Magnetic Form which applies C Shaped Magnet for Hybrid Electric Vehicle

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ABSTRACT: Currently, electrification for vehicles such as battery electric vehicles (BEVs), plug in-hybrid electric vehicles (PHEVs), fuel cell electric vehicles (FCEVs) and hybrid electric vehicles (HEVs) are attracting a great deal of attention, due to the urgent need to reduce CO_2 emissions created from transportation and energy dependency on crude oil. Honda has set a target achieving two-thirds of total global sales as electrified by 2030. A traction motor is one of the essential components for electrified vehicles. Generally, Interior Permanent Magnet Synchronous Motors (IPMSM) are used as traction motors due to their high torque and power density, high efficiency and ease of use. The design of rotors, which consist of magnets and electrical steel sheets, is important for IPMSM since not only average torque, efficiency and quietness depend on it, but also cost. We have developed a novel rotor, which allows for a degree of freedom in the shape of the magnets.

KEY WORDS: electric hybrid vehicle, power electronics, electric motor, powertrain, magnet

1. INTRODUCTION

In conventional IPMSM, it is generally common to use neodymium sintered magnets in a sheet form.(1)

With the recent development of neodymium sintered magnets and a hot deformation production process, it has become possible to make advantageous use of a degree of freedom in magnet shape.(2)

The application of the degrees of freedom for magnets in the traction motors of HEVs to achieve compactness was examined in the present research. The research managed to achieve both compactness and cost reduction, making it very significant.
The HEVs traction motors used in the mainstream of electrification products as the object of research. The motor specifications are shown in Table 1. Considering constraints on the motor space, interior permanent magnet synchronous motors, which are compact and efficient, were used.

TABLE 1 SYSTEM SPECIFICATIONS

Type	IPMSM
Phase	3
Number of poles	12
Winding pattern	Hair-pin winding, Distribution
Cooling system	Oil-cooled
System voltage [V]	630
Maximum motor power [kW]	135
Maximum rotation speed [rpm]	14500
Maximum motor torque [Nm]	335
Peak efficiency [%]	≦98

For the present research, the shape selected from the degree of freedom in magnet shape was C-shape because it is a viable industrial product that also achieves favorable dimensional variation during production. The research was conducted using this shape. Another reason for this is that it allows a choice between the two magnet manufacturing methods of sintering and hot deformation processing. Adoption of the C-shape also makes it possible to reduce machining processes by the use of near net shape processing. It was found, therefore, that using a C type magnet would make it possible to reduce process costs. (Figure. 2, 3)

Moreover, the selection of hot deformation processing made it possible to achieve a coercivity (H_{cj}) of 1500 kA/m, or higher without including heavy rare earths. If motors are designed with care regarding resistance to demagnetization, then this would contribute to the development of motors without the high-cost risk and procurement risk of heavy rare earths.

The substance of this approach was reported with regard to the design method for traction motors for HEVs use. The present research also addressed the magnetic flux barrier shape by creating a shape with a structure resistant to demagnetization in a way that would produce a motor that satisfies the specifications even without using heavy rare earths if a hot-deformed magnet is selected.(3)

TABLE 2 MAGNET SCHEME

Type	C-shape
Production process	Sintered/ Hot deformed
Residual magnetic flux density B_r [T]	1.39
Coercive force H_{cj} [kA/m]	≥1500

2. DEVELOPMENT DIRECTION FOR NEODYMIUM SINTERED MAGNET

A focus on the progress made in magnet development shows that the highest energy product has recently been approached the theoretical upper limit.(4)

Another development is that, due to price and supply risks, magnet coercivity has been rapidly enhanced since 2011 by reducing the amount of heavy rare earths added.

Meanwhile, attention has focused on the degree of freedom in magnet shape and the degree of freedom in the orientation of magnetization, which were directions with further development potential.

First, a description will be given of the state of rapid development of manufacturing technology providing a degree of freedom in shape and orientation of sintered neodymium magnets.

Figure 2 shows the neodymium sintering processes.

The core technology in the sintered magnet method is press in magnetic field.

This process differs from the conventional one, which involves block molding of the sheet form. Here instead a multi-cavity mold was developed that produces a C-shaped magnet. This produces a near net shape and molds many magnets simultaneously so that mass production has become possible.

The next matter to consider is the hot-deformed magnet.

Figure 3 shows a scheme view of this manufacturing method. The key process in the hot deformation production process is the hot extrusion process.

Development for enhanced moldability was carried out by performing simulation of the hot extrusion die set, and it was found from this that net shape production of a C-shaped magnet is possible.

In this process, the direction in which pressure is applied determines the orientation, and this process therefore handles the two elements of dimensional accuracy and orientation.

Advances in the hot extrusion process make it possible to omit the grinding process, allowing for a reduction in process costs. In their present state, it was found that the above two methods could be applied to mass production of C-shaped neodymium magnets with radial orientation.

Figure 1. Neodymium Sintered Magnet Production Process Scheme

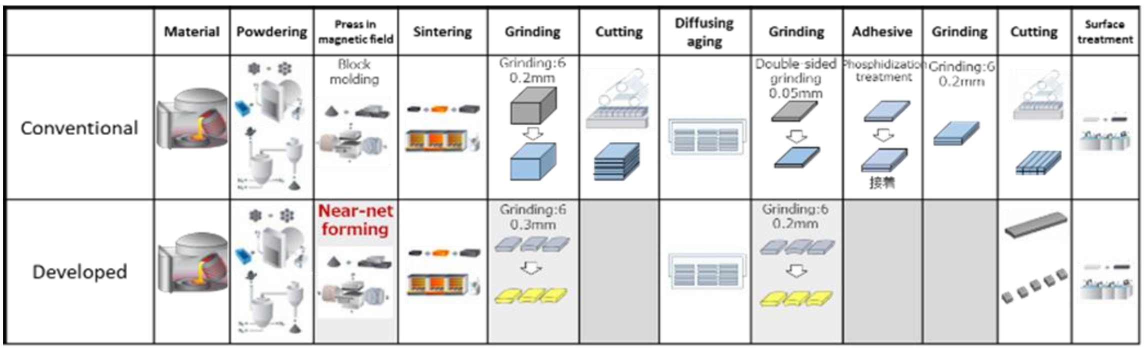
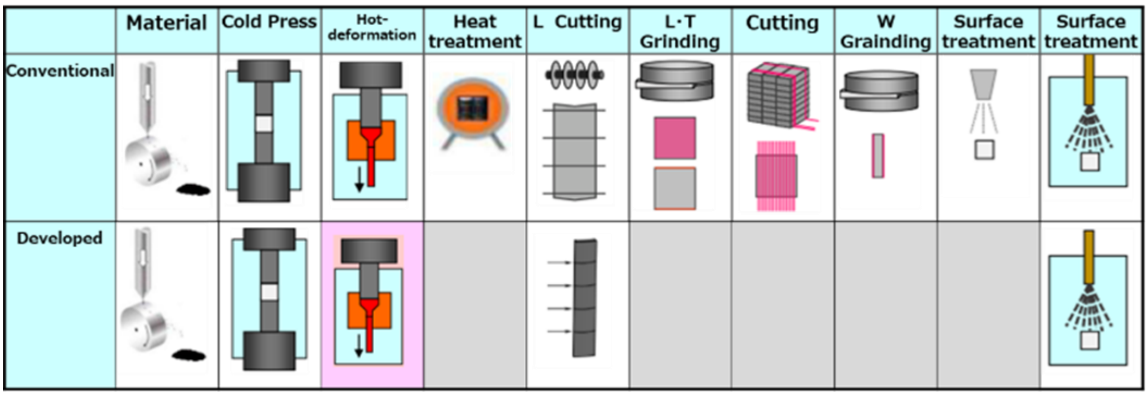


Figure 2. Neodymium Hot-deformed Magnet Production Process Scheme



3. DESIGNING USE C-SHAPED TYPE OF MAGNET

The next matter for attention is the state of development of interior permanent magnet synchronous motors.

The output torque of permanent magnet synchronous motors with a salient pole structure can be expressed by the following Eq. (1), as is well known:

$$T = p\phi_a i_q - p(L_q - L_d) i_d i_q \text{………}(1)$$

Here T is torque, p is the number of pole pairs, i_d is the d-axis current, i_q is the q-axis current, L_d is the d-axis inductance, and L_q is the q-axis inductance.

It is well-known that, in general, when magnetic flux flows ideally on the q-axis, the result is as shown in the figure.3. It is important to place a magnetic flux barrier so that it traces that flow. In order to trace an ideal shape, it is necessary to change the curvature and orientation of the magnet.

By tracing this line of magnetic flux, the highest value of L_q can be achieved. To reduce L_d to the lowest value, it is also necessary to arrange the magnetic flux barrier so that it faces toward the center of the rotating magnetic field. Based on this conceptual approach, a model that uses a C-shaped type magnet to achieve the highest values of L_q–L_d was examined.

In this initial research, a concentrically layered model was designed. This model adopts C-shape type neodymium magnets with a motor that is well-known as a "double-layer type of IPMSM" [(5)]. (Table. 3 Model 1)

This model shows the possibilities for reluctance torque.

At the same time, it suggests some shortcomings in the C-shaped layout.

The first model successfully demonstrated that the benefits realized by reluctance torque are greater than those realized by magnet torque.

With the first model, however, a large torque ripple occurred. The reason for this was that the magnet orientation was centered in the d-axis so that magnetic flux originating in the rotor was concentrated in a single point.

It can be inferred that the concentrically layered layout sharpens the magnetic flux waveform. Even when the concentrically layered layout was optimized, it did not conform to the torque ripple specifications of a HEVs traction motor.

For the next model, therefore, the polar center of the magnet was offset, and a search was made for a model in which the center of orientation was not concentrated. The result was Model 2, which has a shape known as the "inverted-delta type of IPMSM."[(5)] Since the center of orientation was offset, however, the high-frequency components in the waveform of the interlinkage flux have changed.

The greater magnitude of the 11th and 13th components indicates that they are causing torque ripple in the 12th high harmonic component.

For the above reasons, it was found that a C-shaped layered magnet layout with a non-concentric magnet orientation having an offset center should be selected.

Optimization was carried out repeatedly to further increase reluctance torque while simultaneously positioning small holes in order at locations on the ribs that are not subject to stress. This reduce leakage magnetic flux while increasing magnet torque so that it would be possible to trace the magnetic flux barrier along the q-axis magnetic path. Redesign was also carried out while searching for shapes that would be able to mitigate centrifugal stress and cooling stress.

The result yielded success in raising the reluctance ratio. The effect was to achieve a 12.2% enhancement of L_q.

The execution of this procedure resulted in the creation of a model that was able to increase total torque by 3% while also reducing the amount of magnets by 12%.

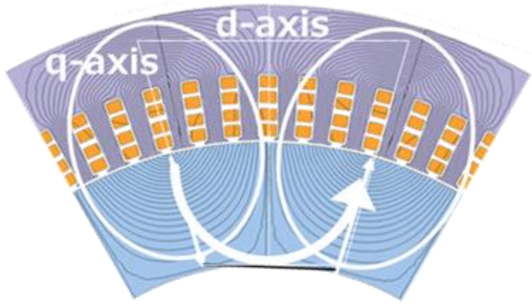
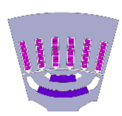
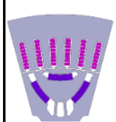
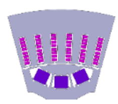


Figure 3. Ideal Flux Line

TABLE 3. SIMULATION MODEL

		Model 1	Model 2	Conventional
Configuration				
Torque	Max Torque [Nm]	317.5	343.5	333.5
	Magnet Torque [Nm]	137.4	147.3	153.0
	Reluctance Torque [Nm]	180.1	196.2	180.5
	L_d [mH]	0.160	0.167	0.164
	L_q [mH]	0.338	0.354	0.341
	M-point	384.5	401	420.5
Max Current [Arms]		335	335	335
Magnet Volume [g]		1060	1060	1205

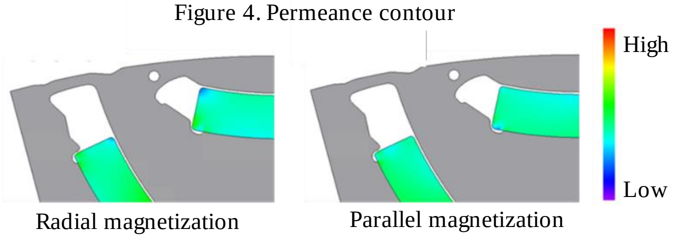
In view of magnetization orientation, there is a difference in motor characteristics. In this motor, the torque of the parallel magnetized motor is suppressed by 0.7% compared to the radial magnetized motor (Table 4). This shows a small difference, which is optimized by maximizing reluctance torque.

TABLE 4. MAXIMUM TORQUE

Orientation	Radial	Parallel
Torque [Nm]	343.5	319.5

Furthermore, magnetization affects magnet permeance and thus motor characteristics. This section shows the motor characteristics using different magnetization directions.

Figure 4. Permeance contour



4. CONCLUSION

Through this research, the magnet's degrees of freedom and its orientation were effectively utilized to create a motor that performs equally or better than conventional IPMSMs, even with a 12% reduction in magnet volume. Additionally, where reluctance motors tend to have NVH issues, this research identified a magnet orientation and rotor shape that could satisfy quietness requirements. It also demonstrated the viability of using neodymium magnets with C-shaped orientation and shape, whether sintered or by means of the hot deformation process. This could lead to a reduction in magnet use, supply and price risks, and enhance the sustainability of rare earth resources. Adequate production technology for dealing with dimensional variation and mass producibility is also expected, making C-shaped magnets an industrial product.

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