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HREE-free Hot-deformed Nd-Fe-B Magnets for xEV

- Highly controlled techniques of shape and orientation-direction -

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ABSTRACT: Nd-Fe-B magnets are required the addition of heavy rare earth elements (HREE) to secure enough coercivities in order not to deteriorate their remanence magnetizations due to the demagnetization field when they are applied to various uses. However, the procurement risk of the HREE is regarded as a particular concern. Daido Steel Co., Ltd. (DS) and Daido Electronics Co., Ltd. (DEC) developed HREE-free hot-deformed magnets composed of ultra-fine crystal grains which shows high coercivities without the HREE addition six years ago. Honda Motor Co., Ltd. (Honda) recently proposed an improved performance motor design for xEV utilizing the shape and orientation controlled magnet which has the ideal magnetic circuit. In order to realize this new design, DS and DEC have developed technology for controlling the shape and orientation of the HREE-free hot-deformed magnets through the net-shape molding process. The newly developed magnet has been begun the preparations for mass production.

KEY WORDS: hot-deformed magnet, xEV, HREE- free, controlling shape, controlling orientation direction

1. INTRODUCTION

Nd-Fe-B magnets, which were independently developed by Sagawa and Croat in 1982(1, 2), have a high energy product and are widely used in various motors such as vehicles and air conditioners. In order for Nd-Fe-B magnets to exhibit enough coercivity for being used in various applications, the addition of heavy rare earth elements (HREEs) (Dy, Tb) is necessary. Actually, the Nd-Fe-B magnets mounted on the traction motors of hybrid electric vehicles (HEVs) or electric vehicles (EVs) contain HREEs.

On the other hand, the procurement risk of the HREE is regarded as a particular concern. The HREE production is unevenly distributed in China, and the HREE prices have soared due to the Chinese government's export restrictions in 2011. In addition, the European Union (EU) announced in 2021 a policy to reduce CO_2 emissions in the automotive field by 100% by 2035. In the long run, HREE prices will gradually rise due to the increase in xEV demand (Fig. 1).

Therefore, as an effective method to enhance coercivity with earth-friendly techniques (HREE-free magnets, low-CO_2-emission manufacturing process and so on), the development of the HREE-free Nd-Fe-B magnets with fine crystal grains has been promoted. Hot-deformed Nd-Fe-B magnets were developed by J. J. Croat and his team of General Motors in 1983, industrialized by Daido Steel Co., Ltd. (DS), and now mass-produced by Daido Electronics Co., Ltd. (DEC) in 1992. Rapid-quenched powder with ultrafine crystal grains is molded at high temperature and the process is completed in a shorter time compared to that of sintered magnets, so fine crystal grains can be obtained. The microstructure consists of ultrafine crystal grains of several hundred nm in size, which are 1/10~1/100 as small as the sintered Nd-Fe-B magnets.

Fig. 1 Price trends of Heavy rare earth elements (Dy and Tb)

Fig. 2 HREE-free hot-deformed magnet for Honda-HEV

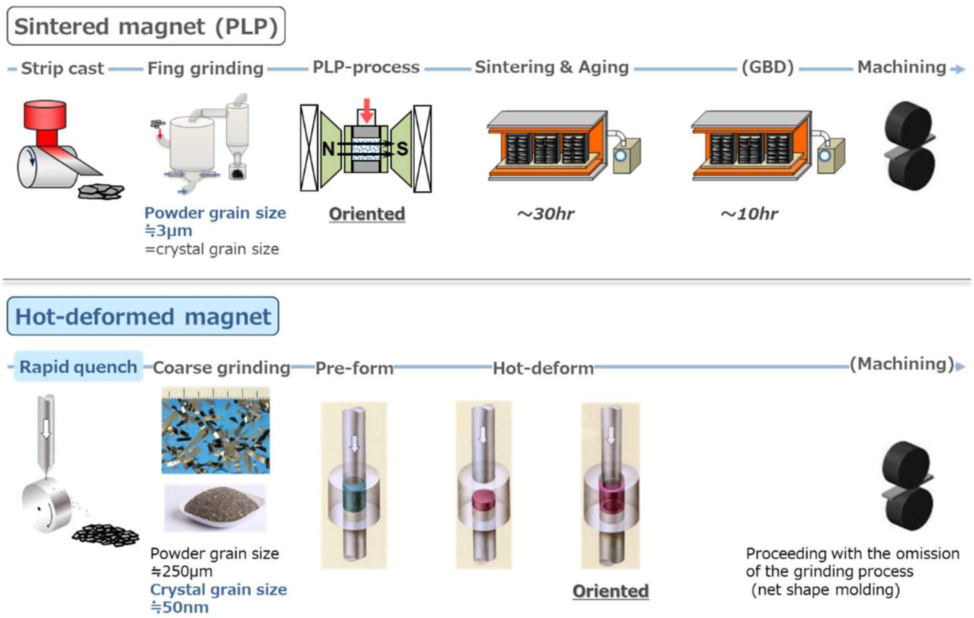

Fig. 3 Schematic illustration of production process of sintered magnets (PLP) and hot-deformed magnets

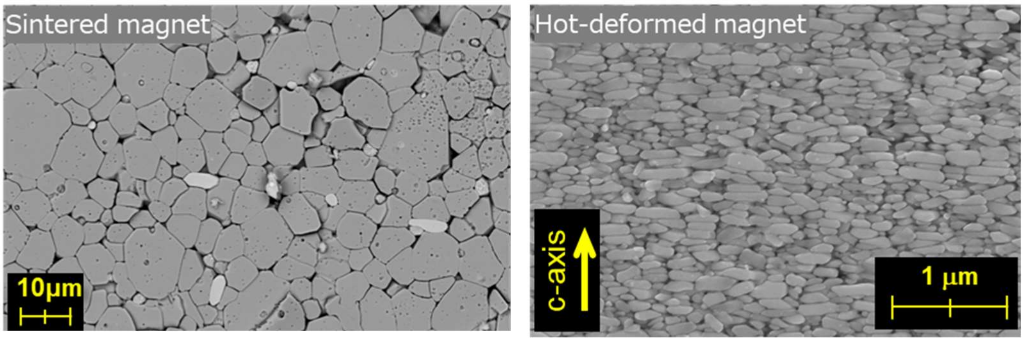

Fig. 4 SEM images of the sintered magnet and the hot-deformed magnet

It is well known that the smaller the crystal grains are, the higher the coercivity is. Additionally, through the entire manufacturing process, we have succeeded in reducing CO_2 emissions by 40% compared to our mass-produced sintered magnets because the hot-deformed process does not require high-temperature and long-time heat treatment consuming a lot of electricity.

In 2016, Honda adopted the first in the world to use the HREE-free hot-deformed Nd-Fe-B magnets for the traction motors in HEVs (Fig. 2) [(3)]. Although the HREE-free hot-deformed Nd-Fe-B magnets, which typically show 1600 kA/m of coercivities at room temperature, are slightly inferior to the HREE-containing sintered Nd-Fe-B magnets in terms of coercivity, Honda has effectively increased the reluctance torque through a magnetic circuit design and raised the motor performance to a practical level.

Recently, Honda reported that the motor torque could be improved by controlling the magnet shape and orientation so that the magnetic circuit is optimized [(4)]. The torques of the IPM motor using a C-shaped magnet with the radial orientation was improved by 3% compared to the conventional block-shaped magnet with an axial orientation on simulation. The HREE-free hot-deformed Nd-Fe-B magnets can be adopted for xEV motors with the above idea even if they are inferior to the HREE-containing sintered Nd-Fe-B magnets in terms of the magnetic properties.

In this paper, we describe the shape and orientation control technology for hot-deformed magnets developed by DS and DEC. We introduce the net-shape molding technique that achieves the size and the shape precision equal to or higher than that of the machining process. We also explain the current level of the orientation accuracy and the evaluation method for C-shaped magnets.

2. CONTROLLING SHAPE OF MAGNET

Hot-deformation process is a method of determining the shape and orientation of magnets by plastic forming in mold. Rapidly solidified Nd-Fe-B magnet ribbons are pulverized to powders and the powders are plastically deformed in a high temperature mold

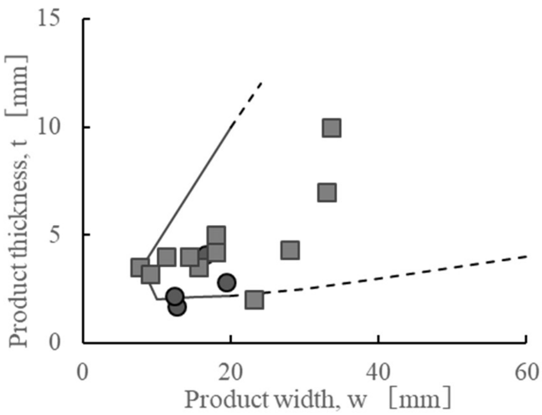

Fig. 5 Range of sizes of hot-deformed magnets

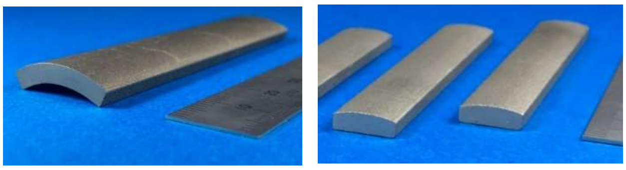

Fig. 6 C-shaped and D-shaped hot-deformed magnet fabricated by net-shape technique

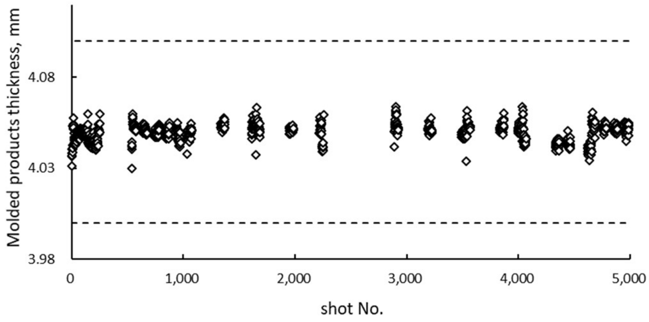

Fig. 7 The change of thickness of hot-deformed magnets In mass production scale (~5,000shots)

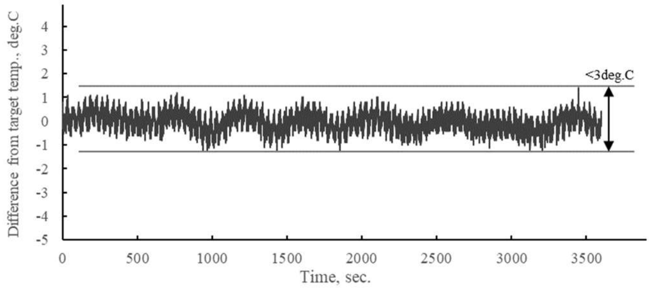

Fig. 8 The change of temperature at mold during hot-deforming

(Fig. 3). In the process, sizing and orientation occur at the same time in a short period of time. The magnets have ultra-fine (~100 nm) crystal grains, which show high coercivity even if it does not contain the HREE (Fig. 4). It has the advantage that various shapes and orientations can be realized if the design of strain in plastic deforming is optimized.

Magnets can be manufactured in various sizes and shapes. The size of hot-deformed magnets ranges 2~10 mm in the magnetization direction, 7~60 mm in the width direction with 60 mm in the longitudinal direction (Fig. 5). There are constraints in the ranges due to the machine installed capacity, the mold strength, and the handling conditions. Since there are many needs for the miniaturization of the magnets for the countermeasures against the resource risk and the potential cost increase, we are expanding recently the area to the narrower and the thinner magnets.

The lineup of the magnet shapes which can be molded is also being expanded. DEC began mass production of the hot-deformed ring-shaped magnets in 1992 and the block-shaped magnets for Honda-HEV in 2016. As described above, since the magnet shape can be determined by the shape of the die, it can be fabricated into any shape. In fact, C-shape and D-shape magnets have already been successfully molded (Fig. 6), and concave-shape, crescent-shape and any other shapes can be molded according to needs from customers.

Also, the development of the net-shape molding technique, in which machining process for sizing become unnecessary, has been completed. Since the magnet size is controlled on the die with the excellent wear resistance, it is possible to achieve the same or higher accuracy as machining (Fig. 7). Since temperature fluctuations during hot-deforming process affect the mold size dimensions by multiplying the linear expansion coefficient, temperature control is performed in the fluctuation range of less than 3 °C (Fig. 8). By consolidating and controlling the factors which affect the shape and dimensions of magnets in the hot-deforming, the mass production process of net shape molding technology was completed.

3. CONTROLLING ORIENTATION DIRECTION

In this section, we introduce orientation control technology for the hot-deformed Nd-Fe-B magnets of the C-shape with the radially-oriented magnets as an example. As it has already been mentioned in the previous research that the C-shape magnet with the radial-oriented magnets contribute to the improvement of the motor torque, [4] it seems to be important to suppress the orientation deviation from the ideal radial orientation. So, we discuss first the methods to control and measure the orientation directions of hot-deformed magnets which are fabricated by net-shaped molding technique.

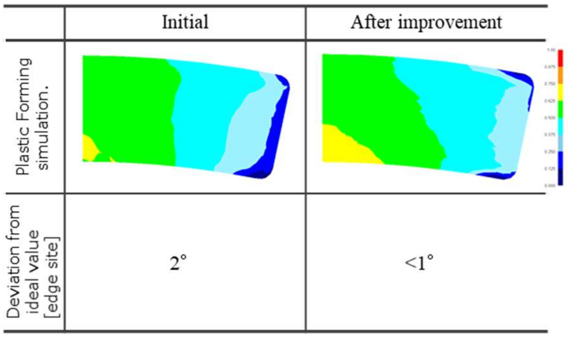

Fig. 9 The improvement of strain distribution at the edge of C-shaped and radially-oriented magnets

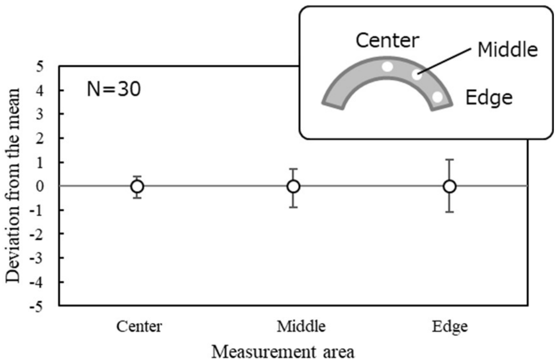

Fig. 11 The precision of orientation direction of magnets (n=30)

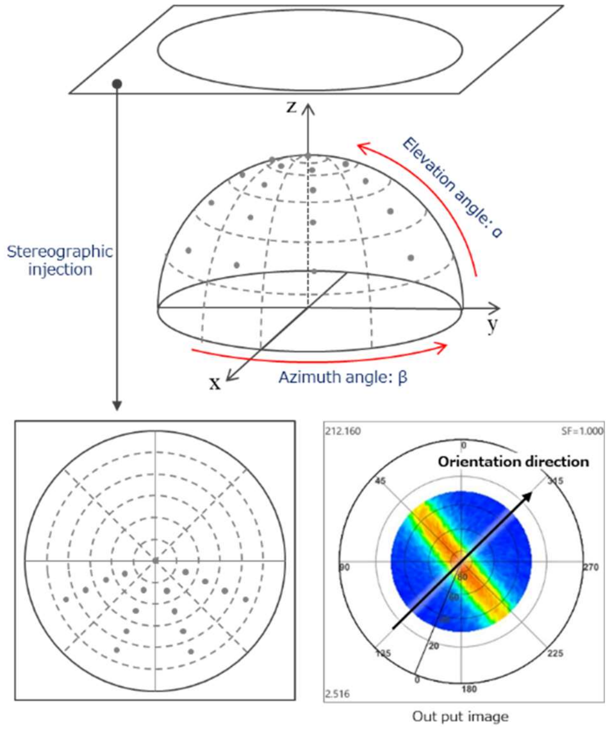

Fig. 10 The schematic illustration to create a pole figure using the stereographic projection

In the case of hot-deformed magnets, it is theoretically possible to achieve an arbitrary orientation state if the distribution changes continuously. The change in shape is described by the strain tensor, and hot-deformed magnets have a feature that the *c*-axis direction of the crystal grains is parallel to the minimum principal strain direction. In the hot-deforming process, the material is plastically deformed by grain boundary slippage with the existence of the molten grain boundary phase, and this was discussed in detail in other literature (5). Therefore, hot-deformed magnets with complex orientations can be manufactured by designing the mold structure.

The orientation direction deviation of the edge part, which is the most concern part in the net-shape molding technique, has also been obtained good result. The orientation of the edge part tends to deviate compared to the center part. This is because the minimum principal strain direction deviates from the ideal direction due to the local stress concentration, but it has been improved by the mold design that takes stress concentration relaxation into account (Fig. 9).

Polar point measurement by the X-ray diffraction is used to confirm the orientation direction of the crystal grains in the hot-deformed magnets (Fig. 10). First, X-rays are irradiated to the area to be of in the irradiation region by selectively extracting diffraction peaks from the {410}, which are lattice planes perpendicular to the {001}. Due to the measurement time required for analysis, the irradiation diameter is limited to more than 1 mm in diameter. Since the direct information from the orientation of the crystal structure is obtained by this method, it is faithful to the basics as a method to obtain the orientation direction.

Actually, the improvement of the orientation deviation at the edge parts is clearly measured by using the XRD pole diagrams. The deviations from the target orientation directions are within ±1° even in the edge (Fig. 11). In this way, it is confirmed that the orientation control accuracy is also improved to the utmost limit. Since the technique is applied to other kinds of shape and orientation, the magnets, which are suitable to each ideal magnetic circuit design by motor manufacturers, have been able to be served.

4. MAGNETIC PROPERTIES

Permanent magnets for xEVs are required to have higher demagnetization resistance than conventional magnets. Automakers are assuming the use of motors in the high rotation range of tens thousands of rpm in order to achieve both high output and miniaturization of motors in xEV. As the rotation speed increases, a high-frequency magnetic field is applied to the magnetic materials, so the induced current also increases

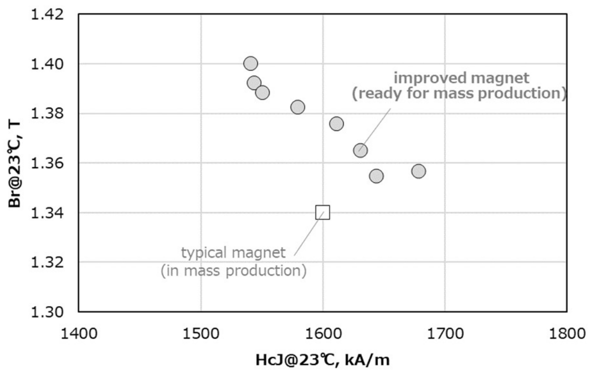

Fig. 12 Magnetic properties of hot-deformed magnets for xEV

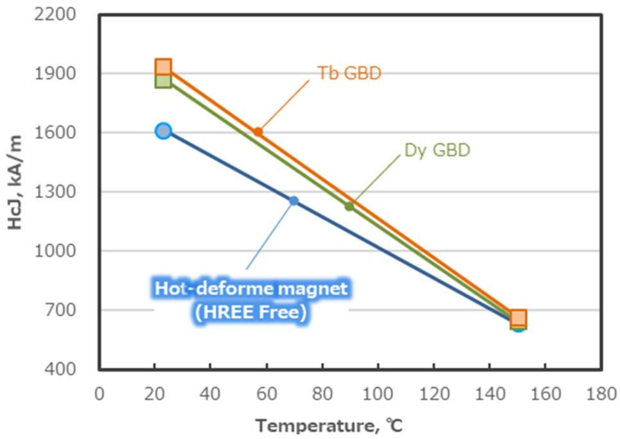

Fig. 13 The temperature dependence of coercivities of sintered magnets and hot-deformed magnets

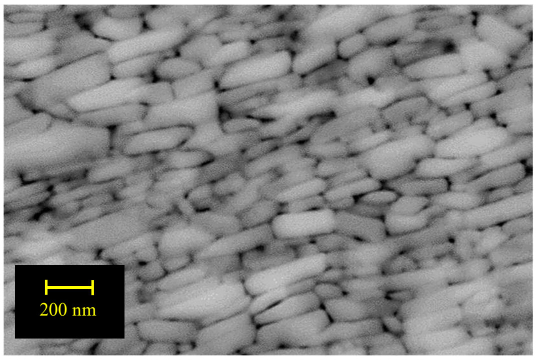

Fig. 14 SEM image: typical HREE hot-deformed magnet (B_r=1.34 T, H_{cJ}=1600 kA/m)

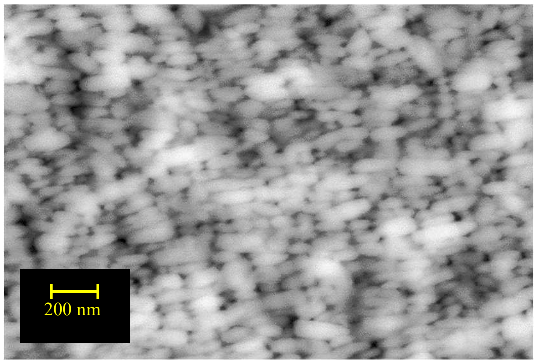

Fig. 15 SEM image: improved HREE hot-deformed magnet (B_r=1.36 T, H_{cJ}=1678 kA/m)

proportionally. The eddy current generated in this way raises the temperature of the magnet, and the maximum temperature in the magnet is expected to be around 200 °C.

For the demand for demagnetization resistance at high temperatures, we are developing hot-deformed magnets with better demagnetization resistance than before. Remanence magnetization and coercivity values at room temperature of typical HREE-free magnets for HEVs are 1.34 T and 1600 kA/m respectively, which is mass-produced in DEC. Recently, the properties of HREE-free hot-deformed magnets for xEV have been improved to 1.36~1.40 T and 1678~1540 kA/m respectively (Fig. 12). It is thought that we have achieved the above improvement by stabilizing the quality of rapid-quenched Nd-Fe-B powders and improving strain design technique in mold.

In addition, hot-deformed magnets have excellent temperature dependence. It has been reported in several papers that the fine crystal grains constituting hot-deformed magnets ensure the above good temperature dependence. The coercivity of hot-deformed magnet is inferior to sintered magnets at room temperature. However, it can be seen that the coercivity of hot-deformed magnet is close to that of sintered magnet at 150 °C (Fig. 13). The coercivities of typical Tb-GBD sintered magnet, Dy-GBD sintered magnet and improved hot-deformed magnet at room temperature are 1935, 1873 and 1615 kA/m respectively. However, at 150 °C those are 668, 648 and 633 kA/m, which are close to each other.

In fact, it has been confirmed that an ultrafine and homogeneous crystal structure can be obtained compared to HREE-free magnets mass-produced for conventional HEVs. Conventional magnets have the distribution of crystal grains although the grain size is much finer than that of sintered magnets (Fig. 14). On the other hand, most recently improved magnet has a grain size of 100 nm or less and has little distribution (Fig. 15). We succeeded in suppressing the grain growth in the hot-deforming process to the utmost extent and achieving homogeneous growth throughout the magnet. It is believed that this microstructure provides high coercivity and good temperature dependence.

It has already completed that basic technological development of magnet materials with improved magnetic properties, and preparations for mass production are currently underway.

5. CONCLUSION

Daido Steel and Daido Electronics have established the techniques for controlling the shape and orientation of the HREE-free hot-deformed magnets. Additionally, the magnetic properties have been improved for xEV applications. With these techniques, we can contribute to the ideal magnetic circuit designs for high performance of xEV motors as several motor manufacturers proposed. s

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