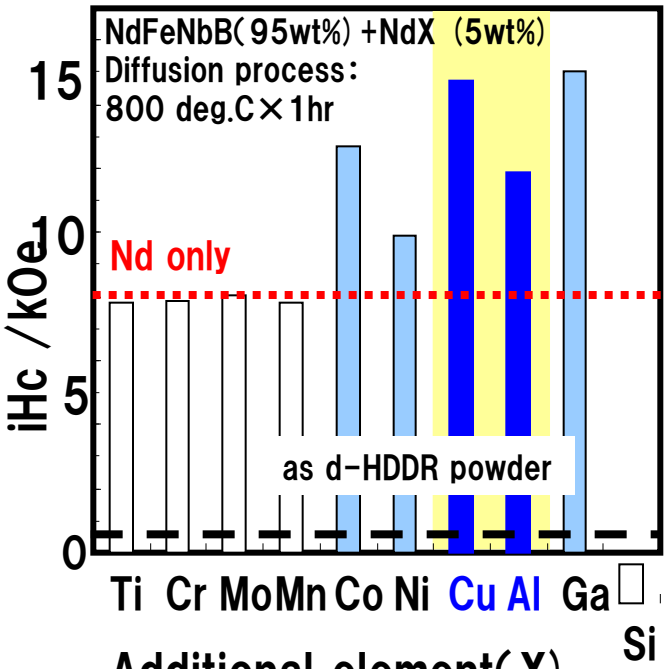
NdCuAl alloy diffusion

Nd rich grain
boundary

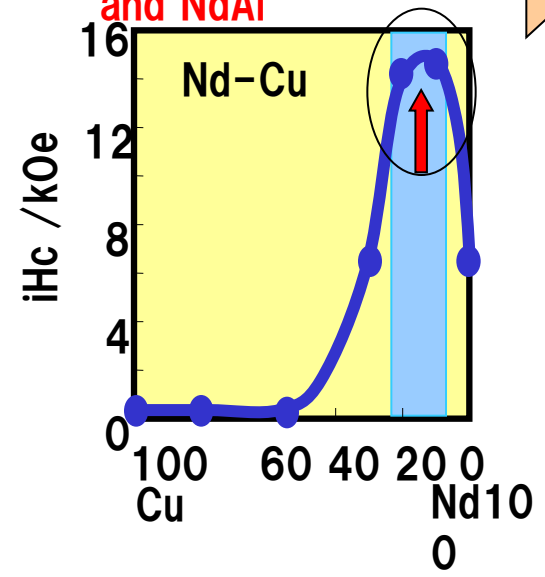
③④Honkura： 09年12月出願 Patent 2009-279314

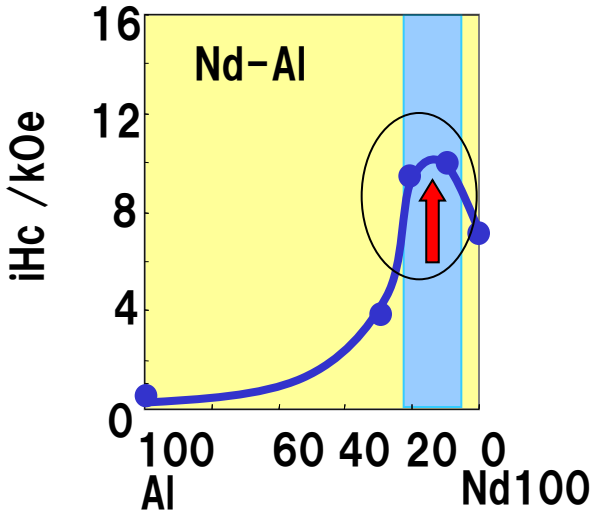
Effects of diffusion elements

Binaly alloy with additional element of 5wt %

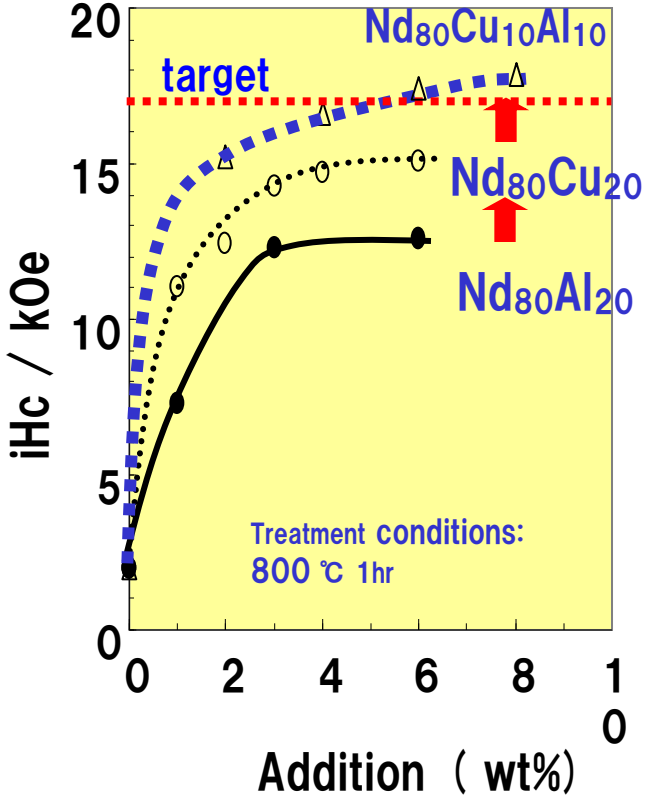


Binaly alloy of NdCu and NdAl





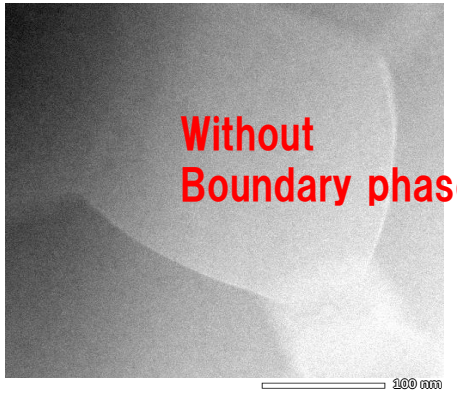
Ternaly alloy of NdCuAl Combination effect of cu and Al



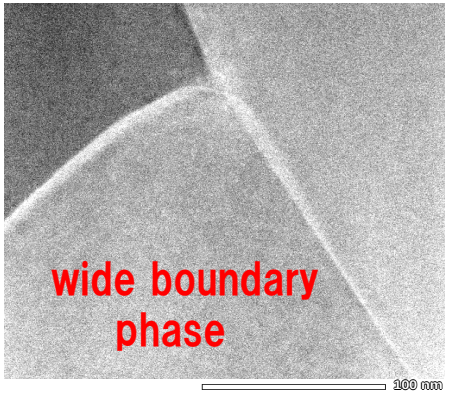
Why NdCuAl diffusion can increase the corecivity ?

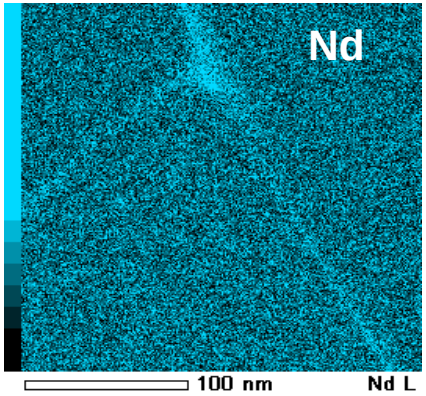
TEM(Trans-Electron-Microscope) observation make clear

After HDDR

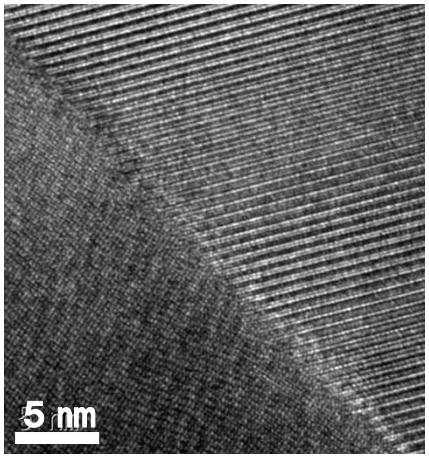


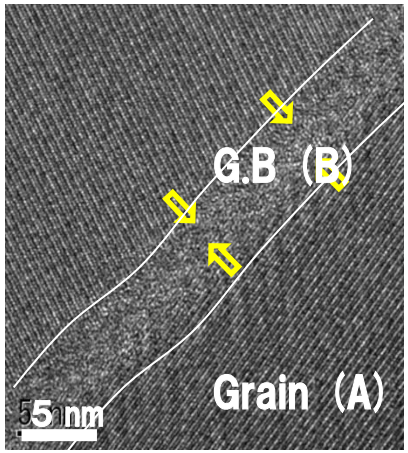
After diffusion of Nd Cu Al alloy

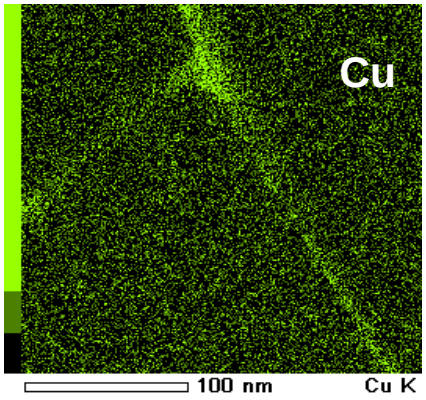




Nd concentration on the boundary

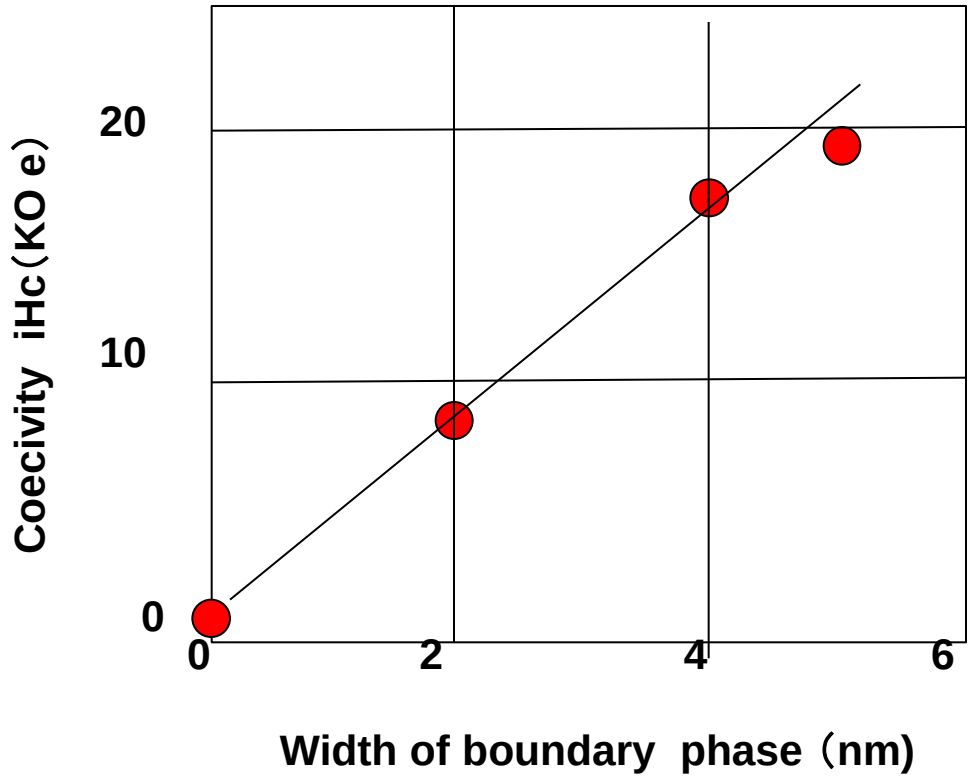






Cu concentration on the boundary

The effect of the boundary phase width on the coecivity

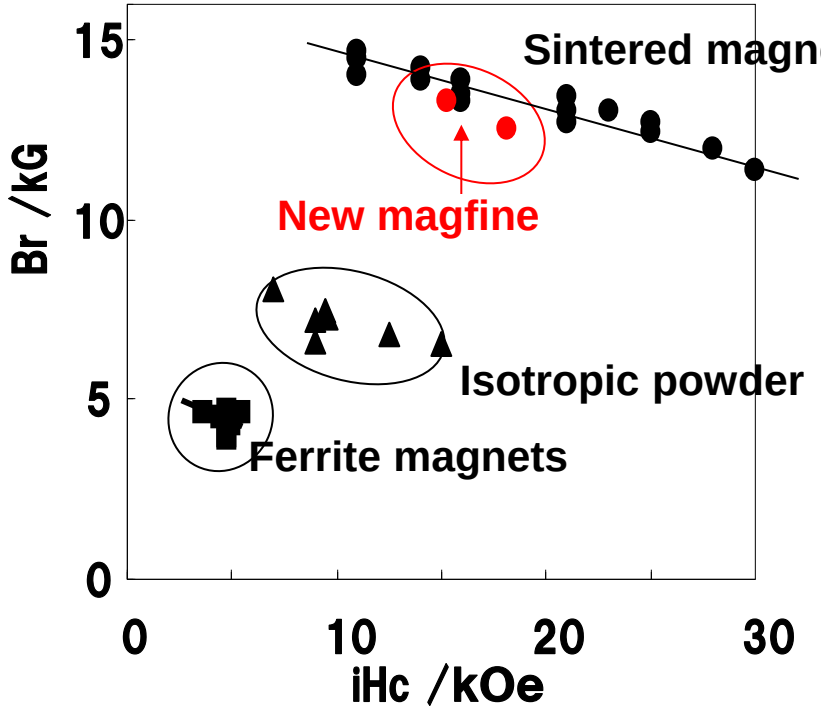


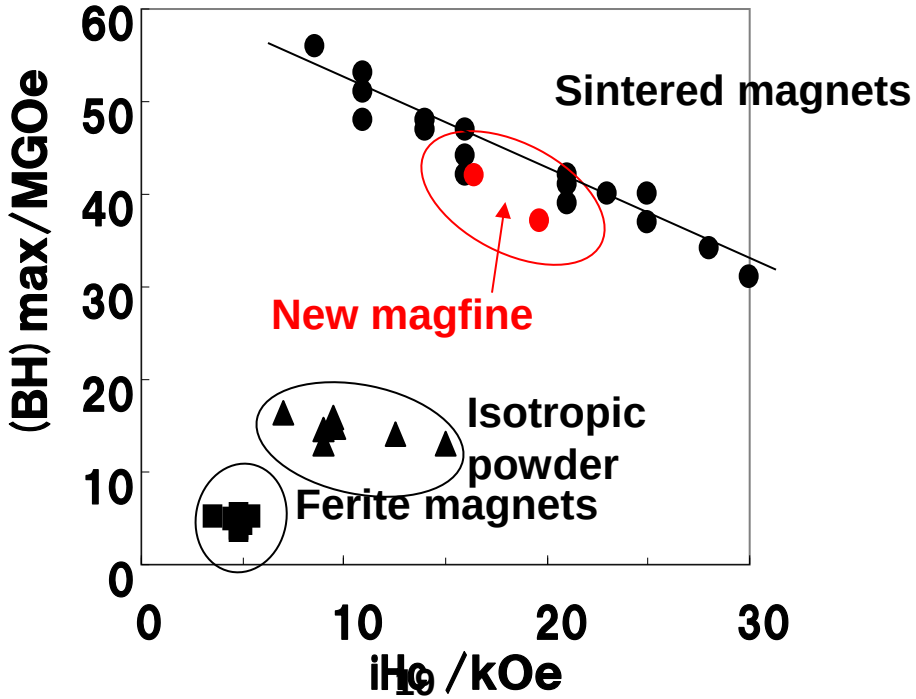
Alloy design for Dy free MAGFINE powder

Alloy design

ttype	compsotion (wt%)	(BH) max	iHc	Br
MF-15P	Nd27.5FeNbB+3%NdCuAl	43MGOe	15 kOe	13.8kG
MF-18P	Nd27.5FeNbB+6%NdCuAl	38MGOe	18 kOe	12.8kG

comparison of magnetic properties with various magnets





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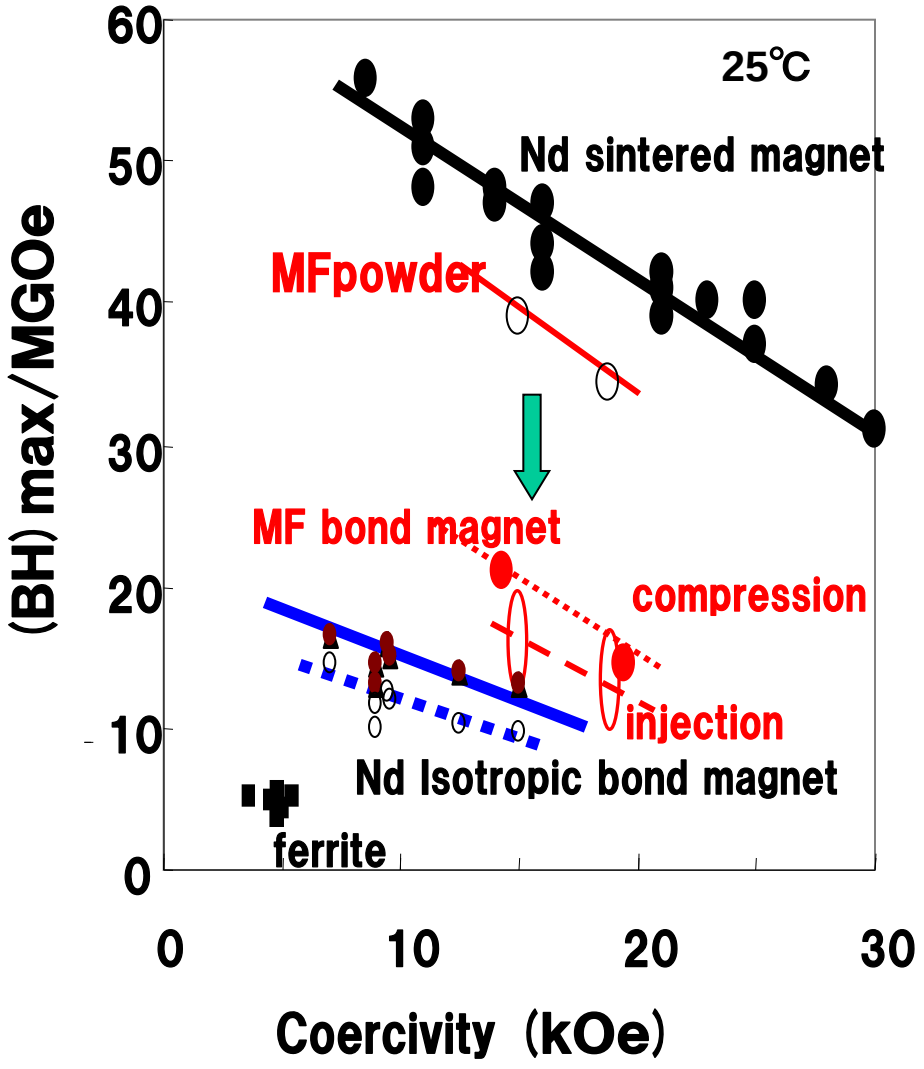
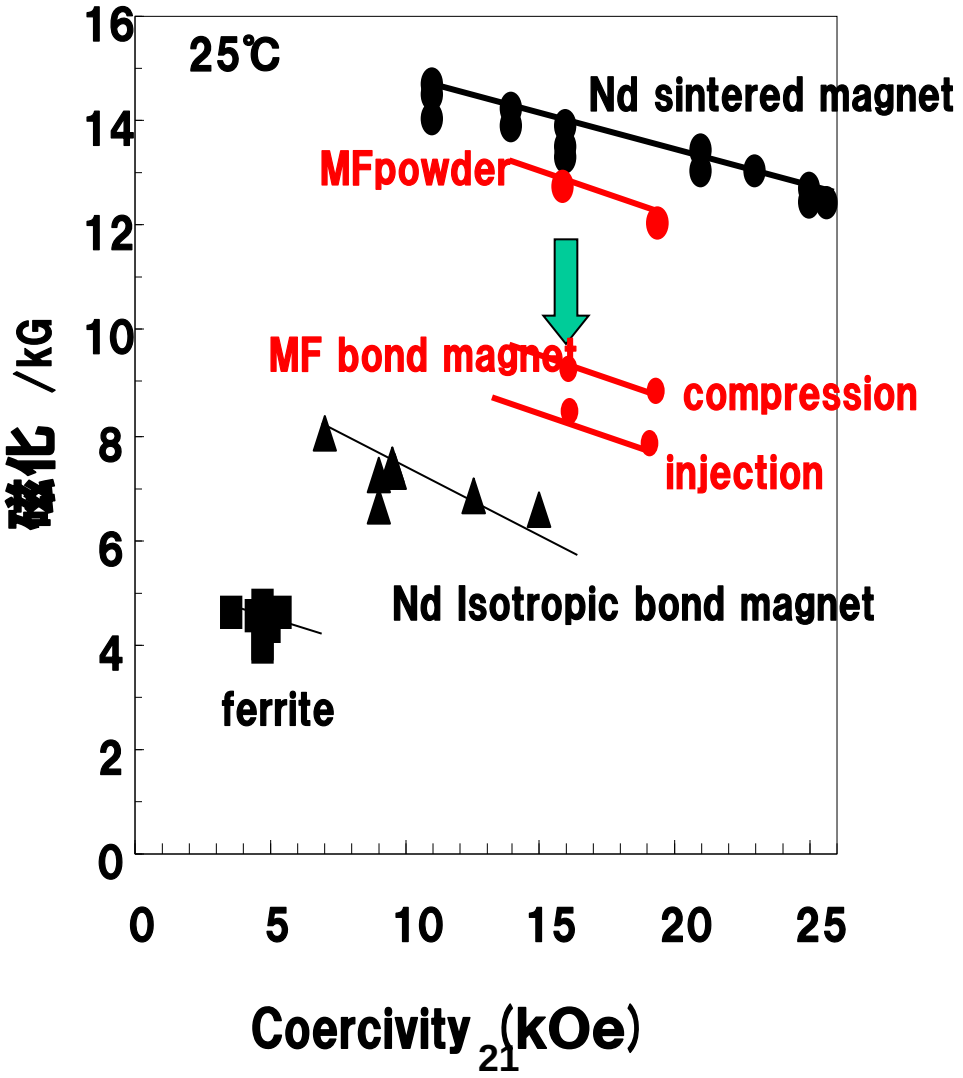
Magnetic properties of MF magnet (compression & injection)

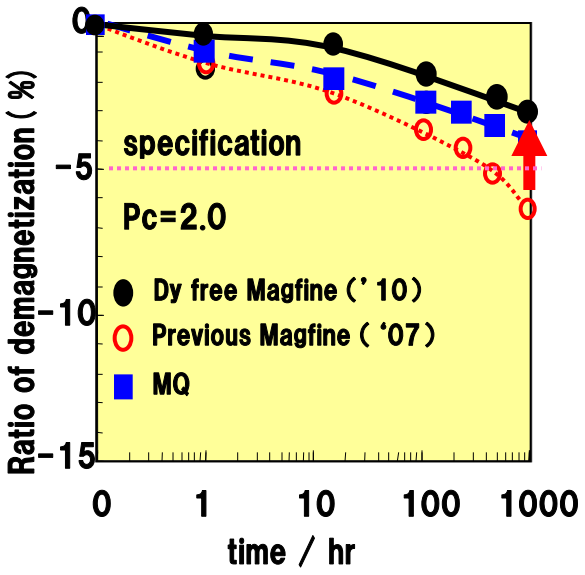




reliability of injection molded magnet compared to compression type

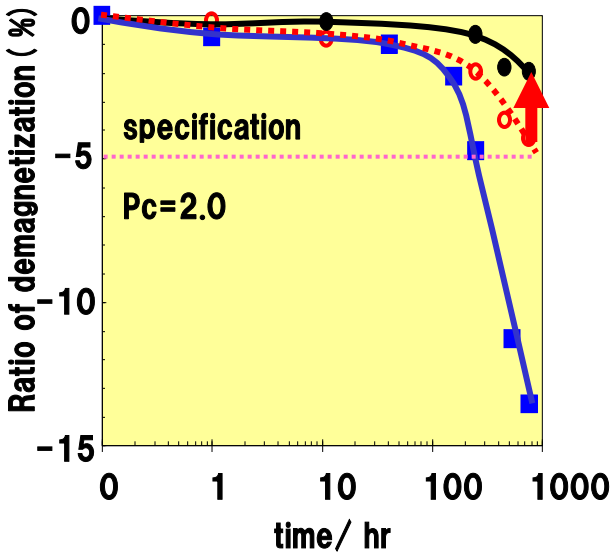
1) compression

a) oxidation (under 150℃)

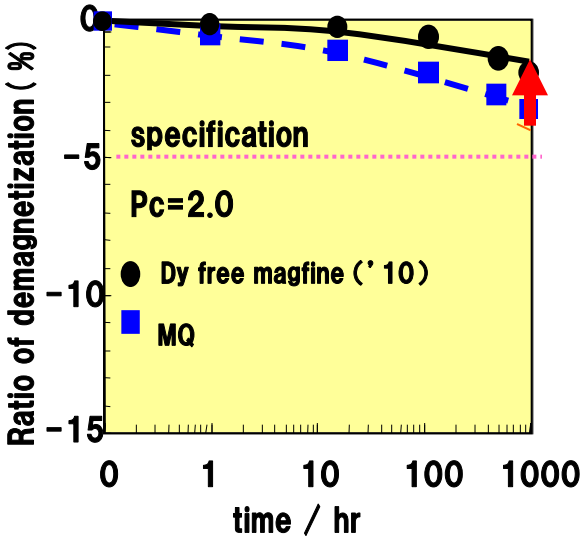


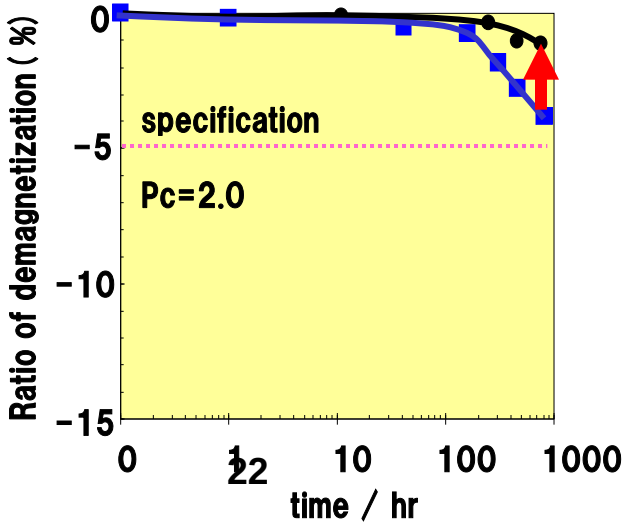
b) corrosion (under 80℃, 95%RH)

Without surface coating



2) Injection





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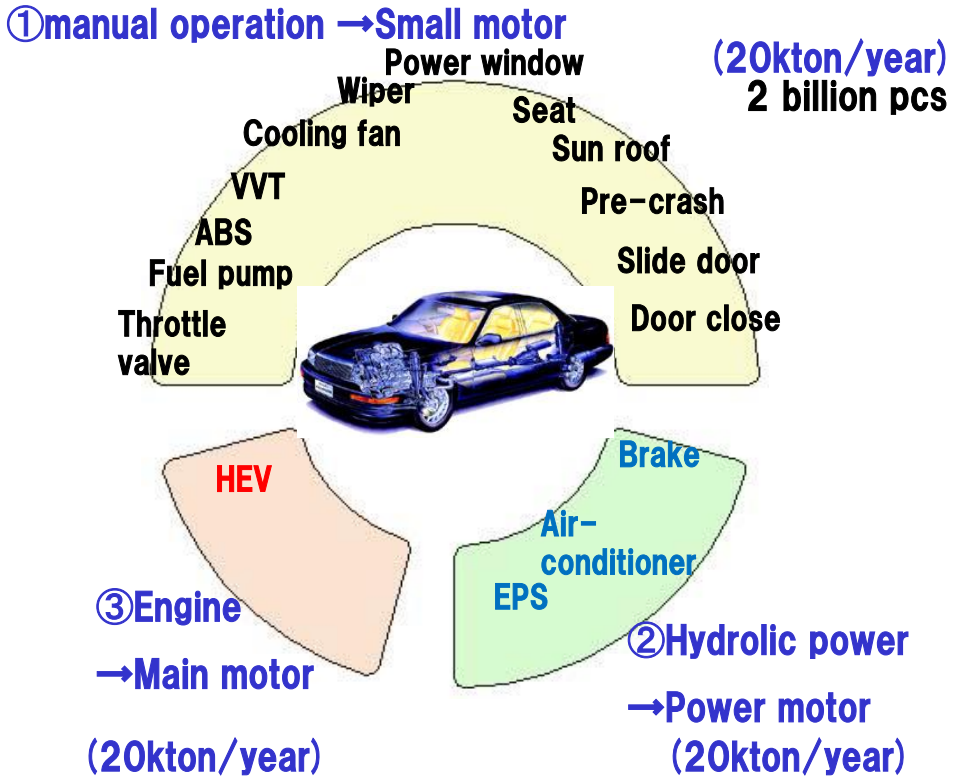
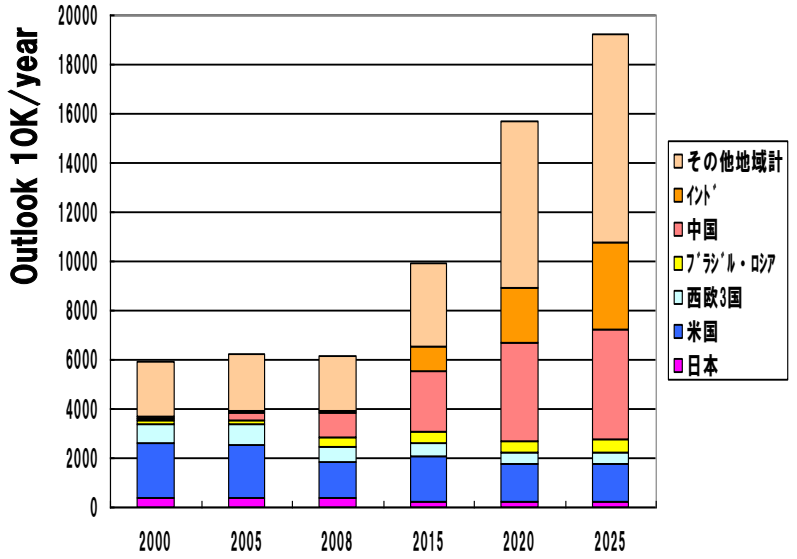
Trends of Automotive use motor



Increase of motor numbers per one car

Future outlook report 2011-2025
Automotive industry Nikkei BP consulting Mr.Sakae Tanaka



Car Production will be doubled in 2020

- Increasing mainly in emerging countries
- Advanced countries may keep the current level.

First MAGFINE application to small DC brush motor with 40w

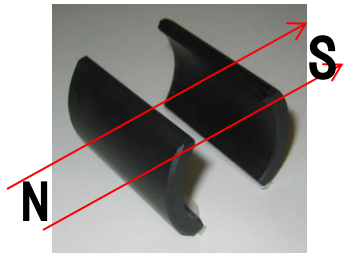
Ferrite seat motor

465g

465g

(BH)max:4MGOe

Ferrite magnet Axial alignment

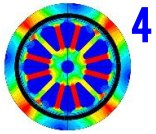


80g t=5mm

Weight reduction
50%

MAGFINE seat motor for seat

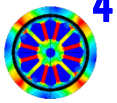
In 2005
235g



Weight reduction
40%

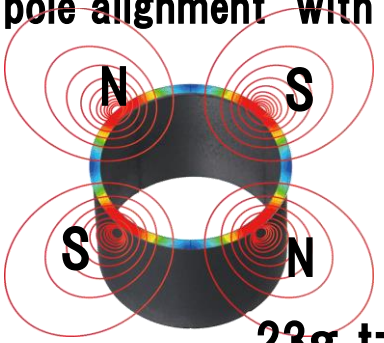
1n 2013
140g

Rotation speed
3000 → 6000rpm

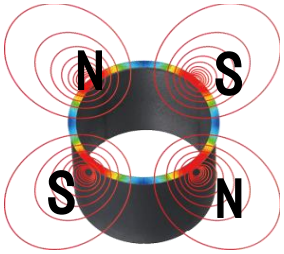


MAGFINE magnet (BH)max:20MGOe

4 pole alignment with radial alignment



23g t=1.5mm



8g t=1.0mm

Performance of Seat motor

50% Lighter 50W Motor for Automobiles Applications for 1mm-ring Magnet

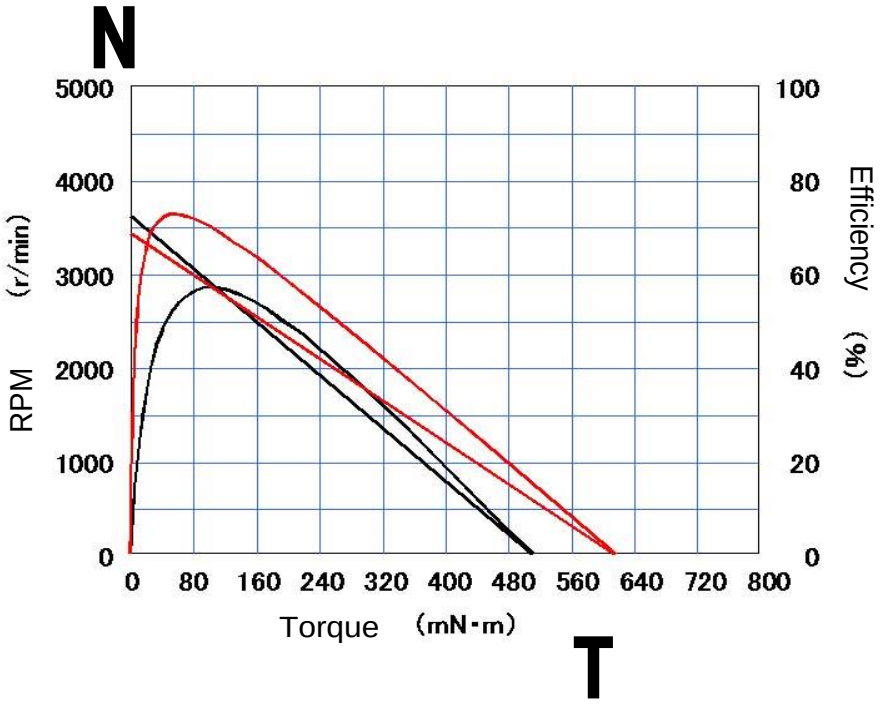
No. 01

Proposal	Change 2-pole sintered ferrite magnet to 4-pole MAGFINE 1mm thickness magnet
Performance	Torque +20% / Max efficiency +15% / 10% lower cost (Aichi Steel estimate)
Applications	Power seat motor etc.

Motor body φ 45xL68mm
Motor weight 465g
Ferrite
Magnet weight 80g

MAGFINE
1mm-ring magnet

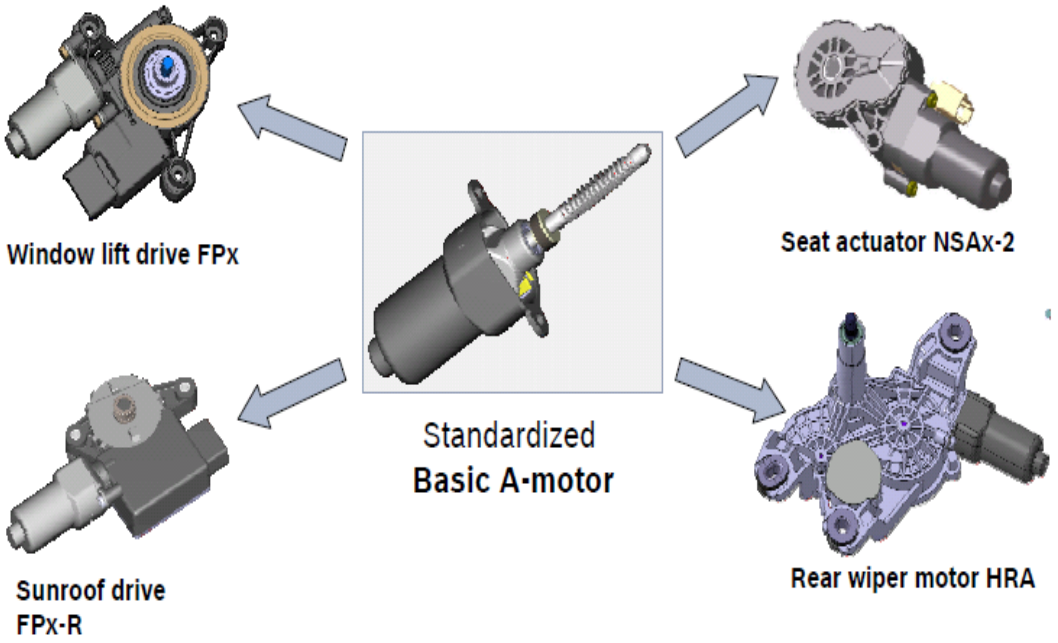
Motor body φ 37xL38mm
Motor weight 235g
MF14C
(4-pole semi-radial alignment)
Magnet weight 16g



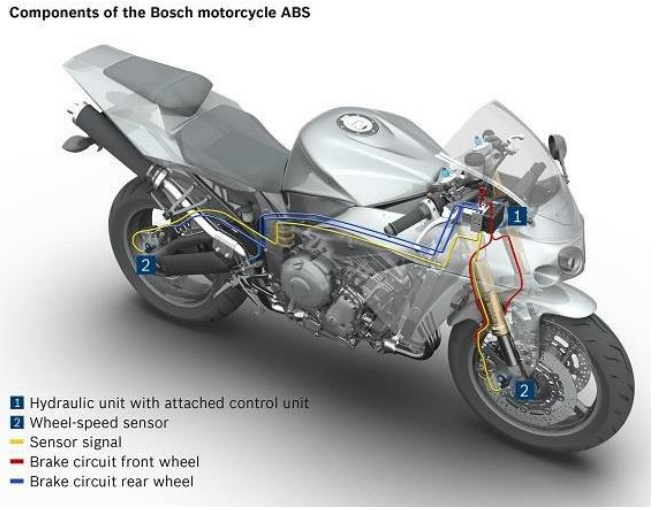
Extension of weight reduction MF motors

■ Modular system using common motor with 30w

- Seat / Wiondow / Sunroof / Rear Wiper



■ ABS motor by Bosch 100w

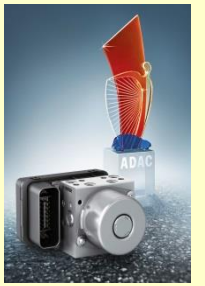


■ Power Tool of Makita

300W

50W

In 2006
TOYOTA development award

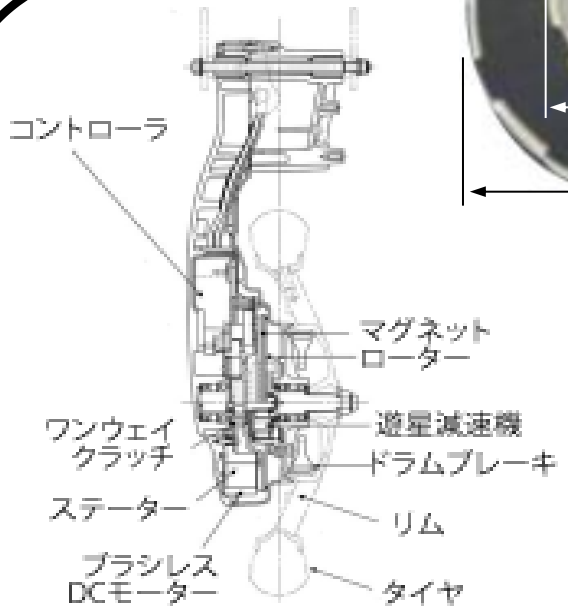


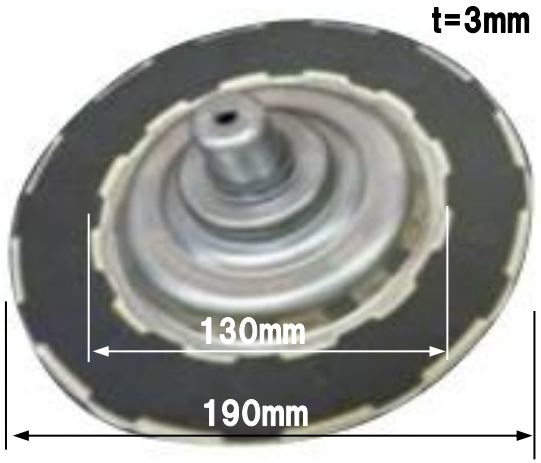
100W

In 2010
Bosch Innovation Award(

YAMAHA developed E-bike motor using MAGFINE

Max power of 1.4Kw with Flat shape motor
by using injection molded MAGFINE with 12-poles

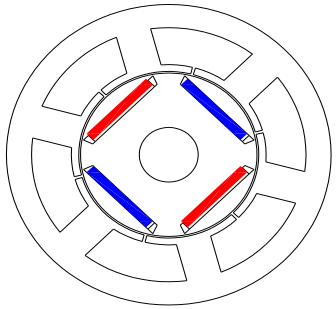
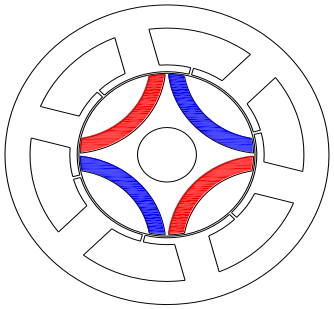
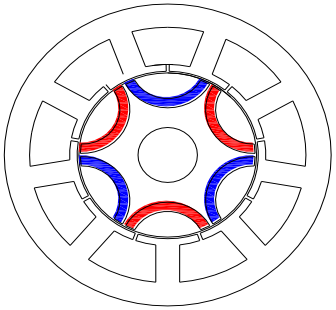
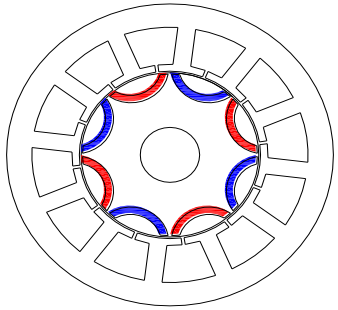




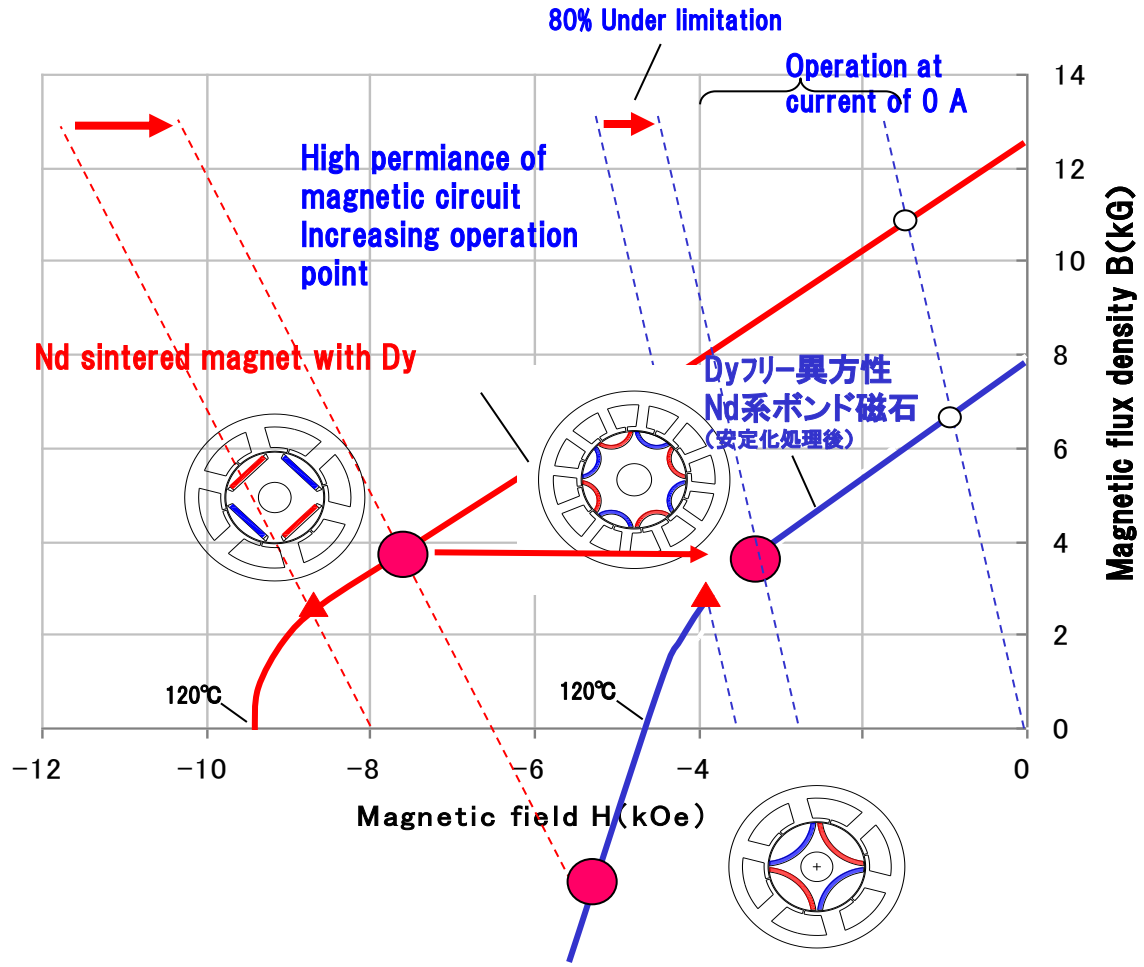
Rated power:600W, Max. power 1.4kW

Injection molding : MFP15 Magnet weight : 277g

Develop Dy free MF motor for Compressor with 1 kw

Item	Dy-Nd Sint. magnet Br:13kG, iHc:21kOe 4pole-6slot	MAGFINE MF18P(PPS) Br:8.2kG, iHc:14.7kOe 4pole-6slot	6pole-9slot	8pole-12slot
Design				
Rating torque (@4Arms, 3600rpm)	3Nm	3Nm	3Nm	3Nm
Rotor outer diameter D	φ50mm	φ50mm	φ60mm	φ60mm
Rotor length L	35mm	45mm (30%up)	35mm	35mm
Magnet thickness tm	2.7mm	4.5mm	3.3mm	2.8mm
Magnet weight (CR, comparison ratio with Nd sint.)	70g(1.0)	150g(2.1)	130g(1.8)	105g(1.5)
Rare earth weight (g)	Nd 21, Dy3.5	Nd 45Dy0	Nd 39, Dy0	Nd 32, Dy0

How to design power motor using Dy free MAGFINE with low coercivity of 18Koe



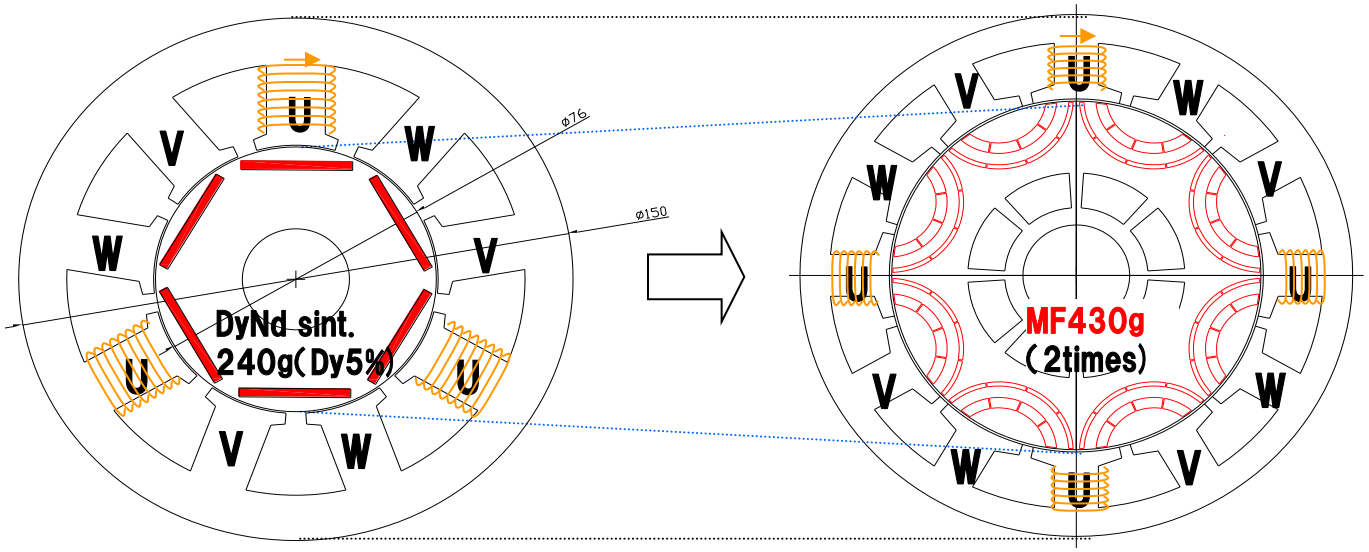
Guideline of MF motor.

1) multi- pole structure.
2) reluctance torque
3) suitable curve shape
4) demagnetization of electromagnet
5) cost competition .

IPM motor design with the power of 5Kw or 30Kw

Torque T_{total}:13Nm (Tm12.4, Tr 0.6 (5%))

Torque T_{total}:13Nm (Tm11.2, Tr 1.8 (14%))



Rotor diameter 76Φ

Rotor diameter 100Φ

DyNd sint. motor
6p-9slot

Dy free MF motor
8p-12slot

$$T = P_n \left\{ \psi_a I_a \cos\beta + \frac{1}{2}(L_q - L_d) I_a^2 \sin 2\beta \right\} \quad (1)$$

Magnet torque

Reluctance torque

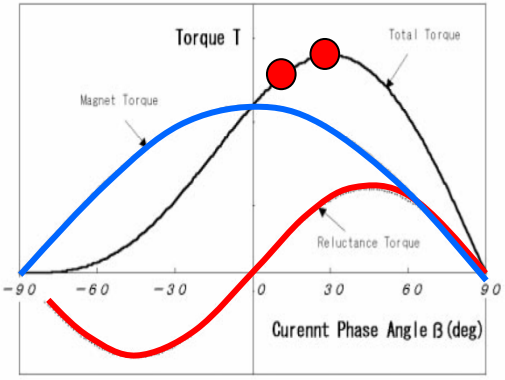
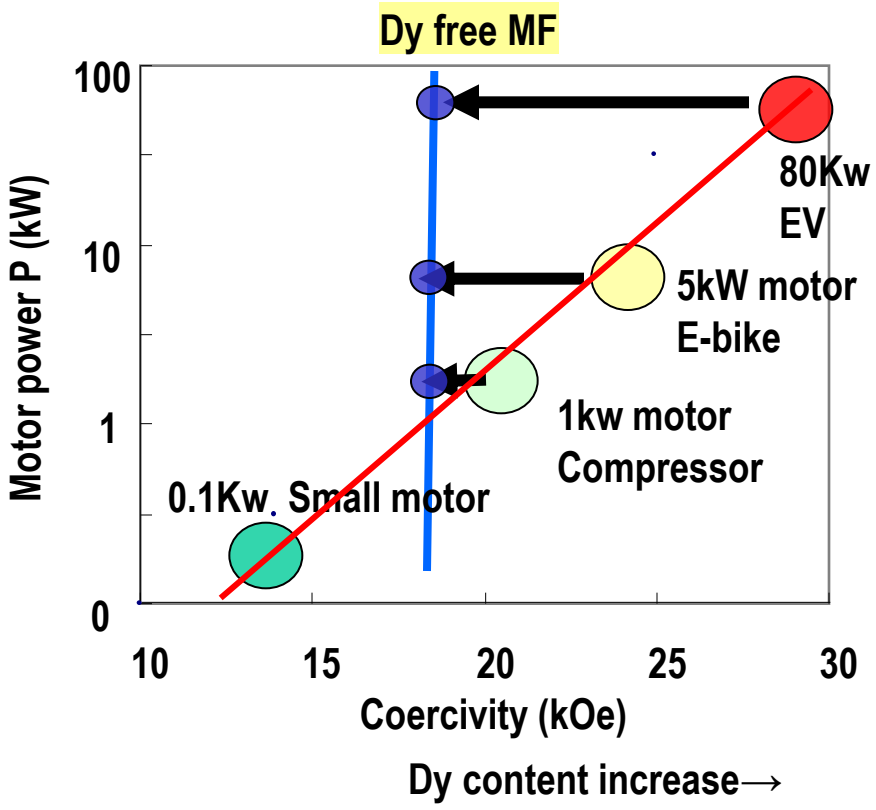


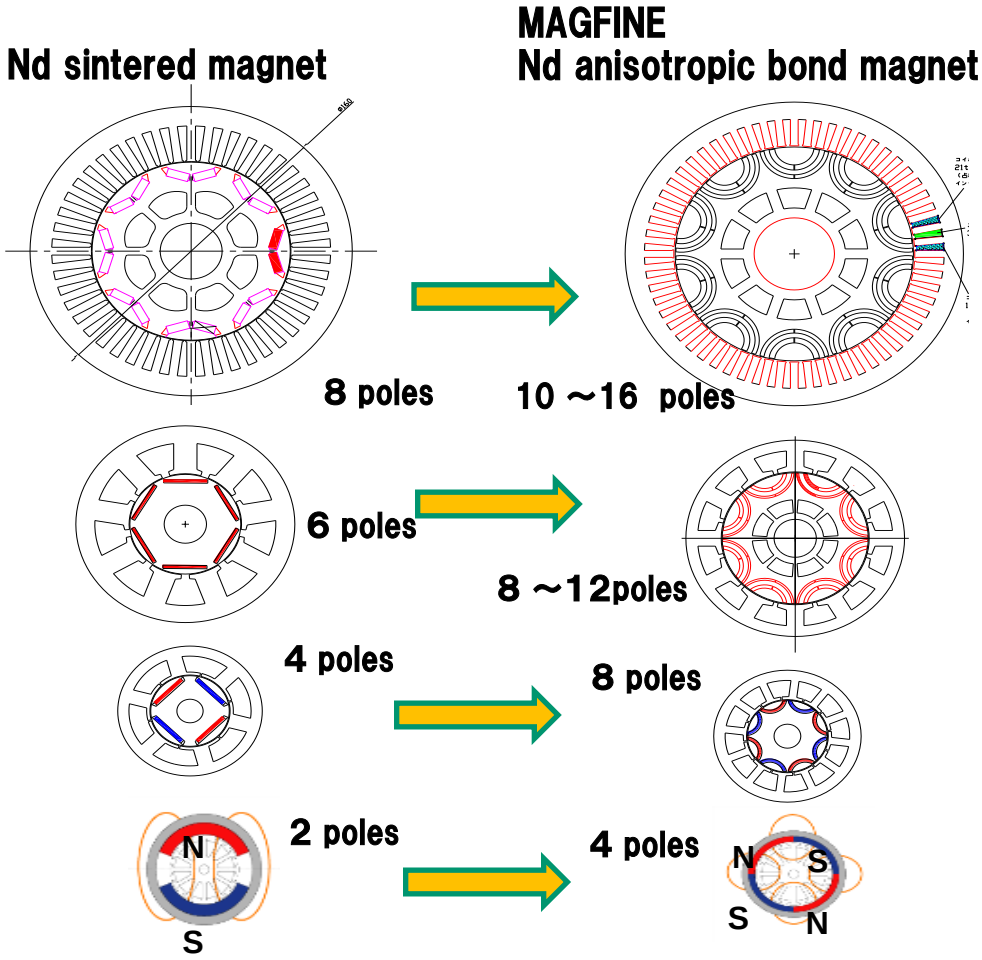
図2 磁石トルクとリラクタンストルク

Fig. 2 Magnet torque and reluctance torque.

New proposal to innovate the motor design using MAGFINE

Dy free Nd bond magnet with coecivity of 18KOe can make EV motor design due to optimal design by increase of magnet poles , two layer magnet structure and increase of rotor diameter



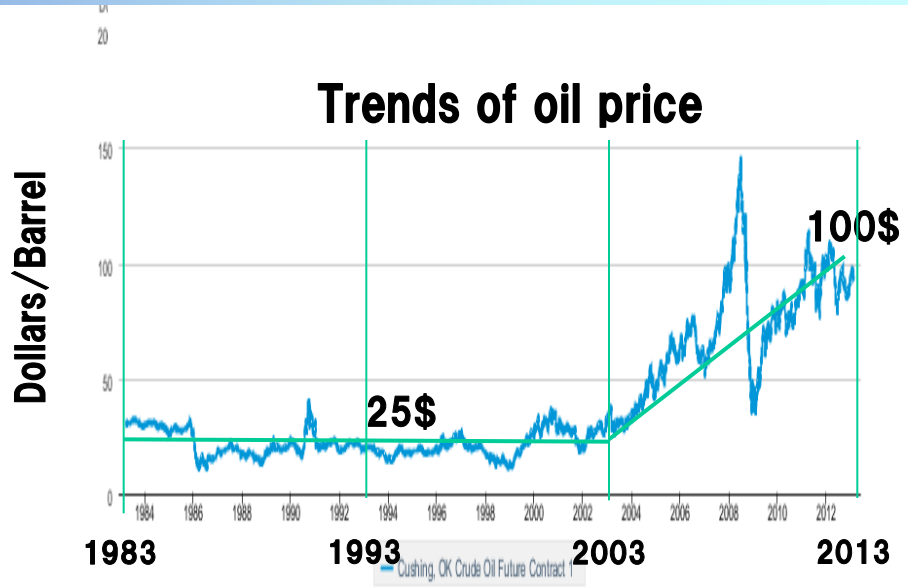


The development of Dy free MAGFINE and its applications to Motors

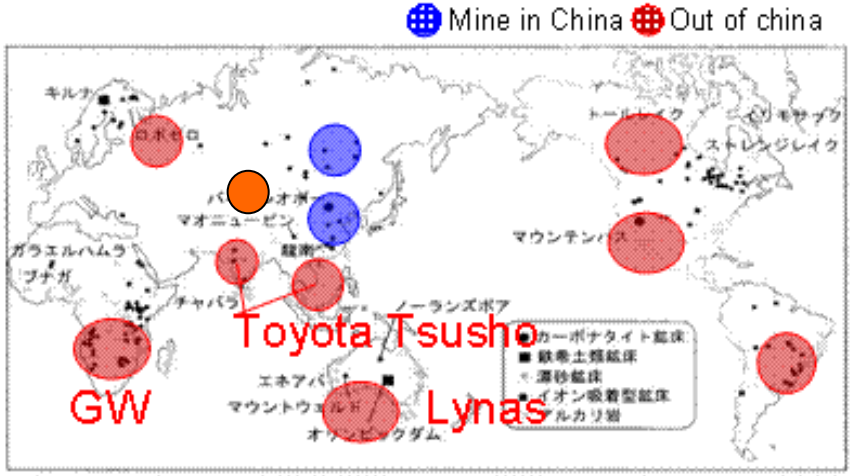
§ 1 Background
§ 2 Development for Magfine powder
§ 3 How to produce Magfine bonded magnet
§ 4 Motor applications of Magfine bonded magnet
§ 5 Future scope

Resources of Energy and rare metal meet shortage .

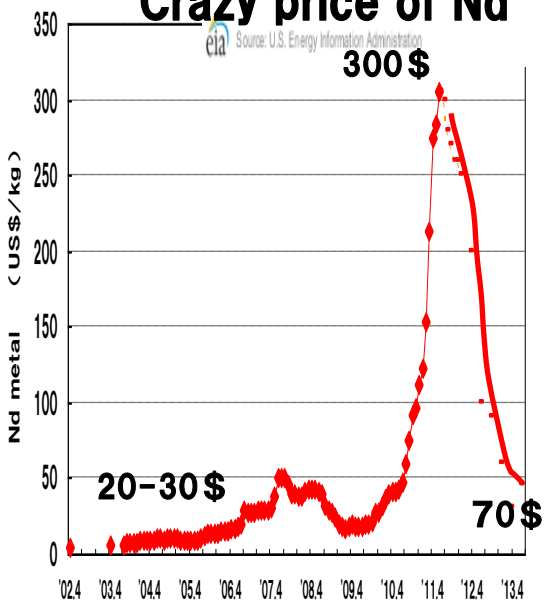
1） oil price Increases rom 25$ to 100$
2） Worry of Rare earth supply chain
due to monopoly production of China
Nd price : 30$/kg→300$/kg
Dy price : 10 times larger to Nd)



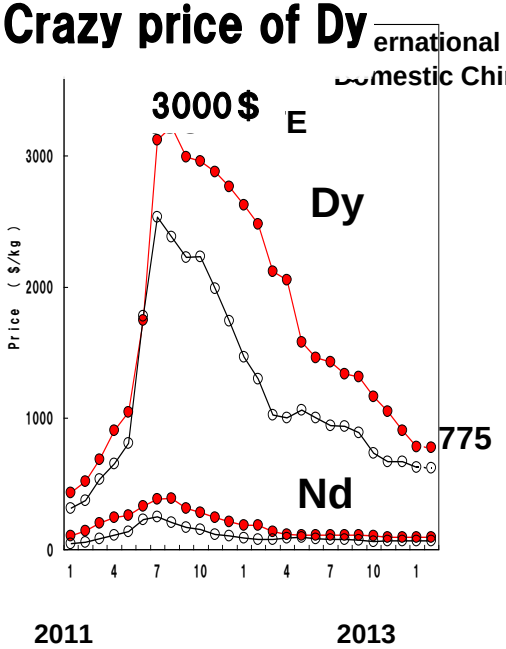
Location of rare earth mines



Crazy price of Nd



Crazy price of Dy



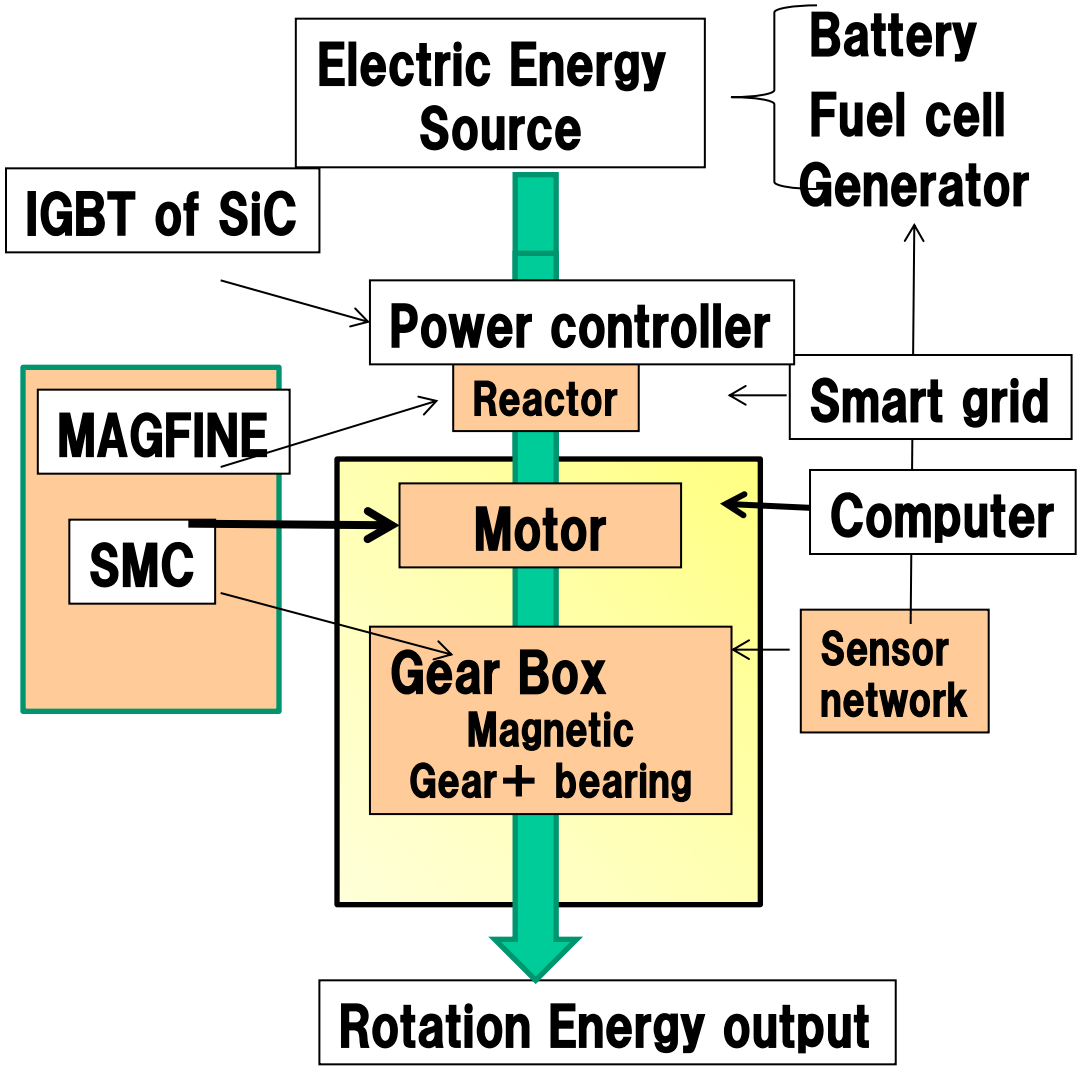
Improvement of the motor efficiency from the loss of 30% to 5% will be achieved by developing PM motor system with the high rotation speed

Trend of high rotation speed motor
- EV motor:: 6K⇒13.5K RPM⇒ 30K RPM
- Cleaner : 30K⇒100K RPM
- small motor 3K⇒30K RPM

How to achieve

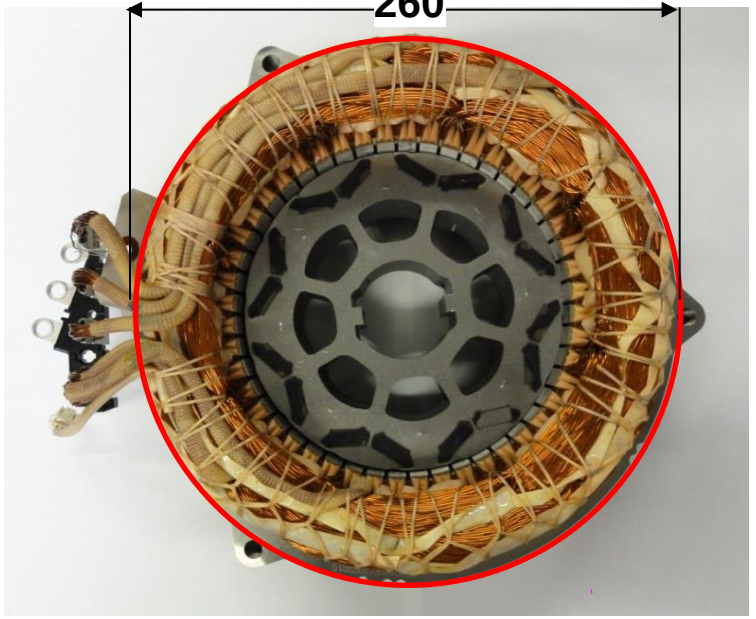
1)developmet of new materails
- magnett :: NdFeB anisotropivc bonded magnet)
- yoke :: SMC with nano cryatalline Fe powder

2) new design for PM motor with high rotation speed
- EV motor
- reactor
- magnetic gear



Next generation EV motor using 3rd generation MAGFINE

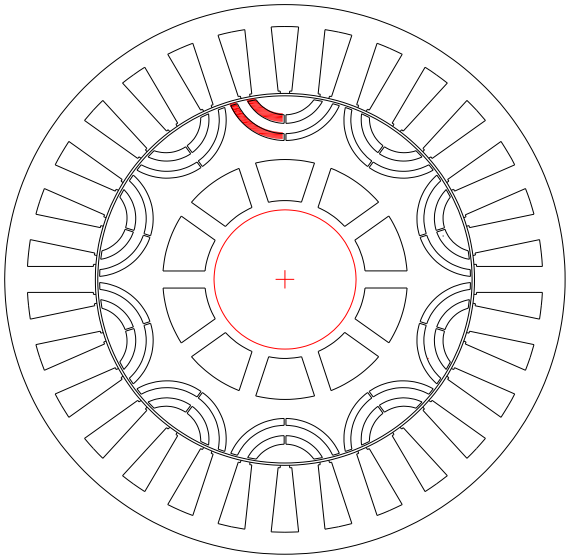
8pole-48Slot L 50mm



Ndsintered magnet : 766g
Cost of Nd+10Dy : 590$

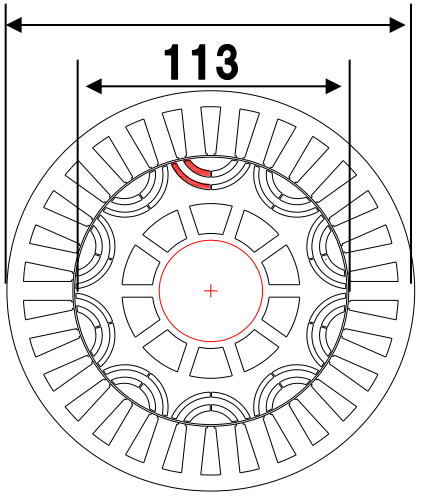
High freedom of motor design

10pole-30Slot L 75mm



Magfine : 1480g (1.9 times)
Cost of Nd+10Dy : 444$

Future motor with
Rotation speed of
30Krpm from15Krpm
Achieve 50% downsizing



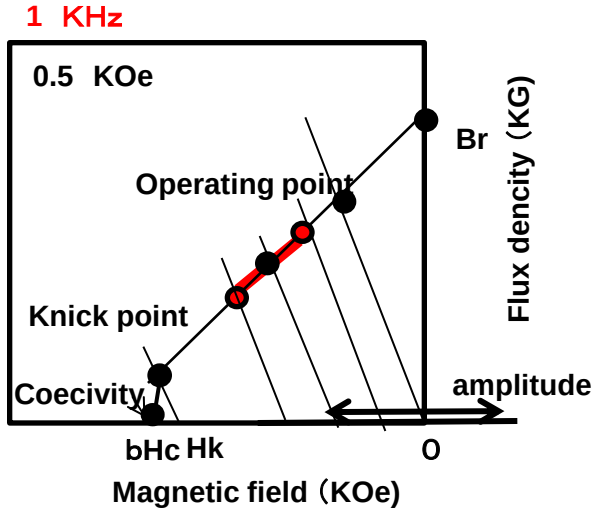
When 3rd generation Magfine will be developed,

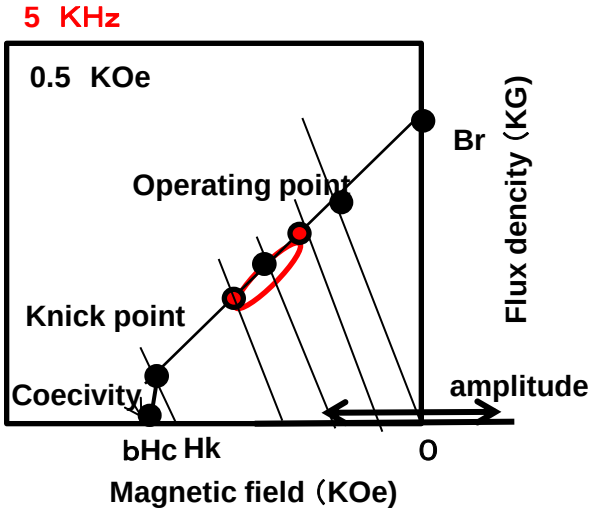
Future EV motor with High speed rotation must use 3rd generation MAGFINE instead of Nd sintered Magnet

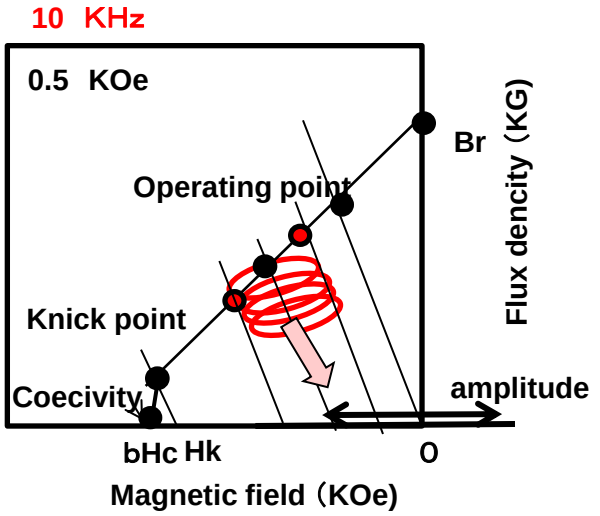
Demagnetizing of magnets under high frequency magnetic field

DC reverse field of 3KOe, 1KHz of ±300 Oe , 10 KHz of ±300 Oe

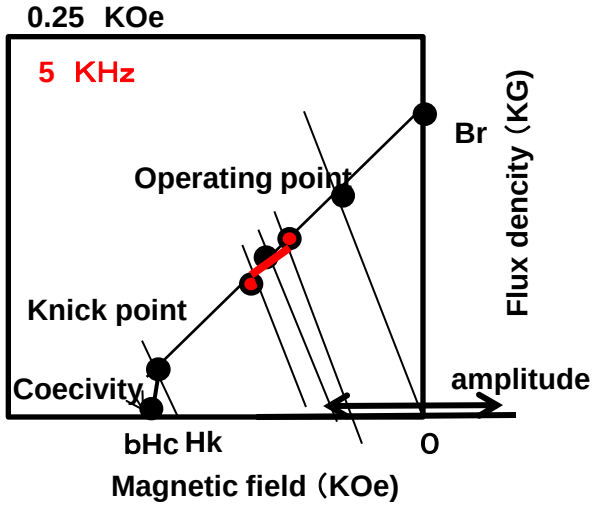
Dependency on the frequency

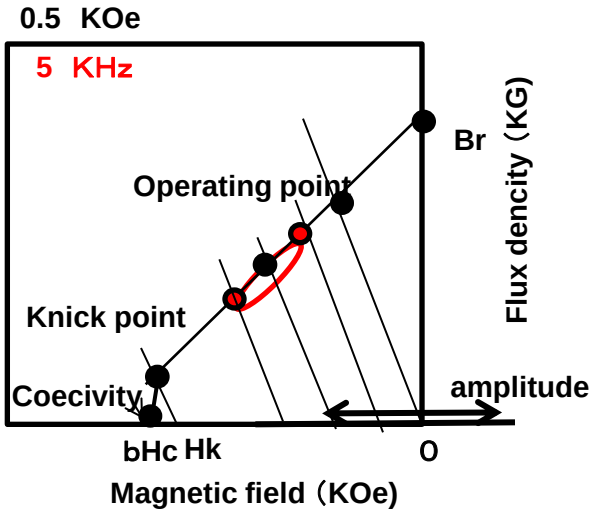


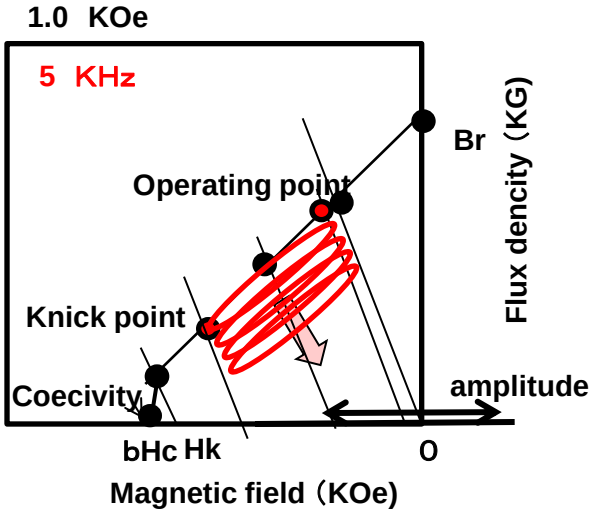




Dependency on the magnetic amplitude





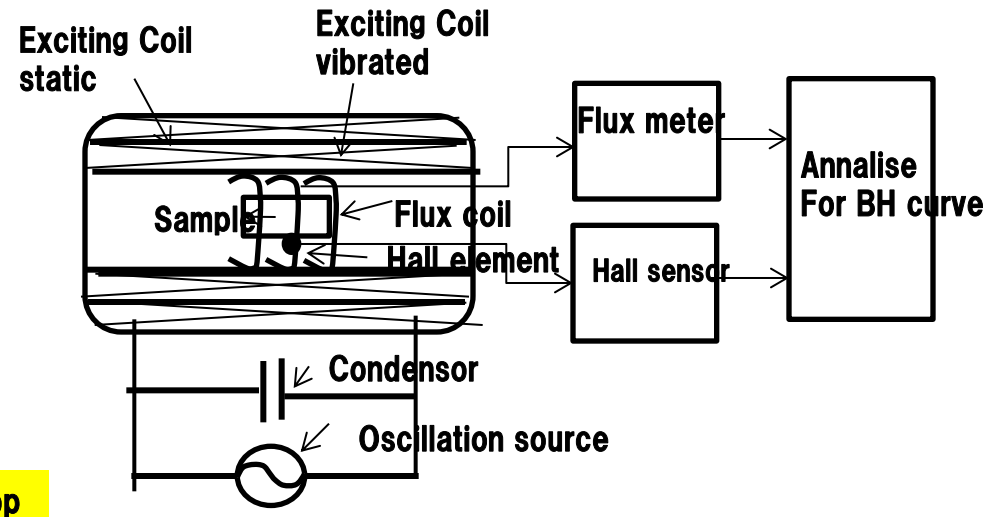


Method for measuring the demagnetizing under high frequency magnetic field

Equipment

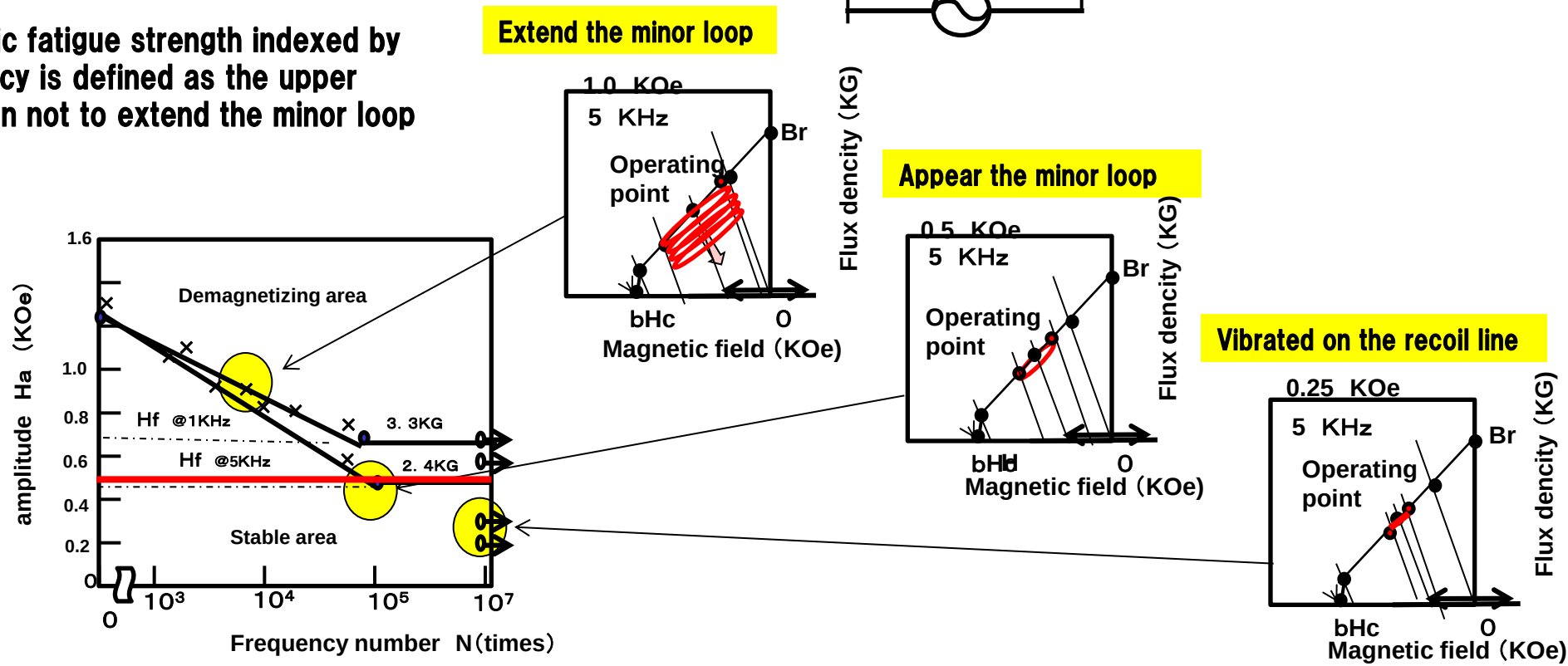
frequency 0～10KHz
amplitude 0～0.5KOe
Static field 0 ～4KOe

Sample size
:7mmΦ×7mm



Evaluation

Magnetic fatigue strength indexed by frequency is defined as the upper limitation not to extend the minor loop



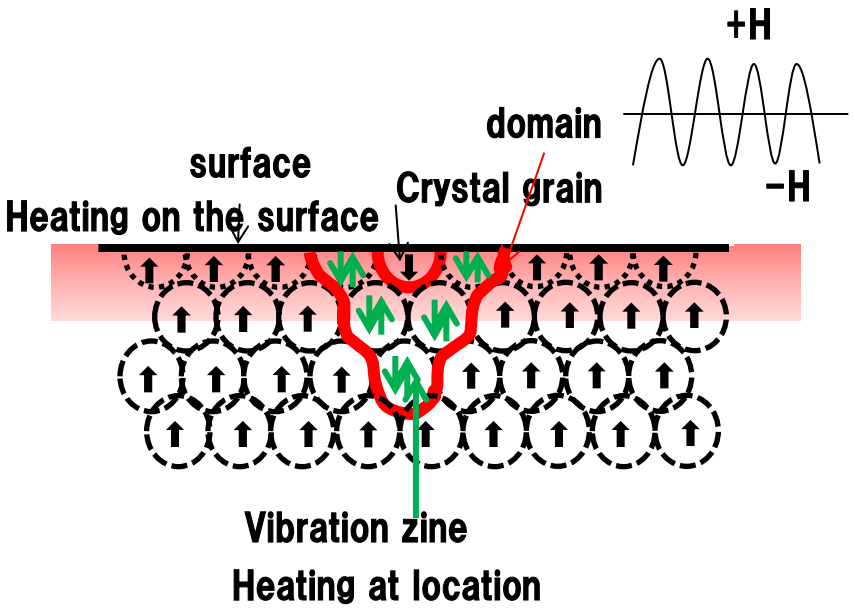
Discussion on the magnetic fatigue strength

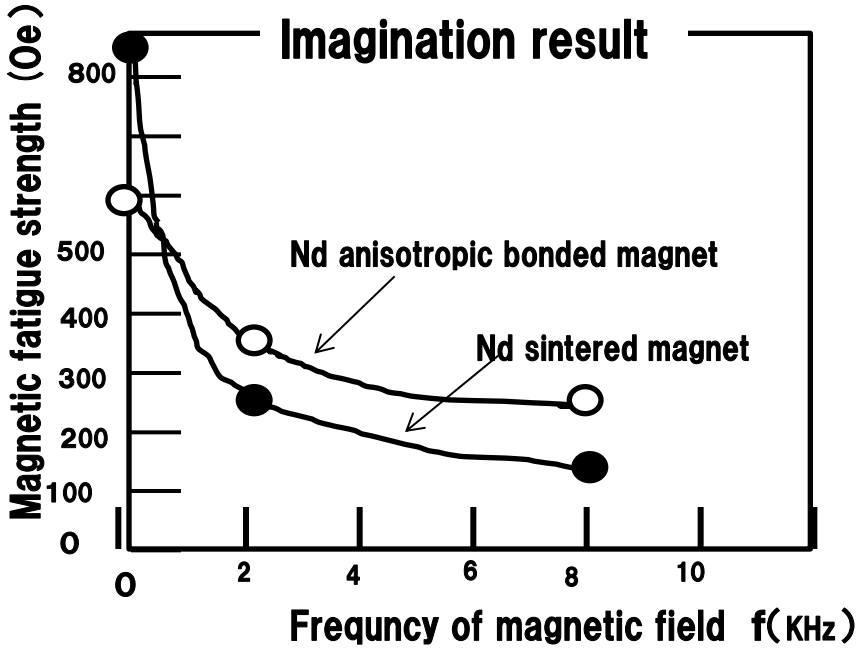
Why magnetic fatigue strength is smaller than coecivity ?

- Heated surface by eddy current makes reverse magnetic domain easy under weak magnetic field.
- The wall of reverse magnetic domain is vibrating by frequented field to make local heating zone.
- These heating extend the reverse magnetic domain to make minor loop growth.

Nd anisotropic bonded magnet is expected to have better magnetic fatigue strength than that of Nd sintered magnet because

- have 1000 times bigger resistance
- have 10,000 times smaller crystal grain size





Introduction to Energy Magnetics Study Group of MSJ

1）New strategy of MSJ is to challenge Energy field.
Target is to reduce Energy Loss from 30% to 5%

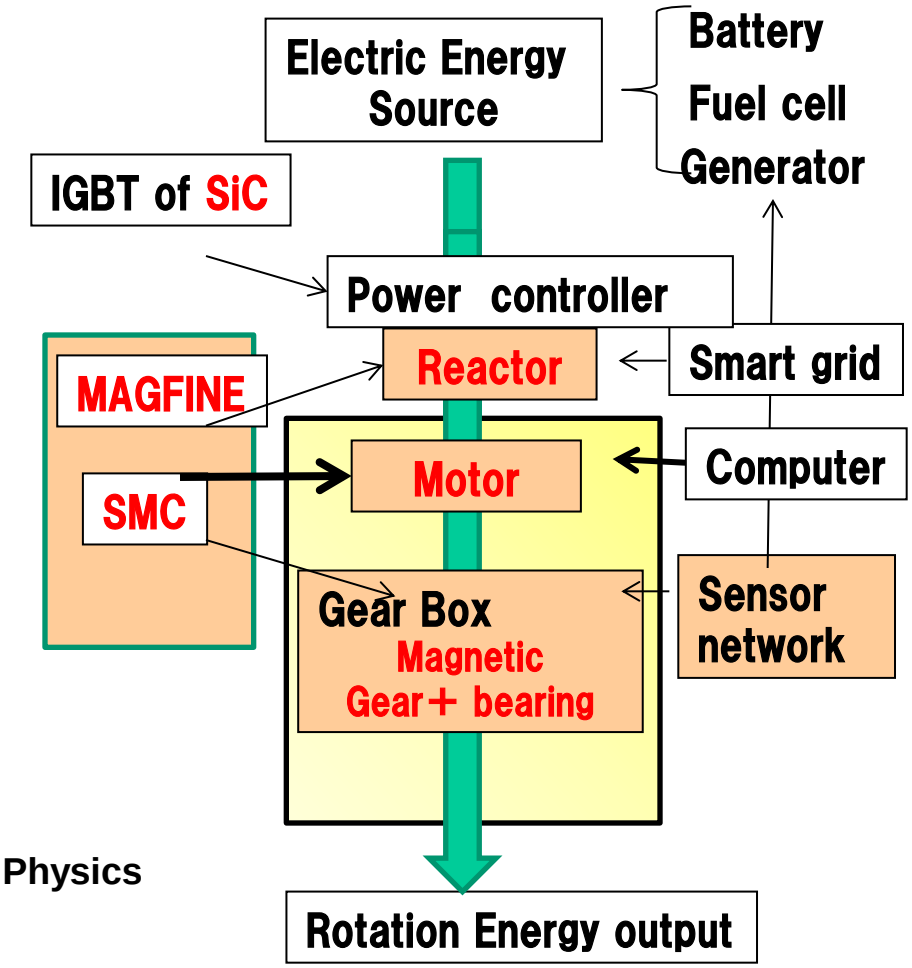
2）Progress
- Sep. in 2013 Symposium
- Dec.　establish the study group
- next June hold the meeting

3）topics
①develop new magnet and magnetic materail
improve basic performance and magnetic fatigue strength
②Mechanism by micro-magnetics analysis
③How to design high speed rotation EV motor
④make new design of Transformor
- magnetic gear and bearing
- reactor

⑤develop base R&D technique
- FEM analysis treated high frequency fenomina
- Equipment and deta base

⑥MEMS generator

4）co-operation
- Asian magnetic societies
- Electrical Engineers of Japan and The Japan Society of Applied Physics



Summary

（1）develop Dy free Nd anisotopic bonded magnet

（2）develop the mass production technology of Magfine
- d-HDDR furnace
- micro capsule
- press molding
- injection molding

（3）develop new designed motor using MAGFINE
- 75% weight reduction small motor for automotive use
- IPM motor using Dy free MAGFINE for compressor
- Axial motor for Electric bike

（4）Challenges to new research
- develop 3rd generation type of MAGFINE by achieving perfect anisotropy
- improve motor efficiency for developing high speed rotation motor
- research demagnetizing under high frequency strong magnetic field


Thank you for your attention
Mt. Fuji