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Newly Developed Grain-Oriented Electrical Steel with Good Punchability Suitable for EI Cores*



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Synopsis:

A grain-oriented electrical steel RGE without forsterite (Mg_2SiO_4) undercoating is recently developed aiming at the application to EI lamination transformer cores. The life of stamping dies in using RGE sheet is ten times longer than in using conventional grain-oriented steel sheet with forsterite undercoating. The iron loss of EI core stamped from RGE sheet is superior or equivalent to that using conventional one. This comes from the excellent magnetic property of RGE in the transverse direction that consists the one-fifth length of the magnetic circuit in the EI lamination core. In addition, high efficiency in the noise reduction is expected when RGE is applied to choke coil because RGE has smaller high frequency iron loss.

1 Introduction

EI lamination cores are widely used in small transformers and home electric appliances. They are composed of E and I pieces that form a magnetic circuit inside coils. E and I pieces are continuously stamped from steel sheets as illustrated in **Fig. 1**. This way of stamping is so economical that no scraps are produced. EI lamination cores are manufactured not only from electrical steels but also from other soft magnetic materials such as ferrite and permalloy because of the good efficiency and productivity in manufacturing.

The major material for making EI lamination cores used in small power supplies is non-oriented electrical steel with low Si content. Within the magnetic circuit of EI lamination core, 4/5 of the magenetic direction corresponds to the rolling direction, and 1/5 to the transverse direction. Therefore, the magnetic flux along the rolling direction is dominant in the EI lamination core. Grain-oriented electrical steel shows better performance in the EI lamination core because it has excellent magnetic properties in the rolling direction. Grain-oriented steel is used in adapters for power supplies or ballast for tubular fluorescent lamps when the reduction of power loss is required.

On the surface of commercial grain-oriented electrical steel, a forsterite (Mg_2SiO_4)—base coating is formed during the final annealing in the production process. Forsterite coating is obtained form a solid chemical reaction between MgO used as an annealing separator and SiO_2 that formed on the surface during decarcurization annealing in the previous process. In addition, another tension coating consisting of phosphate and colloidal SiO_2 is applied onto the forsterite coating in order to provide insulation and to reduce iron loss. The forsterite coating has also acts as a binder between the base metal and the tension coating to increase adhesion strength.

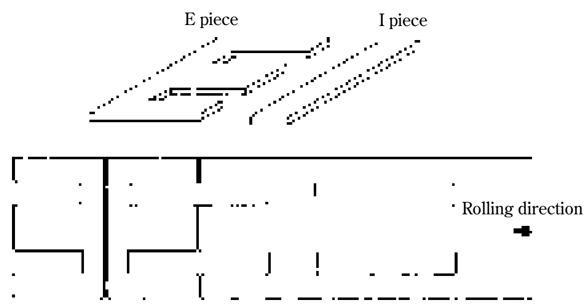

Fig. 1 Stamping method of E and I pieces from steel sheet

Unfortunately, because forsterite coating is much harder and thicker than usual insulation coating applied to the non-oriented electrical steel that the life of stamp-

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ing dies is very short when the grain-oriented electrical steel sheet is used. Therefore, grain-oriented electrical steel without forsterite coating is desired by manufacturers that stamp EI lamination cores. In response, Kawasaki Steel just recently developed RGE a new grain-oriented electrical steel without forsterite coating.

2 Estimation of the Punchability

The punchability of RGE without forsterite coating and of conventional grain oriented steel (CGO) was investigated. On the surface of RGE, an inorganic insulation coating that is usually applied to non-oriented electrical steel is formed.

In the punching test, ϕ15 mm discs were continuously stamped using stamping dies made of the steel (SKD11). Initial burr height of the stamped discs was adjusted to 10 μm. Burr height was measured after a certain number of punching strokes. The relation between the burr height and the number of punching strokes is shown in **Fig. 2**. When the burr height was 50 μm, RGE required ten times as many punching strokes as CGO has. As was proved in this test, RGE helped to increase the life time of the stamping die.

In addition, steel sheet is wound when troidal transformer core is manufactured. The insulation coating must not be removed during the winding. Using a ϕ10 mm cylinder, RGE and CGO sheets were wound at an angle of 180°.

The surface appearance after the winding test is shown in **Photo 1**. It is obvious that the forsterite coating on CGO was partially removed but that on RGE was completely intact. This confirms that RGE has such a good adhesivity of the insulation coating that the winding by ϕ10 mm cylinder is possible. RGE is suitable for the use where severer winding is needed.

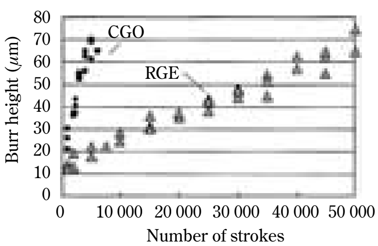
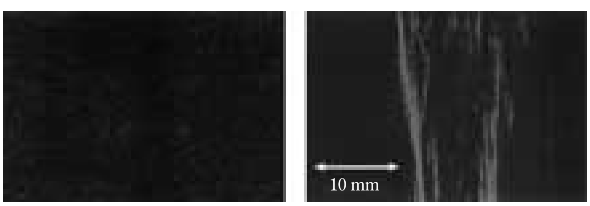


Fig. 2 Dependence of burr height on number of strokes for RGE and CGO



(a) RGE (b) CGO

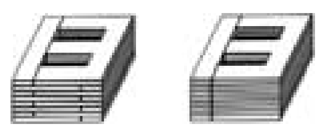
Photo 1 Appearance of the surface after the rolling by ϕ10 mm cylinder

3 Magneric Properties of the EI Lamination Core

Table 1 shows the iron loss and the magnetic induction at 50 Hz of RGE and CGO sheets containing 3% Si with a thickness 0.35 mm in the rolling directions (RD) and transverse directions (TD) after the stress relief annealing at 1 073 K for 2 h. Compared with CGO, RGE has higher iron loss in the rolling direction, but has much lower iron loss in the transverse direction. The iron loss in the transverse direction at magnetizing flux density 1.7 T is failed because of a large distortion in the exciting current wave.

Using these steel sheets, EI lamination cores having a width of 55 mm (EI55) and the height 4.2 mm were created using the two lamination stacking methods shown in **Fig. 3**(a) and Fig. 3(b). The iron loss and the exciting current with the magnetizing flux densities from 0.5 T to 1.7 T were measured at a frequency of 50 Hz. The lamination stacking method shown in Fig. 3(a) has alternate-lap joint , which is frequently applied in the lamination using grain-oriented electrical steel sheet. In this method, E and I pieces are interlaminated alternately utilizing their excellent magnetic properties in the rolling direction.

The method shown in Fig. 3(b) has butt joint. The application of butt joint to grain-oriented steel is disadvantageous because magnetic flux always occurs in the transverse direction. In addition, air gaps existing



(a) Alternate-lap joint (b) Butt joint

Fig. 3 Lapping method of EI lamination core using (a) Alternata-lap joint, (b) Butt joint

Table 1 Iron losses and magnetic flux densities of RGE and CGO after stress relief annealing at 1 073 K for 2 h

Specimen	Direction	Iron loss					Magnetic flux density	
		$W_{5/50}$ (W/kg)	$W_{10/50}$ (W/kg)	$W_{13/50}$ (W/kg)	$W_{15/50}$ (W/kg)	$W_{17/50}$ (W/kg)	B_8 (T)	B_{50} (T)
RGE	RD	0.14	0.51	0.89	1.24	1.66	1.79	1.95
	TD	0.39	1.06	1.85	2.80		1.34	1.54
CGO	RD	0.10	0.41	0.73	0.98	1.29	1.87	1.98
	TD	0.63	1.70	2.41	3.44		1.35	1.55

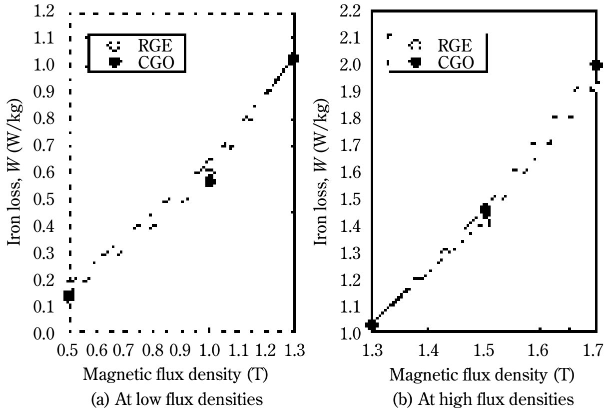


Fig. 4 Iron loss of the EI core made up from RGE and CGO sheets using the alternate-lap joint

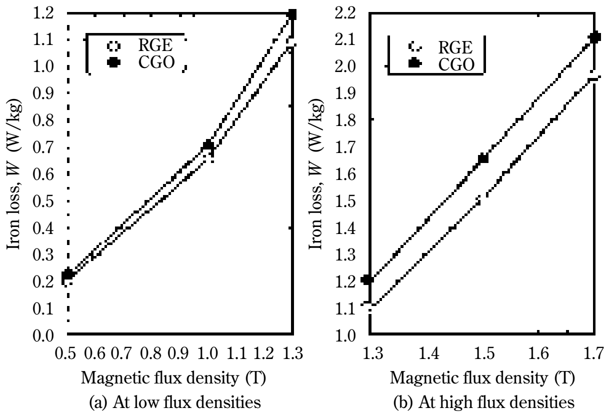


Fig. 5 Iron loss of the EI core made up from RGE and CGO sheets using the butt joint

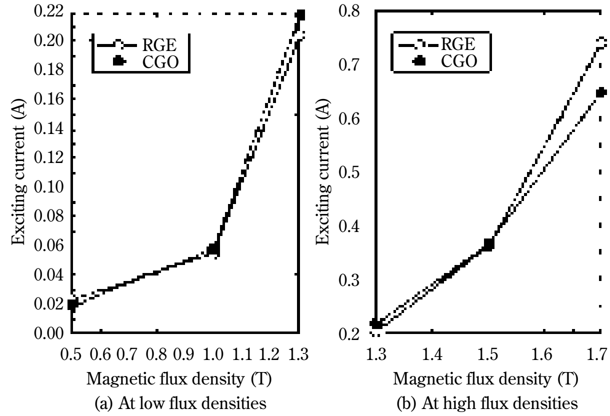


Fig. 6 Exciting current of the EI core made up from RGE and CGO sheets using the alternate-lap joint

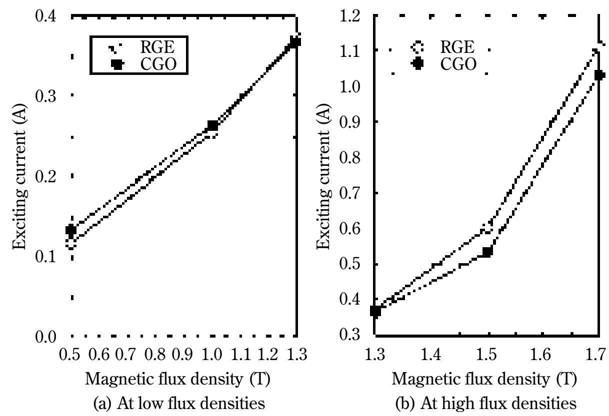


Fig. 7 Exciting current of the EI core made up from RGE and CGO sheets using the butt joint

between E and I pieces increases the exciting current.

Measured iron loss and exciting current versus magnetizing flux density using alternate-lap joint are shown in **Fig. 4**(a) and 4(b), respectively. At low magnetizing flux densities under 1.0 T, CGO shows better iron loss, while at high magnetizing flux densities over 1.5 T, RGE has less iron loss.

Measured iron loss and exciting current versus magnetizing flux density using butt joint are shown in **Fig. 5**(a) and (b), respectively. Using butt joint, RGE showed less iron loss for all values of magnetizing flux densities, with this advantage increasing as the magnetizing flux density increases.

The exciting currents of RGE and CGO versus magnetic flux density in alternate-lap joint is shown in **Fig. 6**(a) and (b), respectively. The difference in exciting current between RGE and CGO is small. **Figure 7**(a) and (b) show the exciting current of RGE and CGO, versus magnetic flux density in butt joint, respectively. Although the exciting current is increased, the difference is small. These results indicate that using RGE sheet and applying butt joint can increase the efficiency of manufacturing without significant iron loss.

4 Correlation between Iron Loss of the Material and that of EI Lamination Core

In the magnetic circuit of EI lamination core, approximately 4/5 of the length corresponds to the rolling direction and 1/5 to the transverse direction. Considering this geometrical distribution, the estimated iron loss (W_{est}) is calculated as

$$W_{est} = (4W_L + W_C) / 5 \quad \cdots\cdots (1)$$

where W_L is iron loss of the material in the rolling direction and W_C is that in the transverse direction.

A comparison of W_{est} with measured iron loss of EI lamination core W_{mea} with magnetic flux density is shown in **Fig. 8**. Here, W_{est} in most cases is in good agreement with W_{mea}. This result ensures that, even if the iron loss in the rolling direction is inferior, the iron loss of EI lamination core stamped from RGE sheets is at least equivalent to that using CGO, because RGE has small iron loss in the transverse direction.

A careful look at Fig. 8 reveals that in RGE using alternate-lap joint, W_{est} gives quite a good agreement

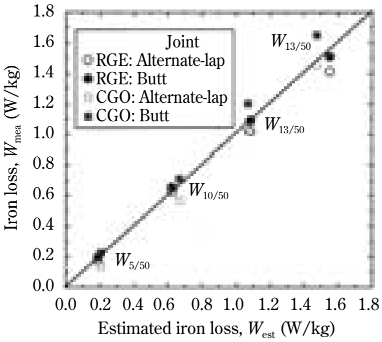


Fig. 8 Relation between estimated iron loss W_{est} and measured iron loss W_{mea} in RGE and CGO

with W_{mea} under magnetic flux density of 1.3 T, while under high magnetic flux densities, W_{est} is smaller than W_{mea}. In CGO using alternate lap, W_{est} is larger than W_{mea} under 1.3 T of the magnetic flux density.

In the cross-section of alternate-joint, E and I pieces are alternately stacked. Magnetic flux flows in the rolling direction of the I pieces, and in the transverse direction of the E pieces. The permeability of CGO in the rolling direction is much higher than in the transverse direction. This may be because at low magnetic flux densities, the magnetic flux in the cross-sectional area of the EI lamination core is mainly accumulated into I pieces in which the magnetizing direction is parallel to the transverse direction. In such a case, the contribution of I pieces, i.e., that of iron loss in the rolling direction, is decisive. That may be the reason why CGO with less iron loss in the rolling direction has lower iron loss of EI lamination core than using RGE at low magnetic flux densities.

On the other hand, at high magnetic flux densities, I pieces can no longer cover all the magnetic flux, so a considerable amount of magnetic flux flows into E pieces. In such a case, the contribution of E pieces, i.e., that of the iron loss in the transverse direction, increases. That may be the reason why the iron loss of EI lamination core using RGE is less than that using CGO which has less iron loss in the rolling direction at high magnetic flux densities.

In using butt joint, magnetic flux inevitably flows into E pieces in which the magnetizing direction corresponds to the transverse direction; therefore, RGE with much lower iron loss in the transverse direction shows better performance.

5 The Effect of Tension Coating on the Magnetic Properties in the Transverse Direction

The main difference between RGE and CGO lies in the surface state. On the surface of CGO, forsterite undercoating and another tension coating with a total thickness of approximately 2.5 μm are formed. These

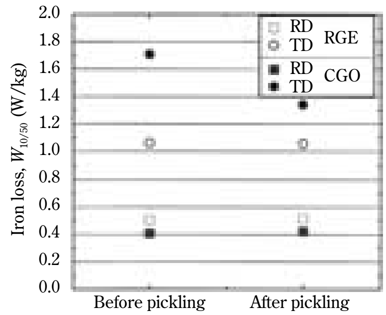


Fig. 9 The change of iron loss after the removal of coatings by pickling

coatings provide approximately 5 MPa of the tension toward the base metal.[1] On the surface of RGE, an insulation coating of 0.3 μm in thickness is formed. When punchability is a major concern, a semi-organic coating is applied, and when smoothness of the surface and weldability are important, an inorganic coating is applied. Neither coating provides the tensile stress.

The effect of the stress coating was investigated by pickling them in 20% HCl at 343 K. As shown in **Fig. 9**, almost no change of magnetic properties was observed in RGE. In CGO, there were small changes in the rolling direction, but, considerable improvement in the iron loss in the transverse direction was observed.

Measurements of DC magnetizing curves in the transverse direction are given in **Fig. 10**. In CGO, magnetizing in the transverse direction was considerably improved by removing the tension coatings. RGE has better magnetic induction under a magnetizing force of less than 400 A/m. Such a high permeability at low magnetizing force is the main cause of the remarkable reduction of the iron loss in the transverse direction in RGE. This result clearly shows that the lack of tension coating gave RGE excellent magnetic properties.

It is well known that in CGO, which does not have high permeability, there is little reduction of iron loss.[2] Summing up, tension coatings applied to CGO are quite

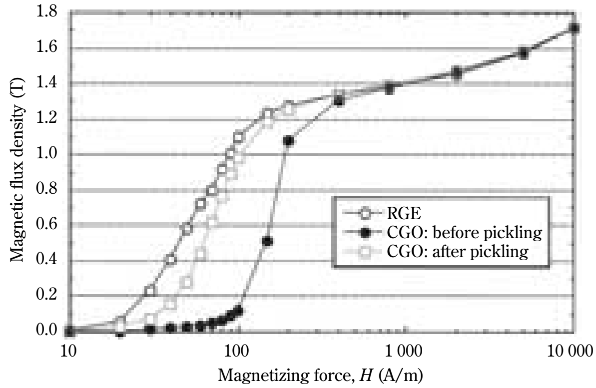


Fig. 10 DC magnetization curve in the transverse direction of RGE, CGO before pickling and CGO after pickling

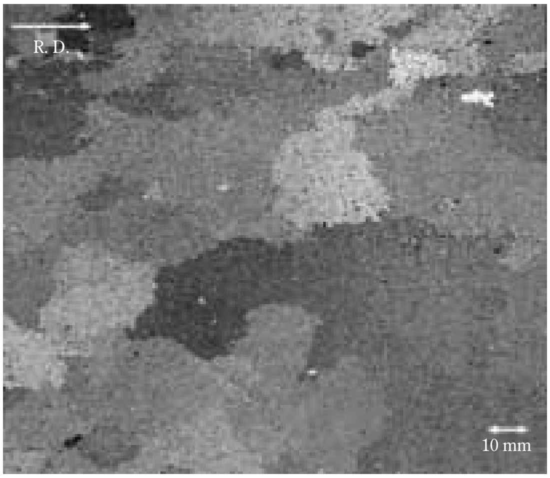


Photo 2 Macro structure of RGE sheet

harmful in the application to EI lamination cores because they deteriorate the punchability and the magnetic property in the transverse direction.

According to Figs. 9 and 10, the iron loss and the flux density at low magnetizing force were still superior to CGO after the pickling. This difference may be attributed to the contribution of small scattered grains inside coarse secondary recrystallized grains as shown in **Photo 2**. Such small scattered grains are not found in CGO.

In further investigation, the structure of the magnetic domains in a demagnetized state in RGE sheets was observed by using SEM. As shown in **Photo 3**, RGE has

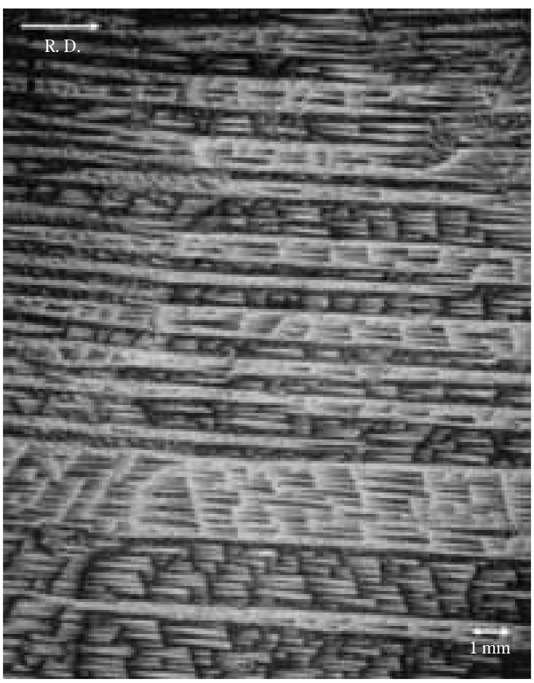


Photo 3 Magnetic domain structure of RGE sheet observed by SEM

Table 2 High frequency iron loss of RGE and CGO after stress relief annealing at 1 073 K for 2 h

		$W_{10/400}$ (W/kg)	$W_{10/1000}$ (W/kg)
RGE	RD	12.0	52.5
	TD	18.9	77.7
	EI core	12.9	55.5
CGO	RD	11.7	53.8
	TD	27.1	98.3
	EI core	14.0	59.6

many types of 90° domains inside the usual 180° domain. The 180° domain did not contribute to the magnetization in the transverse directione; therefore, magnetization in the transverse direction was not induced by the movement of the wall of the 180° domain.

When tensile stress was applied by the coating in grain-oriented electrical steel, the 180° magnetic domain structure was stabilized by the magnetic elasticity effect. Such an effect eased the magnetization in the rolling direction, but hindered it in the transverse direction. In RGE, a number of 90° domains existed, helping the magnetization in the transverse direction. In addition, small scattered grains inside coarse grains may have contribution to the generation of 90° magnetic domains, as the orientations of scattered grains were different from the surrounding domains.

6 High Frequency Iron Loss

One common application of EI lamination cores using electrical steel is choke coils in personal computers for eliminating electric noise. Grain-oriented electrical steel is used to obtain more efficient noise elimination and prevent an increase in temperature. In the application to the choke coil, high frequency iron loss around 400 Hz is an important concern.

Table 2 shows a comparison of high frequency iron loss after stress relief annealing at 1 073 K for 2 h between RGE and CGO in the rolling direction, in the transverse direction and in the EI core created in Section 3. RGE shows small iron loss even in the rolling direction. The advantage is increased in the EI lamination core in which the contribution of the transverse direction is significant. The application of RGE to choke coil should improve noise reduction and help the temperature keep low. The low iron loss may be attributed to the smooth boundary between the base metal and the coating.

7 Conclusions

Newly developed grain-oriented electrical steel RGE without forsterite coating has the following advantages when applied to EI lamination cores:

(1) RGE has such a good punchability that the life of stamping dies used with RGE sheets is ten times

longer than used with CGO having forsterite (Mg_2SiO_4) undercoating.

(2) The iron loss of EI lamination core stamped from RGE sheets is equal to or better than that from CGO sheets, because RGE has excellent magnetic properties in the transverse direction.

(3) The absence of tension coating and the presence of small scattered grains inside a coarse secondary recrystallized grain help to increase the 90° magnetic domains that improve the magnetizing in the transverse direction.

(4) High efficiency in the noise reduction and in the decrease in operating temperature are expected when RGE is applied to choke coil, because it has low high frequency iron loss.

References

1) B. Fukuda, T. Irie, and H. Shimanaka: *IEEE Trans Mag*., **13**(1977), 1977

2) T. Yamamoto and T. Nozawa: *J. Appl. Phys*., **41**(1971), 1539