Development of a Heavy Rare Earth Free Motor with Reduced Rare Earth Usage

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We have developed a motor using an anisotropic bonded magnet, which is mainly composed of samarium (Sm), which is not classified as a heavy rare earth element. In regards to the motor, we have achieved the target performances of "improving motor torque" and "reducing torque fluctuation" by optimizing the magnet shape of the rotor and establishing an original mold design. As a result, we have succeeded in developing a motor with both the same size and the same performance as a conventional motor using sintered magnets which is mainly composed of neodymium (Nd). In addition, since this bonded magnet does not contain either neodymium or heavy rare earth elements (dysprosium (Dy), terbium (Tb) etc.), for which concerns exist regarding potential procurement risks, it also contributes to future procurement stability. This report provides an outline of the development and the results of motor performance evaluation.

Key Words: *motor, IPM, heavy rare earth, sintered magnet, bonded magnet, samarium*

1. Introduction

In recent years, the automotive industry has seen a rising demand for electrification in order to convert to decarbonized fuel as part of efforts to reduce CO_2 emissions, which are a cause of global warming. As such, in line with a rapid increase in demand for motors, there is also an increase in the demand for magnets used in motors. Meanwhile, neodymium and heavy rare earth elements (dysprosium, terbium, etc.) for which crustal reserves are said to be minimal that have conventionally been used in magnets are only found in certain areas. Additionally, the countries where such resources can be found have used these resources for political agendas in recent years, triggering trade friction with various countries, and creating concern regarding latent procurement risk due to instable supply amount affected by cost (**Fig. 1**) and uneven distribution of resources (**Fig. 2**). Moreover, as indicated by the unit price ratio of motor parts in **Fig. 3**, the magnet is the most expensive part of a motor, and there is a demand to reduce this cost.

This report introduces the development process and evaluation results of a motor that has achieved high torque and low torque fluctuation adopting an anisotropic bonded magnet that does not use neodymium or heavy rare earth elements.

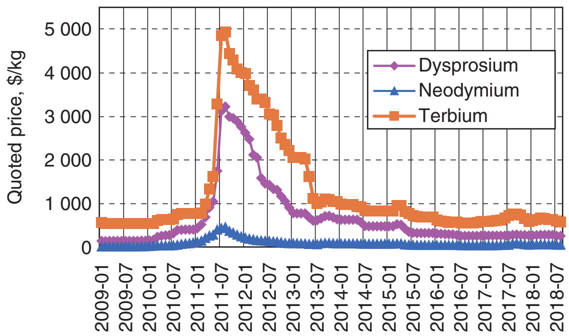

Fig. 1 Heavy rare earth price trends

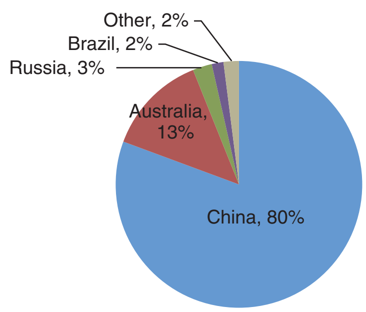

Fig. 2 Uneven distribution of rare earth production

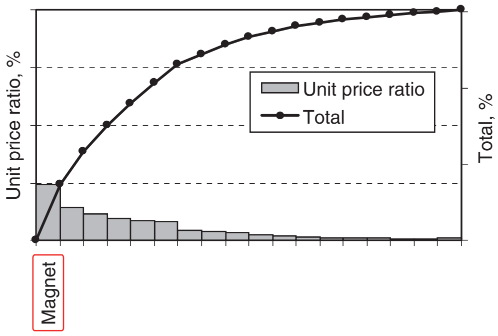

Fig. 3 Pareto chart of motor parts price ratio

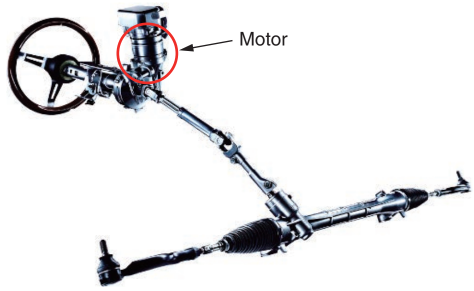

Fig. 4 Electric power steering

2. Overview of Development

2. 1 Magnets for Use

In general, sintered magnets and bonded magnets are used in motors. Sintered magnets are manufactured by melting and alloying the blended raw materials, pulverizing the resulting magnet alloy, arranging in the magnetization direction within a magnetic field, press fitting, then sintering at high temperature. Afterwards, sintered magnets undergo machining or surface treatment to suit the specific application. Characteristics of sintered magnets are their high residual flux density (Br), and the highest magnetic force amongst magnets in practical use. Furthermore, a popular type of sintered magnet is one on which a portion of the neodymium has been replaced with dysprosium or terbium to improve coercive force (Hcj) thus securing heat-resistance. However, of the 17 types of rare earth that exist in total, these elements are categorized as heavy rare earth elements which are scarce throughout the world and distributed unevenly. As such, compared to light rare earth elements, using these heavy rare earth elements as mineral resources is believed to entail risk from the perspectives of stable procurement and material cost.

The motor used in JTEKT's electric power steering (**Fig. 4**) is no exception, and motors using sintered magnets are adopted in cases where high output and heat resistance are required.

Meanwhile, bonded magnets contain resin which serves as binder, such as rubber and plastic, in the magnet powder. Because of the resin content, bonded magnets have lower residual flux density and coercive force than sintered magnets, however can be made into complex and thin shapes through injection molding, therefore less processes are involved as downstream processes are made redundant. Moreover, because bonded magnets are flexible due to their resin content, they offer the feature of being hard to break, which sintered magnets do not offer.

This time, with the aims of 1 through 3 below, we studied magnets for use. When conducting this study, we compared the three types of magnets; a sintered magnet with the main raw material of neodymium-iron-boron (NdFeB) which contains heavy rare earth (dysprosium), a bonded magnet with the main raw material of neodymium-iron-boron (NdFeB) and a bonded magnet with the main raw material of samarium-iron-nitrogen (SmFeN). The results of this study are shown in **Table 1**.

<Aims>

1. Make raw materials such as dysprosium free of heavy rare earth
2. Minimal procurement risk/cost fluctuation
3. Enable cost reduction

Table 1 Comparison of magnet type

	Sintered magnets	Bonded magnets	
	Neodymium-iron-boron	Neodymium-iron-boron	Samarium-iron-nitrogen
Free of heavy rare earth	×	○	○
Residual flux density	○	△	△
Heat-resistance	◎	△	○
Cost (cost per usage)	△	○	○
Procurement risk (cost fluctuation)	△	○	◎
Shape freedom (machinability)	△	○	○

◎: Excellent, ○: Good, △: Possible, ×: Not possible

Consequently, we adopted the samarium-iron-nitrogen bonded magnet, which has good balance overall. However, these magnets have lower residual flux density than sintered magnets, and we proceeded with development of a high torque motor leveraging the

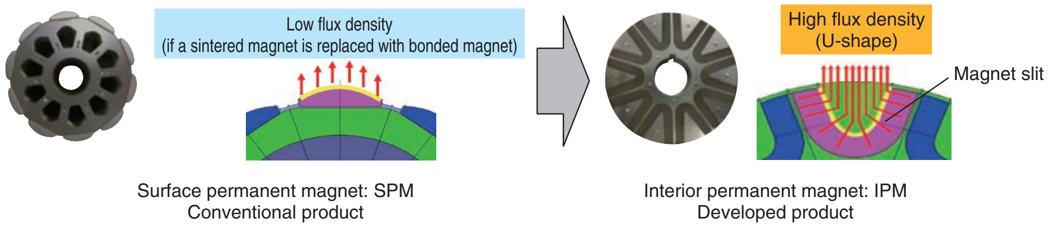

Fig. 5 Comparison of rotor shape

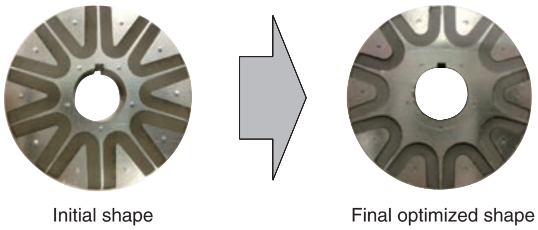

Fig. 6 Comparison of rotor shape development

characteristics of bonded magnets.

2. 2 Rotor Shape

Regarding rotor shape, if we merely replace the conventional surface permanent magnet (SPM) JTEKT has adopted to date with a bonded magnet, torque would be insufficient due to low residual flux density. As such, utilizing one of bonded magnets' advantages of shape freedom (ability to form complex/thin shapes), we adopted the interior permanent magnet (IPM) whereby a magnet is embedded in the rotor core's slit. It is well-known that torque insufficiency can be compensated by adopting a U-shaped magnet which can increase magnet surface area in a limited space (**Fig. 5**).

One problem we faced in the early stages of development was the significant deviation between the results of magnetic field analysis and actual usage results. One reason for this is because the magnet's magnetization ratio and orientation ratio were fixed (100%). However, in an actual operating environment, a magnet's magnetization ratio and orientation ratio are distributed, therefore the main reason for such deviation was that this distribution was not taken into consideration. As such, JTEKT established an analysis technique considering distribution. In concrete terms, we performed both a magnetization analysis identifying magnetic strength distribution from the magnet's magnetization characteristic, as well as an orientation analysis identifying magnetization direction, and improved analysis error by combining these two analysis types. Magnet shape was optimized by performing a parameter study* utilizing this analysis technique. Through this effort, we succeeded in developing a shape that not only increased the surface area of the U-shape, but also achieved the most effective magnetization ratio and orientation ratio (**Fig. 6**). Consequently, we reduced the magnet usage quantity, which heavily impacts cost, by around 20%.

Moreover, by leveraging the advantage of shape freedom, flux leakage was suppressed and torque was improved through being innovative with part of the magnet shape. Also, by smoothing the flux density waveform of the rotor surface, it was possible to suppress torque fluctuation, which is an issue with IPMs, and achieve a value almost equivalent to SPM motors using sintered magnets.

* A technique of setting conditions and shape as parameters and changing these gradually to perform analysis.

2. 3 Manufacturing Process

In the manufacturing process (**Fig. 7**), six processes were required from loading to completion for the current process of SPMs, whereby a sheet-shaped sintered magnet is attached to the surface of the rotor core. However, for the developed process of IPM, a special-purpose mold (iron core + permanent magnet) is used, and securing of the magnet and magnetization can be simultaneously achieved due to injection molding inside the magnetic field. This has made it possible to reduce the number of processes down to two, and leverage the characteristics of bonded magnets. This results in reduced lead-time, lower equipment investment, fewer parts, and higher productivity. Moreover, in order to manufacture products with good stability, we optimized forming conditions by adopting an experimental planning method of selecting flux amount and dimensional change amount as the characteristic values, and extracting condition factors with high contribution. Favorable results were obtained when we confirmed the process capability using these molding conditions.

2. 4 Molding Die

In terms of a molding die to increase a magnet's magnetization ratio and orientation ratio, we fabricated a mold with an original magnetic field application structure through magnetic field analysis (**Fig. 8**). As a result, it was possible to increase the magnetization ratio in the bottom part of the U-shaped rotor core, where it was

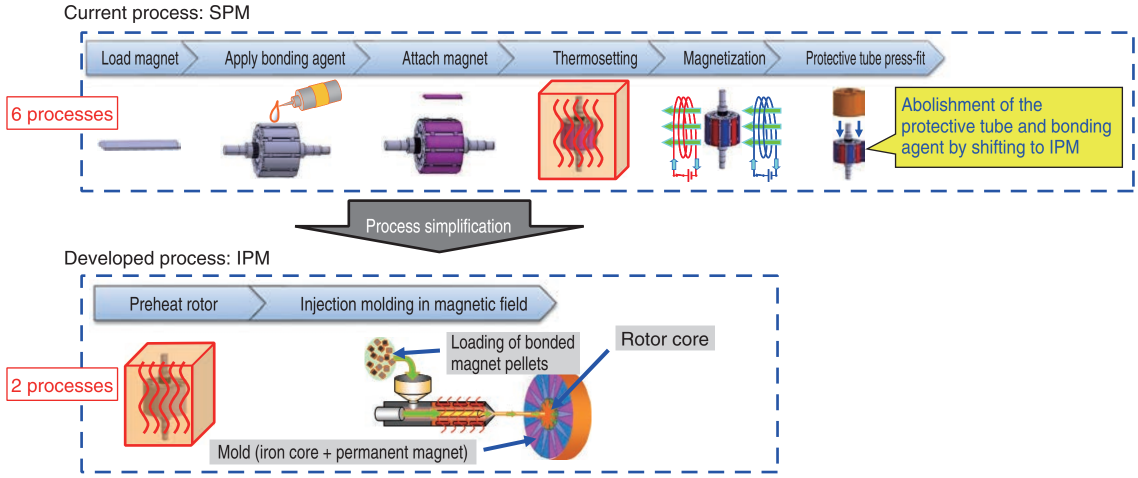

Fig. 7 Comparison of process flow

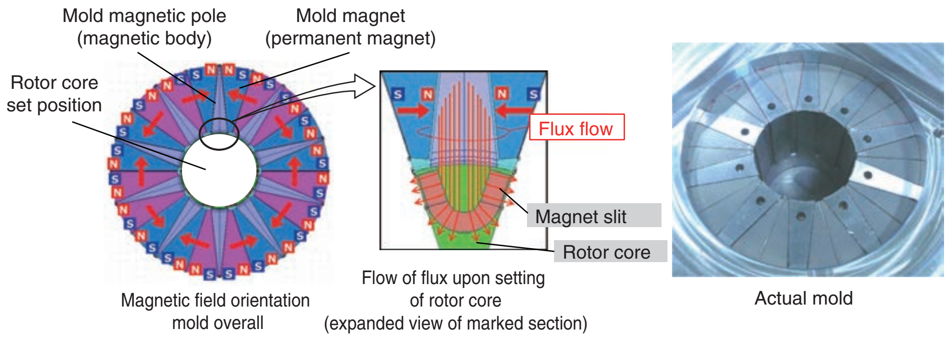

Fig. 8 Molding die

conventionally difficult to improve magnetization ratio due to the orientation magnetic field not being able to reach this section well. Additionally, it became possible to maximize the magnetization/orientation ratio, which helped to improved motor torque.

3. Results

As described above, through optimization of rotor shape (**Fig. 6**) and molding die design (**Fig. 8**), JTEKT successfully improved motor torque by 18% the initial value, thus achieving the target torque enabling replacement of SPM motors using sintered magnets (**Fig. 9**). Furthermore, in addition to innovative ideas regarding magnet shape, we combined common design techniques such as skew angle to reduce cogging torque and torque ripple by 68% and 66% of the initial values, respectively, thus achieving the low target value for torque fluctuation enabling replacement of SPM motors using sintered magnets (**Fig. 10**, **Fig. 11**). These initiatives made it possible to develop an IPM motor using bonded magnets free of heavy rare earth exhibiting high torque/low torque fluctuation performances equivalent to a SPM motor using sintered magnets of equal size, as well as establish the design technique and production engineering thereof. A brush-less type motor was used for this evaluation, and this type of motor comprises of a stator with a coil-based magnetic field and a rotor with magnets.

Moreover, thermoplastic resin is used for the binder, therefore, there is a need to confirm humidity and heat resistance. In this reliability test, we cooperated with a material manufacturer to improve a portion of the bonded magnet material and suppress degradation, thus achieving the target value (**Fig. 12**).

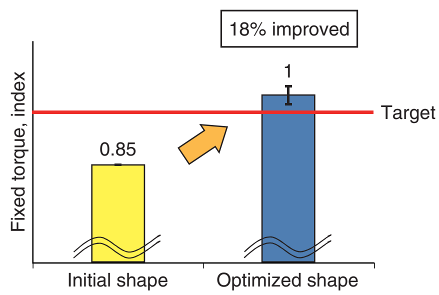

Fig. 9 Results of motor rated torque

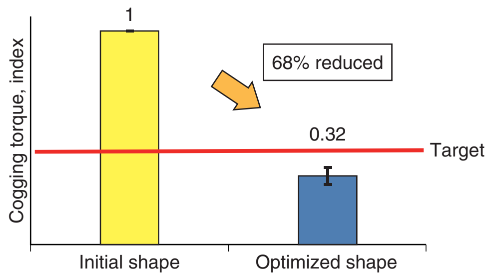

Fig. 10 Results of cogging torque

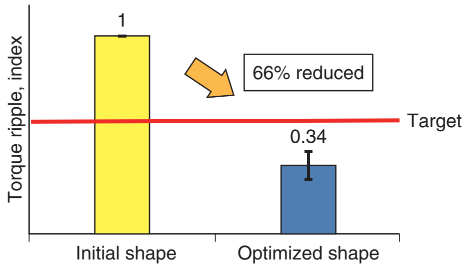

Fig. 11 Results of torque ripple

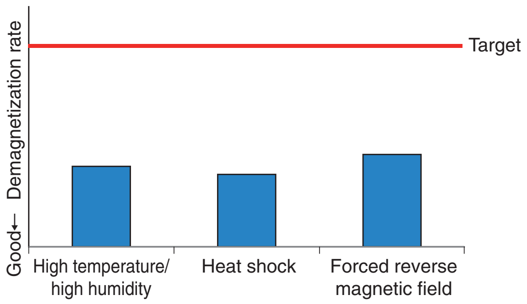

Fig. 12 Results of a reliability test

4. Conclusion

Through optimization of rotor magnet shape taking advantage of the shape freedom of bonded magnets and establishing an original mold design which maximizes magnetization/orientation ratio, we successfully achieved our targets in terms of improving motor torque and reducing torque fluctuation. At the same time, we dispelled the general notion that an IPM motor is more likely to exhibit torque fluctuation than a SPM motor, and developed an IPM motor using bonded magnets free of heavy rare earth capable of performance equivalent to a SPM motor using sintered magnets without changing motor size. Moreover, by adopting magnets with samarium as the main material free of neodymium or heavy rare earth (dysprosium (Dy), terbium (Tb), etc.), we addressed the issue of latent procurement risk.

In this latest development, through simultaneous engineering (SE) by the design divisions and monozukuri divisions, we established our original design technique and production engineering.

Moving forward, in order to respond to various application needs, JTEKT will continue pursuing development initiatives aimed at improving heat-resistance and robustness so that we may contribute to the needs of various customers for electric power steering and electric oil pumps.



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