Requirement of magnetic material for high frequency and high power excited by power electronics

Keisuke Fujisaki
(Toyota Technological Institute)

Electric energy is often converted various energies such as mechanical, light and heat ones due to high responsiveness and high conversion efficiency, and 43% of energy in Japan is consummated as electric energy. The power consumption related to power electronics technology has been dramatically increased recently, and it is expected that 80% of the electric energy will be consumed by the power electronics technology in 2030.

In power electronics technology, we can generate electric power with any voltage and any frequency by using power semiconductors. The markets related to power conversion have been being expanded by downsizing and an increase in power capacity using high-frequency driving. One of the serious factors to prevent expanding the markets are magnetic materials for high-frequency driving. For example, the weight of magnetic devices such as inductors and transformers for the mW to MW class account for 30 - 50% of the total weight. Although the increase in an operating frequency is effective to reduce size of magnetic devices, efficiency for the power conversion typically decreases since the magnetic loss of the magnetic materials increases. A cost analysis for a 20 kVA-uninterruptible-power-supply points out that the cost of inductors for filters is 44% of the total cost, and this value is larger than that for the power semiconductors and the storage capacitors.

Thus, the magnetic materials for high-frequency driving are the bottleneck of expanding the power electronics technology in terms of the difficulties of the reductions in size, loss, and cost. Although the widespread of power semiconductors with high voltage resistant such as GaN and SiC enables to increase the power capacity, we need to develop mass-production technology of the magnetic materials.

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Possible Design and Development of Ultra-high Strength Permanent Magnet Based on Fundamental Conceptual Change in Magnetism

Yoshiyuki Kawazoe
(New Industry Creation Hatchery Center, Tohoku University, Sendai, Japan)

After the discovery of neodymium magnet $Ne_2Fe_{14}B$ in 1984 by Dr. Masato Sagawa, no permanent magnets better than that have been commercialized over 35 years. As a matter of course, a number of developments have been done to improve its properties. In the long history of magnet development, basically experimental findings have led the improvements. Theory basically contributes to explain the phenomena realized by experimental studies. We have proved the fundamental and serious misunderstanding in the origin of magnetism, which has been explained in the standard textbooks that exchange interactions between electrons reduce the system energy for the magnetic ground state. This misunderstanding originated in the old and famous paper by Slater in 1929 just after the invention of quantum mechanics (Ref. 1) which explains well the Hund's first rule (Among the degenerated low-lying states, the highest spin state is the ground state.), and is still introduced in the standard textbooks in magnetism. However, when Slater developed his theory, he did (could) not include the effect from the nucleus, and simply electron-electron interactions were considered.

Slater's explanation of magnetism has been claimed by Davidson (Ref. 2) and other researchers. They basically solved the magnetic ground state in high accuracy including all the interactions between nucleus and electrons, and proved that the effect from nucleus-electron interaction contributes most to reduce the system energy to realize the magnetic ground state, where electron-electron exchange energy even increases the energy. However, these studies are only considered to be for specific cases, and not accepted as a general aspect of magnetism. We have solved the magnetic ground state in atoms and molecules in high accuracy and proved that the Davidson's theoretical explanation holds in general for the magnetism in atoms and molecules (Ref. 3). We have proved based on checking the virial theorem satisfaction. By this way, most of the standard theories in magnetism such as Slater's perturbation theory for Hund's rule, Heitler-London model for hydrogen ground state, Hubbard model for magnetic and superconducting states, etc. are fundamentally incorrect, since they violate the virial theorem (for the equilibrium state $V/T=-2$ should hold, and this is a necessary condition for all Coulombic systems.).

Recent progress in computer power has made it possible to apply the density functional theory (DFT) to compute numerically the magnetic ground state. Although DFT is called *ab initio* simulation, within the theory it is not possible to determine the electron exchange-correlation functional and the researchers introduce parameters, such as LDA+U, hybrid functional, etc. which try to fit to the experimental observations (therefore, not *ab initio* but phenomenology). These phenomenological methods can be checked by virial theorem satisfaction; violation means incorrect. We therefore know now exactly what we should do to be able to predict new permanent magnet; what we should do is to solve the quantum mechanical equation without any parameters. Although this is costly, it is important to have good guidelines for theoretical prediction of new magnet without experimental help, which is time consuming and costly.

We have successfully performed several theoretical predictions of new magnets; (1) Atom cluster based high magnetic moment magnets, (2) Two dimensional magnets with only light weight elements, (3) Carbon based magnets, etc. These new magnets have been predicted with confidence, because we have solved the Schroedinger equation for magnetic ground state with no parameters for fitting to experiments.

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Vector Magnetic Hysteresis Characteristics of Electrical Steel Sheet and its Application

Masato Enokizono[1,2]
[1]Vector Magnetic Characteristic Technical Laboratory, Usa, 879-0442, Japan
[2]Nippon Bunri University, Oita, 870-0397, Japan

Vector magnetic characteristics have been proposed as magnetic characteristics required to effectively utilize magnetic materials for the purpose of reducing the loss and increasing the efficiency of electric machines.[1)]
Conventional magnetic characteristics represent the relationship between magnetic flux density and magnetic field strength in one direction, particularly rolling direction. However, conventional magnetic characteristics are extremely unsatisfactory for design and development to realize low loss and high efficiency of power electrical machines such as motors and transformers. At this time, the magnetic flux density vector **B** and the magnetic field strength vector **H** are not aligned with each other and have a spatial phase difference angle θ_{BH} . In other words, since the magnetic characteristics represent the vector relation between the **B** vector and the **H** vector, they can be generally said to be vector magnetic characteristics.
This can be seen in the dualities established between the electrical characteristics (voltage, current, power factor) and magnetic properties (**B**, **H,** θ_{BH}) of the electrical machines as shown in Fig. 1.[2)] Since it is not possible to satisfy this duality relation from the conventional scalar magnetic characteristics, expressing only the size of **B** and **H**, it is impossible to introduce to the magnetic characteristic analysis and design of electrical machines.

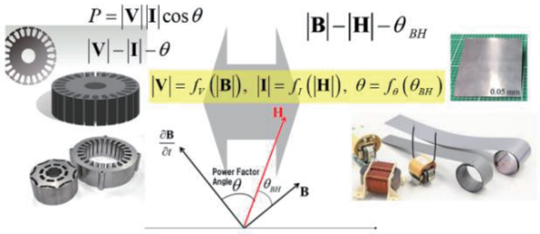


Fig.1 Duality between motor electric characteristics and magnetic material magnetic characteristics.

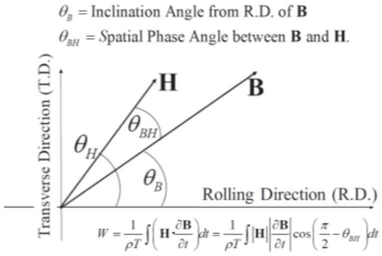


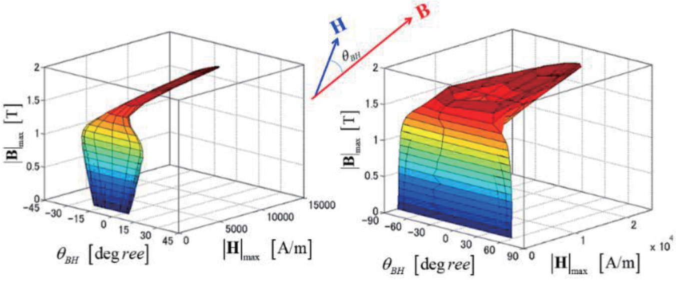
Fig. 2 Definitions of vector characteristic.

In addition, handling of electrical machine is carried out under voltage drive, resulting in the problem of obtaining current and power factor. When voltage is applied, the reactance is larger than the circuit resistance, so the magnetic flux density level is automatically determined. Similarly, in the magnetic characteristic analysis, it is a problem to calculate the **B** vector and **H** vector and the spatial phase difference angle θ_{BH}. These constitute an inverse problem analysis of solving I, cos θ, **H**, θ_{BH} by applying a voltage. In other words, it indicates that the hysteresis loop of magnetic properties is not given but solved. In order to clarify the relationship between **B**, **H** and θ_{BH} constituting the vector magnetic characteristics, we indicate this as shown in Fig. 2.
In the case of the electrical steel sheet, taking the rolling direction as a reference, the inclination angle θ_B of the **B** vector from the rolling direction is defined and represents the vector magnetic characteristic in an arbitrary direction. The spatial phase difference angle θ_{BH} between vectors is expressed as the difference between the inclination angle θ_{H} of the **H** vector and the inclination angle θ_{B} of the **B** vector. The following equation (1) is a magnetic power loss (core loss) calculation formula.

$$W=\frac{1}{\rho T}\int\left(\mathbf{H}\cdot\frac{\partial \mathbf{B}}{\partial t}\right)dt=\frac{1}{\rho T}\int\left(H_x\frac{\partial B_x}{\partial t}+H_y\frac{\partial B_y}{\partial t}\right)dt=\frac{1}{\rho T}\int\left\{|\mathbf{H}|\left|\frac{\partial \mathbf{B}}{\partial t}\right|\cos\left(\frac{\pi}{2}-\theta_{BH}\right)\right\}dt \tag{1}$$

The above expression shows the relationship by introducing θ_{BH}.The ρ is mass density. Figure 3 shows the **B**-**H** characteristic in an arbitrary direction under the alternating magnetic flux condition as the characteristic including

θ_{BH}. Comparing the features of the non-oriented electrical steel sheet and the grain-oriented electrical steel sheet shown in this figure, it is possible to clarify the characteristic difference with respect to the conventional characteristic expression. Instead of the conventional core loss characteristic expression, Fig. 4 newly shows the core loss characteristics in an arbitrary direction.



(a) Non-oriented steel sheet (b) Grain-oriented steel sheet

Fig. 3 magnetic characteristic.

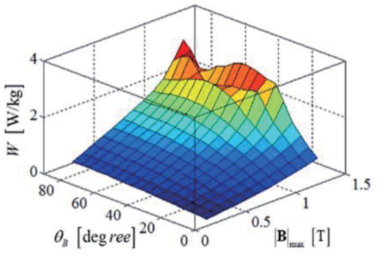


Fig. 4 Core loss of arbitrary direction.

Although basic vector magnetic characteristics can be seen from Fig. 5 and Fig. 6, we show the characteristics $\theta_{BH}-\theta_B-|\mathbf{B}|$ of Fig. 5 and the characteristics $|\mathbf{H}|-\theta_B-|\mathbf{B}|$ of Fig. 6 in order to extract the features due to the difference between the magnetic characteristics and the magnetization process.

From the viewpoint of vector magnetic characteristics, the behavior of θ_{BH} and **H** vectors is also a very important characteristic because it gives the necessary knowledge to the design of electrical equipment. In the magnetic characteristics of the electrical machine core, examining the material characteristics of the **H** vector and θ_{BH} leading to the current and the power factor as described above will lead to the establishment of an effective utilization technique for the electric machine core, providing knowledge necessary for the development and design for loss reduction and high efficiency.

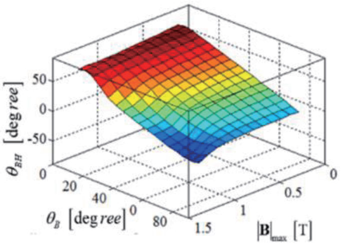


Fig. 5 $\theta_{BH}-\theta_B-|\mathbf{B}|$ characteristic.

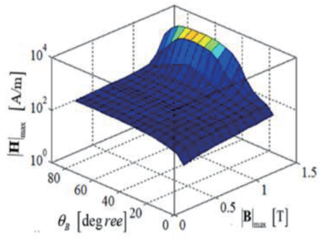


Fig. 6 $|\mathbf{H}|-\theta_B-|\mathbf{B}|$ characteristic.

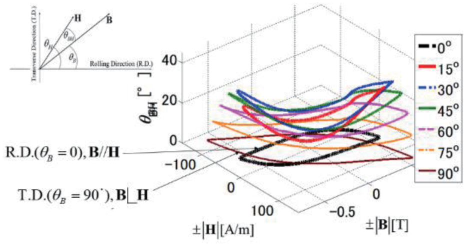


Fig. 7 Vectors magnetic hysteresis loop.

The motor and the three-phase transformer generate rotational magnetic flux in the iron core, and the rotational core loss caused by the rotating magnetic flux is larger than the alternating iron loss. In the magnetic characteristics under the rotational magnetic flux conditions, the involvement of θ_{BH} appears more prominently.

By virtue of hysteresis loop expression of vector magnetic characteristics, it can be sufficiently predicted that θ_{BH} and change of **H** vector affect each other, so we can capture those behaviors as a whole. In addition, it is possible to analyze the influence of various factors governing the core loss increase, and to indicate the utilization technique for development and improvement of materials based on physical phenomena. Vector magnetic characteristics are taken as a waveform of one period about $\pm|\mathbf{B}|, \pm|\mathbf{H}|$ and θ_{BH} when the waveform obtained from Fig. 3 is displayed as $\pm|\mathbf{B}|-\pm|\mathbf{H}|$ and $\theta_{BH}-\pm|\mathbf{H}|$ characteristics, it is drawn as shown in Fig. 7. This vector magnetic hysteresis characteristic clarifies the hysteresis modeling of characteristics and the effect of stress.$^{2)}$

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Measurement of magnetic characteristics of traction motors at driving

H. Nakai [1]
[1]Toyota Central R&D Labs., Inc., Nagakute 480-1192, Japan

The issues for a traction motor of HV, EV are miniaturization, low cost, and low loss. The volume of the motor has been miniaturized by such as high rotation, oil cooling, utilization of flat wires, and high voltage. In order to reduce the cost of the motor, reduction of the use of rare earth elements, which are high-cost materials, was mainly involved. Examples include reducing the amount of magnets by using reluctance torque, and reducing the use of heavy rare earth elements by using grain boundary diffusion magnets. The loss of the motor has been reduced by thinning an electromagnetic steel sheet and increasing the electrical resistance of the sheet. The characteristic of the traction force of a car is that high torque at the time of start (low speed range) and high-speed driving are compatible, and the area used frequently is in the medium speed range. A traction motor often requires a wide operating range, since they cover the entire operating range without a transmission. Furthermore, in a traction motor, it is important to reduce the loss in the medium speed range. In order to reduce the loss in the medium speed range, it is necessary to reduce the iron loss as well as the copper loss. Iron loss generated in the sheet of the motor core is caused by magnetic flux fluctuation in the sheet. The causes of the magnetic flux fluctuation include the arrangement of coils, current harmonic components due to switching operation of an inverter, and changes in magnetic resistance due to the rotation of the rotor. On the other hand, iron loss changes in the state of the sheet also . The difference in the grade of the sheet, the stress applied to the sheet, etc. cause the difference in iron loss. In low loss motor design, it is important to clarify the above factors of iron loss change and incorporate them into the motor design. Our motivation to measure iron loss is to design a low loss motor.

Iron loss measurement is done by reproducing the condition with test pieces. We also measure iron loss in test pieces, which is important. On the other hand, it has not been clarified yet to what extent iron loss measurement in test pieces can reproduce phenomenon for an actual motor where various factors overlap. Therefore, by measuring the actual motor in actual driving conditions, we are challenging the measurement in the actual motor driving condition with the purpose of confirming the certainty of iron loss measurement in test pieces. In order to realize this measurement with the actual motor, we have newly developed a magnetic flux sensor that can measure magnetic flux in three directions inside the motor core without disturbing the flow of magnetic flux$^{1)}$. Figure 1 shows the developed sensor. In order not to disturb the flow of magnetic flux, the developed sensor has 2 ideas. The first idea is that the thickness is 170 micrometers thinner than a magnetic steel sheet by using a layered flexible printed board. The second idea is that it is not necessary to make a hole in a magnetic steel sheet by combining the technique of a needle probe method. Using the needle probe method, the flux in the radial direction can be calculated by measuring the induced voltage between r1 and r2, the one in the circumferential direction can be calculated by the induced voltage between θ1 and θ2. The magnetic flux in the axial direction is calculated by measuring the induced voltage of the square search coil located on the flexible printed board. We have been able to measure the magnetic flux inside the stator core of an actual motor in the actual driving condition using this sensor. In the future, we will measure the actual motor using this sensor, confirm the phenomena that occur with the actual motor, and organize the relationship between the phenomenon of the actual motor and the measurement using the test piece.

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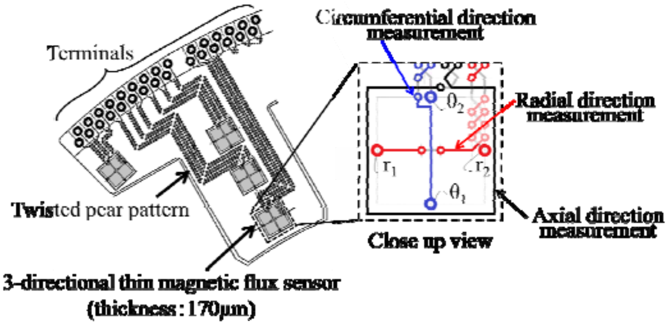

Fig1. Thin sensor capable of measuring 3-dimensional magnetic flux

Requirements for magnetic material used in products for electrified automobiles

Tetsuya Aoki[1], Satoshi Doi[2], Keiichi Okazaki[3] and Takeshi Seno[1]
[1] Metal Eng. Dept., Materials Eng. R&D Div., DENSO Corporation
[2] Development Dept. 1, Advanced Motor Development Div., DENSO Corporation
[3] Advanced R&D Dept., Production Eng. R&D Div., DENSO Corporation

It has been 112 years since the first Japanese gasoline engine car was manufactured in 1907. Today, we are facing a revolution in automotive technology that happens only once in a century. DENSO Corporation, an automotive products manufacturer, has continuously worked to fulfill its mission of developing better products to realize a safe society where people can live in peace and prosperity. Our provision of safe and comfortable mobility has helped enrich people's lives.

Two keywords, CASE (Connected, Autonomous, Shared & service and Electric) and MaaS (Mobility as a Service), represent this revolution. It requires changes in several areas including hardware, software, and infrastructure covering automotive industry processes ranging from development, manufacturing, sales to utilization. To meet requirements, we continuously uphold our mission to contribute to society as we have demonstrated throughout the history of our company. Our product development efforts are aimed at global environment protection realized by increasing the efficiency of electrified products and motor vehicle accident prevention achieved by expanding ADAS (Advanced Driver Assistance Systems) products.

Figure 1 shows an overview of the development of automobile electrical equipment and magnetic material technology through the years. From the 1960s to 70s, DENSO Corporation started applying the concept of "magnetic characteristics" to the components of engine starters and alternators. These components were optimized to work as magnetic circuits taking into account the magnetic saturation and magnetic flux leakage. As the electronic control of engines evolved, the optimization was followed by the development of materials used for magnetic circuits[2)], which are built into parts such as fuel injection valves, fuel pumps, engine rotation angle sensors, and ignition coils. To utilize these materials, we have also worked on magnetic field analysis[3),4)] and developed magnetism evaluation technology. In this report, we introduce, with reference to our history, some cases in which magnetic circuit materials were applied to automotive products made by DENSO Corporation. From the viewpoint of an automotive products manufacturer, we propose requests with respect to the development and application of magnetic circuit materials to prepare for the future electrified society.

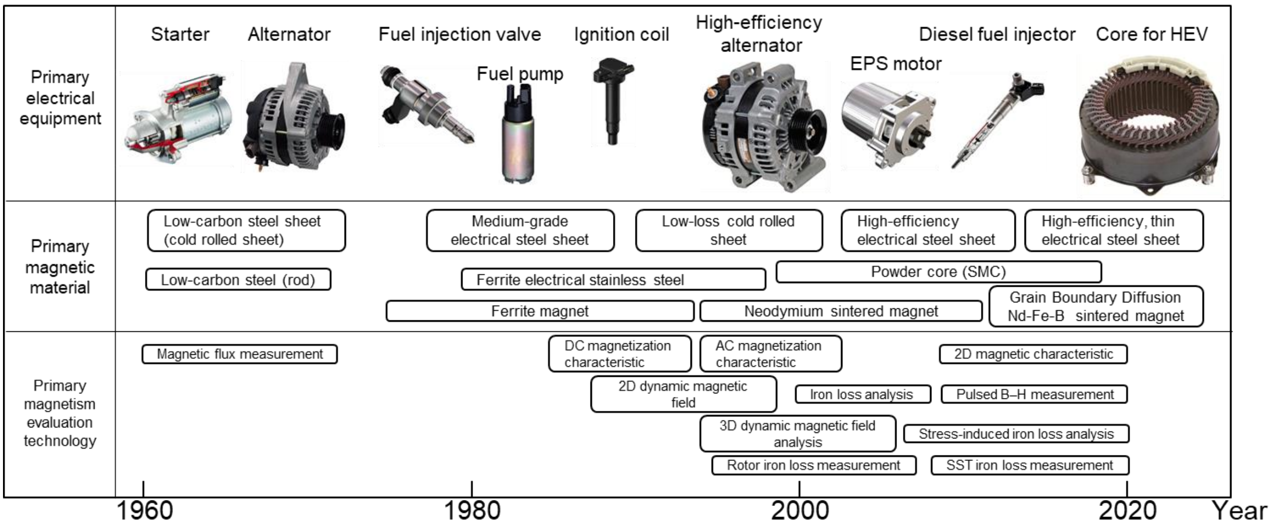

Figure 1. Evolution of automobile electrical equipment and magnetic material technologies at the DENSO Corporation.

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Research of the Motor characteristics with Nanocrystalline Soft Magnetic Alloy Stator Cores

Y. Yamada, S. Makino, and T. Nonaka
YASKAWA ELECTRIC CORPORATION, Kitakyusyu 803-8530,Japan

Recently, a series of nanocrystalline alloys (NANOMET®) that exhibit excellent soft magnetic properties has been developed[1)] and its applications to motor cores have been reported[2)]. In our previous study, we promoted research on the NANOMET® lamination process and constructed a prototype motor with NANOMET® stator cores[3)]. The iron loss of the motor with NANOMET® stator cores was reduced by a factor of >2 compared with that of motors with conventional electromagnetic steel cores. However, the torque density of the NANOMET® stator core is lower than that of an electromagnetic steel core. To improve the torque density of the core, it is necessary to improve both the space factor and flux density. In this study, we fabricated a toroidal core with NANOMET® and an electromagnetic steel sheet and evaluated its magnetic properties. In addition, we investigated the cause of the decrease in the space factor of the NANOMET® stator cores.

A toroidal core was fabricated by laminating NANOMET® and electromagnetic steel sheets. Table 1 lists the specifications of the toroidal cores. The space factors of the core were 98.1% for 35A360 and 87.0% for NANOMET®, respectively. Fig. 1 shows the measurement results of the iron loss characteristics. Compared to 35A360, the core loss of NANOMET® was significantly reduced, and the core loss at 1 T, 400 Hz($W_{10/400}$), was 5.5 W/kg (22% of that for 35A360). Subsequently, to consider the difference in the space factor, the surface roughness of the sheet was evaluated. Fig. 2 shows a comparison of the surface roughness of sheets. The sum of the surface roughness of the obverse and reverse sides of NANOMET® is a factor of ~3 greater than that of electromagnetic steel, and therefore the space factor was decreased.

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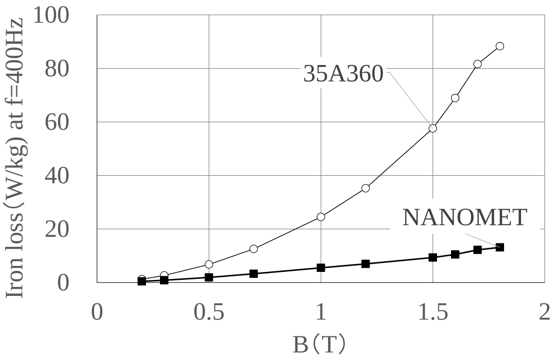
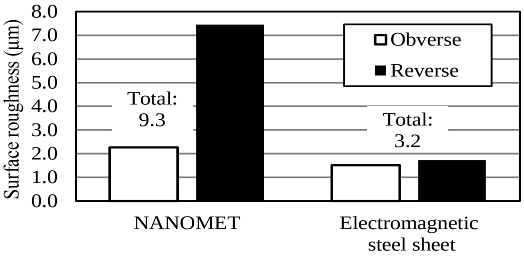
Table 1.　Toroidal core specifications.

Item		Unit	35A360	NANOMET
Thickness	t	mm	0.35	0.025
Weight	W	g	14.7	12.5
Height	h'	mm	4.93	4.84
Density	ρ	g/cm^3	7.65	7.50
Space factor	SF	%	98.1	87.0

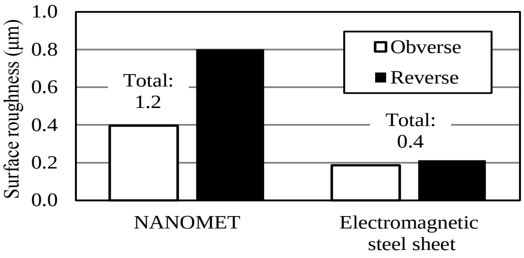


Magnetic flux density (f = 400Hz).

Fig. 1.　Iron loss characteristics.



(a) Maximum height: Rz.



(b) Calculated average roughness: Ra.

Fig. 2.　Comparison of surface roughness.