TECH JOURNAL

Higher performance for neodymium magnets

HAL (High-Anisotropy field Layer) production process

A new method for producing neodymium magnets that takes dysprosium-saving to the extreme

Since they were commercialized in 1983, neodymium magnets (sintered neodymium-iron-boron magnet, TDK product name: NEOREC) have maintained their position as the most powerful type of magnet known to industry. Demand for these magnets continues to grow in many fields, for example actuators that drive magnetic heads on hard disk drives, motors used in industrial equipment and energy-saving appliances, and more recently in the drive motors used in HEVs and EVs. Neodymium magnets are made of two rare earth elements, Nd (neodymium), and Dy (dysprosium) -- which is particularly scarce and expensive; to increase a magnet's coercive force TDK has newly developed its HAL (High-Anisotropy field Layer) production process which achieves dramatic reductions in the amount of Dy used, and still improves magnetic properties. We have succeeded in improving the performance of these magnets by optimally diffusing minimum amounts of Dy into substrates consisting of neodymium magnets that are among the best in the world.

Neodymium magnets were created in the pursuit of compositions with no samarium or cobalt

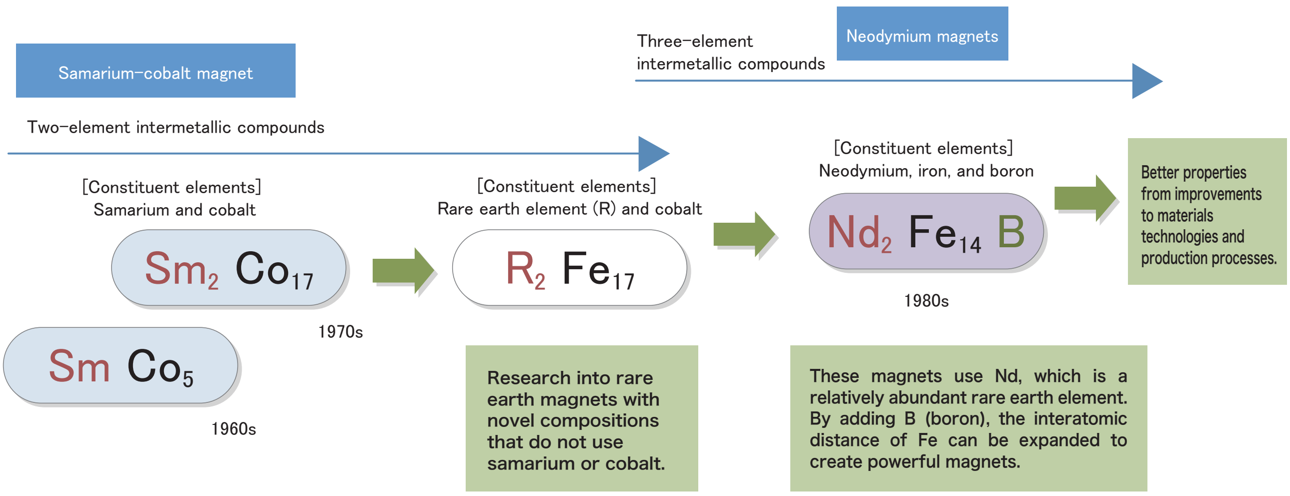
The first rare earth magnet, the samarium-cobalt magnet developed in the 1960s, made an impressive debut as a revolutionary and innovative type of magnet that considerably outperformed alloy magnets; these alnico or alloy magnets were the most powerful magnets of their day, and were the enabling force behind lighter and more compact electronic devices, and the portable audio players that became a global sensation. However, because the supply of these elements was unstable -- samarium was a rare earth element that was in scarce supply, and cobalt could be mined only in certain regions -- scientists around the world carried out research on rare earth magnets with different compositions.

As a result of these efforts, a neodymium magnet was developed that used iron, an inexpensive element, instead of samarium, neodymium, or cobalt. Neodymium is the third most abundant rare earth element in the earth's crust after cerium and lanthanum, and more than 10 times as much of the mineral is mined as samarium.

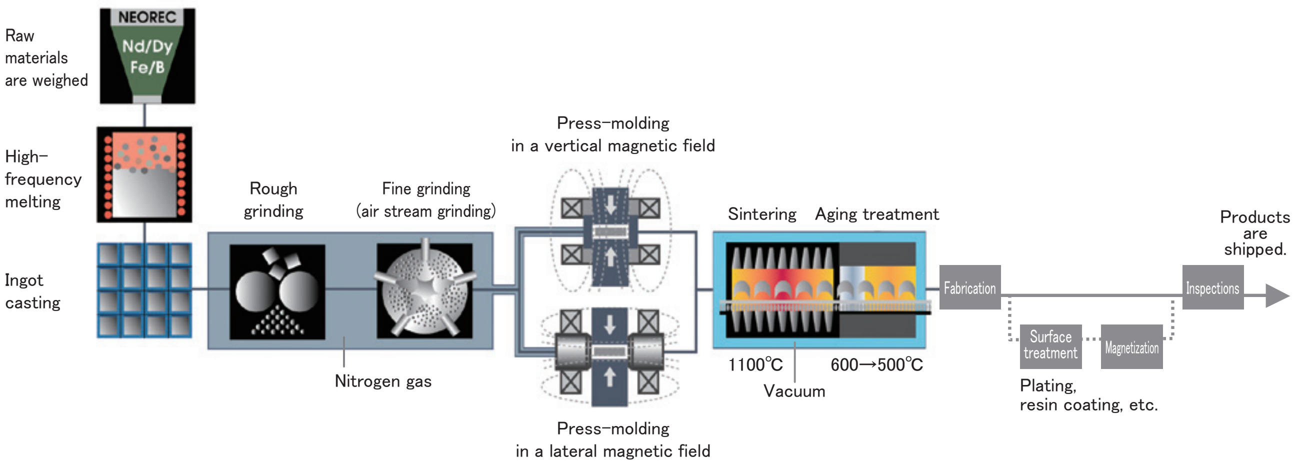
Ferromagnetism refers to the characteristic of elements which attracts them to magnets. And while the most representative of these ferromagnetics are the iron group of elements (iron, cobalt, and nickel); some rare earth elements also exhibit ferromagnetism. The source of a magnet's magnetism is the magnetic moment of its electrons. In iron group elements, the magnetic moment of electrons in the 3d orbit carry the magnetism, while in rare earth elements, electrons in the 4f orbit are involved. Rare earth magnets are based on an ingenious combination of the functions of 3d electrons of iron group elements, and that of 4f electrons of rare earth elements.

A neodymium magnet is a three-element intermetallic compound that contains neodymium, iron, and boron at a basic composition ratio of 2 : 14 : 1. The nonmagnetic element boron is used to increase the interatomic distance of iron by a slight amount. By achieving this exquisite interatomic distance, the orientation of the electrons' magnetic moment becomes fixed, making the metal a powerful magnet.

□Development of rare earth magnets



□Neodymium magnet manufacturing process



Manufactured in a ppm-order, low-oxygen process to eliminate oxides

Similar to electro-ceramic materials, sintered neodymium magnets are manufactured by forming and baking highly pure raw materials. Therefore, a neodymium magnet constitutes a polycrystalline body which is a collection of a large number of fine $Nd_2Fe_{14}B$ crystalline particles.

Since they were first commercialized in 1983, the properties of neodymium magnets have continued to improve every year. The highest maximum energy product (BHmax) -- one of the indices of magnet performance -- of these magnets when they were first invented ranged from 30 to 40MGOe. Current magnets are capable of 59MGOe in the lab, with production neodymium magnets delivering 55MGOe or more. These advances are a result of improvements to material technologies and production technologies.

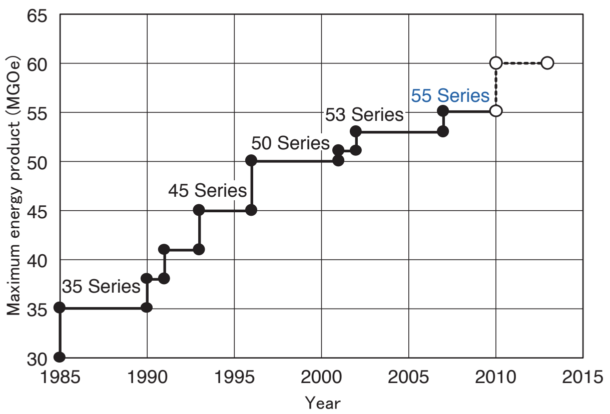
Before they are baked, neodymium magnets are press-formed in a magnetic field. Uniform powder granularity results in better orientation, which leads to a more powerful neodymium magnet.

Controlling the microstructure in the baking process is another key technological area. The polycrystalline body of neodymium magnets consists of three phases: $Nd_2Fe_{14}B$ crystalline particles which make up the main phase, an Nd-rich phase which is produced around these crystalline particles, and grain boundaries or the boundaries between the crystalline particles.

Because it is the $Nd_2Fe_{14}B$ phase which produces the magnet's magnetism, the relative proportion of $Nd_2Fe_{14}B$ must be increased by eliminating impurities as much as possible. Thanks to technological advances, this proportion, which was at around 90% in 1990, has now been improved to 97% or more.

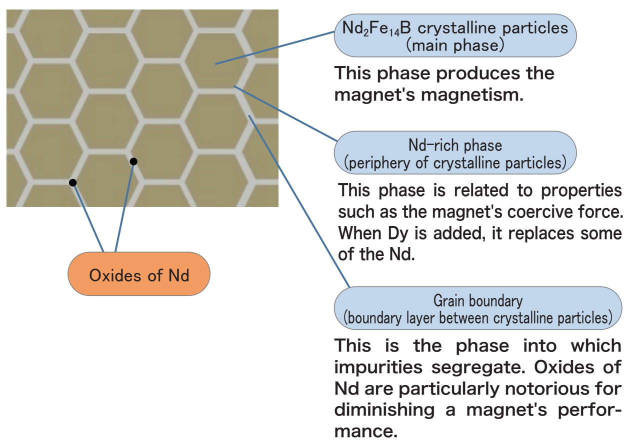
Additionally, we must thoroughly eliminate impurities that segregate into the grain boundaries. The primary impurity is an oxide of Nd (Nd_2O_3) that is created when Nd oxidizes in the manufacturing process. Not only does this Nd oxide not contribute to the magnetic properties of these magnets, it is actually a major factor that diminishes magnet performance. What is more, such impurities cannot be removed once the magnet has been formed. This is why our magnets are made in a low-oxygen environment where oxygen levels are maintained at the ppm level. As you can see, the levels of technology that are required for manufacturing neodymium magnets are significantly more demanding than those required for the simple casting of alloy magnets.

□Advancements in the performance of TDK neodymium magnets (NEOREC)

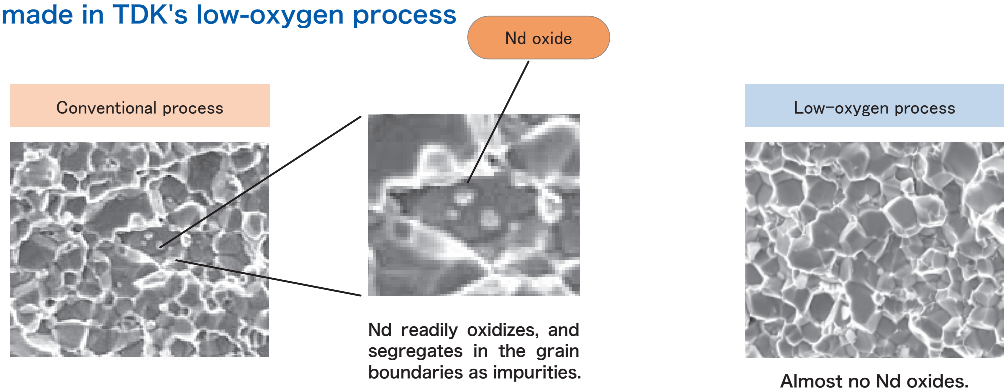


□Diagram of the microstructure in neodymium magnets

<The microstructure of sintered neodymium magnets consist of three phases>



□SEM images of a neodymium magnet manufactured using a conventional process, and one made in TDK's low-oxygen process



Dysprosium is added to improve the coercive force of magnets

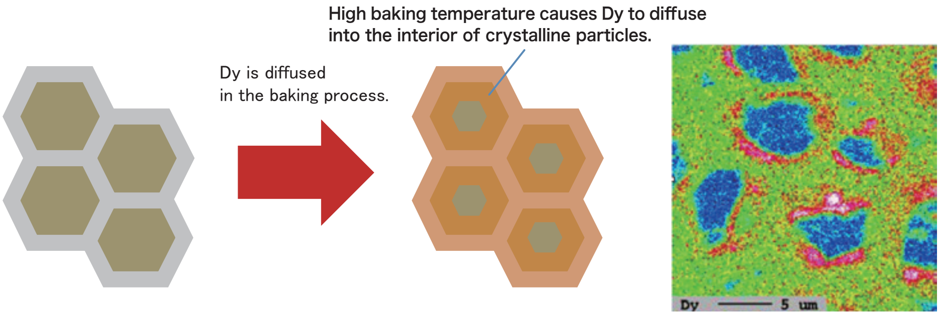
Dy (dysprosium), a rare earth element, is added to improve the performance of neodymium magnets. Dy replaces some of the Nd on the periphery of crystalline particles to improve the magnet's coercive force. However, because Dy is a rare earth element and its price is unstable, researchers have been exploring technologies for reducing the amount of Dy used. TDK's HAL process provides a solution to this issue.

HAL stands for "High-Anisotropy field Layer." Magnetic anisotropy refers to the magnetic moment of electrons which produce the magnetism being aligned in a certain direction, resulting in a particular orientation at which the magnetic material can be readily magnetized.

It has been well known that replacing some of the Nd with Dy has the effect of increasing a magnet's coercive force. An analogy for this would be how the sweetness of oshiruko, a sweet bean soup, can be made more intense by adding a small amount of salt in addition to sugar. In the same way, the adding of Dy in neodymium magnets is analogous to the exquisite salt seasoning of oshiruko; although to add Dy does require rather more sophisticated technology. By increasing the amount of Dy to increase a magnet's coercive force, its residual flux density is diminished; flux density is key to the strength of the magnet.

Also, in the past, a mixing method based on Dy addition was used to create high-anisotropy field layers (HAL structure). This is a process of mixing two alloys in appropriate amounts, one with a low Dy content, the other with a high Dy content, and baking the mixture to uniformly diffuse Dy throughout the formed polycrystalline body of the neodymium magnet. However, as the material had to be baked at high temperatures, a drawback of this process was the Dy would diffuse deep into the crystalline particles. TDK's HAL process provides a solution to this problem. Through a relatively low-temperature heat treatment, this new technology means Dy uniformly gathers non-centrally at the periphery of the crystalline particles, improving the magnet's properties.

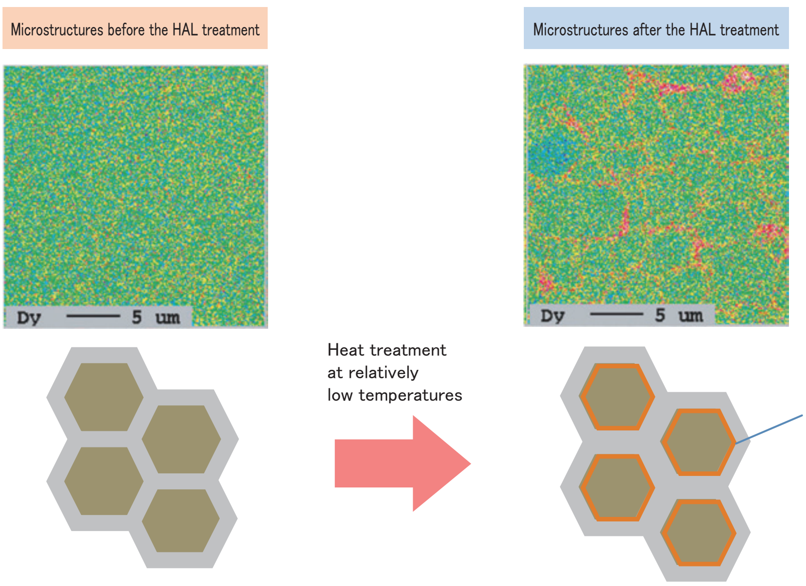
□Internal diffusion of Dy using a conventional mixing process



<Cross section showing Dy distribution in a neodymium magnet made using a conventional mixing process>

Due to internal Dy diffusion, the primary phases, which consist of $Nd_2Fe_{14}B$ crystals (blue areas), have become small.

□Optimum placing of Dy using the HAL process



<Cross section showing Dy distribution in a neodymium magnet made using the HAL process>

Dy gathers non-centrally at the periphery of crystalline particles.

The HAL process achieves better properties while reducing the amount of Dy used

In TDK's HAL process, a Dy source for diffusion is applied to the surface of a sintered neodymium magnet substrate, and then heat treated.

The Dy diffuses throughout the entirety of the material through the Nd-rich phases that surround the crystalline particles. And because the heat treatment used in the HAL process is performed at relatively low temperatures, Dy does not diffuse into the interior of the crystalline particles, and the $Nd_2Fe_{14}B$ phase that has replaced Nd gather non-centrally so as to cover the surface of the crystalline particles. Therefore, the roles of the $Nd_2Fe_{14}B$ phase which produces the magnet's magnetism, and that of the $Dy_2Fe_{14}B$ phase which is related to magnetic properties are clearly distinguished, paving the way for greater improvements to the coercive force.

A good substrate containing only small amounts of impurities is needed to implement the HAL process and achieve uniform Dy diffusion. Dy diffusion can be obstructed by impurities such as Nd oxides that segregate in the grain boundaries, causing uneven Dy distribution.

TDK neodymium magnets are made in a process which maintains extremely low oxygen levels. As a result, these magnets contain only small amounts of those impurities such as Nd oxides that can obstruct diffusion. They are therefore well suited for the HAL process, and enable ideal and uniform Dy diffusion.

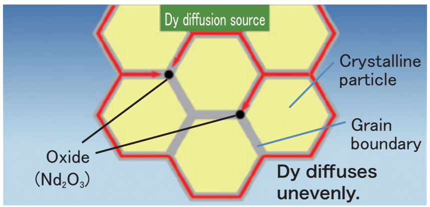
Additionally, sophisticated film-forming technologies accumulated by TDK over the years in the manufacture of magnetic tapes and chip components are applied to make the Dy diffusion source. While coercive force can be improved by replacing Nd at the periphery of crystalline particles with Dy, if this area becomes too Dy-rich, it can result in diminished residual flux density, which is related to the strength of the magnet. This is because the coercive force and residual flux density are in a quid pro quo relationship where an improvement in one results in a diminishment in the other.

By achieving optimum Dy diffusion using a Dy diffusion source that is evenly applied with only the required amount of Dy, TDK's HAL process has succeeded in dramatically improving on the properties of NEOREC55, a top-class conventional magnet. The HAL process -- a marriage between advanced materials technologies and process technologies -- enables smaller and higher-performing motors, and will contribute to the advance of energy savings and more environmentally friendly products.

□Dy diffusion obstructed by impurities

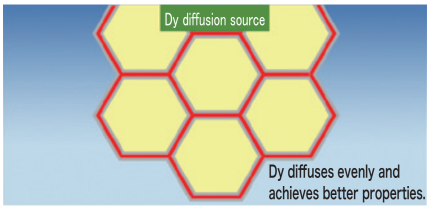
By applying a Dy diffusion source and then applying a heat treatment, the Dy diffuses through the Nd-rich phase at the periphery of crystalline particles.

Substrate with considerable amounts of impurities



The presence of impurities, such as Nd oxides, in the grain boundary layer obstructs diffusion, resulting in uneven Dy distribution and diminished performance.

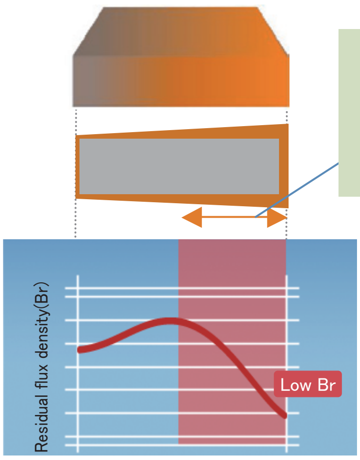
Substrate with only small amounts of impurities



TDK neodymium magnets are made in a low-oxygen process, resulting in only a small amount of impurities. This promotes the uniform diffusion of Dy and improves performance.

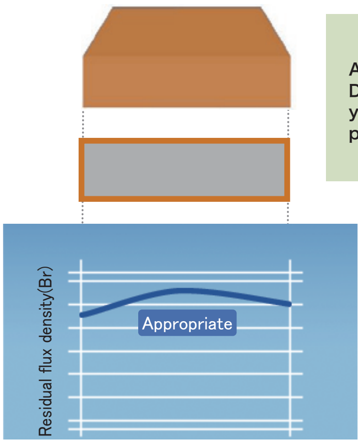
□Performance improvements enabled by the even forming of the source of diffusion

Dy diffusion source is formed unevenly on a neodymium magnet substrate.



Regions with excessive formation of the Dy diffusion source exhibit diminished residual flux density.

Dy diffusion source is formed evenly on a neodymium magnet substrate.



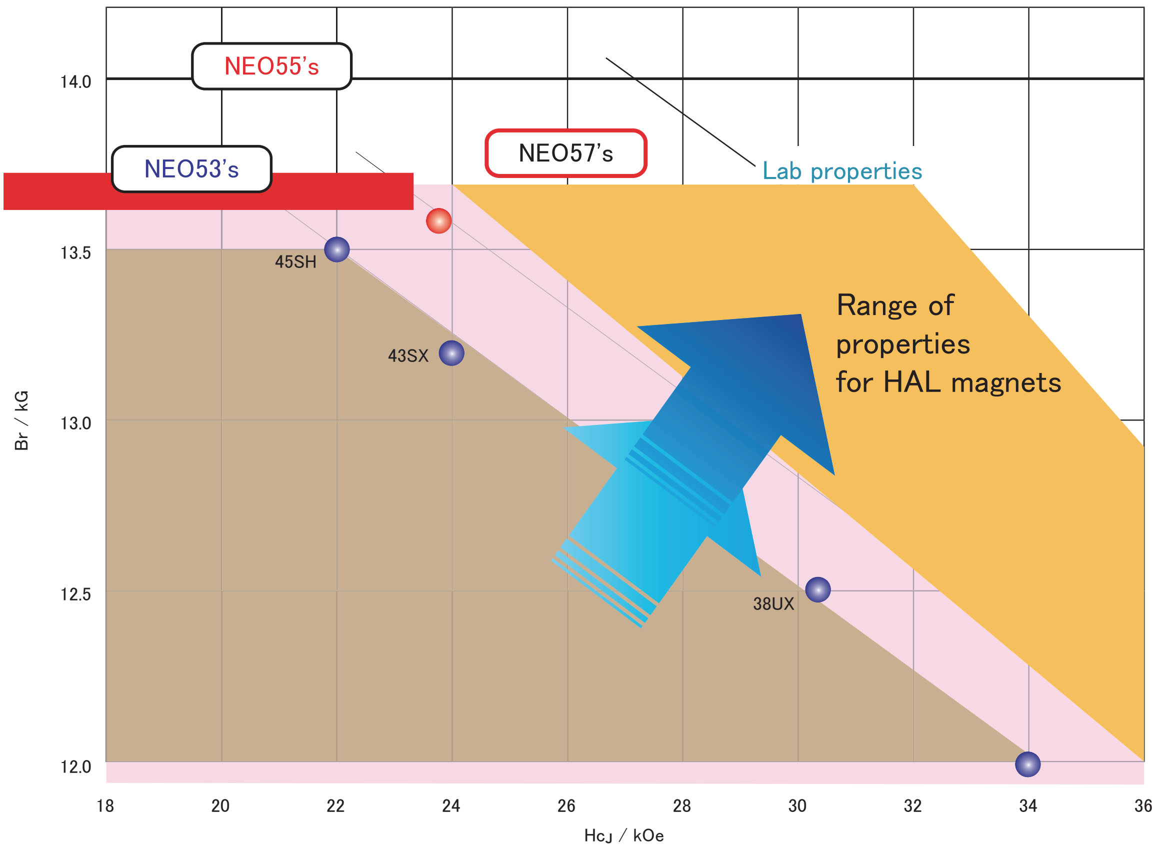
An evenly-formed Dy diffusion source yields appropriate properties.

Main Features

- TDK's HAL (High-Anisotropy field Layer) process diffuses Dy -- a scarce and expensive element that is added to improve performance -- only to those areas in neodymium magnets (TDK product name: NEOREC) where they are needed.
- Magnets with top-class performance are made by optimally diffusing Dy into a neodymium magnet substrate that is made in a low-oxygen process and contains only small amounts of impurities.
- These improvements in magnet performance enable smaller motors and greater efficiencies, and ultimately help achieve dramatic energy savings.
- Remanent magnetic flux density has been improved by 3-5%.
- Uses 20-50% less Dy, a rare earth element.
- By optimizing magnetic field orientation to suit specific applications, designers can achieve both superior magnetic properties and cost benefits.

Main Applications

Optimum for driving/generator motors for HEVs and EVs, as well as a broad range of other high-efficiency motors.



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