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Electrical Steels as a Top-runner for Serving Energy Efficiency Technologies*

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Synopsis:

Kawasaki Steel has developed various types of new electrical steels to contribute to improving the efficiency of electrical appliances, which are struggling under unsparing competition as a top-running group in increasing energy efficiency. As for grain-oriented materials, a material having high flux density, "New RGH", for decreasing the noise of transformers, and an extremely low-iron loss domain-refined material, "New RGH PD" for securing higher efficiency of transformers have been developed. As for non-oriented materials, there have been developed materials having high magnetic flux density, "RMA" series, for improving the efficiency of AC induction motors, and materials having improved iron loss at 400 Hz, "RMHE" series, for inverter-drive DC motors. Moreover, materials having thinner gauge of 0.20 mm, "20RMHP" series, were developed for higher frequency appliances and a new material suitable for appliances designed for around 20 kHz is under development.

1 Diversification of Properties Required of Electrical Steels

Electrical steels are important functional materials used in the cores of power supply and energy transformation systems such as generators, motors and transformers. To ensure energy-saving design and downsizing of these appliances, requests have been made for lower iron losses, higher flux densities, lower prices, and improved formability for mass production.

In order to help reduce the amount of CO_2 emitted into the air, moves to promote energy savings in electrical appliances have been accelerated as exemplified by the adoption of high-efficiency motors in JIS and setting of a JEMA standard for high-efficiency transformers. In recent years, in electrical steels also, various guidelines have been established for the improvement of performance in association with the energy savings in various electrical appliances. This report gives an overview of concrete examples of these trends in both grain-oriented electrical steels and non-oriented electrical steels[1].

First, in the field of grain-oriented electrical steels, requirements for higher magnetic flux densities for low-noise power transformers have been increasing in addition to the trend toward lower iron losses.

Grain-oriented electrical steels are used mainly as core materials of transformers, which transfer power in substations during power transmission. Although the energy efficiency of such transformers is as high as about 98%, the total amount of power lost throughout Japan is enormous[2]. Therefore, an energy-saving effect of as much as 4 650 million kWh would be produced by an efficiency improvement of 0.5%, for example. Furthermore, against the background of the "Law for the Rationalization of Energy Use" (implemented on April 1, 1999), the adoption of high-efficiency transformers, etc. is being encouraged by tax incentives. In order to meet these requirements, it is necessary to develop gain-oriented electrical steels with unprecedentedly low iron losses.

The public is increasingly demanding more comfortable urban environments so the noise environment in urban districts must be improved. In substations located in urban districts, therefore, much money is being spent on equipment for reducing the noise generated by transformers. However, because the costs can be cut by increasing the magnetic flux density of core materials, demand for an increase in the magnetic flux density of

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grain-oriented electrical steels has also become very strong in recent years.

In the field of non-oriented electrical steels, new demands for performance improvement have been made. These demands include (1) increasing the magnetic flux density of electrical steels to reduce copper losses and increase reluctance torque, and (2) reducing high-frequency iron losses suitable for energy savings by the high-frequency operations of electrical appliances, such as inverter control and frequency change control.

In an induction motor, the copper loss caused by the current flowing through a coil accounts for most of all losses. This can be improved by increasing the magnetic flux density of electrical steels[3]. Furthermore, in a reluctance motor in which improved efficiency is aimed at by using reluctance torque, an increase in the magnetic flux density of electrical steels is viewed as the best way to improve efficiency.

At the same time, the technology of inverter control has made rapid progress in various high-efficiency and variable-speed driving motors. In this case, because the operational frequency is higher than in conventional controls, it is necessary to reduce iron losses at frequencies higher than the commercial frequency[3]. Furthermore, it is also necessary to use high-frequency materials as accessory devices for inverter circuits and to prevent high harmonics generated by such devices from flowing backward to a power source. To meet these new demands, it is necessary to use electrical steels that have low core losses in their respective high frequencies.

2 Development of New Products to Meet New Demands

This section briefly describes the main new products that meet the above demands and the features of these products.

2.1 New Products of Grain-Oriented Electrical Steels

The iron loss characteristics of Kawasaki Steel's grain-oriented electrical steels have been improved as shown in **Fig. 1**[4].

Among others, a material with dramatically reduced core losses, "23 New RGH PD", has recently been developed. This new material has the following features: (1) a reduction in eddy-current loss by a decrease in steel sheet thickness (from 0.27 to 0.23 mm), (2) a reduction in hysteresis loss by high alignment of crystal orientation, and (3) a reduction in eddy-current loss by forming a large number of grooves on the steel sheet surface to refine magnetic domains[5].

Because the domain wall thickness is determined by the balance between magnetostatic energy and domain wall energy, the principle of the groove formation method is to increase magnetostatic energy by the demagnetization effect through the grooves to obtain a large number of domain walls, that is, to obtain a magnetic domain refining effect. As shown in **FIg. 2**, grooves are formed on the steel sheet surface, and by increasing the depth of these grooves, the magnetic domain width of a material can be dramatically reduced as shown in **Fig. 3**. Because grooves can be made deep enough without causing an increase in hysteresis loss, a dramatic magnetic domain refining effect can be obtained by this technology[6].

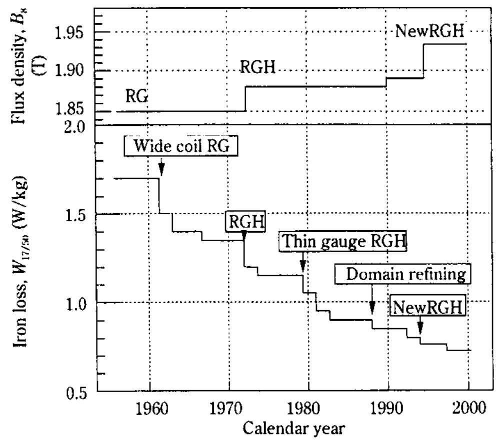

Fig. 1 Historical trend of iron loss and induction improvements in electrical steels produced by Kawasaki Steel

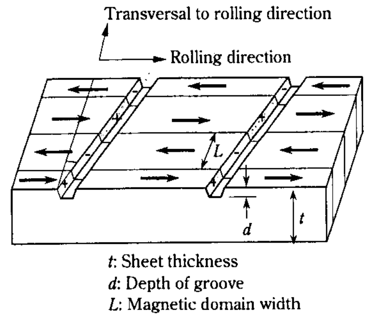

Fig. 2 Profile of grooves formed on steel surface

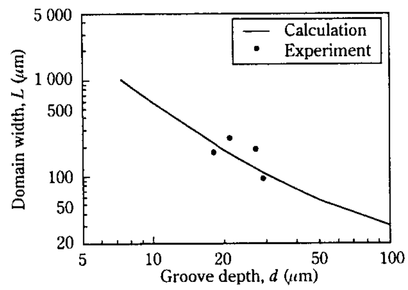

Fig. 3 Dependence of domain width on groove depth shown by experimetal data and calculated one

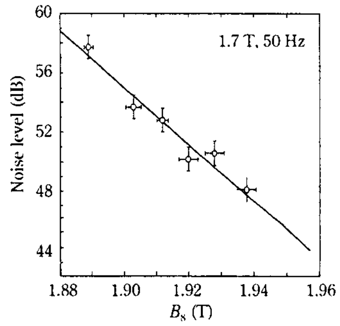

Fig. 4 Relationship between B_8 value and noise of a model transformer

It is apparent, as shown in Fig. 1, that unlike iron losses, it take many years to improve magnetic flux density. In recent years, however, a highly oriented electrical steel, "New RGH", with B_8 of 1.93 T has been developed and this material is enjoying popularity as a core material for low-noise transformers.

Figure 4 shows the results of a measurement of the relationship between the magnetic flux density B_8 of a core material and the noise generated by a transformer, which was carried out using a small 3-phase model transformer. It is apparent from this figure that an improvement in the magnetic flux density of a material contributes greatly to reduction in the noise from a transformer[7].

Tables 1 and **2** show a comparison of the properties of model transformers in which a conventional material, "30RGH105", and the new product "New RGH PD" were used as the core materials. In both the stacked-core and wound-core types, the iron losses of the transformer are greatly reduced. Furthermore, in Table 1 it is apparent that the effect in reducing exciting current and noise is also remarkable[6,7]

Table 2 Magnetic properties of model wound-core transformers

Material	Grade	Magnetic properties of materials		Magnetic properties of model transformer cores	
		B_8 (T)	$W_{17/50}$ (W/kg)	$W_{17/50}$ (W/kg)	BF[2)]
NewRGH	23RGH090N	1.93	0.86	0.87	1.01
	23RGHPD085N	1.89	0.77	0.78	1.01
	27RGHPD090N	1.89	0.84	0.85	1.01
RGH[1)]	30RGH105	1.89	1.03	1.04	1.01

[1)]Conventional material with high permeability
[2)]BF: Iron loss ratio of transformer to material

2.2 New Products of Non-Oriented Electrical Steels

In the field of non-oriented steels, trends in the improvement in motor efficiency are receiving much attention. Work is progressing on improving air conditioner motors, because these motors are in constant operation. As new products in this field, the "RMA series" and "RMHE series" have been developed at Kawasaki Steel[8].

The "RMA series" provides materials in which high magnetic flux densities and low core losses are compatible with each other. This was realized by the preferential growth of grains having orientations that are desirable for magnetic properties in the stress-relief annealing after the punching and stacking of motor cores. Before stress-relief annealing, the grain size is small and the Si content is low, therefore, formability is excellent. However, after stress-relief annealing, the grain size becomes very large because of high purification, etc.

Figure 5 shows a comparison of motor efficiency when the conventional "RM series" and the new "RMA series" are used as the materials for cores of AC induction model motors. The "RMA series" showed high motor efficiency although it is a low-Si material. That was because copper losses could be greatly reduced by increasing magnetic flux density, as, in the case of an induction motor, the proportion of copper losses to total losses is high. The features of the "RMA series" of very high magnetic flux densities and relatively low core losses are fully utilized.

The "RMHE series" provides non-oriented electrical steels having very low iron losses and high magnetic flux densities. In recent years, brushless inverter-drive DC motors have come into widespread use for improving motor efficiency. In motors of this type, a high-frequency magnetic field is applied and a rotor is magnetized by a permanent magnet. For these reasons, the

Table 1 Magnetic properties of model stacked-core transformers

Material	Grade	Magnetic properties of materials		Magnetic properties of model transformer cores			
		B_8 (T)	$W_{17/50}$ (W/kg)	$W_{17/50}$ (W/kg)	$Io_{17/50}$ (A)	$Noise_{17/50}$ (dB)	BF[2)]
NewRGH	23RGH090N	1.93	0.86	1.01	0.74	52	1.17
	23RGHPD085N	1.89	0.77	0.90	0.75	52	1.17
	27RGHPD090N	1.89	0.84	0.99	0.85	53	1.18
RGH[1)]	30RGH105	1.89	1.03	1.21	0.85	56	1.17

[1)]Conventional material with high permeability
[2)]BF: Iron loss ratio of transformer to material

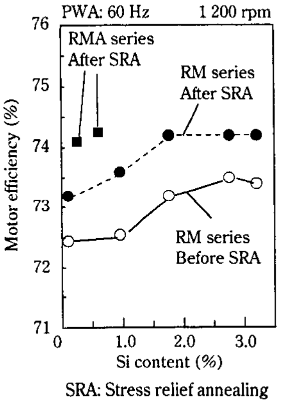

Fig. 5 Effect of Si content, core materials (RM and RMA) and SRA on AC induction motor efficiency

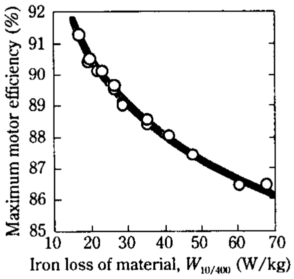

Fig. 6 Relationship between the maximum motor efficiency and iron loss of material at 400 Hz

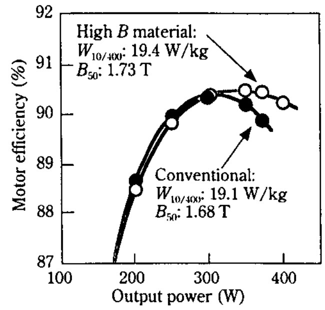

Fig. 7 Effect of flux density of core material on motor efficiency stability

greater part of motor losses is iron losses in the stator. Therefore, a core material must have low iron losses, particularly in a frequency range higher than the commercial frequency.

Figure 6 shows the relationship between the maximum motor efficiency and iron loss ($W_{10/400}$) of material at 400 Hz, which is the results of a measurement in brushless DC motors having a permanent magnet surface mount. From this figure it is apparent that regardless of whether stress-relief annealing is conducted or not, motor efficiency is uniquely determined by iron loss $W_{10/400}$. This suggests that high-frequency iron losses of about 400 Hz are predominant for the efficiency of motors of this type. Furthermore, **Fig. 7** shows the results of efficiency measurements for the output power of motors. Even when materials have the same value of $W_{10/400}$, the "RMHE series" has a wider output range of high efficiency and is obviously superior.

In the case of a low-flux density material, torque decreases abruptly when the output of maximum efficiency is exceeded, so it is necessary to increase the exciting current in order to compensate for this. Because this inevitably causes an increase in copper loss, the efficiency decreases. However, the "RMHE series" can provide high efficiencies in a wide output range because the decrease in torque that results in such a decrease in efficiency is suppressed. Applications of motors with efficiency improved through the use of the "RMHE series" include electric automobiles such as EVs and HEVs as well as everyday electric appliances such as air conditioners.

Progress toward higher frequencies of electric appliances with motors is remarkable. For example, motors installed in personal computers, etc., are driven at high frequencies, and high precision and low dissipation power are required. Thus, the company has developed the "RMHF series", non-oriented electrical steels for applications that require high-frequencies and low iron loss[9].

Applications in this field require that iron losses be low in high frequencies such as 400 Hz, and not in the commercial frequencies such as 50 or 60 Hz. In order to reduce iron losses in the high-frequency range, the Si content could theoretically be increased. However, this method cannot be adopted because it remarkably deteriorates the formability during manufacture and working of products. For this reason, reducing the sheet thickness of a product is the most useful method. However, in reducing the sheet thickness from the present minimum standard of 0.35 mm, there were many problems to be solved, such as a sheet thickness deviation and how to improve rolling efficiency. Now that, these problems have been solved, new products of non-oriented electrical steels of low iron loss with a sheet thickness of 0.20 mm are being marketed as the "20RMHF series." **Figure 8** show an example of efficiency measurement in inverter-drive high-speed model motors carried out by changing core materials and inverter frequencies. It is apparent that efficiency is substantially improved by higher frequencies and adoption of the "20 RMHF series."

3 Future Trends in Development

In the future, there will be increasing emphasis on energy savings and noise reduction, and the demand for lower iron losses of electrical steels particularly for lower iron losses and higher magnetic flux densities in

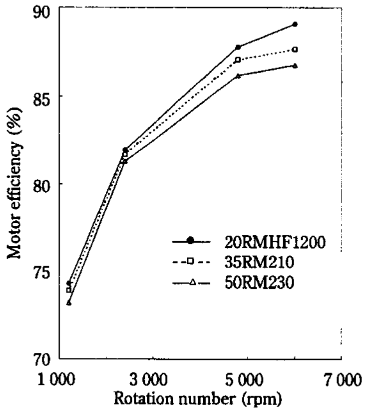

Fig. 8 Effect of core materials on efficiency of inverter power drive motor in high rotational speed

high-frequency ranges, will also continue to grow.

In order to meet these demands, Kawasaki Steel is now developing grain-oriented electrical steels and non-oriented electrical steels in which textures are strictly controlled. As to high-frequency losses, the company is developing electrical steels of small sheet thickness and high electric resistance in which iron losses are dramatically improved. To conclude, let us briefly examine "new electrical steels for high frequencies."

Electric appliances that perform high-output power operations in a very high frequency range like 10 kHz are increasing in number due to the progress in power electronics. Although ferrite has been used in this frequency range, electrical steels of high operational magnetic flux density are preferable for driving high-output electrical appliances. To meet this demand, Kawasaki Steel has developed an electrical steel of a completely new composition system by devoting the technical resources of its Research Laboratories to the development activities. This material has the following striking features. (1) As shown in **Table 3**, this material ensures a higher operational magnetic flux density than ferrite and is excellent in iron loss characteristics near 10 kHz. (2) As shown in **Fig. 9**, it has excellent mechanical properties with high elongation and tensile strength values. (3) As shown in **Fig. 10**, it has excellent formability with hardness values comparable to those of conventional high-grade electrical steels (3%Si). (4) As shown in **Fig. 11**, this material has better corrosion resistance than conventional electrical steels. Because the public

Table 3 Magnetic properties of a newly developed material for high frequency application

Flux density	Iron loss (W/kg)		
B_{50} (T)	$W_{2/5k}$	$W_{1/10k}$	$W_{0.5/20k}$
1.54	19.0	9.5	4.3

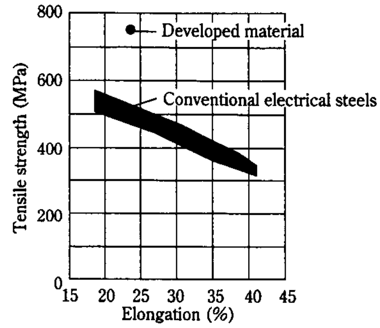

Fig. 9 Comparison of TS-El balance between conventional electrical steels and a newly developed material

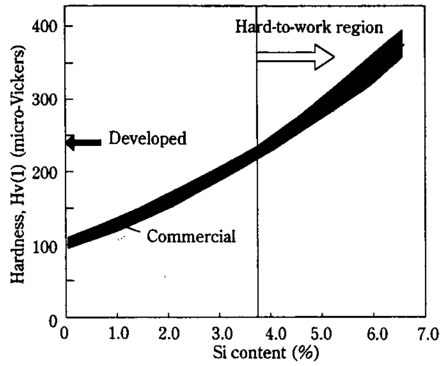

Fig. 10 Comparison of hardness between commercial electrical steels and a newly developed one

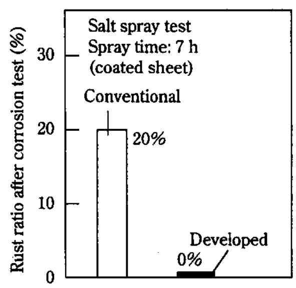

Fig. 11 Example of corrosion resistance; comparison between a conventional electrical steel and a newly developed one

will increasingly be using high-frequency electrical appliances, it is expected that applications in which the characteristics of such materials are made the most of will contine to expand in the future.

Electricity is very useful and increases the convenience. From the standpoint of global environmental conservation and resources savings, however, electricity should be used more efficiently. For this purpose, Kawasaki Steel intends to continue to innovate technologies in electrical steels and to develop new energy-saving products.

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