

Heavy Rare Earth-free Hot-deformed Magnet for Traction Motor

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ABSTRACT

A technology has been developed making it possible to do away with the use of the heavy rare earths dysprosium and terbium, which are added to the magnets employed in traction motors for application in electric vehicles and hybrid electric vehicles in order to increase heat resistance. The research focused on the hot-deformation method of magnet manufacture, which offers greater potential for the realization of heat resistance than the sintering method, the main method of manufacturing the magnets currently in use. The magnetic properties of the developed magnet were boosted by reduction of the temperature for hot-deformation and the optimization of the rate of hot-deformation and the composition design of the magnet material. These approaches made it possible to develop a completely heavy rare earth-free magnet able to be employed in mass-production vehicles.

1. Introduction

Neodymium magnets, formed from an alloy of a rare earth, iron, and boron, were invented by a Japanese researcher in 1982⁽¹⁾. Because they display the highest maximum energy product $[(BH)_{\max}]$ among existing permanent magnets and are able to be manufactured in high volumes using a sintering method, neodymium magnets have found use in a wide range of applications. The neodymium magnets used in EV and HEV are also manufactured using a sintering method, but unlike the magnets used in home electronic appliances, these magnets are exposed to high-temperature and demagnetizing field environments. As a result, high coercivity (H_{cj}), an indicator of a high level of heat resistance, is demanded of these magnets. Heavy rare earths, which increase the anisotropy field of the main phase of the magnets, are therefore added in order to increase H_{cj} . In the case of the heavy rare earth dysprosium (Dy), 5-10 wt% is added; in the case of terbium (Tb), 1-5 wt% is added⁽²⁾. However, the amount of heavy rare earths contained in ores is less than 10% that of light rare earths, and regions of heavy rare earth production are limited. Taking a future increase in the number of EV into consideration, reduction of the volume of use of

heavy rare earths will be essential from the perspectives of the burden on the environment, the risk associated with scarce resources, and cost. It will therefore be necessary to determine a method of increasing H_{cj} other than by the addition of heavy rare earths to the magnet material.

Figure 1 shows a schematic image of the crystalline microstructure of a magnet. The microstructure is made up of a main phase and the grain boundary phase that encloses it. The arrows show the easy axis of magnetization of the main phase crystals. It is known that H_{cj} can be increased by refining the main phase crystals or increasing the thickness

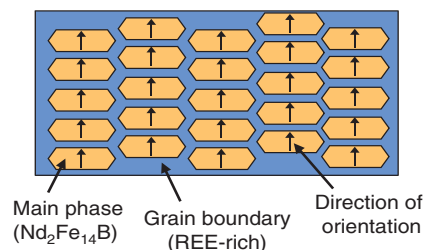


Fig. 1 Schematic image of crystalline microstructure of magnet

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of the grain boundary phase in order to magnetically isolate the main phase crystals⁽³⁾⁻⁽⁵⁾.

However, refinement of the magnetic powders used as raw materials in the sintering process causes oxidation, and in addition is not easy in practice due to the fact that when heated to temperatures of 1000°C or more, the crystals grow to around 5 μm . The research discussed here therefore focused on the hot-deformation method. In this method, the magnet raw materials are melted and rapidly quenched, forming ribbons of crystals on the order of nano-meter (nm)⁽⁶⁾. The material is then hot-deformed at the low temperature of 700°C, producing a microstructure 10% or more finer than the sintering microstructure, on the order of several hundreds of nm⁽⁷⁾. However, due to the specific characteristics of the process of manufacturing hot-deformed magnets, it is not easy to produce magnets with high magnetic properties in high volumes, and the magnets have previously found application only in a comparatively limited range of fields.

2. Development Goals

Figure 2 shows the magnetic properties of sintered magnets, a conventional hot-deformed magnet, and the hot-deformed magnet developed in this research.

The horizontal axis shows H_{cj} at the maximum temperature of a traction motor during operation, and the vertical axis shows remanence (B_r). The performance range necessary for the traction motor is shown outlined by the red broken line. Among the sintered magnets, the addition of heavy rare earths (chiefly dysprosium) increases the anisotropy field, allowing the magnets to realize the demanded performance, while the heavy rare earth-free sintered magnet does not. While the conventional hot-deformed heavy rare earth-free magnet displays higher H_{cj} than the rare earth-free sintered magnet, the level is insufficient for application in a traction motor. The research therefore set out to boost the properties of the magnet by optimization of the production conditions and design of the composition, in order to realize a performance range suitable for use in a traction motor.

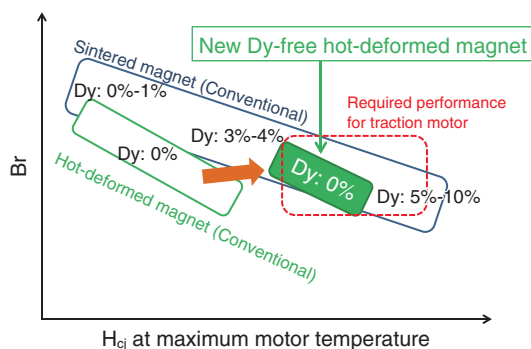


Fig. 2 Relationship between magnetic properties

3. Magnet Manufacturing Methods and Associated Issues

A variety of magnet manufacturing methods exist⁽⁸⁾. Figure 3 compares the characteristics of sintering, the representative method of manufacture of neodymium magnets, and hot-deformation, the method focused on in the present research.

3.1. Sintered Magnets

To produce the magnetic powders that form the starting material for sintering, alloys are melted and cooled into thin sheets, following which they are mechanically crushed to produce a powder ranging in particle size from 3 μm to 5 μm . This powder is cold pressed to form a pressurized powder body. The powder is then poured into the cavity of a die and cold-pressed under an applied magnetic field for crystal alignment. Because each particle of the magnetic powder is a single crystal, orientation is a simple matter, and there is a high degree of freedom in the shape of the pressurized powder body. It is therefore possible to form large blocks, and productivity is high. The pressurized powder body is next placed in a heating oven and aged to complete the magnet.

3.2. Hot-deformed Magnets

The raw material alloys used in the hot-deformation process are melted and rapidly quenched at speeds from 10^5 °C/s to 10^6 °C/s in order to form ribbons. Rapid quenching of the material results in the formation of fine crystals of around 40 nm in diameter. These ribbons are crushed to form a polycrystalline powder with a particle size of around 150 μm . This is the starting material magnetic powder. Because the fine grains in the powder are arranged isotropically, it is necessary to orient the grains and align the easy axis of magnetization. However, because it is not the case that each of the particles in the powder is a single

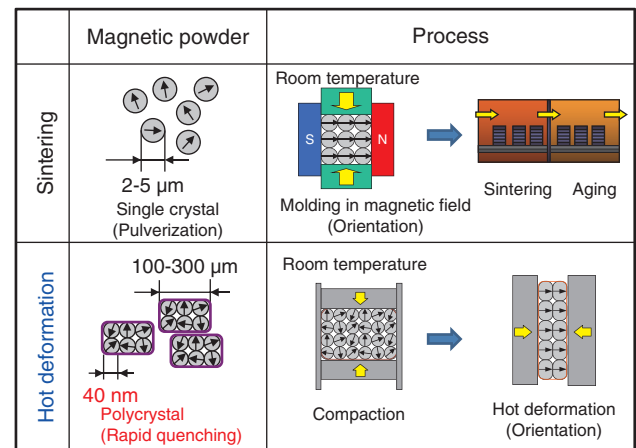


Fig. 3 Magnet manufacturing method comparison

crystal, as in the sintering method, the crystals cannot be oriented using a magnetic field. The crystals are therefore oriented by heating the material and subjecting it to a deformation process. Figure 4 shows the mechanism of this orientation⁽⁹⁾⁻⁽¹¹⁾.

When the crystals are heated, growth is prioritized in a direction perpendicular to c-axis, the easy axis of magnetization, and the crystals become flattened. Following this, when a load is applied on a single axis, torque acts on the flat crystals, and they rotate, becoming oriented in the direction of pressurization⁽¹⁰⁾. Based on this mechanism, pressure is applied to the pressurized powder body on a single axis by heating and extrusion, to form oriented, plate-shaped magnets. However, because it is necessary to uniformly apply pressure to all areas of the pressurized powder body, there are certain restrictions on the shape of the pressurized powder body in order to produce a uniform magnet. The control of variations by setting the conditions of the deformation process therefore represents an issue. In this process, while B_r increases as a result of the orientation of the crystal grains, heating results in crystal growth, reducing H_{cj} . It is essential to consider this trade-off in attempting to boost the properties of the magnet. The fact that high- H_{cj} magnets with microstructures similar to that of the developed magnet generally display a low level of magnetization also represented a concern, and it was necessary to investigate this effect.

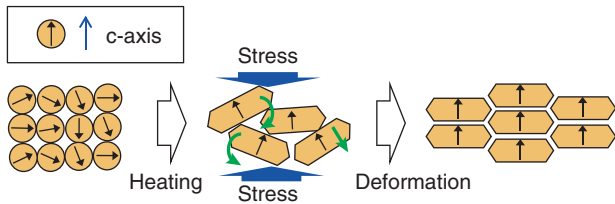


Fig. 4 Model of anisotropic crystal growth

4. Boosting Properties of Hot-deformed Magnet

4.1. Hot-deformation Conditions

Figure 5 shows scanning electron microscope (SEM) photographs of the Dy-free magnet with modified characteristics developed in this research for different hot-deformation temperatures. These results show that as the temperature increases, crystal growth proceeds and the shape becomes flatter, promoting increasing orientation. As indicated above, however, it is necessary to reduce the hot-deformation temperature in order to maintain the microstructure of the magnet. In the case of the developed magnet, therefore, in addition to reducing the hot-deformation temperature in order to refine the crystal grains, the rate of the deformation process was set so as to obtain a relatively high level of crystal orientation in comparison to the conventional method even under the lower-temperature conditions.

4.2. Composition Design

The main phase of a neodymium magnet is an intermetallic compound with the stoichiometric proportions $RE_2T_{14}B$ (RE: Rare earth; T: Transition element). However, because the magnet also has a grain boundary phase, the Total Rare Earth (TRE) in the starting material alloy is greater than the stoichiometric proportion. Figure 6 shows SEM photographs of a low-TRE, low- H_{cj} conventional

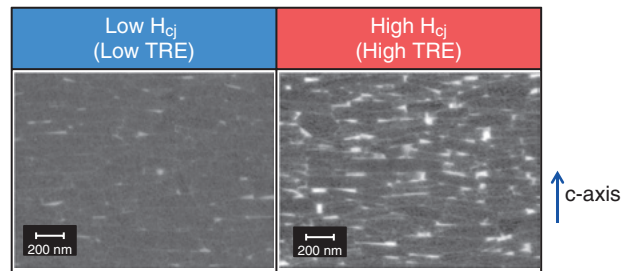


Fig. 6 Crystalline microstructure of hot-deformed magnet

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
Deformation temp.	700°C	725°C	750°C	775°C	800°C

Fig. 5 Grain size of hot-deformed magnet for differing deformation temperatures

magnet, and a modified magnet with high TRE and high H_{cj} . The thickening of the grain boundary phase (the white areas in the photographs) magnetically isolates the main phase, increasing H_{cj} . Increasing TRE within a range in which there is no major decline in the ratio of the main phase has boosted the properties of the magnet.

4.3. Boosting Magnet Properties

Figure 7 shows the magnetic properties of a conventional hot-deformed magnet and the magnet developed in the research discussed here. In the case of the developed magnet, the hot-deformation temperature was reduced, the conditions of the deformation process were optimized, and the composition of the material was designed in order to optimize the grain boundary phase. The refinement of the crystal grains and the realization of increased magnetic isolation of the main phase have increased H_{cj} . In addition, B_r has been increased by maintaining the microstructure while increasing the level of orientation.

4.4. Temperature-dependence

H_{cj} normally declines at high temperatures, and the rate of this decline is dependent on the grain size⁽⁴⁾. The correlation between grain size and the temperature coefficient of H_{cj} (β %/°C) as a secondary effect of the refinement of the grains was verified (Fig. 8).

Figure 9 shows examples of the effect of increasing the temperature coefficient of H_{cj} . The H_{cj} of the hot-deformed magnets close to ambient temperatures is lower than that of the sintered magnet, shown as the solid line. However, at higher temperatures, the hot-deformed magnets display equivalent or greater H_{cj} than the sintered magnet. This is because the temperature-dependence of H_{cj} in the hot-deformed magnets is lower, and the ratio of decline in H_{cj}

is therefore lower. The lower temperature-dependence of H_{cj} in the hot-deformed magnets represents an advantage at high temperatures, when demagnetization becomes an issue in traction motors.

4.5. Magnetization

Figure 10 shows the initial magnetization curve (the first quadrant of the hysteresis curve) for a sintered magnet and a hot-deformed magnet. As the magnetizing field is increased in strength from the zero point of the curve, the sintered magnet becomes saturated and is completely magnetized at around 500 kA/m. In the case of the hot-deformed magnet, the initial magnetization curve displays

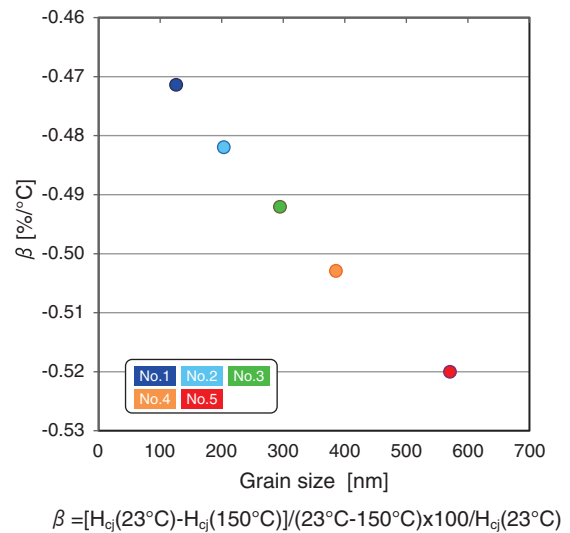


Fig. 8 Relationship between grain size and temperature coefficient of H_{cj} (β)

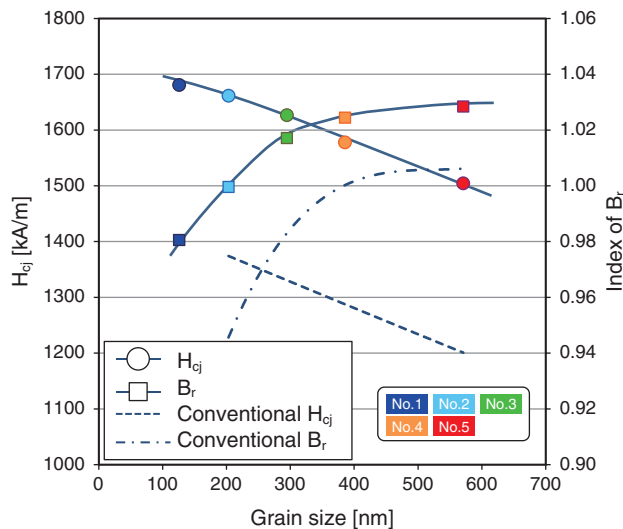


Fig. 7 Relationship between grain size and H_{cj} /grain size and B_r

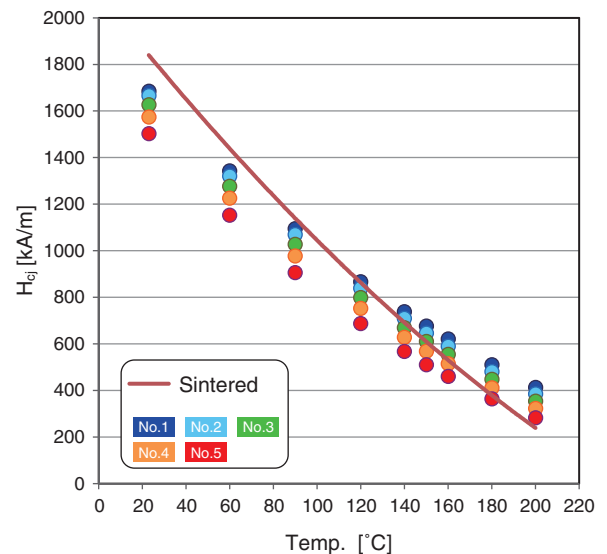


Fig. 9 Temperature-dependence of H_{cj} in hot-deformed magnet and sintered magnet

two stages, and an effective magnetic field equivalent to or greater than the coercivity of the magnet would be necessary for complete magnetization.

Because the crystal grains in the sintered magnet are large, a single grain represents a multi-domain structure. When a magnetic field is applied, the grains readily magnetize due to domain wall displacement. By contrast, because the crystal grains in the hot-deformed magnet are small, both single-domain structures and multi-domain structures exist in the magnet. The two-stage initial magnetization curve is a result of the fact that the grains in the multi-domain structures are magnetized first, followed by those that are single-domain structures.

Figure 11 shows the results of study of the magnetic domain structure of each magnet using magnetic force microscopy. The sintered magnet is characterized by multi-domain structures, in which multi-domains divided by domain walls exist on each grain. In the hot-deformed magnet, by contrast, the majority of grains are single-domain structures without domain walls. This

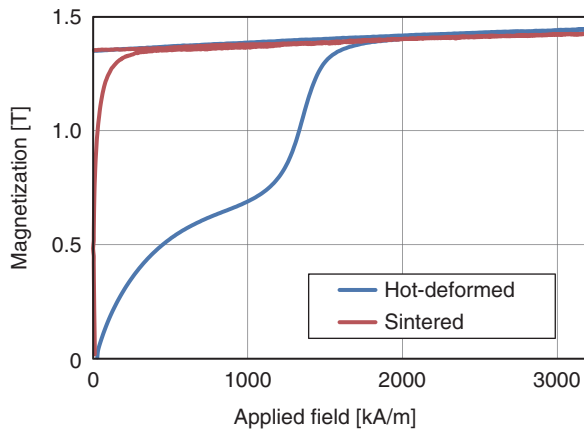


Fig. 10 Magnetization profile

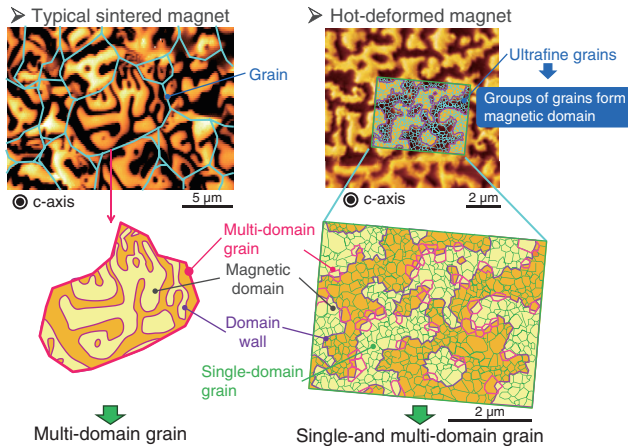


Fig. 11 Magnetic domain structures (Magnetic force microscope image)

further substantiates the difference observed in the initial magnetization curves of the magnets.

The results discussed above indicated that a larger applied magnetic field would be necessary in order to magnetize the hot-deformed magnet, making it necessary to consider the production technology and respond via the voltage setting of the magnetization power source.

4.6. Realizing Uniformity of Properties

The ability to form stable products following the modifications to the production process was verified. Magnets were cut from a formed magnet, and the magnetic flux originating in B_r was measured for each magnet (Fig. 12). With regard to variations in magnetic flux, optimization of tool design and formation conditions during the hot-deformation process made it possible to realize a process capability index (C_p) of 5.90 in relation to the range demanded for HEV.

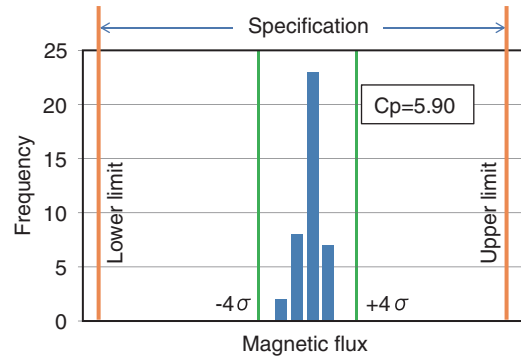


Fig. 12 Dispersion on magnetic flux

5. Conclusions

The research discussed in this paper developed a heavy rare earth-free, hot-deformed magnet for a traction motor. Refinement of the magnet microstructure through hot-deformation at a low temperature, the realization of a high level of orientation through the optimization of the rate of the deformation process, and the magnetic isolation of the main phase through design of the grain boundary phase increased H_{cj} and B_r . The ability of the method to output a stable product in mass production was verified. The development of the new magnet will make it possible to mass produce traction motors for electric vehicles displaying a level of performance equivalent to or higher than conventional traction motors without the use of high-cost heavy rare earths, the production of which is unevenly geographically distributed.

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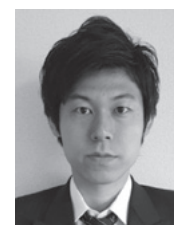
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