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TRANSLATED PAPER

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Research on motor with nanocrystalline soft magnetic alloy stator cores

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Abstract

We built a prototype motor with NANOMET stator cores. NANOMET is one of the several nanocrystalline soft magnetic alloys [1]. The motor iron loss and other characteristics of NANOMET were compared with 35A360, which is one of the widely used conventional electromagnetic steel sheets, and the effectiveness of the new material is shown. This paper describes the methods to build NANOMET stator cores, and presents the evaluation results of the prototype motor.

KEYWORDS

high flux density, high torque, IPM motor, low iron loss, nanocrystalline soft magnetic alloy, NANOMET

1 | BACKGROUND AND OBJECTIVE

Low iron loss materials are desired as means for improving the efficiency of EV motors, industrial motors, robot motors, and the like. In 2010, NEC Tokin (not Tokin) released a nanocrystal soft magnetic material called NANOMET (previously known as "SENNTIX III"). This material has iron loss equivalent to that of iron-based amorphous alloy (hereinafter referred to as "amorphous"),[1,2] and is characterized as having higher saturation magnetic flux density than "amorphous". Moreover, it is thought that low iron loss and high torque density will be achievable in a well-balanced manner by using the NANOMET in motors.

Reference (3) is a study in which NANOMET was actually used in a motor. In this prior study, an un-heat-treated quenched ribbon of NANOMET was processed and, thereafter, heat treated. In this study, we conceived of a novel approach in which we attempted to fabricate a prototype of a stator core using heat-treated NANOMET ribbon, which is difficult to handle.

As such, in this paper, we will first discuss the machining and fabrication methods of the stator core. Then, we will confirm the iron loss characteristics of the prototype motor that comprises the core, and demonstrate that NANOMET is useful for reducing the iron loss in motors.

Note that, NANOMET is a trademark owned by Tokin Corporation and Tohoku Magnet Institute, and the NANOMET ribbon used in this study was created in the NEDO project with Tokin: "Development of Magnetic Materials for High-Efficiency Motors for Next-Generation Automobiles."

2 | NANOMET

Figure 1 illustrates the electromagnetic characteristics of the conventional electromagnetic steel plate 35A360 found in References (3–5), "amorphous," and NANOMET. NANOMET is a Fe-Si-B-P-Cu-based nanocrystal soft magnetic material. Due to its low coercivity (Hc) and material thinness (25 μm), it has iron loss as low as that of "amorphous".[2] Also, its saturation flux density (Bs) is higher than that of "amorphous" and is about the same as 35A360. As such, we expect that a NANOMET stator core will achieve high torque density and low iron loss that are substantially equal to those of a conventional electromagnetic steel plate.

NANOMET is formed into a ribbon by rapid solidification from the molten alloy thereof and, thereafter, is subjected to heat treatment to impart low iron loss characteristics.[3] As such, there is a concern about decreased core space factor when replacing the electromagnetic steel plate with

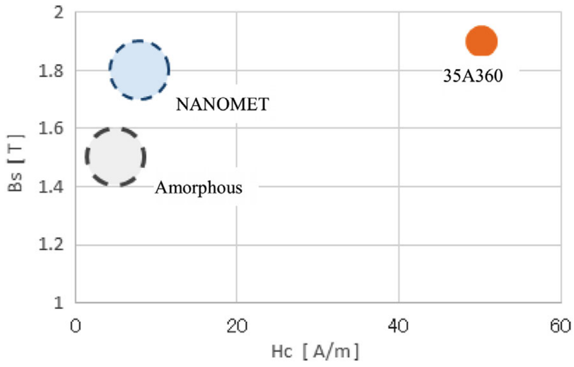

FIGURE 1 The magnetic characteristic of NANOMET [Color figure can be viewed at wileyonlinelibrary.com]

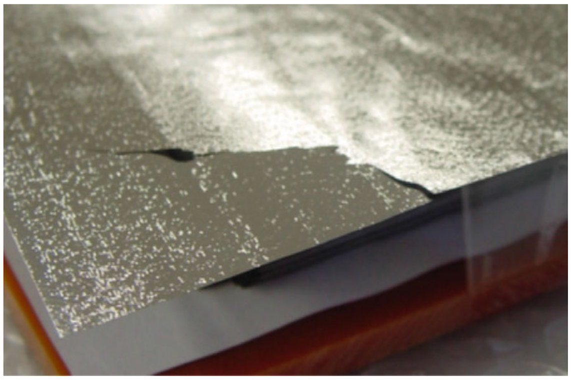

FIGURE 2 Cracked NANOMET sheet [Color figure can be viewed at wileyonlinelibrary.com]

NANOMET and stacking multiple layers of the ribbon. Moreover, since NANOMET is a hard and brittle material, die cutting and other types of cutting are difficult, which complicates the machining method for the stator core. If we call a product obtained by cutting NANOMET ribbon to predetermined dimensions a NANOMET sheet, we see that, in Figure 2, the NANOMET sheet is thin and brittle to the point of breaking when simply lifted by a finger.

3 | FABRICATION OF STATOR CORE

Before fabricating the NANOMET stator core, the following items must be confirmed:

(1) The NANOMET ribbon can be cut to equal lengths;
(2) The four corners of the cut NANOMET sheets are aligned and the sheets can be blocked by compressing them to the target core space factor and applying an adhesive; and
(3) The NANOMET sheets can be machined by wire cutting.

The tool illustrated in Figure 3 is used to perform the cutting of item (1). In Figure 3, we see that, instead of cutting, the

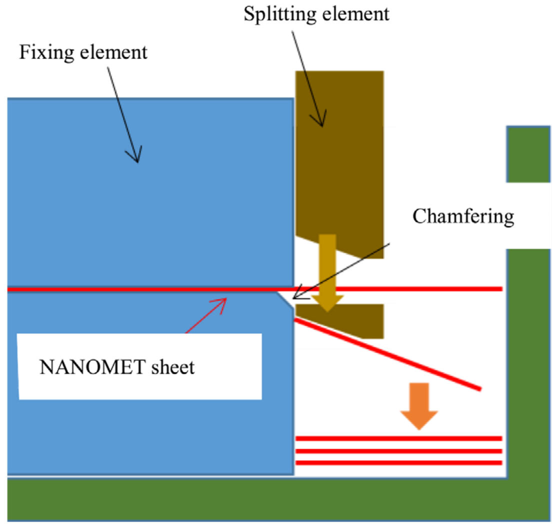

FIGURE 3 NANOMET splitting component [Color figure can be viewed at wileyonlinelibrary.com]

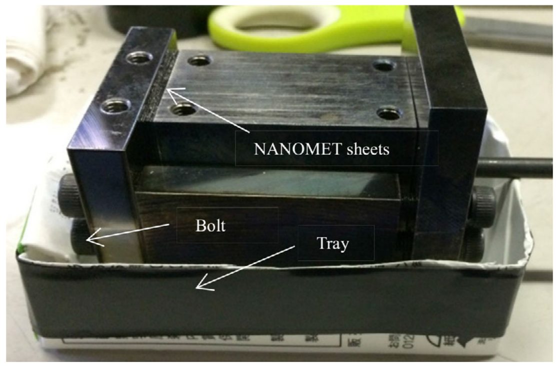

FIGURE 4 The adhesion work of NANOMET sheets [Color figure can be viewed at wileyonlinelibrary.com]

NANOMET ribbon is split in a straight line to fabricate sheets of identical dimensions. In Figure 3, the NANOMET ribbon is moved a predetermined length to the right and, in this state, is fixed by top and bottom fixing elements. Then, the splitting element is moved downward along the fixing elements and applies pressure to the NANOMET ribbon, thereby causing the NANOMET ribbon to split. The resulting NANOMET sheets are stacked.

The fixing elements used in the splitting are used without modification in the compressing and adhesion work mentioned in item (2). Figure 4 depicts the work of bonding the NANOMET sheets. In Figure 4, 88 NANOMET sheets with aligned corners are compressed without modification using a bolt, and are submerged about 1/3 in a tray that is filled with a highly impregnating adhesive. Figure 5 illustrates the impregnation/adhesion. The highly impregnating adhesive is impregnated into the gaps between the NANOMET sheets by capillary action. After the sheets have been impregnated with the adhesive, they are heated and cured. Thus, a NANOMET

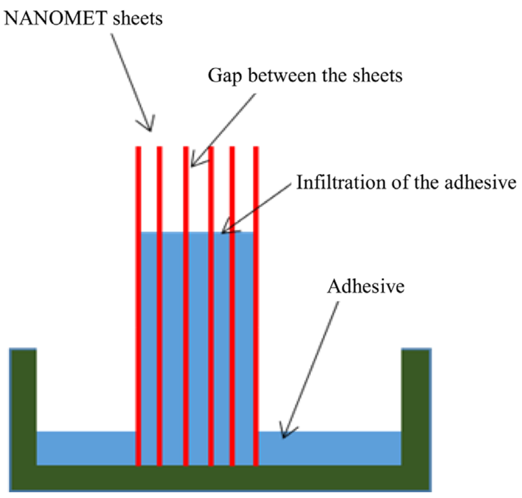

FIGURE 5 The illustration of impregnating adhesive [Color figure can be viewed at wileyonlinelibrary.com]

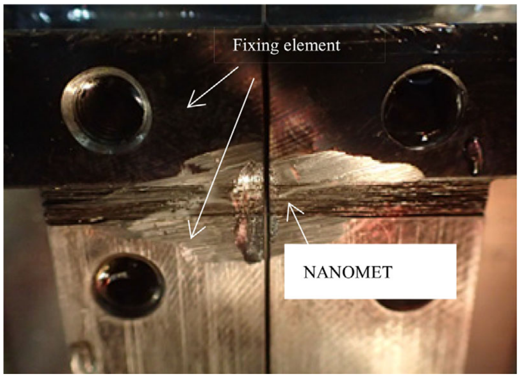

FIGURE 6 NANOMET performing a wire cutting [Color figure can be viewed at wileyonlinelibrary.com]

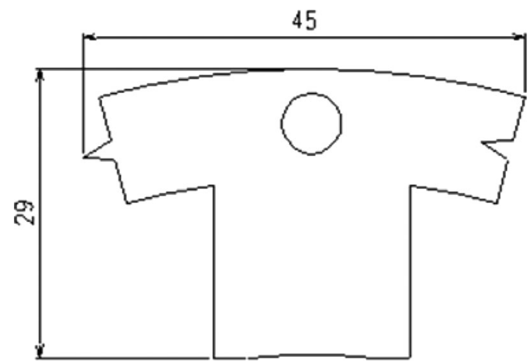

FIGURE 7 The shape of stator core

FIGURE 8 The trial manufactured stator core [Color figure can be viewed at wileyonlinelibrary.com]

core block is obtained. Note that the viscosity of the adhesive was 50 mPa·s, and was heated and cured overnight (at least 12 hours) in a constant temperature chamber set to 130°C.

For item (3), we confirmed that a NANOMET ribbon with a width of 30 mm could be cut every 40 mm, and that the block obtained by stacking and adhering 88 of the NANOMET sheets could be machined by wire cutting.

Since wire cutting is a type of electrical discharge machining, one of the electrodes needs to be the workpiece. As such, the entire 88 NANOMET sheets (stacked to about 3 mm) has to conduct as an electrode. In order to make all of the sheets conductive, the NANOMET was machined while still mounted on the fixing element. Figure 6 depicts the NANOMET that has been wire cut. In order to prevent roughening of the hard and brittle NANOMET surface, we set the machining speed of the wire cutting to the lowest speed possible. As a result of these preliminary checks, we confirmed that the fabrication of a NANOMET stator core is possible.

Next, we acquired the required number of bundles of 80 × 120 mm NANOMET sheets with a thickness of 42 mm (about 1680 sheets) and fabricated a prototype stator core. The size of the stator core was limited to the width of the NANOMET sheets (80 mm). Since we assumed application to an EV motor, it would have been ideal to demonstrate effectiveness in lowering iron loss for capacities of that size, but the size of the sheets did not allow for the fabrication of an integrated core. Therefore, we fabricated a split core instead of an integrated core. As illustrated in Figure 7, our stator core had a shape that fit in 29 × 45 mm space, and could be fabricated from a block of NANOMET sheets with a width of 80 mm. We arranged 12 of these split cores to form a stator core with an outer diameter of 167 mm.

Figure 8 is a photograph of the one section of the stator core. The space factor of the split core was set to about 82%, which is recommended by the material manufacturer for maximum performance, and the heating/curing conditions were set as instructed by the adhesive manufacturer to three hours at 120°C. We also fabricated a 35A360 with the same dimensions, compared the prototype motor described in the following section with a motor using the 35A360, and evaluated the performance of the prototype motor.

TABLE 1 Specification of prototype motor

Stator outer diameter (mm)	167
Stack length (mm)	46
Coil-end length (mm)	66
Winding resistance/phase (mΩ)	23.4
Number of Poles	10
Number of slots	12
Mass (kg)	14

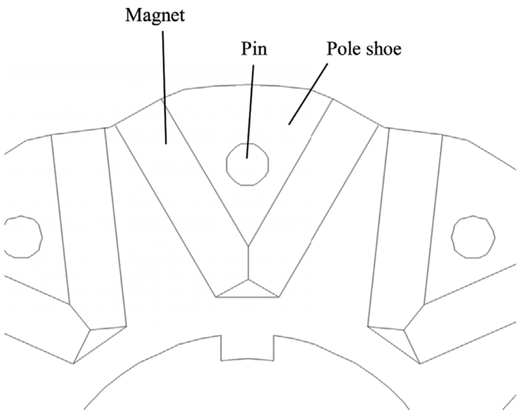

FIGURE 9 The structure of rotor

4 | PROTOTYPE MOTOR

Table 1 shows the specifications of the prototype motor. The purpose of the evaluation was to confirm the iron loss lowering effects of NANOMET and, also, to confirm the degree to which the torque characteristics of the motor decrease due to the saturation flux density and the core space factor of NANOMET being slightly inferior to those of conventional electromagnetic steel plates.

For the prototype motor, the previously reported electromagnetic component design of the concentrated flux IPM motor[6] was used. This design is known to increase the flux density at the teeth of the motor. As design values, the average value of the flux density was about 1.3 T at the gaps and about 1.7 T (unloaded state) at the teeth. Since the magnetic load, torque density, and iron loss of the motor is large, our strategy when setting the design values involved first lowering the iron loss and then making improvements to reach torque density equal to that of a conventional electromagnetic steel sheet.

Figure 9 illustrates a rotor comprising a concentrated flux IPM structure. Magnets of sufficient volume are arranged in a V-shape to form one pole. The flux generated by the two magnets concentrates at the pole shoe, thereby increasing the flux density of the gap. Bridges are omitted so as to reduce leakage flux, and each pole shoe and magnet are fixed, with a pin, to the side plates on both axial sides.

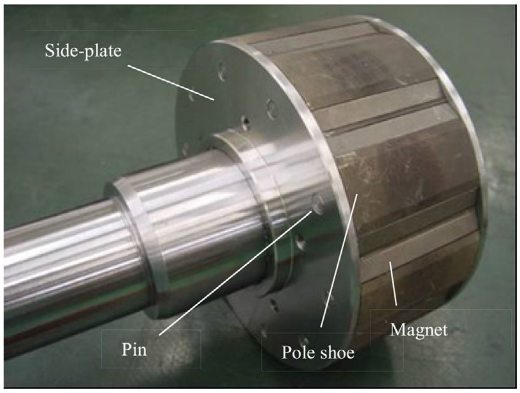

FIGURE 10 The prototype rotor [Color figure can be viewed at wileyonlinelibrary.com]

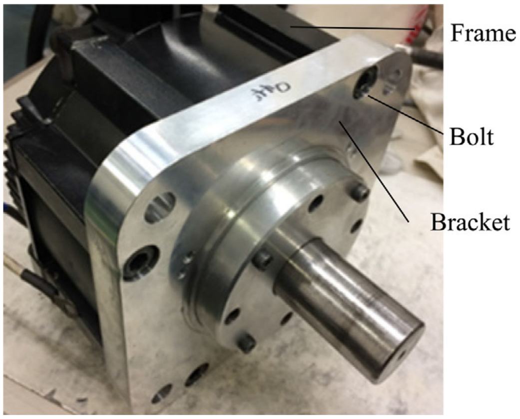

FIGURE 11 The prototype motor [Color figure can be viewed at wileyonlinelibrary.com]

Figure 10 is a photograph of the prototype rotor. The pins that pass through the pole shoes are held in the side plates, and the edges of the magnets are embedded in the side plates, thereby preventing the magnets from falling out. The rotor core, including the pole shoes, was fabricated using 35A360, and the side plates were fabricated using non-magnetic stainless steel.

Figure 11 is a photograph of the prototype motor. We used a structure for the prototype motor that allowed for easy disassembly by removing bolts. As depicted in Figure 12, once the motor is disassembled, the stator can be taken out together with the stator core. Once removed, the stator core can be replaced.

Figure 13 is a photograph of the integrated molding coil. In this figure, the stator core is removed. The integrated molding coil is formed by integrally molding, with resin, a coil with a press-molded outer shape. The 12 stator core sections are mounted on the integrated molding coil, bolts are inserted in the holes of the stator core shown in Figure 12, and the bracket shown in Figure 11 is attached. The frame is separately attached using the bolts shown in Figure 11.

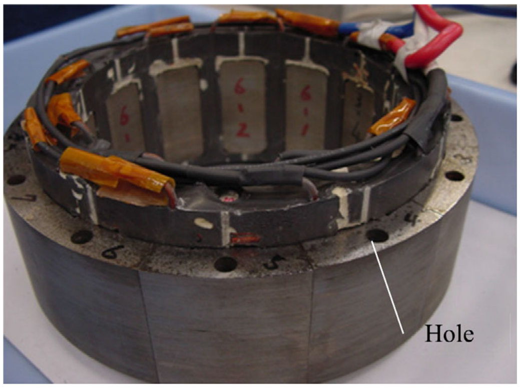

FIGURE 12 The stator with stator core [Color figure can be viewed at wileyonlinelibrary.com]

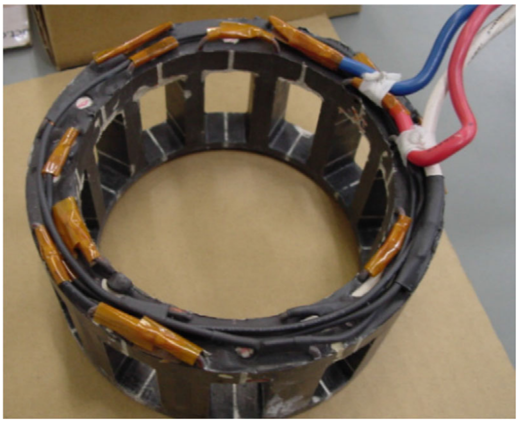

FIGURE 13 The integrated molding coil [Color figure can be viewed at wileyonlinelibrary.com]

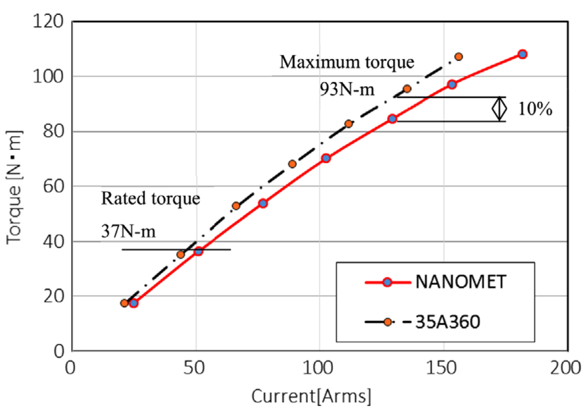

FIGURE 14 Comparison of the torque [Color figure can be viewed at wileyonlinelibrary.com]

5 | EVALUATION

5.1 | Restraint torque test

Figure 14 compares the torque generated by the two types of stator cores when installed in the motor. Note that DC power was applied with the output shaft of the motor fixed, and the generated torque was measured. In Figure 14, the phase current conversion value when operating is shown on the horizontal axis. The results of the comparison show that the torque generated at the current value where the prototype motor (35A360) with the 35A360 stator core reaches the maximum torque setting value of 93 N-m is about 10% greater than the torque generated by the prototype motor (NANOMET) with NANOMET stator core. In other words, we see that, with the NANOMET stator core, the torque density of the motor decreased about 10%. We measured the induced voltage in order to identify the cause of this decrease. Also, we measured the weights of the stator cores and calculated the core space factors.

TABLE 2 Comparison results of measurements

Material	EMF (mV/min)	Mass (g)	Sf (%)
NANOMET	25.3 (86.6%)	2605 (84.7%)	82.4 (86.4%)
35A360	29.2	3077	95.4

Table 2 compares the measured values of the induced voltage, the stator core weight, and the core space factor. The induced voltage (EMF) is the effective value of the measured waveform, the weight is the measured value of the stator core unit, and the core space factor (Sf) is a value calculated from the measured values of the core weight/dimensions and the density of each material (35A360: 7.65 g/cm^3, NANOMET: 7.5 g/cm^3). The measurement results of the induced voltage show about a 13% reduction of the NANOMET stator core compared to the 35A360 stator core. As such, reduced flux linkage is the main the cause of the decrease in torque. Additionally, if we look at the results of measuring the mass, we see that the mass of the NANOMET stator core is about 15% less than that of the 35A360 stator core. The same rotor was used and, as such, the reason why the flux linkage of the NANOMET stator core decreased even though the magnetomotive force was the same was most likely because the magnetic path cross-sectional area of the core of the NANOMET iron core was 15% smaller and the magnetic path resistance increased due to the increase in the magnetic density of the core. Since the decrease in mass is caused by the decrease in the core space factor, we need to increase the core space factor and get the mass of the stator core close to that of the 35A360 in order to remedy the torque decrease.

5.2 | No-load torque test

To measure the no-load torque, we measured, with a torque meter, the torque necessary to rotate the prototype motor from the outside. The magnitude of the no-load iron loss generated at each rotational speed can be measured as the magnitude of the torque. We can consider the difference between the torque of the motor with the 35A360 stator core and the NANOMET

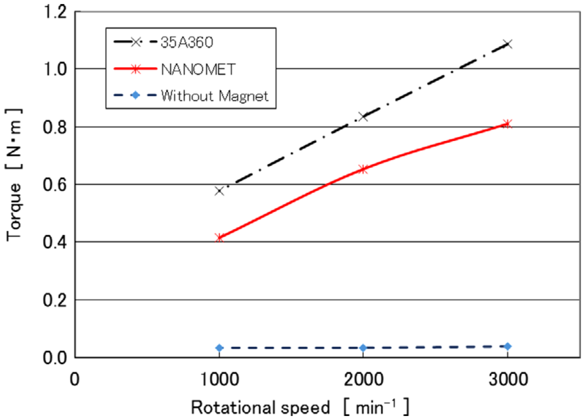

FIGURE 15 Comparison of the no load torque [Color figure can be viewed at wileyonlinelibrary.com]

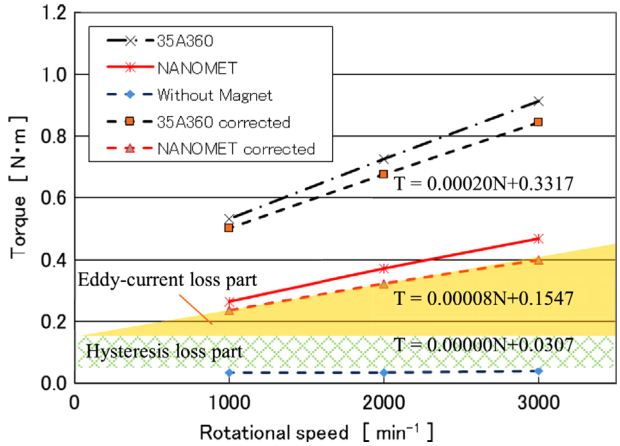

FIGURE 16 Comparison of the no load torque without coils [Color figure can be viewed at wileyonlinelibrary.com]

stator core to be the difference in the iron loss between the two motors. Figure 15 compares the no-load torque of the two motors. We compared the no-load torque at 1000, 2000, and 3000 min^{-1} for the motor with the 35A360 stator core (35A360) and the motor with the NANOMET stator core (NANOMET). In addition, measured values for a rotor without magnets (without magnet) are shown as torque due to mechanical loss. As shown in Figure 15, by changing the stator core from the 35A360 to the NANOMET stator core, it is possible to reduce the stator core iron loss to a value equal to just under 30% of the no-load torque.

5.3 | Iron loss that occurs in stator core

If we consider that the no-load loss consists of iron loss, mechanical loss, and other stray loss, Figure 15 shows the no-load torque caused by these losses. We see that the iron loss of the motor with the NANOMET stator core is less than the iron loss of the motor with the 35A360 stator core. However, in order to confirm the degree of reduction caused by the core change, we will attempt to isolate the torques caused by iron loss and the stray loss.

In the prototype motor, we are using an IPM rotor that concentrates the flux of the magnets and increases the gap flux density. As such, the stray loss due to magnet magnetomotive force is great.[6] As such, we attempted to remove the stray loss in order to compare the iron loss in the stator cores. First, we confirmed the stray loss such as the eddy current generated in the coils. Then, we removed the coils and measured the no-load torque with only the stator core. Next, we confirmed the stray loss such as the eddy current that occurs in the magnets mounted on the rotor. We divided each of the 20 magnets into five sections, fabricated a prototype of a rotor that reduces the eddy current generated in the magnets and the like, and compared the measurement results. Thus, we confirmed the minimum value of no-load torque due to the loss.

Figure 16 compares the no-load torque from which the stray resistance of the coils has been removed. The measurement values with the two stator cores and the corrected torques (eg, NANOMET *corrected*) obtained by subtracting the minimum value of the torque caused by stray loss such as the eddy current that occurs in the magnets mounted on the rotor are shown in Figure 16. A first-order approximation equation is added to the measurement values for the two corrected torques and for the rotor without magnets. Iron loss consists of hysteresis loss and eddy current loss and, in each approximation equation of the torque, the intercept when the rotational speed is 0 corresponds to the torque for the hysteresis loss, and the slope corresponds to the torque for the eddy current loss. In terms of the corrected torque for the case with the NANOMET stator core, at each rotational speed, the shaded portion represents the hysteresis loss torque (hysteresis loss part), which is a constant torque and is not dependent on the rotational speed. The portion colored in light-brown represents the eddy current loss part, and the torque increases proportional to the rotational speed.

We compared the approximate equations in which the torque of a case with the rotor without magnets is subtracted from the corrected torques of the two stator cores. In consideration of these results and also that the two corrected torques include stray losses that are yet unidentified, we can conclude that using the NANOMET results in hysteresis loss that is about 1/3 or less and eddy current loss that is about 1/2 or less that of the 35A360.

As explained for Table 2, the induced voltage of the NANOMET stator core was 13% less than that of the 35A360 stator core. The cause for this decrease is the increase in magnetic path resistance caused by the 15% decrease in mass, and we should see an increase in the flux density of the core part of the NANOMET stator core. According to the general theory of iron loss, iron loss is proportional to the square of magnetic flux density. If we can increase the core space factor and make the mass of the space factor similar to that of the 35A360, we should be about to reduce the magnetic flux density and also further reduce the iron loss that occurs in the NANOMET stator core.

Let us consider the low iron loss characteristics of NANOMET as a material (see Figure 1) and the deviation of the iron loss reduction rate from that of the 35A360 stator core. Some possible reasons for the reduction in hysteresis loss holding at about 1/3 include degradation of coercivity caused by residual stress on the splitting surface when machining to the shape of the stator core, and the influence of the hysteresis loss that occurs in the rotor core. Some possible reasons for the reduction in eddy current loss holding at about 1/2 include it being impossible to satisfactorily suppress the eddy current that occurs in the magnets mounted on the rotor even when divided into fifths, and that there is eddy current loss caused by leakage flux that occurs somewhere other than in the stator core and the coils. Reducing the mechanical loss and countering the stray loss leads to increased iron loss lowering effects of the NANOMET motor.

In the prototype motor with the NANOMET, the torque constant was reduced about 10% and, as such, about 10% more current was needed to generate the same torque and the copper loss increased about 20%. In this case, at rated output, the increase in loss exceeds the decrease in no-load loss. Therefore, it is clear that efficiency would decline in load testing. As such, when applying NANOMET to a motor, if the objective is to improve efficiency, it is critical that the mass of the stator core be similar to that of a conventional electromagnetic steel plate. Moreover, the core space factor must be increased to maintain high torque density.

6 | CONCLUSION

In this study, we conceived of a novel approach of forming heat-treated NANOMET ribbon, which as difficult to handle, into a motor core, and fabricated a prototype. In our evaluation of the prototype motor, we concluded that, with the NANOMET stator core, the hysteresis loss was about 1/3 and the eddy current loss was about 1/2 less than that of a conventional electromagnetic steel plate, thus confirming that applying NANOMET to a motor will result in a reduction of iron loss. Topics for further study include methods to increase the core space factor in order to develop a motor that achieves by even lower iron loss and higher torque density in a well-balanced manner.

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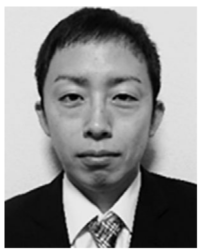

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