

Magnetic Form of Heavy Rare-Earth Free Motor for Hybrid Electric Vehicle

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ABSTRACT

As heavy rare earth elements are becoming less prevalent, because one-tenth as often in ore deposits as light rare earth elements. Future usage of need to be reduced heavy rare earth, because of resource risks and costs. As such, a method was developed to recover reductions in coercive force and prevent demagnetization temperature from reducing without adding any heavy rare earth elements.

First, a heavy rare-earth-free magnet was developed by hot deformation, which limits growth of crystal grain size, and relationships were clarified between coercive force and optimal deforming temperatures, speed, and total rare earth amounts for heavy rare-earth-free magnets.

Second, it was made clear that the permeance coefficient can be increased by reshaping the flux barriers, and that the developed hot deformed magnet can be adopted.

In this study, a new motor was developed using heavy rare-earth-free hot deformed magnets with performance and marketability equal to or higher than those of traction motors equipped in one-motor sport hybrid systems.

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1. Introduction

Amidst demands for the automotive industry to consider environmental impact and reduce CO₂ emissions, development of electric vehicles (EVs) is increasingly active. Neodymium iron boron magnets (neodymium magnets) currently produce the greatest maximum energy product (BH)_{max} and are used in traction motors for EVs and hybrid EVs (HEVs). As these magnets operate in high-temperature environments with strong demagnetizing fields, however, they require high heat resistance, or coercive force (H_{cj}). Accordingly, heavy rare earth elements with their high anisotropic magnetic fields are being added to increase H_{cj} values.

The leading rare earth deposits are not distributed evenly, however, with production in recent years limited to the countries shown in Figure 1. Further, as heavy rare earth elements occur less than one-tenth as often in ore deposits as light rare earth elements, usage needs to be reduced in light of the risks and cost of working with such a scarce resource.

Without heavy rare earth added, neodymium magnets will have reduced H_{cj} at high temperatures in strong demagnetizing fields. Therefore, to reduce the amount of heavy rare earth used, engineers need to reduce the demagnetizing fields acting upon magnets and increase magnet permeance to allow use of low-H_{cj} magnets. As magnetic fields are affected by the shape of the rotor into which the magnets are inserted, rotor shapes that match such low-H_{cj} magnets need to be researched.

In terms of recent study for rotors, Kamiya et al. reported their research on how the angle and number of beams in V-shaped magnet arrangements relate to rotor strength and torque(2).

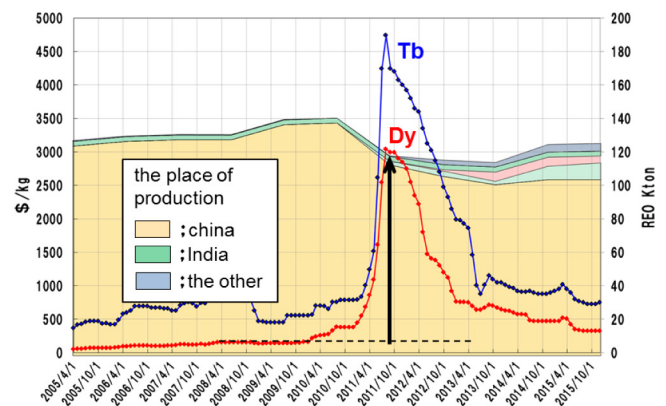


Figure 1. Global production of rare-earth oxides (1)

Also, while patents that create gaps close to the flux barrier in order to prevent magnetic short-circuits or change the order of the main and leakage magnetic flux are currently trending, neither of these applications has been implemented in an HEV traction motor.

Therefore, this study covers magnetic shapes that satisfy performance for HEV traction motors using hot deformed magnets having low H_{cj} but use absolutely no heavy rare earth elements.

2. Motor Description

The motor in this study is a traction motor equipped in Intelligent Dual Clutch Drive (i-DCD)(3), a one-motor hybrid system suitable for compact-class cars.

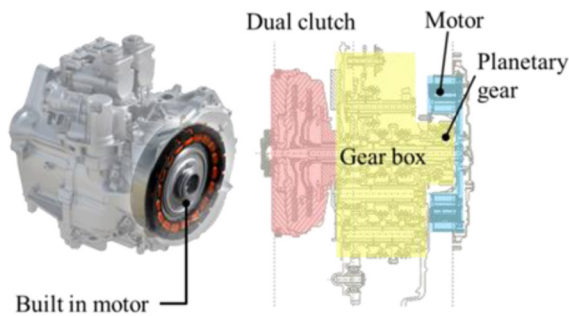


Figure 2. Layout of one-motor sport hybrid system

As shown in Figure 2, the i-DCD system is an efficient hybrid system with a powertrain consisting of one motor mounted within a dual-clutch transmission. Initially offered on 2016 Japanese model hybrid minivans, the system has since been equipped on various models of compact cars, sedans, and SUVs.

Motor demand specifications are given in Table 1. Given the motor space constraints, a compact, efficient Interior Permanent Magnet Synchronous Motor (IPMSM) has been adopted.

Table 1. One-motor sport hybrid system specifications

Type	IPMSM
Phase	3
Number of poles	6
Coil turns	55
Cooling system	Oil-cooled
System voltage [V]	173
Maximum motor power [kW]	22
Maximum motor torque [Nm]	160
Volume [L]	2.57
Peak Efficiency [%]	≤ 96

3. Methodology for Achieving a Heavy Rare-Earth-Free Magnet

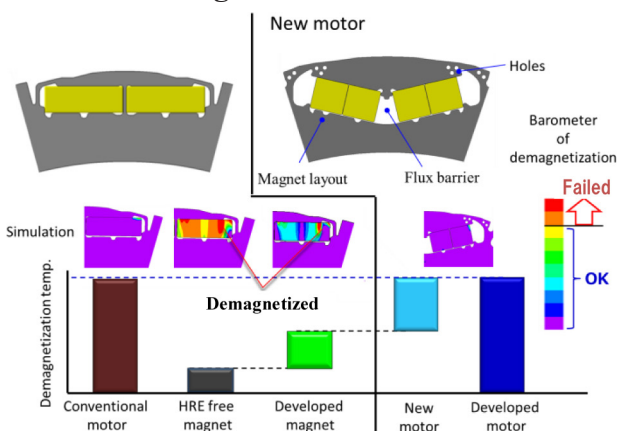


Figure 3. Scheme for heavy rare-earth free magnet

IPMSM have reluctance torque, generated by the difference between magnetic torque as generated by the magnet and the magnetic attraction force. Given the differences between the torque phases, the electric current phase is advanced in order to draw maximum torque in use. This applies a strong demagnetizing field upon the magnet, which will tend to be demagnetized.

Conventionally, high- H_{cj} sintered magnets are used to combat this inherent tendency for demagnetization. In order to use low- H_{cj} magnets, the number of winds in the coil can be reduced or the electric current levels can be lowered to weaken the demagnetizing field. However, in order for the IPMSM to remain usable in the one-motor hybrid system and achieve the target performance, these variables and volume cannot be changed.

Demagnetization is caused by the operating point entering the irreversible flux loss range due to B-H curve ranges reduced by temperature or to the anti-magnetic field generated by electric current from the stator.

Improving permeance is effective in resolving the demagnetization. However, as increase permeance is generally understood to reduce torque, striking a balance between demagnetization and torque can be challenging.

As shown in Figure 3, heavy rare-earth-free sintered magnets demagnetize at low temperatures.

In this study, the authors researched how to improve the demagnetization temperature by first determining trends in heavy rare-earth-free magnets. Then focusing on hot deformed magnets and researching how to advance their special qualities, also considering magnet shape and arrangement of the magnetic circuit and flux barrier shape.

4. Hot Deformed Magnets

It is known that magnets consist of main phase crystals surrounded by a grain boundary phase, and that H_{cj} can be raised by breaking up the main phase crystals or thickening the grain boundary phase to magnetically isolate the main phase crystals(4)–(6). Therefore, this study focused on developing a hot deforming method. Hot deforming produces a thin strip of nanometer-order (nm) crystalline by rapidly quenching melted raw magnetic material(7) at low temperatures around 700°C(8). As such, hot deforming allows for finer magnetic structures of a few hundred nanometers, less than one-tenth the size of those formed with sintering.

4.1 Conditions for Hot Deforming (Temperature and Processing Speed)

Figure 4 depicts scanning electron microscopic (SEM) images at different deforming temperatures for the heavy rare-earth-free magnets with properties improved in this development study. As the crystals grew and shapes flattened more the higher the deforming temperature rose, it was found that orientation was advancing. However, since deforming temperatures need to be reduced in order to maintain a finer magnetic structure, the temperature during the hot deformation process was reduced for this study to produce finer

crystal grains. Also, the plastic deformation speed was set so that relatively higher orientation degrees could be attained than with conventional methods even at the lower temperatures.

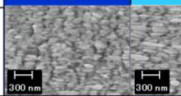
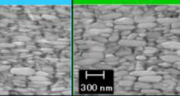
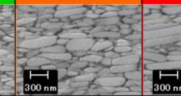
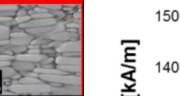
No.	No. 1	No. 2	No. 3	No. 4	No. 5
SEM image					
Grain size	126 nm	203 nm	295 nm	386 nm	571 nm
Deformed temp.	700°C	725°C	750°C	775°C	800°C

Figure 4. Grain size of hot-deformed- magnet at different deformation temperatures

4.2 Composition

The stoichiometric composition ratio of the main phase of neodymium magnets is an intermetallic compound represented as $RE_2T_{14}B$, where 'RE' is for rare earth and 'T' is for transition element. Given that there is also a grain boundary phase, however, the total rare earth amount (TRE) in the raw material alloy is actually greater than the stoichiometric composition ratio. Figure 5 depicts SEM images of both a conventional magnet with low TRE and H_{cj} levels and an enhanced magnet with higher TRE and H_{cj} levels. Thickening the grain boundary phase (white areas) helps to keep the main phase magnetically isolated and increase H_{cj} levels. TRE was increased within the range where main phase proportions were not greatly decreased, helping to enhance characteristics.

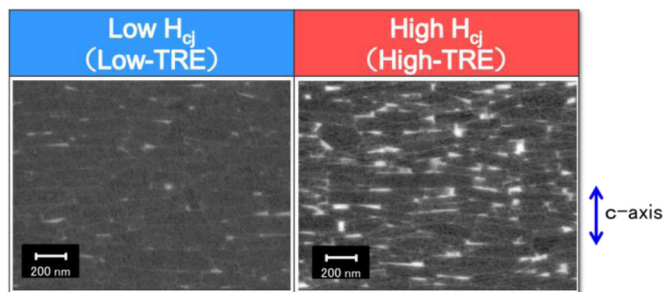


Figure 5. Crystalline structure of hot deformed magnet

4.3 Results

Figure 6 shows the magnetic properties of a conventional hot deformed magnet and the developed magnet. The composition of the developed magnet was determined such that hot deformation temperature would be lowered, plastic deformation conditions optimized, and grain boundary phase optimized as well. Refining the crystal grains and enhancing magnetic isolation for the main phase served to increase H_{cj} levels by 6%. Also, enhancing the degree of orientation while keeping the microstructure intact increased remanence (B_r) by 2%

While H_{cj} levels generally fall at high temperatures, the rate of decrease is dependent upon grain size(5). As a side effect of the finer crystal grains, a correlation was observed between the temperature coefficient of H_{cj} (β /%°C) and grain size (Figure 7).

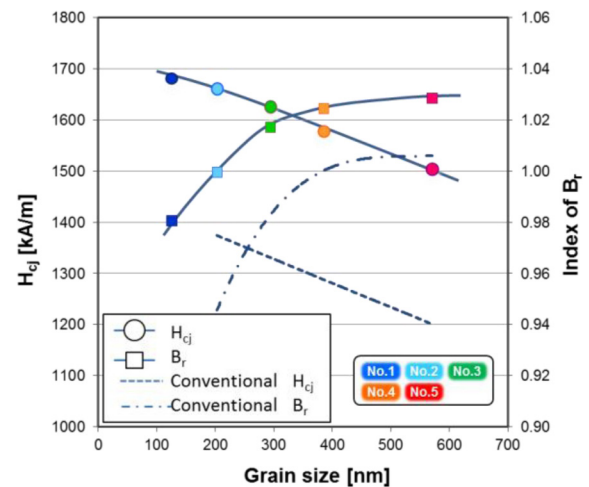


Figure 6. Relationship between grain size, H_{cj} , and B_r

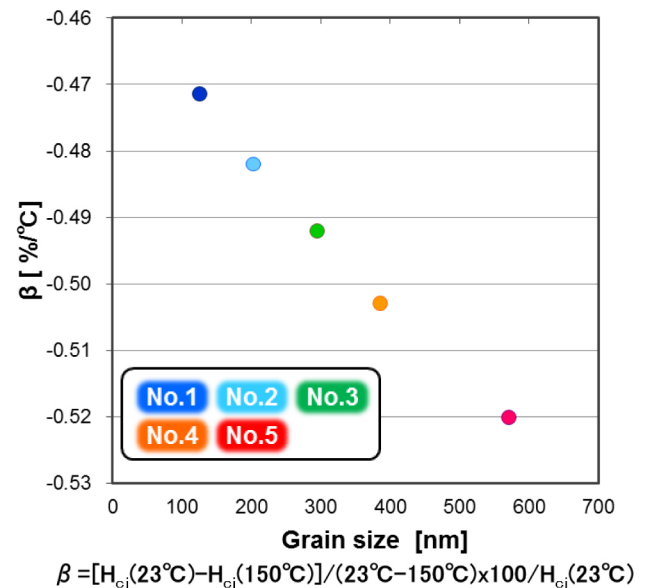


Figure 7. Relationship between grain size and temperature coefficient of H_{cj} (β)

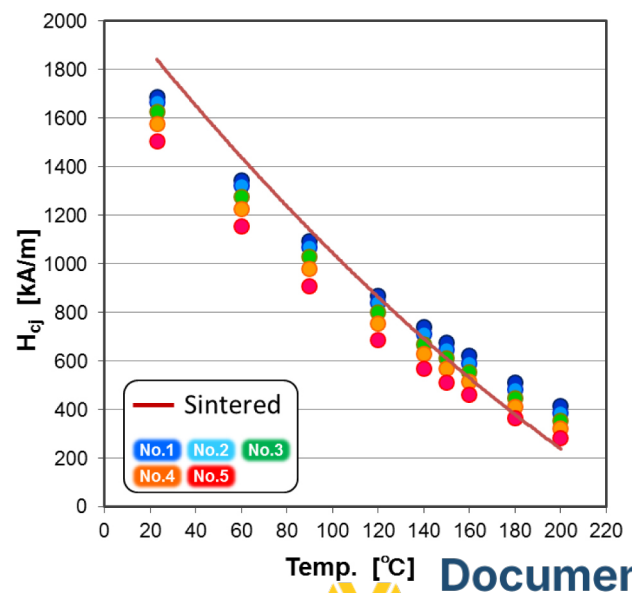


Figure 8. Temperature-dependence of H_{cj} in hot-deformed magnets and sintered magnets