

# The progress of Energy Magnetics to improve Motor Energy efficiency

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The energy supply problem becomes very serious day by day due to background that the world economy is getting huge by shifting from the developed nations economy of 700 million people to the global economy with 7 billion people. The manufacture of automobiles, home appliances and information devices is exploding twice after 20 years. In order to solve energy supply problem, new research into electric vehicles, energy efficient appliances, renewable energy, and the smart grid has been progressing rapidly. In automotive field, a lot of applications of motors expand by replacing from the engine, the hydraulic machines and small devices operation of which three categories on motors applications are shown in Fig.1.

MSJ held the first Energy Magnetics Symposium in 2013 at Sapporo to discuss on the challenges of magnetics technology to solve the energy supply problem and established the study group working on the Energy Magnetics (EMSG) in the beginning of this year. The EMSG held the first meeting and plans to organize the second EM symposium focusing on how to improve the efficiency of PM motor by the means of high rotation motor design

Energy Magnetics on PM motor consists of the reactor to increase the electric voltage, the motor to transfer the electric energy to kinetics energy through the magnetic energy and magnetic transmission to use magnetic gear and bearing. These systems in Fig.2 request high performance magnets and magnetic materials. The most important target must be how to improve the energy efficiency of EV motor system from the loss of 30% at present to the loss of 5% in future.

Nowadays The EV traction motors have been developed to make various designs using the suitable magnets shown in Fig. 3. The kinds of IPM motor designs have been proposed to have one layer, two layer and 4 layers of magnet as well as SPM motor design, spoke type motor and axial motor design. These developments have been challenged by some kinds of magnets which are Nd sintered magnet, Nd anisotropic bonded magnet and ferrite magnet.

The rotation speed of the EV motors increased from 6000rpm to 12000rpm to achieve the improvement in the efficiency and the motor weight. However the more increase of the speed must meet the heating up problems for Power control unit caused by silicon on-resistance, the heating up of Nd sintered magnet caused by eddy current and transmission caused by frictional heat. Power control unit will be solved by the development of SiC IGBT instead of Si and the frictional heat of transmission will be solved by the development of magnetic gear.

The heat up of Nd sintered magnet under IPM motor operation is caused by vibrating magnetic field with the frequency of 200Hz by rotation speed of 200Hz, of 1200Hz, 2400Hz, 3600Hz, 4800Hz by slot harmonics and of 5400Hz, 10800Hz by carrier harmonics shown in Fig.4. The magnet is damaged to fall into demagnetizing. Next generation type IPM motor must be operated under more high speed of 30Krpm controlled by more high carrier frequency of 20KHz. The heating up problem of Nd sintered magnet must become serious to be impossible to use.

EMSG makes first challenge to solve this magnet problem by the development of Nd anisotropic bonded magnet free from heating up problem caused by eddy current, by the development on the measuring equipment to examine the magnetic fatigue coecivity against the vibrating magnetic field and by establishment of the database on the magnetic fatigue coecivity of various magnets and by the research on how to make nucleation of reverse magnetic domain and its expansion using micro magnetics analysis technique. And Final target must be to develop the computer simulation technique to make design on high speed motor.

EMSG holds the second Energy Magnetics Symposium in the annual congress of MSJ and will invite 14 experts to introduce the basic research progress on the magnetic fatigue coecivity caused by vibrating magnetic field and the development on the bonded magnet and the status of EV motor development.

In this symposium, I hope that the magnetics researchers will have interest in the challenges of Energy Magnetics to solve the energy supply problem and join to EMSG project.

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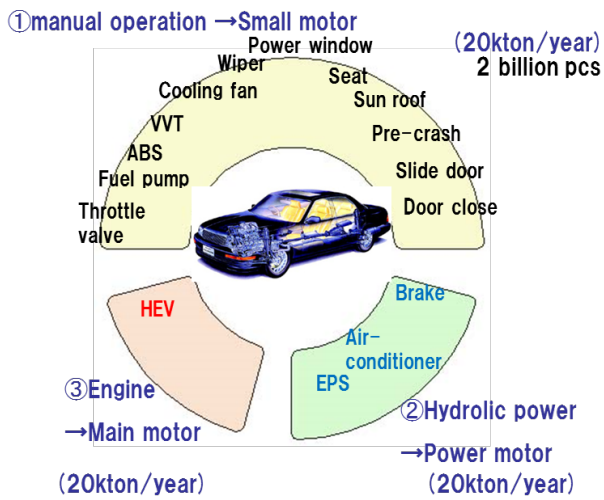


Fig.1 automotive use motors replacing from Engine, hydraulic system and manual operation.

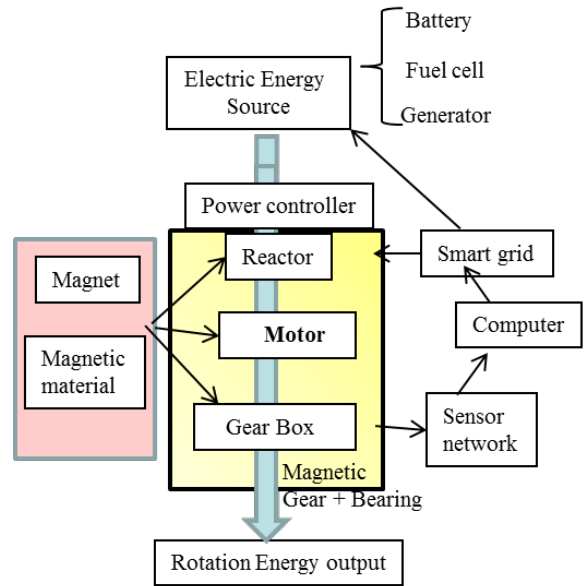


Fig.2 Energy Magnetics challenges to improve Efficiency by Advanced Magnet and Magnetic Materials

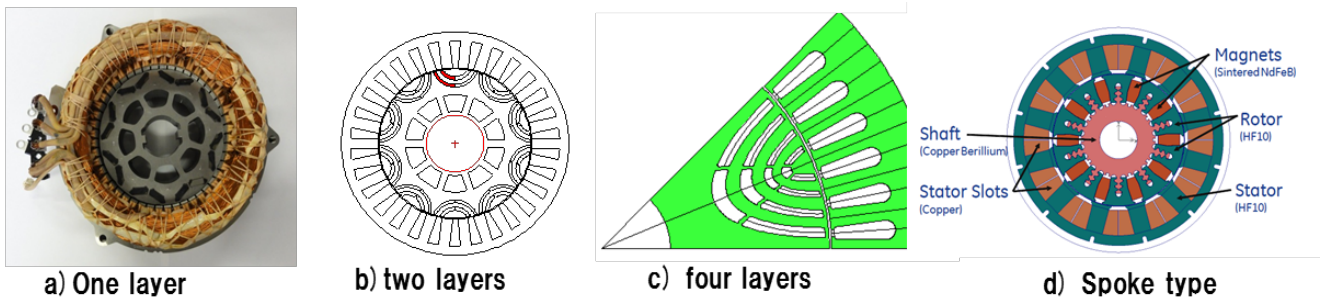


Fig.3 some IPM motor designs for EV traction motors.

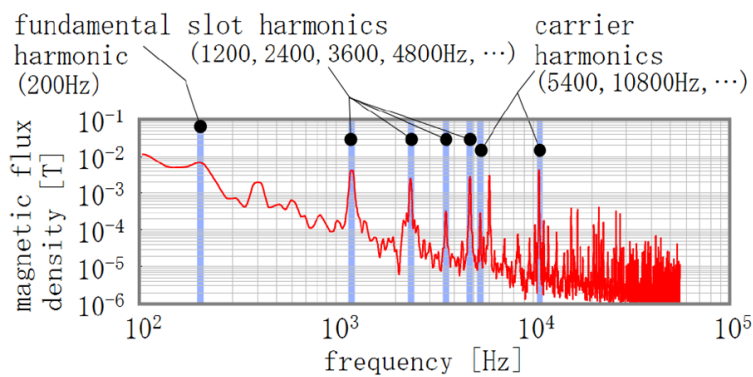


Fig.4. Result of frequency analysis

# Advanced Magnetic Material Requirement for Higher Efficient Electrical Motor Design

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In order to realize the energy saving society, higher efficient electrical apparatus is required. Magnetic material is used in it to obtain higher magnetic flux density <sup>1)</sup>.

3 kinds of electromagnetic theory are used in the electromagnetic apparatus <sup>2)</sup>. The one is Faraday's law as shown in the next equation. A transformer is considered to be its application.

$$\text{rot}\vec{E} = -\frac{\partial\vec{B}}{\partial t}$$

The next is Maxwell stress as shown in the next equation. An electrical motor or generator is considered to be its application.

$$\vec{F} = \iint_{\text{ThinSteelPlate}} [\vec{T}_m] \cdot \vec{n} dS, \text{ here } [\vec{T}_m] = \frac{1}{\mu_0} \begin{bmatrix} \frac{1}{2}(B_x^2 - B_y^2 - B_z^2) & B_x B_y & B_x B_z \\ B_y B_x & \frac{1}{2}(B_y^2 - B_z^2 - B_x^2) & B_y B_z \\ B_z B_x & B_z B_y & \frac{1}{2}(B_z^2 - B_x^2 - B_y^2) \end{bmatrix}$$

The last is magnetic energy as shown in the next equation. A reactor in an electrical circuit is considered to be its application.

$$E = \int \vec{B} \bullet d\vec{H}$$

High magnetic flux density is usually obtained by the magnetization as shown in Fig. 1. The magnetization is derived by external magnetic field, and it is derived from a current which flows in magnetic coil within the electrical apparatus. The current is derived from a voltage in electrical circuit. The variable voltage and variable frequency are used in the electrical motor or smart grid, which are expected to be a future technology, and are realized by power electronics technology.

Usually, magnetic properties of magnetic material are measured by linear amplifier excitation with no harmonics components as shown in Fig.1. It is decided by JIS or IEC <sup>3,4)</sup>. However, an electrical circuit based on power electronics is applied to the electrical apparatus to realize the variable voltage and variable frequency. So the different magnetic properties from linear amplifier excitation are required for the 3 kinds of electromagnetic apparatus.

The electrical motor is usually excited by PWM inverter to obtain the variable velocity drive system. So the magnetic properties of magnetic material are shown in Fig.3. A lot of minor loops, which are derived from the carrier frequency of PWM inverter excitation, are observed in the major loop of the fundamental frequency. Iron loss becomes about 30 - 50% large <sup>5)</sup>.

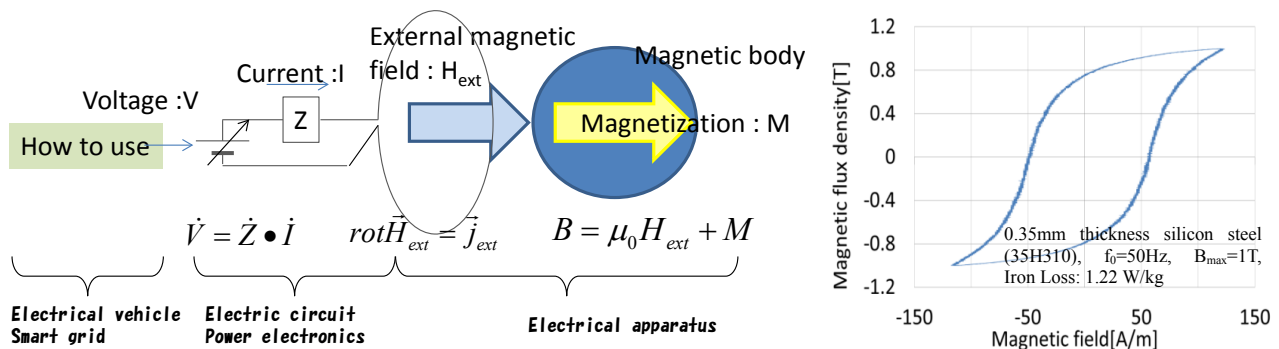


Fig. 1 Magnetic material application for electrical apparatus. Fig.2 Magnetic hysteresis curve excited by linear amplifier.

The reactor is often used in the chopper circuit, where electrical energy from power source storages in some period of chopping carrier frequency. So the magnetic properties required for the reactor are only a small minor loop within the major loop.

Future transformer is expected to be operated in high frequency, which is possible to be realized by power electronics technology, in order to become small to be a one-100th or so<sup>6)</sup>. So the required magnetic properties for the high frequency transformer are shown in Fig. 5. High frequency as well as high magnetic flux density is required.

Permanent magnet is also required for the dynamics magnetic properties in being applied to PM motor<sup>7)</sup>. Because of space harmonics components and time harmonics ones, which are derived from the slot shape of stator core and the PWM inverter excitation, harmonics components of magnetic fields are supplied to the permanent magnet. They increase the loss of the electrical motor.

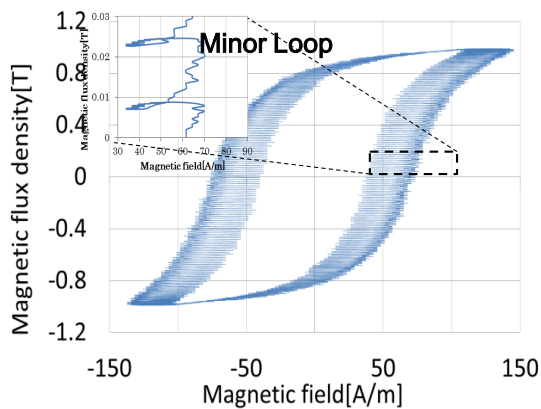


Fig. 3. Required magnetic hysteresis curve excited by PWM inverter (35H310, PWM inverter excitation ( $m = 0.8$ ), Iron Loss: 1.65 W/kg)

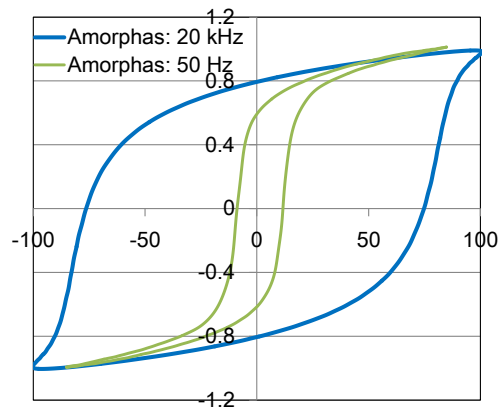


Fig. 5. Required magnetic hysteresis curve applied to high frequency transformer. (Amorphous, 2605HB1, Thickness: 23 $\mu$ m,  $B_{max}=1.0$  %,  $f_0=50$  Hz, 20 kHz)

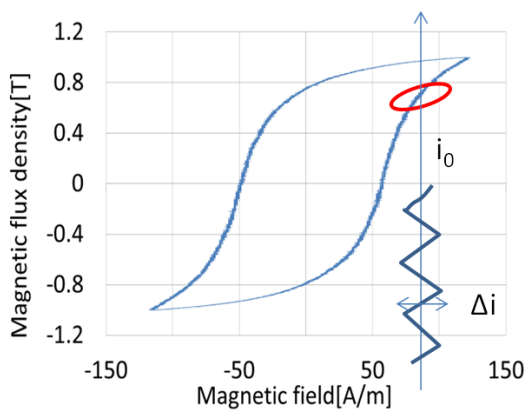


Fig. 4 Required magnetic hysteresis curve applied to reactor in chopper circuit.

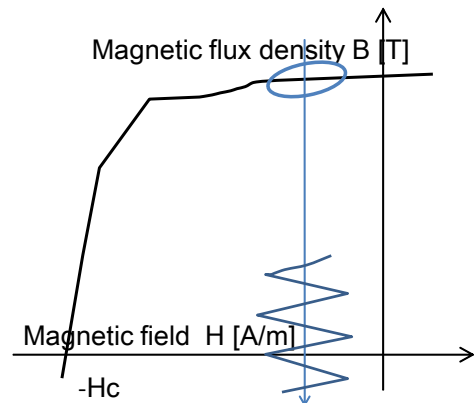


Fig. 6 Dynamic magnetic hysteresis curve of permanent magnet used in IPM motor

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## Measurement of magnetic flux density on permanent magnet surfaces for IPM motor

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### 1. Introduction

The purpose of this study is to establish a technique on measuring magnetic flux density when an Interior Permanent Magnet (IPM) motor operates and to clarify higher-harmonic wave component causing a factor of generating an eddy current loss of permanent magnet.

The eddy current is generated inside of a permanent magnet by variable magnetic flux when the motor operates. This heating loss caused by the eddy current may become factors of degradation of conversion efficiency and thermal demagnetization.

### 2. Measuring technique

Fig.1 shows the structure of the measuring technique. It is constructed such that a signal amplification circuit is installed on the rotor, extracting amplified signals from a magnetic flux density sensor to the fixed side by a slip ring. The sensor is mounted on a magnet surface. The sensor measures AC component of magnetic flux density generating eddy current loss. Further, the magnet surface temperature is measured simultaneously using a thin film temperature sensor.

Fig.2 shows the construction of the mounted magnetic flux density sensor. For the search coil layer, patterning is conducted on the upper and lower surfaces of a flexible sheet of polyimide and the layer is electrically connected with a through hole. Both surfaces are covered with insulating layers, and the total thickness of the sensor is 74  $\mu\text{m}$ .

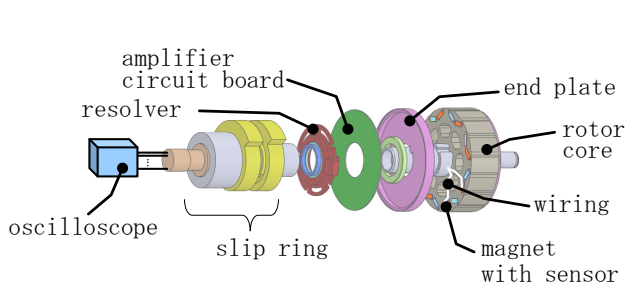


Fig. 1. Measurement setup

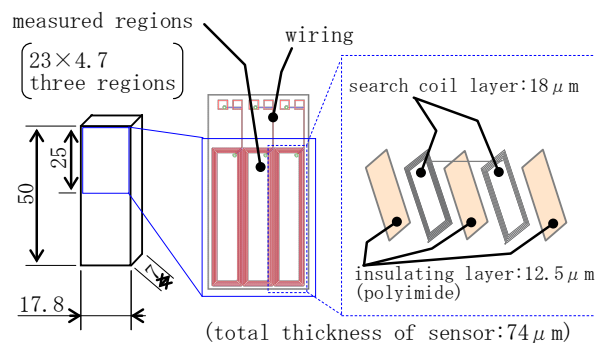


Fig. 2. Magnetic flux density sensor

### 3. Measurement result

Table.1 shows measuring conditions. The measurement of magnetic flux density of the magnet surface is conducted under PWM control by a general purpose inverter intended for the IPM motor with 4 pole pairs and 48 slots.

Fig 3 shows a time waveform for the measured magnetic flux density, and Fig 4 shows the frequency analysis results. Each component of the fundamental harmonics, slot harmonics and carrier harmonics of the magnetic flux density has been quantified. Assuming that the eddy current loss for the permanent magnet is proportional to the square of the magnetic flux density and the square of the frequency, it is estimated that the eddy current loss by the carrier second harmonic components (10800 Hz) accounts for an overwhelming 67% of the total.

Table.1. Measurement conditions

rotation speed [rpm]	3000
torque [N·m]	40
carrier frequency [kHz]	5.4
inverter input voltage [V]	650
magnet temperature [°C]	39

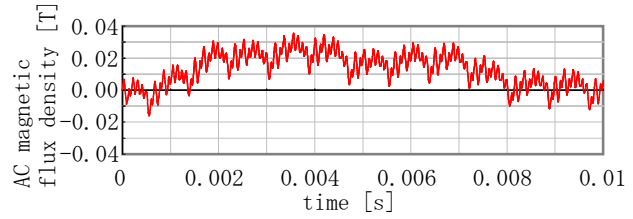


Fig.3. Waveform of AC magnetic flux density

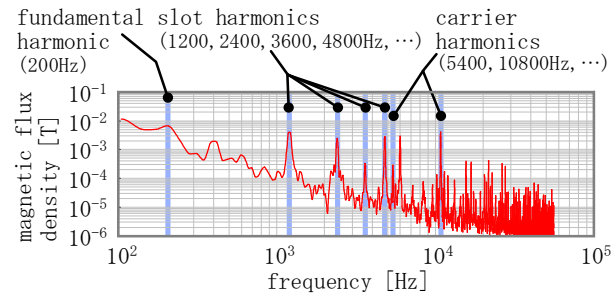


Fig.4. Result of frequency analysis

#### 4. Summary

We have established the technique for measuring magnetic flux density on magnet surfaces by using a magnetic flux density sensor when the motor operating. This technique enables us clarify higher-harmonic wave components of magnetic flux density as a factor in the generation of eddy current loss in permanent magnets.



# Behavior of a permanent magnet used for a high efficiency motor under a high frequency magnetic field

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The development of high efficiency motors is accelerating as energy problems become more serious. Many magnetic materials are used in high efficiency motors, and the demands on the properties of the magnetic materials are changing greatly by the use of power electronics<sup>1)</sup>.

For example, in soft magnetic materials such as electrical steel, increases in iron losses of 20% to 60% caused by the inverter excitation have been reported<sup>1)</sup>.

On the other hand, hard magnet such as permanent magnets, as the electric resistivity of rare earth sintered magnets is very low in comparison with ferrite sintered magnets, the eddy current loss on the surface of the magnet can not neglect. As a result, the measurement and numerical analysis of losses under AC magnetic fields based on NdFeB sintered magnets has been studied<sup>2), 3)</sup>.

With recent high speed motors, larger magnetic fields are applied to the magnet and the frequencies of those fields are higher, and as a result the problem of magnet losses will become more important.

However, up to now the studies of these problems were restricted to estimates of magnet losses, while studies of their magnetic phenomena or the behavior of the magnets have not been carried out. In order to study the magnetic behavior of magnets under high frequency fields, we have started up the Energy Magnetics Special Meeting, and intend to study the issues in depth.

Among these issues, a method for magnetic measurement under the high frequency magnetic field will be a problem.

For understanding the magnetic behavior of magnets, the DC BH tracer has been the main tool to date. Therefore, we plan to develop an experimental device and to measure magnetic behavior using this device under a high frequency magnetic field. Fig.1 is a conception of the device being planned now.

It is planned to produce a frequency of 10kHz and magnetic field of 330Oe by using a pulse electric current in a multilayered winding solenoid coil. In this presentation, we report the outline, performance, and problems of the high frequency magnetic field emitting device, and actual measurement results to clarify the types of issues facing this development.

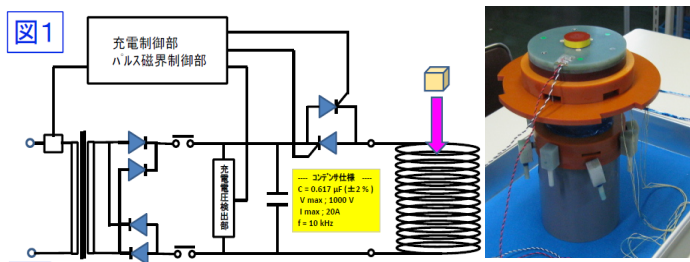


Fig.1 The concept of high frequency magnetic field device.

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## FEM Analysis of Hysteresis Using a Thermodynamic Model

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Thanks to great advances in computation technologies and computer performance, today FEM analysis can handle models that fairly closely approximate actual magnetic fields. However, modeling of magnetic materials is almost always carried out by considering only isotropic nonlinear characteristics; no general method has been established that addresses anisotropic nonlinearity and hysteresis. Highly accurate analysis of magnetic fields requires faithful reproduction of magnetic materials' magnetization characteristics. Since needs for highly accurate analysis of magnetic fields are expected to increase in the future, faithful modeling of such characteristics is an urgent matter.

The magnetic characteristics of magnetic steel sheets can be measured highly accurate with the aid of today's technologies. Given this fact, we examined anisotropic nonlinear magnetic characteristics in detail. Our results suggest that the magnetic characteristics of magnetic steel sheets can be formulated from a thermodynamic perspective. On the basis of this suggestion, we successfully reproduced the magnetic characteristics using the free energy of magnetic materials. However, free energy, which is a state quantity determined from physical quantities (e.g., magnetic flux density and temperature), seems difficult to use to address history-dependent characteristics such as hysteresis.

By contrast, the spontaneous magnetization of ferromagnetic materials can be formulated thermodynamically on the premise that a magnetic material has multiple possible local minimum values of free energy.

Since spontaneous magnetization is thought to contribute substantially to the occurrence of hysteresis, it seems history-dependent characteristics can be formulated on the assumption that when in thermal equilibrium, magnetic materials are not in a state having the minimum value of free energy but rather in a state having one of the local minimum values. However, formulation of hysteresis of actual magnetic materials requires the existence of free energy having a considerably complex form; such a complex free energy form is inappropriate for numerical modeling. Therefore, we take the following two-step approach to hysteresis analysis.

First, free energy is smoothed by removing local stabilization points; after smoothing, the equilibrium state of magnetic materials can be determined from the minimum value of free energy.

Next, an irreversible process as seen in frictional phenomena is introduced in order to take the influence of local minimization into consideration; consequently, magnetization characteristics can be treated as a history-dependent process. The effect compared to friction can be formulated by introducing a quantity called the hysteretic magnetic field, which corresponds to frictional force.

The free energy in question is a function of magnetic flux density and temperature. Accordingly, variable transformation from magnetic flux density to magnetic field intensity allows us to introduce a thermodynamic potential similar to the Gibbs free energy. In a state with a fixed magnetic field at a fixed temperature, the magnetic materials' thermodynamic potential takes its minimum value.

This approach enables us to formulate finite elements for numerical analysis by applying the variational method to the thermodynamic potential.

Compared to conventional FEM, which is based on the weighted residual method, this FEM, which is based on the variational method, offers substantial advantages in that it allows us to address spontaneous magnetization and hysteresis in a simpler manner.



# Magnet Behavior in High Frequency Field Using Micromagnetic Simulator

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## 1. Introduction

Bonded Magnet is one of the most important and useful permanent magnets industrially. It enables to achieve complex shapes and is superior in strength to other kinds of magnets. Above all, NdFeB anisotropic bonded magnet is used for motors of automobiles and magnetic hard disk drives and sensors utilized in a wide variety of products<sup>1)</sup>. It will be expected for motors of hybrid vehicles (HV) and electric vehicles (EV) to realize smaller size and higher rotational speed. However, we have to pay attention to ‘magnetic fatigue’ of the magnet itself. Motors will be applied high frequency field with a maximum frequency of 10 kHz and average amplitude of 40 kA/m (0.5 kOe) at high temperature in near future. It will also be applied a static field of approximately 240 kA/m (3 kOe). As a result, high frequency field and thermal stress might demagnetize NdFeB anisotropic bonded magnetization. It is called ‘magnetic fatigue’.

In this study, magnet behavior in high frequency field and high temperature was simulated using micromagnetics simulator. A simple grain model and basic magnetic characteristics were assumed, and behaviour of magnetic fatigue was simulated.

## 2. Micromagnetics simulator

It is important to make sure magnet behaviour in high frequency field in order to calculate a dynamic magnetic reversal process. The simulator is based on Landau-Lifshitz-Gilbert equation as follows;

$$\frac{d\mathbf{M}}{dt} = -\gamma(\mathbf{M} \times \mathbf{H}_{eff}) + \frac{\alpha}{M_s} \left( \mathbf{M} \times \frac{d\mathbf{M}}{dt} \right). \quad (1)$$

$\mathbf{M}$  is the magnetization and  $\mathbf{H}_{eff}$  is the effective field which is the sum of external fields, static field, anisotropy field and exchange field. A stochastic thermal field was, however, not considered since grains could be regarded as thermally stable because of large volumes and high anisotropy.  $\gamma$  is the gyromagnetic ratio, and  $\alpha$  is the damping factor.

Magnetic characteristics at room temperature are shown in Table 1. Intergrain exchange energy was assumed as 0, because non-magnetic grain boundary isolates grains perfectly. The saturation magnetization ( $M_s$ ) was assumed to decrease according to the Brillouin function, and the anisotropy constant ( $K_u$ ) was  $k \times M_s$  ( $k$ : coefficient depends on temperature) to fit an experimental data.

Fig. 1 shows a grain model. Each grain is a hexagonal prism with a grain size of 200 nm, and it is not divided into small cells since the grain diameter is smaller than the critical diameter in between single domain and multidomain, and then grains were assumed to reverse according to the Stoner-Wohlfath model.

## 3. Results and discussions

In studying magnetization behaviour in the high frequency, damping factor  $\alpha$  is one of the indispensable parameters. When the frequency is high, precession of the magnetization depends on  $\alpha$  and effects on magnetization reversal. Therefore, we looked through the damping constant  $\alpha$  dependence of magnetization behavior,

M-H loops with different temperatures are shown in Fig. 2 (a). While the temperature increases the magnetization decreases, but the shapes of the M-H loops were not changed. M-H loops with different damping factor  $\alpha$  at 400 K are shown in Fig. 2 (b). M-H loops are almost equivalent between both damping factors. Fig. 3 shows the cycle of the frequency dependence of magnetization behaviour applying a high frequency field. Damping factor  $\alpha$  was changed from 0.01 to 1. X-axis is the cycle of the frequency, namely elapsed time. An external field ( $H_{ext}$ ) was  $-0.33 \times H_k$ , where  $H_k$  is an anisotropy field. The frequency was 10 kHz with the amplitude of 40 kA/m and the standard deviation of C-axis

orientation distribution ( $\sigma_{C\text{-axis}}$ ) was 5 degree. The temperature was 400 K. From this graph, though the high frequency field keeps oscillating the magnet, magnetization seems to be stable at first sight, but magnetization oscillates slightly as shown in Fig. 3 (b) and (c). The cycle of oscillation is equal to that of the high frequency field. It was also found that magnetization decreased with decreasing  $\alpha$ . Therefore, If  $\alpha$  is small, the external field causes to demagnetize the magnet.

Table 1 Magnetic characteristics at 293 K

$M_s$ (T)	$K_u$ (MJ/m <sup>3</sup> )	$\sigma K_u / \langle K_u \rangle$ (%)	$\langle H_k \rangle$ (kA/m)	Intergrain Exchange (J/m <sup>2</sup> )
1.61	4.9	0	6077	0.0

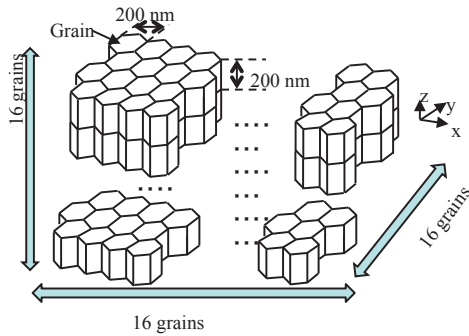


Fig. 1 Grains are hexagonal prism with grain size of 200 nm

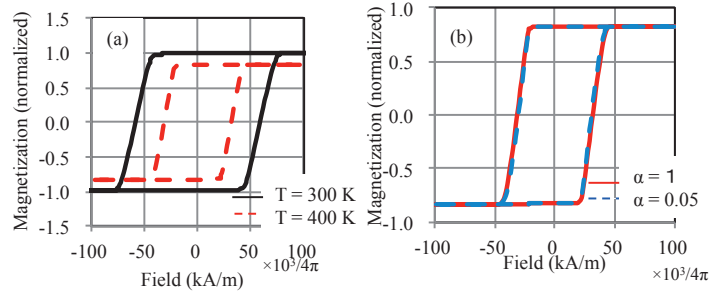


Fig. 2 (a) Temperature dependence of M-H loop at  $\alpha$  of 1 and (b)  $\alpha$  dependence of M-H loop at T of 400 K.

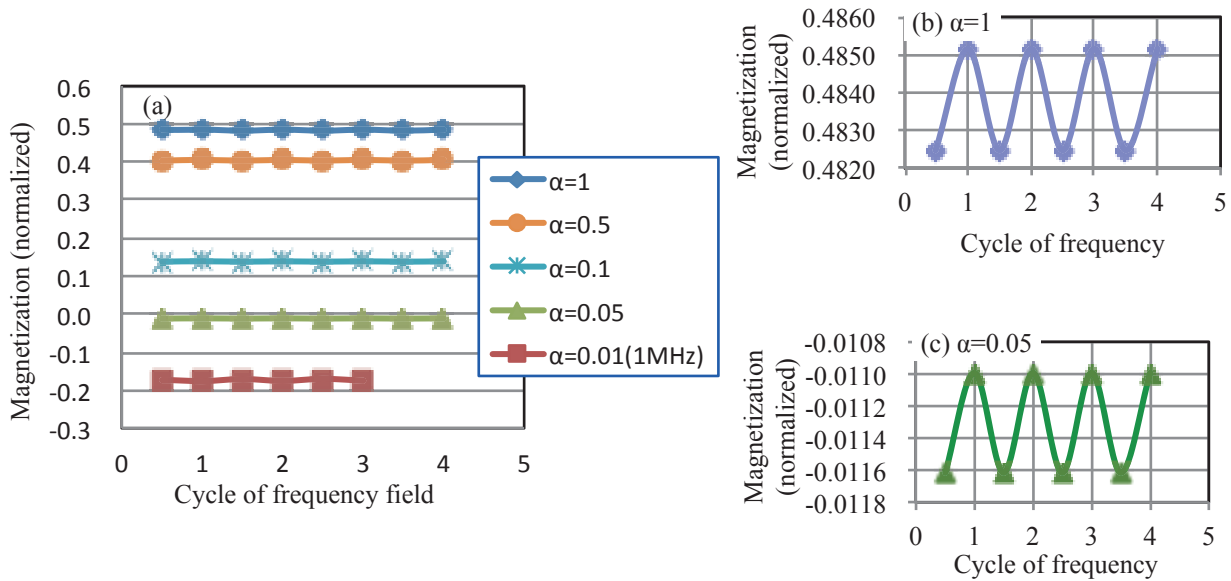


Fig. 3 Damping factor  $\alpha$  dependence of magnetization behavior at high frequency field (a)  $\alpha = 0.01 - 1$ , (b) enlarged graph at  $\alpha$  of 1, and (c) enlarged graph at  $\alpha$  of 0.05

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# Development of Dy free NdFeB anisotropic bonded magnet with high performance

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## 1. Introduction

The need for lighter motors in increasing automobile fuel efficiency is high and NdFeB anisotropic bonded magnets with high magnetic performance and freedom of design are effective in realizing motor size and weight reductions. The magnetic powder used in NdFeB anisotropic bonded magnets is manufactured by the d-HDDR process utilizing the high temperature reaction between NdFeB and hydrogen<sup>1)</sup>. This bonded magnet has five times higher magnetic force than standard ferrite one and its near-net-shape characteristic enable easy application to motors. The anisotropic bonded magnet has been used for downsized / lightweight seat motors. The coercive force was improved by grain boundary diffusion treatment of Nd-Cu-Al alloy into NdFeB magnetic powders after d-HDDR treatment<sup>2)</sup> instead of Dy addition. This alloy forms Nd-rich grain boundaries and isolates the crystal grains after diffusion process. As a result, it intercepts the magnetic interaction between the crystal grains and leads to increase of the coercive force up to 20kOe. Currently, this anisotropic magnetic powder was molded to bonded magnet with high performance by compression molding and injection molding magnet with mixture of several resins.

## 2. Compression molding magnet

The magnetic properties of NdFeB bonded magnet was easily decreased due to oxidation under using atmosphere. We successfully developed a magnet powder coating technology leading to improved reliability of the bonded MAGFINE magnets towards an automotive specification level of flux loss below 5% after 1000h exposure at 150deg.C. This coating layer was created on the magnetic powder surface with thickness of approximately 200nm (Fig.1). This powder has good stability under the oxidation atmosphere compared to conventional MAGFINE powders without coating.

During the compression molding, the NdFeB magnetic powders were pressed under high pressure of 9ton/cm<sup>2</sup> and induced the damage of powder cracking. This leads to degradation in magnetic performance, in particular the squareness ratio. A compound made of d-HDDR magnet powder coated with resin, fine SmFeN powder and lubricant can produce molded blocks with a high density of 6.0 g/cm<sup>3</sup> at a low molding pressure of 1 ton/cm<sup>2</sup>. In addition, by enabling molding at a low pressure, the loss of squareness of the magnet powder was reduced to 0.5%. From the above, through kneading and the addition of fine powder and lubricant, the surface treatment of d-HDDR magnet powder achieved high density magnets at a low molding pressure and a compound capable of controlling the reduction in loss of squareness(Fig.2).

## 3. Injection molding magnet

Two type resins of Polyamide 12 (PA12) and Poly Phenyl Sulphide (PPS) are used for anisotropic injection-molding magnet of MAGFINE. The PA12 type injection-molding magnet has good remanence Br up to 8.7 kG, however, low reliability under high temperature over 120deg.C. On the other hand, the PPS-type magnet has low Br up to 7.4 kG, however, high reliability under high temperature and some solvents. This difference is caused from physical characteristics of binder resin such as resin polarity, melting viscosity, and so on. The authors selected the polar-type polymer with higher melting point compared with polyamide 12 and similar viscosity as polyamide 12 in order to develop the injection-molding magnet with both high performance and high reliability at high temperature. The alignment ratio of magnetic powder in magnet was increased under the increase of resin polarity. During magnetic powder alignment, the melted resin was expanded to magnetic powder homogeneously due to high affinity with magnetic powder surface. It decreased the powder surface friction with magnetic powders and led to high alignment ratio. From this, we successfully developed injection-molding magnet with Br=8.3kG by using selected polymer binder (Fig. 3).

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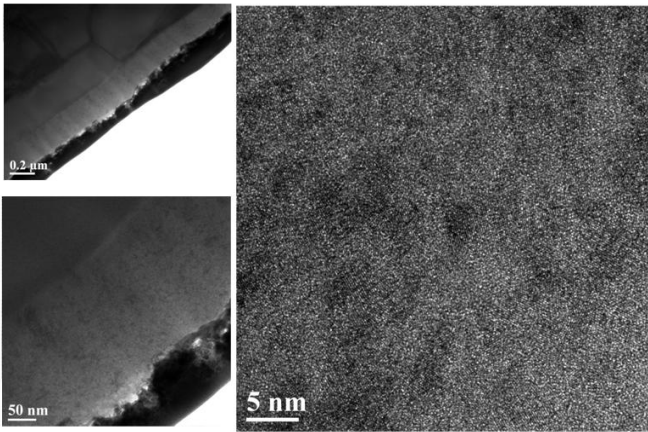


Fig.1. TEM observation results of magnetic powder surface with surface coating.

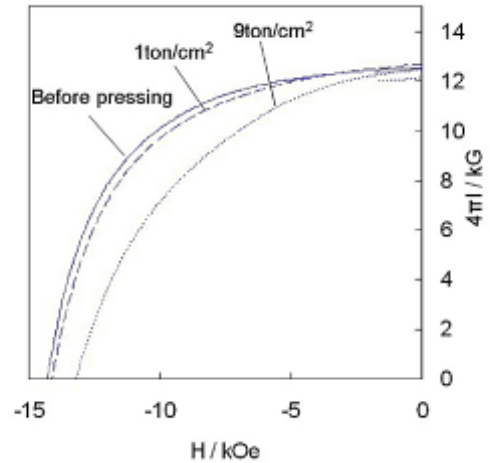


Fig.2. Demagnetization curves before and after molding.

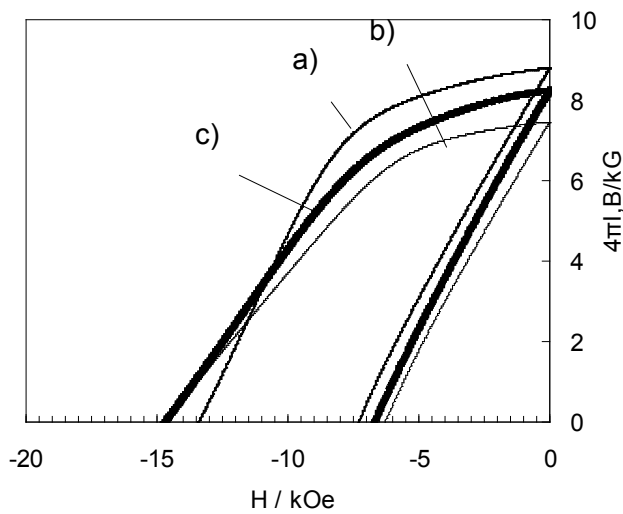


Fig.3. Demagnetization curves of injection molding magnets with a) PA12 binder, b) PPS binder, and c) selected-polymer binder.

## Recent Progress in Fe-based nanocrystalline soft magnetic alloys and their applications

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More than 25 years have passed since Fe-Cu-Nb-Si-B nanocrystalline alloys which are typical alloys of FINEMET<sup>®</sup> had been discovered<sup>1)</sup>. Fe-Cu-Nb-Si-B nanocrystalline alloys are formed to cores and the cores are used in current transformer for ground fault interrupters, common mode chokes (CMC) in EMI filter and high frequency transformers. This is because high permeability from low frequency up to 100 kHz, a high operating magnetic flux density  $B_m$  owing to relatively higher saturation magnetic flux density  $B_s \approx 1.2$  T than that of competitors and low core losses for example core loss at 0.2 T at 100 kHz,  $P_{2/100k} = 48$  W/kg.<sup>1)</sup> For CMC core, there are requirements of downsizing of core as well as improvement of frequency dependence of impedance. Since amount of heat limits the  $B_m$ , and less core loss makes less heat especially in the high frequency transformers, further reduction of core loss enables to use in higher  $B_m$ , resulting in downsizing of core.

In electrical distribution transformers (50Hz / 60 Hz), also energy efficiency has to be improved considering increase of recent energy cost and requirement of CO<sub>2</sub> emission reduction. Fe-based amorphous alloy based transformers show much higher energy efficiency than that based on conventional grain-oriented silicon steel. However, because of low  $B_s \approx 1.6$  T, this is about 80% of grain-oriented silicon steel, physical size of Fe-based amorphous alloy based cores tends to be larger than that based on grain-oriented silicon steel when the same output of transformers was designed.<sup>2,3)</sup> The reason is as follow;  $B_m$  in transformer cores is determined by core loss, noise, frequency and voltage fluctuation in transformers etc. Practically  $B_m$  is about 80 – 85% of  $B_s$ , thus  $B_m$  of grain-oriented silicon steel and Fe-based amorphous alloys based cores is limited around 1.6 - 1.7T and 1.3 - 1.45 T, respectively.

In this presentation, we would like to introduce our research and development to increase  $B_m$  of cores for both high and low frequency applications and new products based Fe-Cu-Nb-Si-B nanocrystalline.

Combination of thinner ribbon thickness (18  $\mu\text{m}$   $\rightarrow$  13  $\mu\text{m}$ ) and magnetic field annealing for Fe-Cu-Nb-Si-B nanocrystalline alloy improved frequency dependence of impedance and decrease core loss, and succeeded in developing new CMC cores (FT-3K50T) and high frequency transformer cores (FT-3TL)<sup>4,5)</sup>.

For low frequency applications, we aimed to create an alloy with nanocrystalline phase with high Fe content. The concept of material design was to realize high  $B_s$  with high Fe content, bcc-Fe phase and excellent soft magnetic properties by randomness of nanocrystalline structure. By adding 1.5 at.% of Cu in basic Fe-B amorphous alloy system, precipitation of primary crystals at as-melt-spun state was confirmed. A nanocrystalline phase of average grain size of about 20 nm was obtained after annealing this ribbon at 390°C for 3.6 ks.<sup>6)</sup>

The mixing heat of Fe and Cu is positive, and hence it suggests that in the quenching process, over saturation of Cu occurs in the supercooled glassy state and that results in the aggregation of Cu clusters. The Cu clusters help to nucleation of primary crystals and crystallization arose from primary crystals, and increase content of B in amorphous matrix lead to nanocrystalline structure resulting excellent soft magnetic properties without adding Nb. After the discovery of this material, further improvement of soft magnetic properties was made for Fe<sub>bal</sub>Cu<sub>1.4</sub>Si<sub>5</sub>B<sub>13</sub> nanocrystalline alloy of which single strip ribbon exhibits core loss at 1.5 T at 50 Hz,  $P_{15/50}$  of 0.29 W/kg, that is about one half of grain-oriented silicon steels, with  $B_s$  of 1.8 T, that is about 10% higher than that of Fe-based amorphous alloys.<sup>6)</sup> However, due to primary crystals in as-melt-spun state, the ribbon is brittle and difficult to handle. To solve this issue, the perspiration of primary crystals at as-melt-spun state has to be avoided what is similar to conventional Fe-Cu-Nb-Si B alloys and/or Fe-M-B (M = transition metals) alloys.<sup>1,7)</sup> These alloys exhibit amorphous phase in as-melt-spun state and become nanocrystalline phase by annealing.<sup>1,7)</sup> Conventional Fe-based nanocrystalline alloys contain at least 2 at.% of a heavy non-magnetic element such as Nb, since decrease of them results in deterioration of

soft magnetic properties when applying normal annealing, for example heating rate of 5 °C/min. Therefore their  $B_s$  is 1.2~1.7 T.<sup>1,7)</sup> It is necessary to reduce the amount of Nb to increase  $B_s$  maintaining nanocrystalline structure. On the other hand, it is known that higher heating rate in annealing process brings about finer nanocrystalline structure.<sup>8)</sup> With combining concepts of less Nb to achieve higher  $B_s$  and high heating rate annealing to achieve excellent soft magnetic properties, Fe<sub>bal</sub>Nb<sub>1</sub>Cu<sub>1</sub>Si<sub>4</sub>B<sub>12</sub> alloy ribbon was developed. Single sheet of this alloy annealed with heating rate of more than 3°C/s up to 450°C exhibits  $B_s$  of 1.78 T and  $P_{15/50}$  of 0.20 W/kg.<sup>9)</sup> The cores made by this material has a high potential to become a next generation high  $B_m$  magnetic core not only for transformers but also for reactors and motors.

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## RECENT DEVELOPMENTS OF NON-ORIENTED ELECTRICAL STEEL SHEET FOR AUTOMOBILE ELECTRICAL DEVICES

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In recent years, there has been a strong demand for improving the fuel economy of automobiles in an effort to protect the global environment. To improve the fuel economy, hydraulic drive parts in automobiles have begun to be replaced with electrical drive devices, such as electric power steering (EPS) and electric brake systems. Moreover, a hybrid electric vehicle (HEV) has been developed, and the market is being expanded. In an HEV, some high-frequency electrical devices such as traction motors, generators, air conditioner motors and reactors are used. Therefore, the amount of both motor and actuator use increases, and they are playing an important role in automobiles. Non-oriented electrical steel sheets are used as the core material for such electrical devices, and they are contributing to the improvement in the efficiency of the apparatus.

In this paper, recent developments of non-oriented electrical steel sheet for automobile electrical devices, such as HEV traction motors, EPS motors and high-frequency reactors, are reviewed and discussed.

In HEV traction motors, high torque, high efficiency and small size are demanded. In order to satisfy such demands, the internal permanent magnet (IPM) type motor is mainly used in Japan. Non-oriented electrical steel sheets for HEV traction motors should have high magnetic flux density for high torque, low iron loss for high efficiency and high strength for reliability. JFE Steel has developed electrical steel sheets for energy efficient motors<sup>1)</sup>, and it is suitable for HEV traction motors. The developed material achieved low iron loss and high magnetic flux density by high purification and texture control. Moreover, JFE Steel has developed thin-gauge electrical steel sheets for high frequency motors. This material shows lower iron loss than that of conventional products in high-frequency range (Fig.1).

Some of the HEVs are equipped with a converter/inverter for power conversion. The properties of low iron loss in the high frequency range for compactness, together with low noise for quietness are required in the core material for this application. JFE Steel developed a 6.5% Si steel sheet, which shows low iron loss and low noise in the 400Hz to 10kHz so it is the optimum material for high frequency reactors (Table 1).

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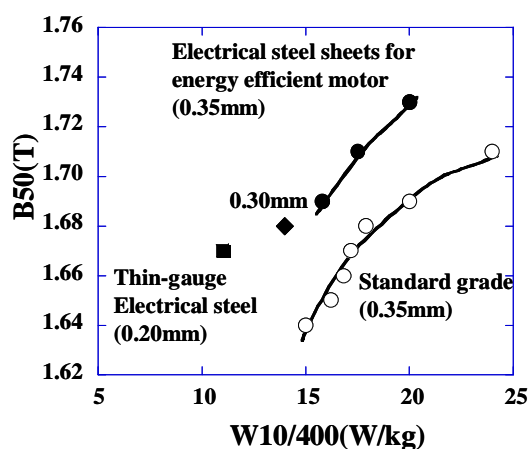


Fig.1 Magnetic properties of thin-gauge electrical steel sheet

Table 1 Magnetic properties of 6.5% Si steel sheet

Materials	Thickness (mm)	Saturation magnetization (T)	Iron loss W <sub>10/400</sub> (W/kg)	Magnetostriction λ <sub>10/400</sub> (×10 <sup>-6</sup> )
6.5%Si steel	0.10	1.80	5.7	0.1
Grain oriented electrical steel sheet (Si:3wt%)	0.10	2.00	7.2	-0.8
	0.23	2.00	7.8	
Non-oriented electrical steel sheet (Si:3wt%)	0.20	2.00	10.4	7.8
	0.35	2.00	14.4	
Fe-based amorphous	0.025	1.50	1.5	27

## Research and Development of Next Generation Motors and Its Future Issues

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This paper introduces research and development of next generation motors for electric vehicles (EVs) and hybrid electric vehicles (HEVs) in Hokkaido University, including a traction motor for HEV and an in-wheel axial-gap motor for electric city commuters. Some design points of the motors and its future issues are described, associated with characteristics of magnetic materials.

Fig. 1 shows proposed structure of a traction motor for hybrid electric vehicles without rare earth materials. Using ferrite magnets, axial gap structure and segment rotor structure are adopted to obtain high performance comparable to the traction motor with rare earth magnets for HEVs. The stator core having 24 tooth is made of SMC core and a 3-phase 10-pole concentrated winding is wound around the stator core. In order to generate reluctance torque, the rotor is structured by building the ferrite PMs and the SMC cores into the rotor support component. In spite of the rare-earth-free motor using the ferrite PM that the energy product is about 1/10 of the rare earth PM, the maximum torque reaches 75.3% of the high-performance PMSM using the rare earth PM in the same volume. The ratio of the reluctance torque is very big of 49.2%, when the maximum torque is generated. The prototype can fulfill an equal output power of 50 kW at the same volume as the high-performance radial gap type PMSM of the second-generation Toyota Prius.

Fig.2 shows proposed structure of a ferrite PM in-wheel motors with axial-gap structure for electric city commuters. The motor is characterized by the sophisticated structure incorporating a reduction gearbox into the inner side of the stator to generate large output torque. In the other side of the stator, a resolver as a position sensor is installed for closed control of the motor. The ferrite PM is used instead of rare earth PM and the coreless structure is adopted to minimize demagnetization of the permanent magnets and to eliminate the rotor iron loss. Three prototypes are constructed and evaluated. Some experimental results will be shown in the presentation.

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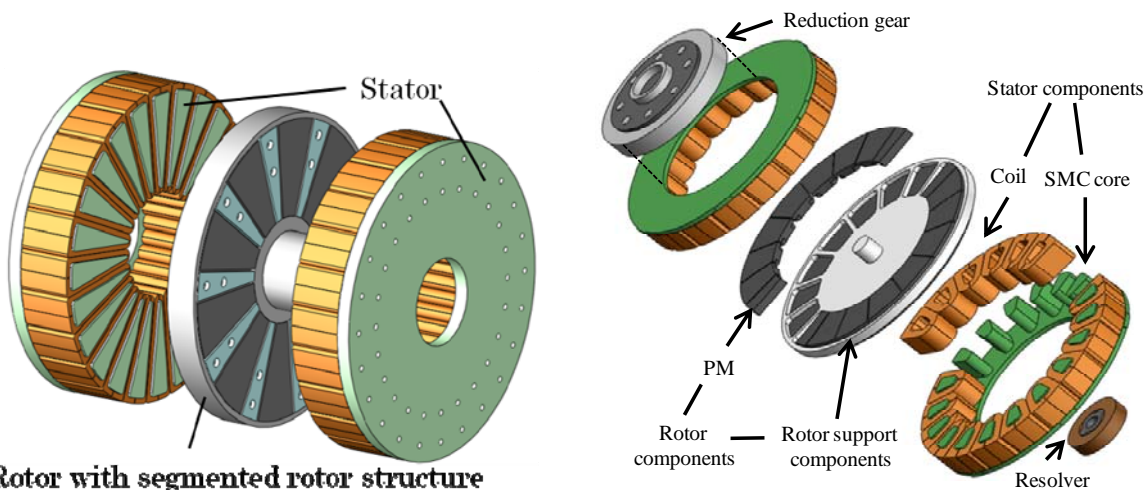


Fig.1 Traction motor for HEVs without rare earth materials. Fig.2 In-wheel axial-gap motor for city commuters.

# Movement of Traction Drive Motor for EV/HEV

## - High Performance Design-concept and Issues of Permanent Magnet Motor for Toyota Prius -

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Permanent magnet motors were improved remarkably, after Nd-Fe-B magnets were invented in the first half of the 1980's, and high power semi-conductor has made progress. Since then permanent magnet motors for EV/HEV traction drive have been developed rapidly with high performance of output. The reason is because it is attempting the optimization of the system-wide driving force which included the final gear ratio of running drive of cars such as engine and reduction gear in addition to motor design technique as electrical appliance. Figure 1 shows the cut model photograph of the trans-axle which introduced into Toyota Prius from the 1st generation to the 3rd generation, and the concept of the motor downsizing. The motor size is 38 % smaller in the 2nd generation and moreover 74 % smaller in the 3rd generation than that in the 1st generation. We have make progress in downsizing with the three concepts as follows. The first is Nd-Fe-B magnets with high performance, the second is higher system voltage, the third is higher rotation speed. In the motor specification of the 3rd generation Prius, the system voltage is 650V and the maximum rotation speed is 13500rpm.

The issues for realizing the three concepts are as follows;

- (1) Insulation technology for higher system voltage: That keeps distance among coils or between coil and stator.
- (2) Design to downsize high speed reduction gears, to strengthen rotor against centrifugal force at the highest speed and to reduce losses of motors for higher rotation speed: The improved design of machine elements is shown in Fig.1. And the improved design of motor is shown in Fig.2.
- (3) Cooling technology: Traction motor is cooled by ATF (Automatic Transmission Fluid) because the motor and reduction gears are in the same trans-axle case. The cooling system using ATF is shown in Fig.3.

It is composed of differential gear which is slinging ATF, catch tank, oil pump which deliver ATF to the heating site and water jacket

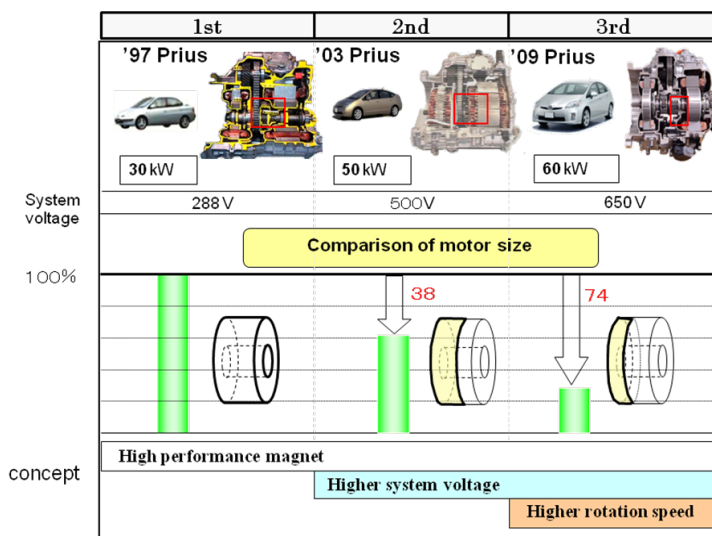
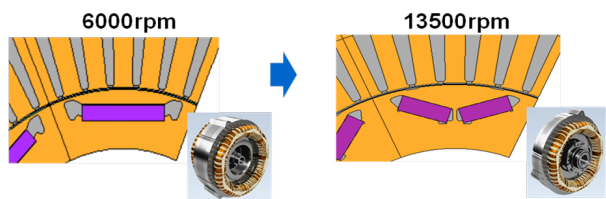


Fig. 1 Concept and Characteristics of Trans-axle Unit for 1st-3rd Prius



(1) 2nd Prius (2) 3rd Prius (V-Shape)

Fig. 2 Arrangement of Rotor Magnets for 2nd and 3rd Prius

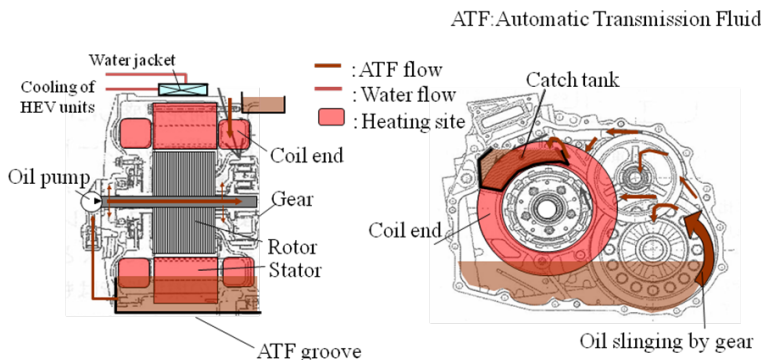


Fig. 3 Cooling system using ATF

## Development of Axial Flux Permanent Motors with Amorphous Cores

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In electrical machines, the use of rare-earth magnets enables smaller motors to perform with higher power and efficiency. Over the past 30 years, electrical machines equipped with rare earth magnets have been used in a wide variety of industries such as automotives, home appliances, electronics, and power plants. With increasing demand for green energy products, rare earth magnets have become virtually indispensable in the industrial market. However, the limited supply of rare earth elements such as neodymium and dysprosium has made the development of alternative technologies for high efficiency motors a top priority. This research aims at increasing motor efficiency without relying on rare earth metals by using a novel motor design to decrease losses within the motor.

Non-rare earth magnets, such as ferrite or ceramic permanent magnets are typically 50% to 70% weaker than rare earth magnets. Increasing the output of a motor using these weaker magnets is extremely difficult with conventional radial-flux permanent-magnet (RFPM) motor. In this research, the axial-flux permanent-magnet (AFPM) motor with double-rotor and single-stator is proposed to obtain larger output torque. Fig.1 shows the structure of a RFPM motor and Fig. 2 shows the structure of an AFPM motor with double-rotor and single-stator. Furthermore, amorphous magnetic materials (AMMs) have features of extremely low iron losses, and high magnetic permeability, which can improve motor performance when combined with low energy magnets [1] and [2]. However, commercial amorphous metal is typically processed as 0.025mm thick tape. Amorphous tape is very hard and brittle, which makes stamping or pressing difficult.

This paper presents the development of amorphous cores for electrical motor's application. A new method to process low iron loss amorphous cores is introduced. The concepts of designing AFPM motors are introduced. The design, manufacturing and test results of 11kW industrial motor are presented. This motor delivered 93% efficiency at full load, which places the motor in the IE4 level in the efficiency standard IEC60034-30, as published by the International Electrotechnical Commission (IEC).

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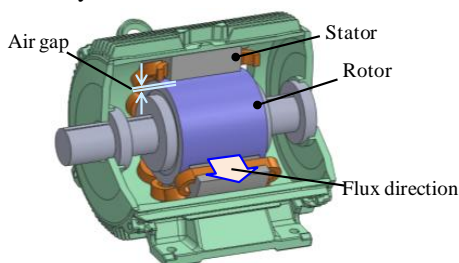


Fig.1 Radial-flux permanent-magnet motor.

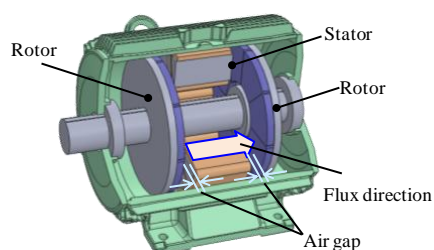


Fig.2 Axial-flux permanent-magnet motor.

Some of these developments are granted by the New Energy and Industrial Technology Development Organization(NEDO) through the "Funding program for development of realization technology for replacement and reduction of rare-earth metal".

## Development of High Density and Low Loss Powder Magnetic Core for Reactor in Hybrid Vehicles

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<sup>3</sup>DAIDO STEEL CO., LTD.

Automobile usage has expanded throughout the world in recent years and has become one of the foundations of human society and economic activity. However, one of the repercussions of this trend is environmental issues such as global warming due to CO<sub>2</sub> emissions and air pollution. Consequently, there is a growing need for the development of hybrid and other low-emission vehicles. As part of these efforts, Toyota is working to popularize hybrid vehicles (HVs) by developing lower cost technology to help provide reasonably priced vehicles for the customer.

The subject of this presentation is the reactor, which is a part used in the boost converter inside the power control unit (PCU) in HVs. The purpose of the reactor is to increase the output of the HV system while lowering costs by reducing the required battery capacity of the vehicle. A reactor must be capable of stably achieving the inductance required for boosting the voltage of the system. At the same time, a reactor must also prevent overheating and achieve low core loss and low vibration to reduce noise inside the vehicle. For these reasons, the optimum core material is thin ( $t=0.1$  mm) electrical steel sheets with low magnetostriction. These sheets have low core loss and generate extremely low amounts of magnetostriction. However, since these sheets are expensive, a lower cost core material needed to be developed.

A new type of powder was developed for the reactor and a high density powder compaction technique was adopted<sup>1)</sup>. We focused on a high density powder compaction using net shaping, which is a technology capable of reducing manufacturing process and increasing material yields.

- (1) The particle shape of the Fe-Si magnetic powder was controlled to a spheroidal powder.
- (2) The surface of the powder was coated with a newly developed SiO<sub>2</sub> insulator.
- (3) The high density compaction technique increased the strength of the powder magnetic core.

As a result, the magnetic flux density was increased by approximately 35% and core loss was reduced by approximately 40% (Fig.1). The reactor core with equivalent electromagnetic characteristics to electrical steel sheets, for which is difficult to achieve with conventional powder magnetic cores, was developed and a great cost reduction was achieved. This is the first powder reactor core in the world to be installed in a vehicle (Fig.2, the third generation Prius that was launched in 2009).

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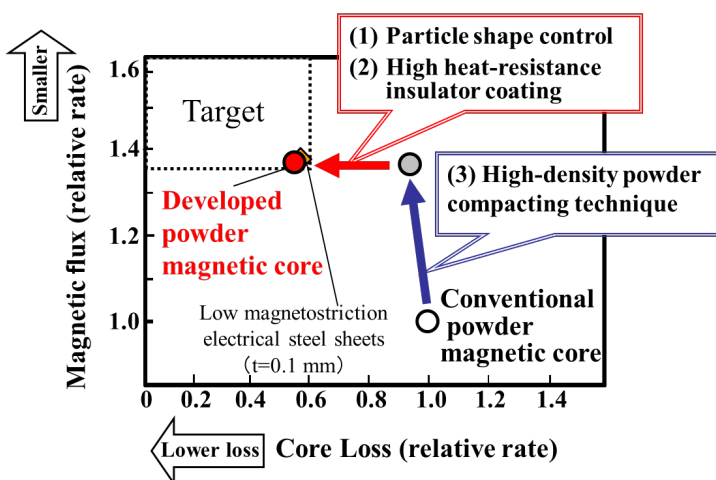


Fig.1 Positioning of Developed powder magnetic core

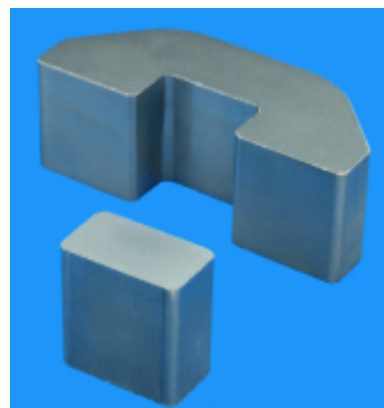


Fig.2 Developed reactor core



## Measurement technology of new permanent magnets and motors for development of high efficiency motors.

T. Kondo, S. Araki, Y. Sanga, Y. Asano, A. Yamagiwa

(Technology Research Association of Magnetic Materials for High-Efficiency Motors (MagHEM))

Recently, the demand for high-efficiency motors has been increased for saving the energy. However, the high energy product magnets without heavy rare-earth elements, of which ores are eccentrically located in some areas, are necessary to apply for high-efficiency motors of Hybrid Electric Vehicles (HEVs). Therefore, Technology Research Association of Magnetic Materials for High-Efficiency Motors (MagHEM) was founded in 2012 and consists of nine companies, an incorporated administrative agency, and an organization<sup>1)</sup>. The objective of MagHEM is the development of innovative magnetic materials by 2017 and 2022 and high-efficiency motors of HEV using these materials. In this paper, we introduce the activities for developing high-efficiency motors in MagHEM.

First, we show the development of motor material evaluation techniques for the development of high-efficiency motors using new magnetic materials developed by MagHEM. It is necessary to evaluate the demagnetization characteristics of magnets in a high-temperature environment because HEV/EV motors are used in this environment. However, the demagnetization state is not uniform in the magnet owing to the nonuniformity of the magnetic properties and the strength of the magnetic field applied by the armature coils. Furthermore, the flux density is only measured on the surface of the magnet to evaluate the demagnetization state, and the state inside the magnet is estimated by using FEA. Therefore, we develop a method to evaluate the three-dimensional demagnetization state including the inside the magnet by cutting the magnet into the cubes, as shown in Fig.1, and measuring the B-H characteristics of each magnet cube.

Further, it is important to establish a high-precision motor-loss measurement technology, especially the iron loss, for accurate evaluation of the motor efficiency. The mechanical loss generated in the bearings makes it difficult to precisely evaluate the iron loss in a conventional measurement system. Therefore, we are developing a high-precision motor-loss measurement system that dramatically reduces the mechanical loss in the system, as shown in Fig.2.

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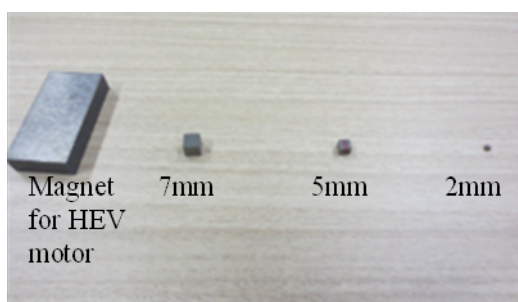


Fig. 1 Magnet cut into cubes.



Fig. 2 High-precision motor-loss evaluation system.