High-performance Materials for Electric Drive Solutions

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OVERVIEW: Hitachi's first product was a 5-HP electric motor produced in 1910. This was the first step in the long history of Hitachi motors. Insulator technology is an important issue. The research in this field started in 1912. In 1914, varnishes for electrical insulation were successfully developed. This was the start of Hitachi's development of its own structural materials for motors. The principles of electric motors have remained unchanged during the last century. On the other hand, major improvements have taken place in materials, application techniques for materials, computational science, and precision measuring technology. In the future, it is expected that electric motors will continue to be used in a wide range of applications such as industrial machinery, automobiles, and home appliances where they will play an important role in preventing global warming.

INTRODUCTION

HITACHI is working on preventing global warming, recycling resources, and protecting the ecosystem with the goal of creating a sustainable society. In the field of global warming prevention, Hitachi is working on plans to build energy infrastructure with low carbon dioxide emissions and manufacturing products with low energy consumption.

Based on sources such as the "Summary of Electricity Supply and Demand" published by the Agency for Natural Resources and Energy at the Ministry of Economy, Trade and Industry, annual electricity demand in Japan is about 999,000 GWh (2005 figures). Broken down by type of equipment, electric motors consume about 57% of all energy, lighting consumes 14%, and heating consumes 10%. Therefore, decreasing motor power consumption is a major issue.

In the automotive industry, the shift to hybrid and electric vehicles is being accelerated by the depletion of petroleum resources. This is one of factors behind the strong demand for highly efficient electric motors and has led to the rapid development of permanent magnet motors that use rare earth magnets.

This article describes the latest technologies and considers the issues facing the key materials used in these motors, especially permanent magnets, core materials, wire, and varnish, in terms of their role in reducing motor losses and minimizing the burden on the environment.

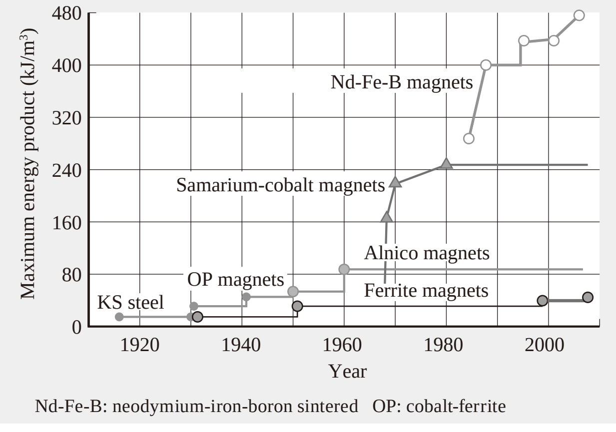


Fig. 1—Trends in Permanent Magnet Materials.
Improvements to the performance of Nd-Fe-B sintered magnets have played a major role in making electric motors smaller and more efficient.

ISSUES FACING KEY MOTOR MATERIALS

Since the invention of KS steel by Dr. Kotaro Honda in 1917, the development and mass production of permanent magnets has been ongoing, primarily in Japan and the USA, and has included alnico magnets, barium ferrite magnets, manganese-aluminum magnets, and samarium-cobalt magnets. Subsequently, Nd-Fe-B (neodymium-iron-boron) sintered magnets were invented in Japan in 1982. Because the magnetic energy of Nd-Fe-B magnets is much greater than other forms of magnet, they are used in small high-efficiency motors and are an essential component in automotive electric motors. However, because supplies of metals such as the Nd (neodymium) used in magnets and the Dy (dysprosium) used to improve magnets' heat-tolerance are mainly supplied from countries like China and Mongolia, they are treated as strategic materials and face issues that include price volatility and security of supply.

Si-Fe sheet is used for motor cores. Si-Fe sheet cores can provide an easy path for magnetic flux. Si-Fe sheet was invented in 1900 by Robert Hadfield in the UK who discovered that energy losses can be reduced by adding silicon to the iron. The losses referred to here are called iron loss or core loss. It represents the energy that is consumed during magnetization, primarily in the form of heat. Reducing iron loss is essential for energy efficiency and progress has been made in technologies such as adding silicon and making electrical steel sheets thinner. Progress is also being made on the development and commercialization of amorphous metals with higher permeability and lower iron loss than these Si-Fe steel sheets, and it is expected that this new material will prove useful in electric motors.

The wires used in electric motors are called "enameled wire." Developing heat-resistant enameled wire is an important challenge for reducing the size and improving the efficiency of motors. Also, because the process of wire winding seeks to wind or insert as much wire as possible into the slots (this is called "improving the space factor"), it requires a coating with sufficient surface strength that it is not damaged in this process. There is also increasing demand for improvements to insulation breakdown performance to cope with the surges (short-duration pulses of high voltage) produced by the electrical control systems used to drive these motors. To meet this requirement, research into amide-imide, ester-imide, and the addition of nano-silica has been commercialized.

The main role of motor varnish is to prevent the enamel insulation from being rubbed off by friction between the wires wound and inserted into the slit grooves and between the wires and core material. This is referred to as using varnish to bind the coil. The requirements for the binding varnish include its ability to permeate into the gaps between coil wires, its adhesive strength, and its heat tolerance. It also plays an important role in allowing the heat generated in the coil to escape and protecting the coil from water and dust.

On the other hand, environmental considerations make it desirable to reduce the level of VOCs (volatile organic compounds) in the varnishes. VOC is the generic term for volatile organic compounds that enter the atmosphere as gases and are one of the causes of photochemical oxidation. Thinner is typically added to varnish to reduce its viscosity and it is then used in a process whereby either the entire motor, stator, or rotor is immersed in varnish or the varnish is dripped onto specific slits. This is followed by drying and hardening processes. The thinner volatiles during these processes result in releasing of VOCs, including toluene, styrene, and xylene. This made it necessary to switch to using a solvent-free varnish that does not use thinner. To minimize resource usage, the current trend adopts a falling-drop method that can apply the varnish appropriately so that only the required amount is used and only in the locations where it is needed. Also, varnish that hardens quickly and at low temperature is needed to reduce the energy consumption of the overall process.

Varnishing is performed in the later stage of motors production processes. The main concern in this step is the affinity between the wire enamel and binding varnish. A practice of mixing a lubricant with the enamel to make its surface more slippery has been adopted to facilitate wire winding and satisfy objectives such as making motors smaller and the winding process faster. In some cases, however, this material can create new problems such as repelling the binding varnish or reducing its adhesive strength. Although experimental measures including long-term durability testing are needed to check this, methods that apply quantum and Newtonian mechanics to compute estimates of the adhesive strength between the copper wire enamel and binding varnish are being investigated.

MAGNETIC MATERIALS

Permanent Magnets

Permanent magnets are one of the materials that play an important role in determining motor performance. Fig. 1 shows how the performance of permanent magnets measured in terms of maximum energy product (density of magnetic energy) has improved over time. In particular, the ability to use Nd-Fe-B sintered magnets with genuinely high energy products in electric motors thanks to improvements in their coercivity (resistance to becoming demagnetized) (and heat tolerance) has played a major part in making permanent magnet motors smaller and more efficient.

Improvements in the coercivity (and heat tolerance) of Nd-Fe-B sintered magnets have in the past been achieved by adding heavy rare-earth elements such as Dy and Tb (terbium) that improve the anisotropic magnetic field of the material. However, because the spontaneous magnetization of these heavy rare earths has an anti-parallel relationship with

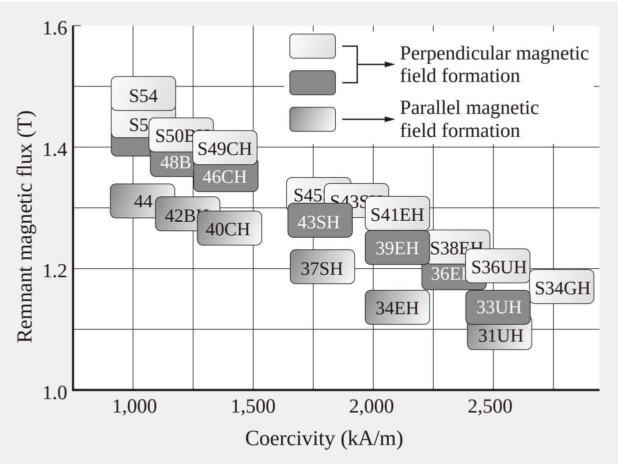


Fig. 2—Characteristics of Nd-Fe-B Sintered Magnets.
The product range includes a variety of different grades to suit diverse customer needs.

the spontaneous magnetization of Fe (iron) in the $Nd_2Fe_{14}B$ (neodymium-iron-boron) crystal lattice, there is a trade-off between the heat tolerance and maximum energy of the magnet.

Fig. 2 shows the characteristics of Nd-Fe-B sintered magnets.

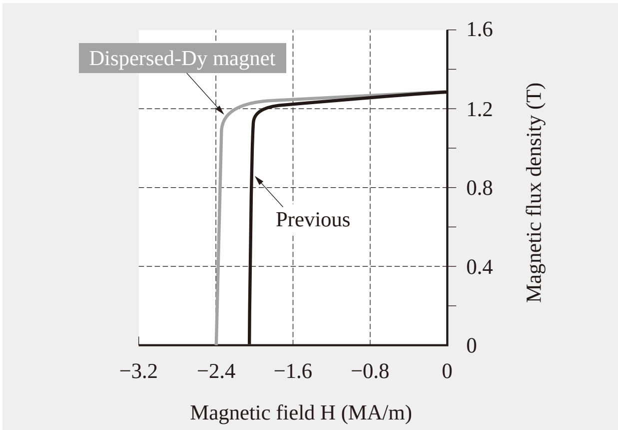
In response to diverse customer requests, Hitachi Metals, Ltd. has deployed a variety of proprietary process technologies including wet processes to supply Nd-Fe-B sintered magnets with quality levels that match the best in the world (see Fig. 3).

However, there remains a deep-seated expectation among customers for further improvements in performance and reductions in the cost of Nd-Fe-B sintered magnets in order to reduce equipment size and cost now that large quantities of these magnets are being used in applications such as powertrain motors for hybrid vehicles and compressor motors for air conditioners.

Fig. 3—Nd-Fe-B Sintered Magnets.
Magnets can be supplied in the shapes customers require.

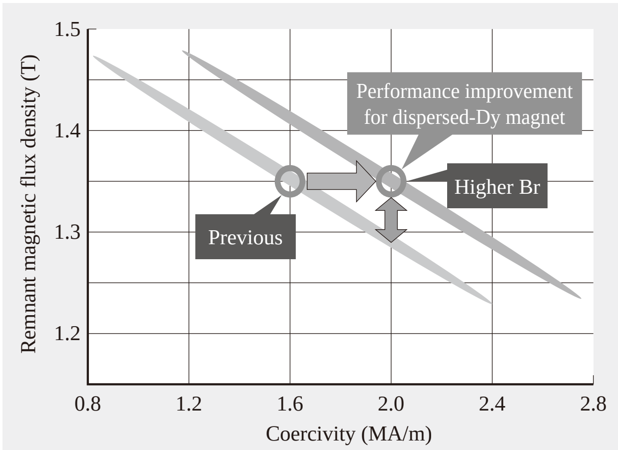
Improving the performance of Nd-Fe-B sintered magnets requires the development of new processes that can overcome past restrictions (the problem that increasing the energy product reduces heat tolerance). Another problem is the high price volatility of rare earths resulting from the fact that sources of these materials are currently limited largely to China alone. Because of this situation, reducing the use of rare-earth elements, particularly heavy rare-earth elements (Dy), is an important issue in providing customers with a secure supply of Nd-Fe-B sintered magnets.

Hitachi Metals has succeeded both in improving performance and reducing use of Dy by studying the diffusion behavior of rare-earth elements and



Dy: dysprosium

Fig. 4—Demagnetization Curve for Dispersed-Dy Magnet.
The dispersed-Dy magnet has improved coercivity (resistance to becoming demagnetized).



Br: remnant magnetic flux density

Fig. 5—Performance Improvement Due to Dy Dispersion Process.
The Dy dispersion process can also be used to increase Br (achieve a high energy product).

magnetization reversal mechanisms in Nd-Fe-B sintered magnets and controlling the distribution of Dy through the permanent magnet (see Fig. 4 and Fig. 5). Although Nd-Fe-B sintered magnets with low Dy content produced using this proprietary Dy diffusion process are subject to restrictions including magnet thickness and specific surface area, the coercivity is approximately 25% better than that of magnets produced using the previous process. As a result, the process allows the magnets' thermal characteristics (loss of magnetism due to heat) to be significantly improved while maintaining the same magnetic flux density (Br) as the previous process. Alternatively, if the thermal characteristics are kept the same as magnets produced by the previous process, the new process can be used as a way of improving the energy product.

Magnets made using this Dy diffusion process are already entering full-scale production for specific applications. In terms of their abundance in the Earth, rare-earth metals are quantitatively not that rare. However, locations where these materials are mined for use in magnets are limited and this results in problems such as price volatility and uncertainty of supply. Hitachi is currently working on recycling technology for recovering the magnets from motors and reusing the rare-earth materials they contain as a way of making effective use of these materials and ensuring a reliable supply of magnets.

Soft Magnetic Core Materials (Amorphous Materials)

Amorphous materials have lower iron loss than electrical steel sheet, a feature that is taken advantage of by using the material for winding cores in highly efficient transformers for electricity distribution (see Fig. 6). However, sheets of amorphous materials are very thin (approx. 25μm) with a high hardness (Hv) of approximately 900 making them difficult to punch and form into laminated cores. Accordingly, Hitachi has been investigating how to use amorphous materials as winding cores in electric motors in order to take advantage of their low iron loss characteristics. To reduce the losses caused by eddy currents due to the rotating magnetic field when a winding core is used as a stator in a rotating machine, an axial gap structure was selected instead of a radial gap structure. Table 1 lists a comparison of the characteristics of an amorphous material and electrical steel.

The iron loss for the amorphous material in a 50-Hz, 1.3-T magnetic field is less than one-tenth that of standard non-directional electrical steel. This is because the material has low coercivity, which is

TABLE 1. Comparison of Material Characteristics

The low coercivity and high electrical resistivity of iron-based amorphous metal give it excellent iron loss characteristics with hysteresis loss and eddy current loss both less than for electrical steel.

	SA1 iron-based amorphous metal	35A300 electrical steel sheet
High magnetic saturation flux density (T)	1.56	2.10
Coercivity (A/m)	6	45
Iron loss (W/kg)*	0.07	1.90
Resistivity (μΩm)	1.30	0.5
Sheet thickness (mm)	0.35	0.025
Tensile strength (GPa)	1	0.52
Hardness (Hv)	900	187

* Iron loss at 1.3 T/50 Hz

Fig. 6—Amorphous Ribbon.
This wide Fe-based amorphous ribbon is produced using a melt spinning process with excellent productivity.

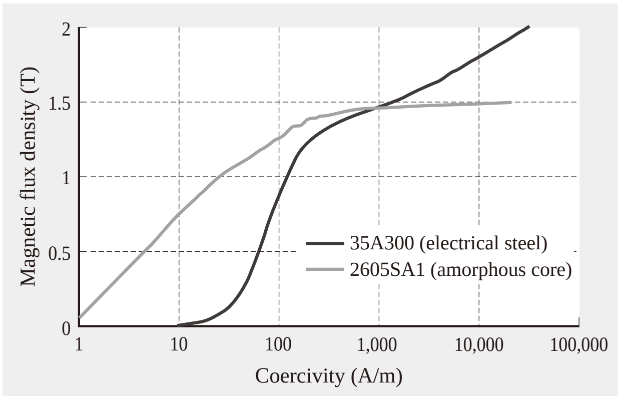


Fig. 7—Comparison of Excitation Performance of Amorphous Material and Electrical Steel Sheet.
The amorphous material causes the magnetic flux to saturate at a low excitation field strength.

Table 2. Specifications of New Motor
The specifications of the new motor were determined with the aim of achieving equivalent chassis size, output, and efficiency to existing radial gap motors that use rare-earth magnets.

Phases	3
No. of stators	12
No. of rotor poles	8
Motor size (mm)	ϕ100 × 60
Rated speed (rpm)	3,000
Rated torque (N · m)	0.64
Output	200
Rotor magnet	Sintered ferrite

what determines its hysteresis loss, and approximately double the resistivity of electrical steel sheet, which is what determines its eddy current loss. Fig. 7 shows a comparison of the excitation performance of a laminated amorphous core and electrical steel sheet.

Table 2 lists the specifications of a newly developed motor. The motor has an 8-pole, 12-stator configuration and a three-dimensional FEM (finite element method) analysis that considered the space factor of the amorphous cores was performed to verify that the desired torque could be obtained using ferrite sintered magnets in the rotor. Fig. 8 shows the structure of the new axial gap motor. A prototype of the motor achieved a high efficiency of 85% under rated conditions (see Fig. 9). Further improvements to the structure of the prototype motor achieved even higher efficiency by reducing cogging torque. Fig. 10 shows the motor's output characteristics. Hitachi is currently drawing on technology from across the group to commercialize amorphous-core motors in anticipation of producing an innovative motor that can take advantage of the superior iron loss characteristics of amorphous materials.

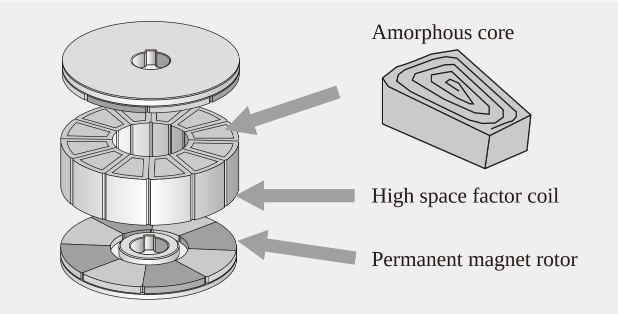


Fig. 8—Structure of Axial Gap Motor.
The motor has an axial gap design with an amorphous winding core and double rotors with ferrite sintered magnets.

Fig. 9—New Motor.
The motor is designed for easy assembly with twelve amorphous winding cores located around the circumference.

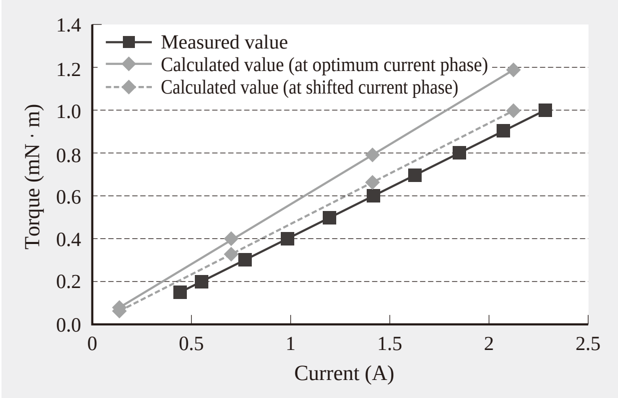


Fig. 10—Output Characteristics of New Motor.
The torque characteristics measured on the prototype motor matched the design simulation.

MOTOR WIRE MATERIALS

As the 21st century proceeds, the growing awareness of global environmental problems is seeing motors being made progressively smaller and more efficient to save energy. The requirements for the heat-resistant enameled wire used in these motors include improved slot space factor, better adhesion to impregnating varnish, and ability to withstand high-voltage drive under inverter control.

Against this background, Hitachi Magnet Wire Corporation has been working to support the adoption by its customers of more sophisticated electric drive technology by developing enameled wire through improvements to existing material technologies. It intends to continue developing advanced products that are even easier to use.

(1) Improving coil insertion performance and impregnating varnish adhesion of heat-resistant, self-lubricating enamel wire

Increasing the wire space factor to improve motor efficiency makes it more likely that the coating will be scratched when the coil is inserted. Also, high

Table 3. Examples of Key Characteristics of New Heat-resistant Self-lubricating Wire (ϕ0.82 mm, type 0)
Although the low-insertion-force type has poor adhesion to the impregnating varnish, coil insertion performance is good.

Parameter	New self-lubricating amide-imide wire (KMK-22A)		Amide-imide wire (AIW)	Remarks
	Standard type	Low-insertion-force type (under development)		
Static friction coefficient	0.045	0.045	0.12	Inclining method
Coil insertion force (index)	100	70	>120	68% space factor
Adhesion to impregnating varnish (index)	90	60	100	Unsaturated polyester, NEMA method

NEMA: National Electrical Manufacturers Association

output requires a high degree of adhesion with the impregnating varnish. In response to these challenges, Hitachi utilized advanced surface analysis techniques to develop two different types of self-lubricating amide-imide coating. New standard-type and low-insertion-force-type heat-resistant, self-lubricating enamel wires are being developed that use these as the outermost layer of the enamel.

Table 3 lists some examples of the main characteristics of the self-lubricating amide-imide wire. The standard type strikes a balance between ease of coil insertion and adhesion with the impregnating varnish whereas the low-insertion-force type has somewhat inferior varnish adhesion but has low coil insertion force making it suitable for concentrated windings and other severe winding applications. The aim for the future is to use the low-insertion-force type as the basis for further improvement of the varnish adhesion.

(2) Heat-resistant enameled wire with strong ability to withstand inverter surge

Measures are needed to prevent partial discharges from damaging the skin of enameled wire due to the surge voltage that occurs in applications such as high-voltage drive of automotive electric motors or when inverter control is used to make equipment more energy efficient.

Although inorganic materials are typically less susceptible to damage by partial discharge, they are hard and brittle making them less flexible. However, Hitachi has succeeded in combining flexibility with surge resistance by creating a nano-composite of silica nano-particles in EI (poly ester-imide) or AI (poly amide-imide) resin. In particular, its KMKED-20E ester-imide enameled wire designed to give good protection from inverter surge was first introduced in Japan for use in industrial motors in 2000. The enamel structure includes an outer surge-protection layer of self-lubricating amide-imide that is coated onto the wire. Fig. 11 shows the dispersion of silica nano-particles in the enamel and Fig. 12 shows the V-t life of the wire. Compared to standard heat-resistant wire [AIW (amide-imide wire) and EI/AIW (ester-imide/amide-imide wire)], the life at 1.1 kVp of the new enameled wire is more than 1,000 times longer and the self-lubricating amide-imide outer layer coated onto the wire gives it good winding characteristics.

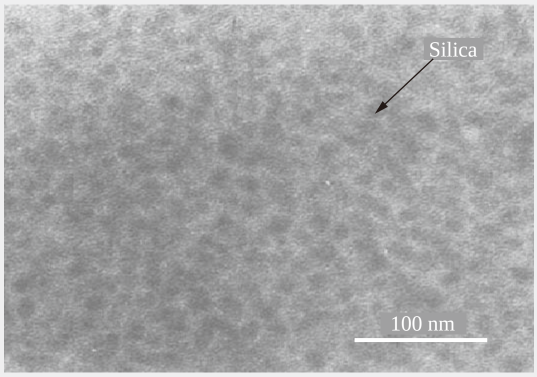


Fig. 11—Dispersion of Nano-silica.
The transmission electron microscope image of the ester-imide base shows how the nano-silica is evenly dispersed.

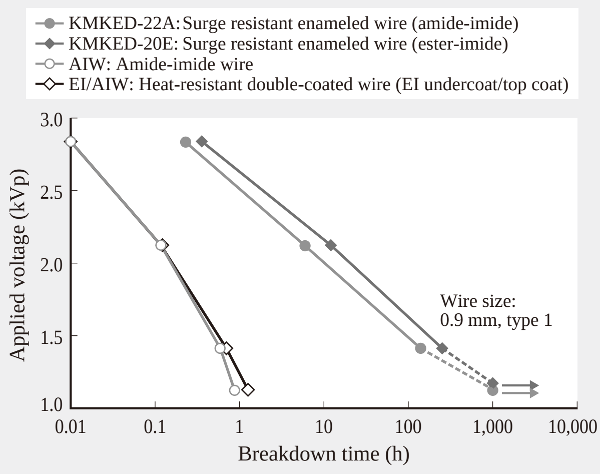


Fig. 12—V-t Life of Surge Resistant Enameled Wire (Sine Wave).
The 1.1 kVp life of the surge resistant enameled wire is more than 1,000 times longer than that of standard heat-resistant wire.

Hitachi intends to continue working on development and commercialization aimed at reliability, functionality, and other improvements, including improving the reliability of rectangular wire so that it can be used to achieve higher space factor, better flexibility to allow the coil end to be made smaller, and improving the mechanical strength and varnish adhesion of self-lubricating wire.

VARNISH INSULATION

The main insulators used in motors are as follows.

(1) Coating used on enameled wire
(2) Impregnating varnish
(3) Finishing varnish
(4) Powder coating
(5) Casting resin
(6) Insulating paper or film
(7) Insulating tape, tube for enclosing bare wire tips, coil binding thread

Appropriate materials are chosen to meet the desired motor specifications. The following section looks specifically at the impregnating varnish.

Impregnating varnish is used to hold the coil together, suppress vibration, dissipate heat, protect against moisture and dust, and provide additional insulation. Processing techniques include dipping and drip-feed application and the coil is typically preheated to drive out moisture prior to applying the varnish.

Table 4 lists the different types of impregnating varnish that have been supplied by Hitachi Chemical Co., Ltd.

TABLE 4. Different Types of Impregnating Varnish Supplied by Hitachi Chemical Co., Ltd.
Hitachi Chemical got its start in 1912 with the commencement of research into insulators. Since then, it has utilized a wide variety of materials development technologies to devise products suitable for changing technologies.

Year	Activity
1912	Recognizing that it would need to supply its own insulators if it was to start domestic production of electrical machinery in Japan, Hitachi, Ltd. embarked on a program of research and development (formation of Hitachi Chemical).
1914	Production of coil impregnating varnish commenced. • Oil-based varnish
1940	• Phenolic varnish
1950	• Phenolic modified oil-based varnish
1960	• UP varnish • Phenolic modified alkyd varnish • Silicone varnish • Epoxy ester • Melamine modified alkyd
1965	• Epoxy varnish
1970	• Heat-resistant alkyd
1975	• Flexible high-strength UP varnish
1980	• UV-curable UP varnish
1985	• Highly heat-resistant UP varnish
1990	• Quick-curable UP varnish
1996	• UP varnish with low-odor hardener • Epoxy varnish for hermetic motors • Insulating varnish production plant commissioned in Malaysia.
2000	• Water-soluble varnish for motors • Heat-resistant varnish with heat-conducting filler
2004	• RoHS-compliant varnish (elimination of lead, etc.)
2005	• Insulating varnish production plant commissioned in Guangdong Province, China

UP: unsaturated polyester UV: ultraviolet
RoHS: Restriction of the Use of the Certain Hazardous Substances in Electrical and Electronic Equipment

The table shows how the different types of impregnating varnish have been characterized by their heat resistance, humidity resistance, faster setting speed, high strength, chemical resistance, environmental performance, and other technical changes.

In particular, motor varnishes with low VOC levels have been formulated in response to the growing awareness in recent times of the need to protect the environment. VOC is the generic name for volatile organic compounds that enter the atmosphere in gaseous form and are recognized as a cause of atmospheric pollution. Because of recent legal restrictions relating to environmental measures (restrictions on VOC emissions) and voluntary action by businesses, there is a need for efficient ways of minimizing emissions.

To minimize the release of VOCs during varnish application in the field of electrical insulators, catalytic combustors are being fitted to varnish processing equipment to act as treatment systems that can prevent VOCs from being released externally.

However, a proportion of the VOCs still escape to the atmosphere creating a need for varnishes with low levels of VOCs.

Meanwhile, rapid advances being made in increasing the output and reducing the size of automotive motor/generators, industrial motors, and other similar equipment are resulting in higher coil temperatures during operation which in turn means that the materials used must be able to withstand high levels of heat.

In seeking to achieve environmentally considerate manufacturing, Hitachi Chemical has developed a low-VOC varnish for motors that reduces the levels of VOCs released during varnish application to one-fortieth that of previous varnishes. Compared to previous varnishes, this new low-VOC varnish

TABLE 5. Characteristics of New Low-VOC Varnish
The newly developed varnish which has yet to be released has excellent heat-resistant characteristics and contains significantly less VOC than the existing WP-2820(GN) varnish.

Item	New low-VOC varnish	Existing WP-2820 (GN)
Features	Low VOC, heat-resistant	Strongly adhesive
Base resin	Unsaturated polyester	Unsaturated polyester
Flashpoint of main ingredient (ºC)	180	31
Curing agent	CT-50, 1.5%	CT-50, 1.5%
VOC (%)*1	<1	40
Heat-resistance temperature (ºC, MW35C)*2	200	180
Adhesive strength (N, 23ºC)*3	680	630
Varnish application method	Drip	Dipping, drip
Curing conditions (ºC/h)	130/1	130/1

VOC: volatile organic compound
*1: Determined by measuring the weight loss that occurs during curing when 5.0 g of varnish is taken on a metal dish (60-mm diameter)
*2: Thermal degradation promotion test using helical coil and twisted-pair wire
*3: Stracker method (2.0-mm diameter AIW)

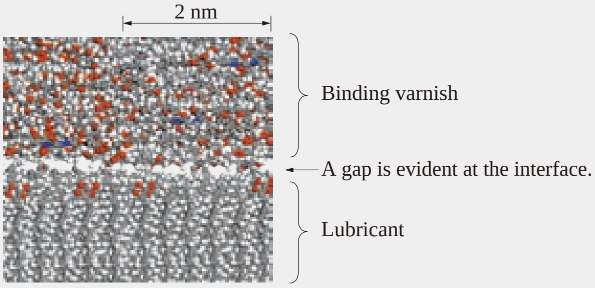


Fig. 13—Adhesive Interface between Enamel Coating Surface and Binding Varnish.
An atomic-scale representation of the interface structure obtained by solving the fundamental equations of quantum and classical mechanics.

provides both lower levels of VOCs and high heat-resistance (200°C) (see Table 5). It is anticipated that this varnish will be used in fields such as the automotive industry where there is strong demand for more compact motors with higher output.

USE OF SIMULATION IN DESIGN OF NEW MATERIALS

In the past, the conducting of experiments has been the most commonly used technique for determining structure and composition when designing the materials described in this article. However, recent progress in computational science and computing capability has made it possible to predict the physical properties of materials by solving the fundamental equations of quantum mechanics (Schrödinger's equation) and classical mechanics (Newton's equation of motion) for the behavior of electrons and atoms respectively, and this has opened up the potential for using simulation to design materials. Examples include the ability to predict the magnetic properties of magnetic materials used in motors or the electrical characteristics of wires. The following section describes a more intuitive example in which simulation is used in material design to determine the adhesive strength between enamel coating and the varnish used to hold the enameled wire in place.

The need for high-density winding of enameled wire has strengthened in recent years in order to make motors smaller and improve their performance. However, concerns that forming highly dense windings will result in abrasion or other damage to the enameled wire have led to the use of enameled wire and its lubricant separates itself onto the surface of the enamel coating. Because the lubricant is present on the surface to which the binding varnish is meant to adhere, there is a need to design a binding varnish with excellent adhesion strength to the lubricant.

Fig. 13 shows the structure of the interface between the lubricant and binding varnish obtained by solving Schrodinger's equation and Newton's equation of motion. The small spheres in the figure represent atoms, with oxygen shown in red, carbon in grey, hydrogen in white, and nitrogen in blue. This provides an indication of the tensile force (energy) at the interface where the two materials are bonded and the adhesion strength can be estimated by calculating how much energy is needed to separate the two materials (see Fig. 14). This energy required for separation is called the delamination energy. For example, the delamination energy for the situation shown in Fig. 13

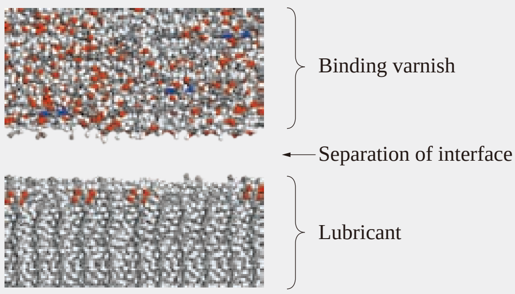


Fig. 14—Interface between Lubricant and Binding Varnish after Separation.
This shows the case after a tensile force (energy) has been applied to separate the bond interface shown in Fig. 13.

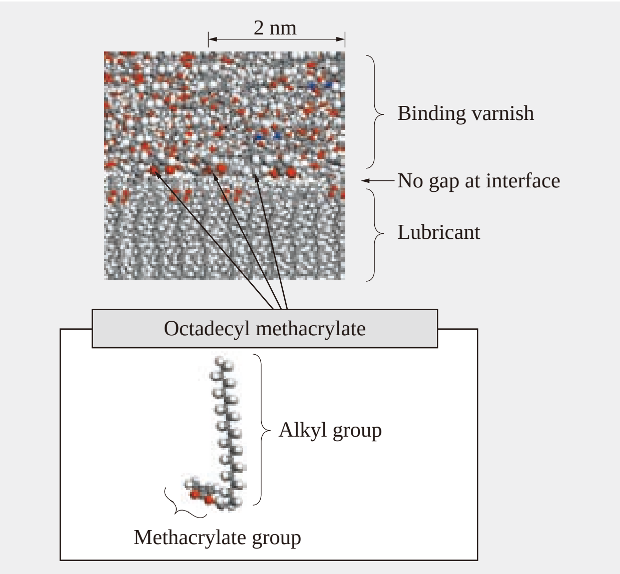


Fig. 15—Interface When Additive Molecules Are Included in Binding Varnish.
The additive molecule's methacrylate group moves downward and the alkyl group moves upward to create a tighter interface than that shown in Fig. 13.

and Fig. 14 is 0.0885 J/m^2. In contrast, the estimated delamination energy for the interface formed when octadecyl methacrylate is added to the binding varnish to a concentration of 1% (see Fig. 15) is 0.121 J/m^2, an improvement in adhesion strength of approximately 37%. Fig. 15 also shows how the added molecules (shown as large spheres) form a tighter interface with the methacrylate group (functional group with two oxygen atoms) moving downward and the alkyl group (functional group with CH_2 chain) moving upwards. The result is that the gap in the interface visible in Fig. 13 is no longer present.

In this way, simulation not only provides a numeric estimate for the improvement in adhesion strength, the atomic-scale picture also provides an understanding of the detailed mechanism responsible for that improvement and it is anticipated that the technology will be able to be utilized for identifying a wide range of new materials in the future.

CONCLUSIONS

This article has described the latest technologies and considered the issues facing the key materials used in electric motors, especially permanent magnets, core materials, wire, and varnish, in terms of their role in reducing motor losses and minimizing the burden on the environment.

It is expected that in the next five or more years motor output density will increase from its current level of 2.5 kW/kg to reach 4.5 kW/kg. This will place strong demands on motor materials in terms of their heat-resistance, machinability, and other characteristics. The Hitachi Group includes companies that produce materials to underpin higher motor performance and efficiency, and by working together these companies believe they can supply the divisions responsible for motor design and production with suitable materials.

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