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Newly Developed Grain-Oriented Electrical Steel Suitable for Application to Segmented Core Motors†

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Abstract:

A new grain-oriented electrical steel sheet, "JGE," without a forsterite (Mg_2SiO_4) undercoating was developed. Because JGE has no hard coating such as forsterite, the lifetime of stamping dies is about ten times longer than with conventional grain-oriented steel sheets. Iron loss at the area between the tooth and yoke of the motor core is remarkably reduced using JGE. Therefore, the maximum motor efficiency of segmented core motors using JGE is higher than that with the highest grade of non-oriented steel sheet. Based on these results, JGE offers important advantages as a material for application to segmented core motors.

1. Introduction

From the viewpoint of environmental protection, reducing energy loss in various kinds of electronic and electric equipment, machinery and vehicles has become an increasingly important subject. In particular, there has been growing interest in the development of new electric and hybrid vehicles. In order to obtain higher performance in various types of motors used in these vehicles and other electric equipment, motor structures have been changed[1,2] and several properties of motor core materials such as electrical steels have been improved.

JFE Steel developed a new type of grain-oriented electrical steel (GO) called JGE that does not have a forsterite (Mg_2SiO_4) undercoating[3,4]. Since a forsterite undercoating is very hard, GOs are rarely used for products that require punching, such as motor cores. On the other hand, since non-oriented electrical steel (NO) has poor magnetic properties in the rolling direction (RD) of the steel sheet in comparison with GO, the use of NO in punched materials is disadvantageous for the viewpoint of energy consumption. Because JGE has both good punchability and good magnetic properties, it is expected to solve these problems.

2. Magnetic Properties and Punchability

The magnetic properties of JGE at 50 Hz in the rolling direction (RD) and transverse direction (TD) are shown in **Table 1**. For comparison, the table also includes the properties of a conventional GO "JG155" and a high-grade NO "JN210". In this table, $W_{10/50}$ shows iron loss at 1.0 T, 50 Hz and B_8 shows magnetic flux density at 800 A/m. All samples had the same thickness of 0.35 mm. As shown in this table, the magnetic properties of JGE are almost the same as those of JG155 and better than those of JN210 in the RD. In the TD, JGE has much lower iron loss than JG155. It should also be noted that, as shown in **Table 2**, the iron loss of JGE at higher frequencies is much better than that of the other materials. It is considered that JGE has superior properties at high frequencies because it contains many fine grains in large secondary grains, contributing to refinement of the magnetic domain width[3].

The punchability of JGE and JG155, which has a forsterite undercoating, were investigated. In the punching test, ϕ15 mm discs were continuously stamped using stamping dies made of the steel (SKD11). The burr height of the samples was measured after a certain number of punching strokes. The punchability of a steel sheet can be evaluated from the number of strokes when the burr height reaches 50 μm. In these results, the

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Table 1 Magnetic properties of samples at 50 Hz

Specimen	Direction	Iron loss		Magnetic flux density	
		$W_{10/50}$ (W/kg)	$W_{15/50}$ (W/kg)	B_8 (T)	B_{50} (T)
JGE	RD	0.51	1.24	1.79	1.95
	TD	1.14	2.89	1.35	1.55
JG155	RD	0.41	1.02	1.83	1.97
	TD	1.57	3.58	1.38	1.47
JN210	RD	0.85	1.86	1.52	1.69
	TD	1.04	2.06	1.46	1.64

Table 2 Magnetic properties of samples at high frequencies

Specimen	Direction	Iron loss	
		$W_{10/400}$ (W/kg)	$W_{1/5\,000}$ (W/kg)
JGE	RD	11.4	11.2
JG155	RD	12.9	14.4
JN210	RD	14.5	11.9

punchability of JGE was about 10 times better than that of JG155[3)]. The disadvantage of the poor punchability of GOs having a forsterite undercoating does not give rise to problems when they are used in huge transformers. However, it can be a serious problem in use in motor cores having complicated shapes. We believe that JGE is suitable for application to such motor cores.

3. Magnetic Measurement Using T-shaped Sample

A segmented motor core is composed of small pieces having a T shape. It can be predicted from this T shape that the magnetic properties in both the horizontal and vertical directions are important. Application of JGE in segmented motor cores may efficiently take advantage of its improved properties because JGE has good magnetic properties in both the RD and TD. In addition, because the shape of the piece is complicated, the punchability of the material is also important. From this viewpoint, GOs with inferior punchability are unsuitable for application to this type of core. For this reason, we did not carry out further investigation of JG155, which is a conventional GO.

In this section, we will present the results of magnetic property measurements using a T-shaped sample, which simulates a segmented core motor part.

Figure 1 shows an illustration of the apparatus used to measure the magnetic properties of the T-shaped sample. In this paper, the horizontal part of the T-shaped sample is called the yoke and the vertical part is called the tooth. The direction of the tooth was aligned with the RD of the sample in order to take advantage of the good magnetic properties of JGE. The apparatus contains three exciting coils which can excite the sample independently. In order to simulate the magnetic flux current in real motors, the magnetizing frequency was set to be 150 Hz, and the phase shift between each magnetization waveform was 30°. The amplitude of the waveform on the tooth is 1.75 times larger than that of the yoke. These measurement conditions were obtained by investigation of real motors. Iron loss of the sample was calculated from both the magnetic flux density and the magnetization intensity obtained from this measurement. **Figure 2** shows the normalized iron losses of JGE and JN210 measured by the apparatus. It was found that the iron loss of JGE was much lower than that of JN210. For further investigation, the local flux distributions and local iron losses of both samples were measured using the needle probe method[5)]. **Figure 3** illustrates the measurement positions of local magnetic properties on the T-shaped sample, and **Table 3** shows the obtained local iron losses. The numbers in Table 3 correspond to those in Fig. 3. As shown in Table 3, the local iron losses of JGE were smaller than those of JN210 at all positions.

Figure 4 shows the local flux distributions of each sample at positions No. 2 and No. 4. Local flux distribution is defined as the locus of the maximum flux densities in all directions on the plane of the sample. In the case of No. 2, the locus shapes of JGE and JN210 are similar to each other and extend in the tooth direction, which coincides with the RD of the sample. Because the iron loss of JGE in the RD is much lower than that of

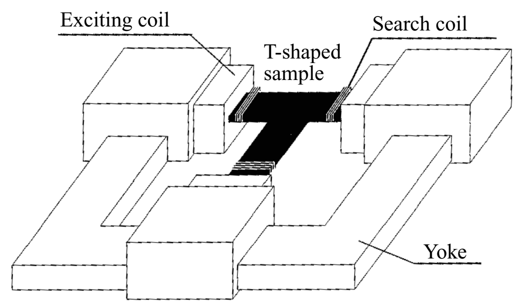

Fig. 1 Illustration of experimental apparatus

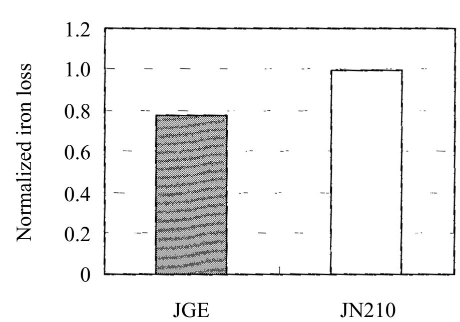

Fig. 2 Normalized iron losses of T-shaped samples made of JGE and JN210

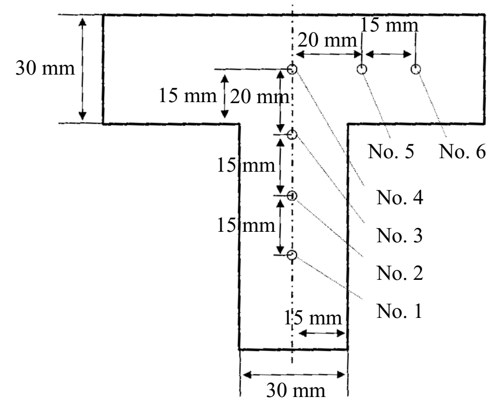

Fig. 3 Illustration of measurement positions of T-shaped sample

Table 3 Magnetic properties of samples at high frequencies

Specimen	Local iron loss (W/kg)					
	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6
JGE	3.5	3.59	2.17	1.24	1.69	1.63
JN210	5.39	5.35	4.27	2.78	2.63	1.94

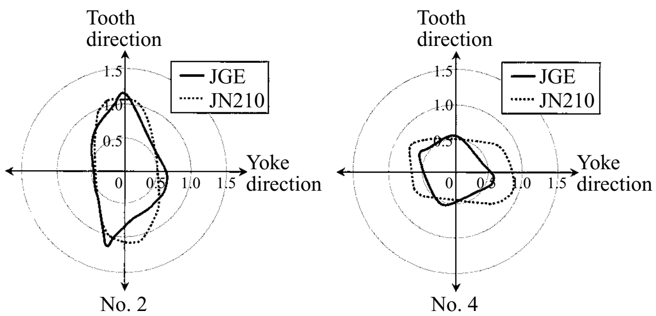

Fig. 4 Illustration of local flux distributions in JGE and JN210

JN210 as shown in Table 1, JGE is considered to have lower local iron loss than JN210. In the case of No. 4, the shape of the local flux distribution of JGE is smaller than that of JN210. In addition, the distribution in JGE is lozenge-shaped, while that in JN210 is rectangular. This indicates that the magnetic flux current also passes between the tooth direction and the yoke direction in JN210. Therefore, the local iron loss of JN210 increases in proportion to the increase of the magnetic flux and is higher than that of JGE. It is presumed that this difference occurred because JGE has the axis of hardest magnetization in the <111> direction, which is between the RD and TD, but JN210 does not possess this magnetic anisotropy.

4. Application to Segmented Motor Core

Most motors used in electric and hybrid vehicles in Japan are of the brushless DC type[6–8]. Therefore, we investigated segmented core motors of this type. In order to evaluate the material dependence of various types of motor performance in segmented core motors, the model motor technique was used. Stator cores were made from JGE and JN210. The size and shape of the stators were the same in all cases, and the same rotor was used. **Photo 1** shows the apparatus for measuring motor performance. The specifications of the brushless DC motor used in the test and its drive circuit system are shown in **Table 4**. Rated power output was 300 W. The rotor was of a surface-mounted permanent magnet-type using a rare-earth alloy magnet with 8 poles. After adjusting the drive voltage of the test motor by PWM pulse width and setting it at a predetermined no-load rotational speed, a torque was applied with a load motor and motor performance was measured by the sweep of rotational speed. The types of motor performance measured were motor efficiency and torque-rotational speed characteristics.

Figure 5 shows the maximum motor efficiency of each sample obtained by this technique. JGE had higher maximum motor efficiency than JN210. **Figure 6** shows the efficiency maps of motors in which the two types of materials were used in the respective cores. The area of high efficiency over 90% was wider with JGE than with JN210. **Figure 7** shows the torque dependence of the efficiency at 1 500 rpm. This figure reveals that JGE has higher efficiency than JN210 at torques over 2.3 Nm.

It is clear from these results that JGE is capable of providing excellent performance in segmented core motors.

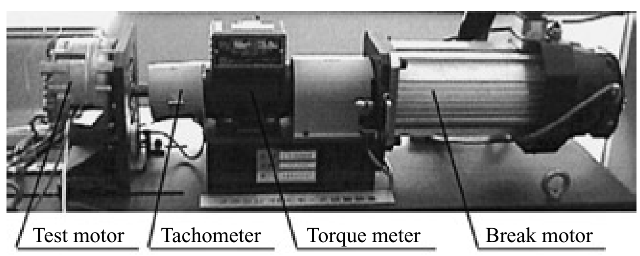

Photo 1 Model motor testing machine

Table 4 Specifications of tested brushless DC motor

Motor type	Surface-mounted permanent magnet-type brushless DC motor
Rated power	300 W
Input voltage	48 V (DC)
Stator dimensions	ϕ140 (OD) × ϕ84 (ID) × 66 (H) mm
Number of slots	12
Rotor dimensions	ϕ83 (OD) × 66 (H) mm
Number of poles	8

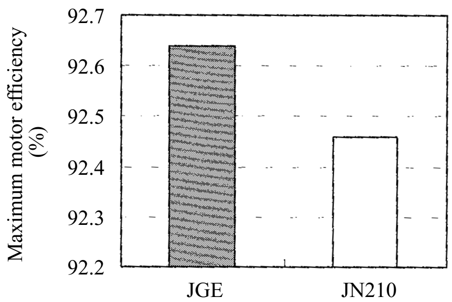

Fig. 5 Maximum motor efficiency of model motors made of JGE and JN210

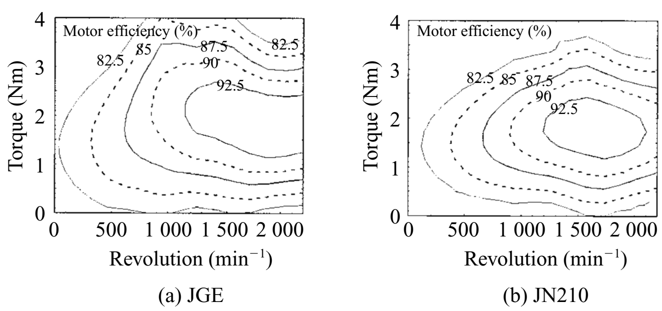

Fig. 6 Motor efficiency maps obtained from model motor measurement

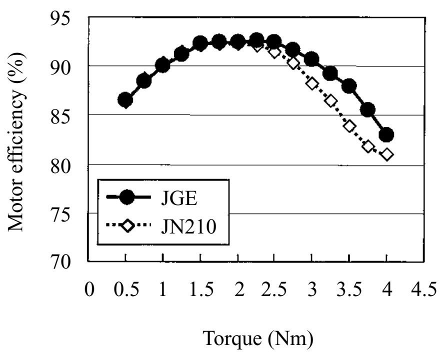

Fig. 7 Torque dependence of motor efficiency at 1 500 rpm

5. Conclusion

A new grain-oriented electrical steel, JGE, without a forsterite undercoating was developed. The properties of JGE were compared with those of a conventional GO (CGO) and a high-grade NO. The following results were obtained:

(1) The iron loss of JGE at higher frequencies is greatly superior to that of the other electrical steels because JGE does not have a forsterite undercoating.

(2) The punchability of JGE is about 10 times better than that of CGO. This result suggests that the use of JGE will contribute to increase a stamping die life compared with that with CGO.

(3) From magnetic measurements using the T-shaped samples, both the local and total iron losses of JGE are lower than those of high-grade NO (JN210). This result is attributed to the difference in the local flux distribution.

(4) JGE displays higher maximum motor efficiency and motor efficiency in the high torque range than JN210. Therefore, JGE is a suitable material for segmented motor cores.

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