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Non-Oriented Electrical Steel Having Excellent Punchability for High-Efficiency Motors

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Synopsis :

Non-oriented electrical steels (RMHE and RMHF) for high-efficiency motor have recently been developed for the purpose to meet customers requirements from the viewpoint of energy saving and efficiency enhancement of motors. The steels are characterized by an improvement in their texture. The advantages of these new materials are not only their low iron loss but also appropriate hardness and high magnetic flux densities. Their hardness, Hv1, is controlled 20 points less than that of conventional material having similar iron loss, which leads them to excellent punchability in customer use, especially in the use of high-efficiency motors. These developed materials boost the spread of high-efficiency motor and contribute to saving energy.

The body can be viewed from the next page.

Non-Oriented Electrical Steel Having Excellent Punchability for High-Efficiency Motors*



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Non-oriented electrical steels (RMHE and RMHF) for high-efficiency motor have recently been developed for the purpose to meet customers requirements from the viewpoint of energy saving and efficiency enhancement of motors. The steels are characterized by an improvement in their texture. The advantages of these new materials are not only their low iron loss but also appropriate hardness and high magnetic flux densities. Their hardness, Hv1, is controlled 20 points less than that of conventional material having similar iron loss, which leads them to excellent punchability in customer use, especially in the use of high-efficiency motors. These developed materials boost the spread of high-efficiency motor and contribute to saving energy.

1 Introduction

Electricity has the characteristics that it can be transported comparatively easily and securely and that it can be converted into motive power, heat or light. Furthermore, electricity is capable of efficiently driving electric machinery and information apparatus which cannot be operated with other types of energy. For these reasons, more than 40% of our total energy is consumed in the form of electricity. The total domestic power demand in 1999 was 934.7 billion kWh[1] making Japan the world's fourth largest energy consumer.[2] **Figure 1** shows the profile of electric power consumption in Japan.[1,3] The largest consumer is industry, consuming 48% and then home use and office/shop use, consuming 29% and 21% respectively. Among the various kinds of electric machinery, the largest amount of power or 52% of the total power demand (486 billion kWh) was consumed by motors in 1999. If the efficiency of all motors could be improved by 1%, it would reduce electric power consumption by about 6 billion kWh/y. This amount corresponds to over 100 billion yen/y in money or to the output of nearly one nuclear power station or of 5 to 6 fossil fuel power stations. The capacity of electric power generation in Japan is planned so as to meet the peak demand in summer, therefore, if the matter is studied taking a reduction of power stations and a review of power station contruction in the future into consideration, the economic effect of a 1% improvement in motor efficiency can be assumed to be greater.

Trial calculations on electric power consumption before COP3 predicted there would be a further increase

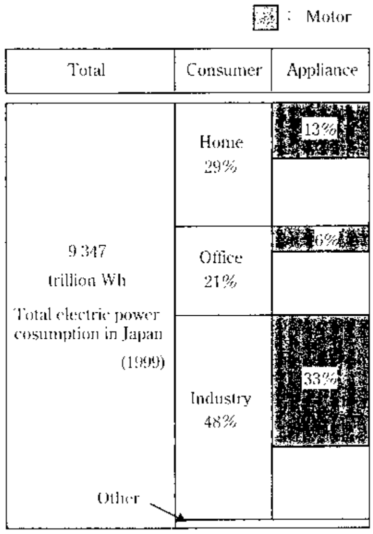

Fig. 1 Profile of electric power consumption in Japan[1,3]

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in consumption in the ten years thereafter. However, in order to reduce the exhaust of environmentally disruptive materials generated by electric power generation such as CO_2, SO_x, NO_x, severe targets for energy saving have been imposed on each country. Following the enforcement of the Revised Energy Saving Act in April 1999, various actions to save energy by the improvement of motor efficiency have been concretely in progress in Japan. The actions, which have been taken so far, include introduction of the top-runner system for home-electric products, standardization of high-efficiency common-use motors according to JIS standards and promotion of electric motor driven cars and hybrid cars in the automobile industry field. With such requirements in the market in the background, Kawasaki Steel has developed new brands of electrical steel, the new RMHE series and the upper grade RMHF.

2 Punchability of Electrical Steel as a Material for Motor Cores

In producing motor cores, materials are cut into a predetermined shape by punching a non-oriented electrical steel plate using a press machine and then the cut pieces are layered to form cores. After applying stress relief annealing (SRA) to these cores, windings are wound and motor cores are assembled into the final form by putting various parts on these cores (SRA is not applied in some cases). In order to improve the efficiency of this production process, the materials are required to have a superior punchability. Other properties ordinarily required for non-oriented electrical steel are low iron loss and high magnetic flux density. In order to achieve a higher efficiency and further compactness of products by reducing various energy losses in motors such as iron loss, copper loss and mechanical loss, it is effective to lower the iron loss as well as to increase the magnetic flux density of the core material (electrical steel). On the other hand, it has become more popular to utilize brushless DC motors using permanent magnets and to achieve higher efficiency by using an inverter, therefore, there exists a requirement for electrical steel also to be suitable for such constructions and for such control methods. More concretely speaking, electrical steel is required to be a material having a low iron loss property both in the commercial power frequency range and also in the high frequency range, as well as be a core material with an extremely low iron loss for automobile driving motors, ultra high rpm motors or high-efficiency compressors for which a further improvement in efficiency is needed. In order to meet these requirements, one method is to increase electric resistance of cores through various ways such as to increase the Si content and the other is to produce thin electrical steel thinner than 0.35 mm, which is the standard thickness.

However, these methods all worsen punchability. Therefore, it is an indispensable condition in developing electrical steel to achieve a low iron loss and a high magnetic flux density and at the same time, to make the material have an excellent punchability.

3 Required Material Properties for High-Efficiency Motors

3.1 Material Properties Required for Improvement of Motor Efficiency

The knowledge on the magnetic properties of electrical steel and motor efficiency in the past was mostly related to AC motors.[4)] In recent years, however, other knowledge has been gained as PWM (pulse width modulation) controlled inverter driven motors became popular. The properties required for non-oriented electrical steel are described hereunder for each kind of motor.[5)]

(1) AC Induction Motors (**Fig. 2**)

(a) With motors of this type, secondary copper loss arises in the rotor, therefore, the percentage of copper loss in the total loss in motors is high. Therefore, application of materials with a high magnetic flux density, which makes reduction of excitation current in motors possible, improves motor efficiency. (Fig. 2)

(b) In addition to the above, lowering the iron loss in material also directly reduces iron loss in motors thus improving motor efficiency.

(2) Brushless DC Motors (**Figs. 3, 4**)

(a) With motors of this type, loss in motor cores is the governing factor for the total loss, therefore, the dependence of the motor efficiency on iron loss in motor cores is greater than with AC induction motors. The loss in motor cores has a particularly strong correlation with iron loss in the high frequency range (e.g. $W_{10/400}$) beyond the frequencies of commercial power, reducing the iron loss in the core material is effective at improving motor efficiency. (Fig. 3)

(b) The effect of increasing the magnetic flux density, which contributes to the reductioin of copper loss, is smaller than that with the AC induction motor. In

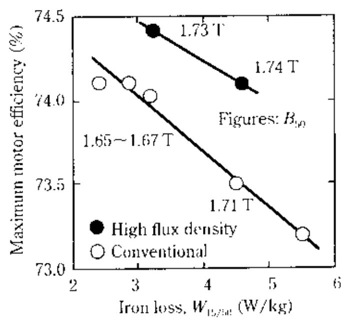


Fig. 2 Relation between maximum efficiency of induction motor and iron loss of core material

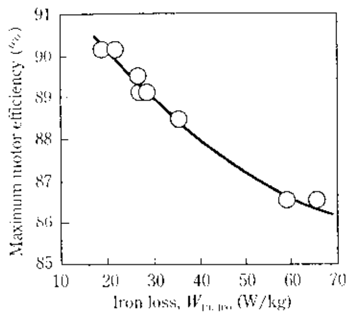


Fig. 3 Relation between maximum efficiency of brushulcss DC motor and iron loss at 400 Hz of core material

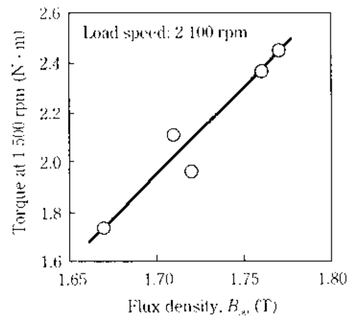


Fig. 4 Influence of flux density B_{50} of core material on torque of brushless DC motor at 1 500 rpm

the high output range, however, there is a trend that greater improvement can be expected in efficiency with high flux density materials.

(c) By increasing the magnetic flux density of the core material, it becomes possible to achieve a higher torque motor design. (Fig. 4)

As explained above, in order to improve motor efficiency, it is necessary to pursue lower iron loss as has been done since long ago and to develop iron core materials having the required high magnetic flux density at the same time. Especially, through the application of inverter drive represented by PWM control to motors, it has become important to consider the high frequency property denoted as $W_{10/400}$ in the frequency range beyond the commercial power frequencies as a representative property of materials for motor cores.

3.2 Other Required Properties

(1) Excellent Punchability

Generally speaking, wear-down in the punching process is accelerated as the hardness of the steel plate increases. For high-efficiency motors, therefore, electrical steel must be a product such that both the magnetic properties are superior and the hardness is adjusted to an appropriate value in order to suppress wear-down of metallic molds in the punching process.

(2) Improvement of Magnetic Properties after Stress Relief Annealing

Non-oriented electrical steel is layered to form motor cores after being cut by punching to predetermined shapes using metallic molds by motor core manufactures and then is annealed to relieve stress at 750~800°C as necessary in most cases. Stress relief annealing is applied to remove the strain generated by pressing and to lower the iron loss. Stress relief annealing is applied under various conditions requested by individual customers, therefore, electrical steel must be such that it is minimally influenced by the annealing conditions and that if there is any change, it should be a steady enhancement of the iron loss through this process.

4 Essential Points of Development

The company has developed non-oriented electrical steel that satisfies the above-mentioned various properties required for high-efficiency motors and developed those of the RMHE series. Electrical steel of this series is such that wear-down of metallic molds in punching motor cores is suppressed and at the same time, its magnetic flux density is high and iron loss is low. The essential points of this development are described hereunder.

4.1 Improvement of Punchability

The effects of the Si, Al and Mn contents on the hardness of electrical steel are shown in **Fig. 5**. By optimizing the contents of the major components including Si, Al and Mn, a material was developed having a low hardness and low iron loss.

4.2 Magnetic Properties

To enhance the magnetic properties, it is important to improve the steel plate's texture. Various means to control the texture have been well known, such as the proper selection of the rolling reduction, elemental components, etc.[6] In the materials developed, the texture was improved by adding Sb[7,8] as necessary. **Figure 6** shows a comparison between the textures of 2% Si steel with and without Sb addition in terms of inverse pole inten-

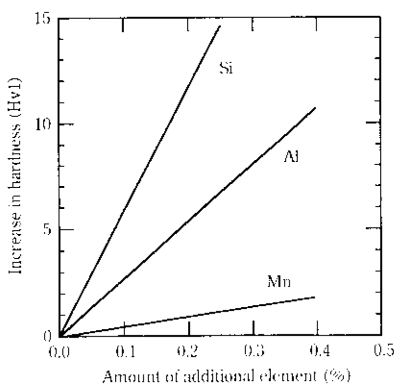


Fig. 5 Effect of Si, Al and Mn contents on hardness

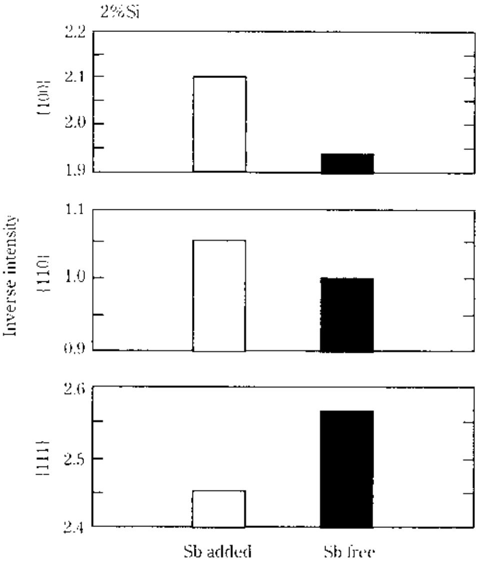


Fig. 6 Effect of Sb addition on inverse pole intensity of material

sity. It can be seen that by adding Sb, the (110) and (100) texture, which are advantageous magnetic properties, increase and the (111) texture, which worsens iron loss and magnetic flux density, decreases.

4.3 Reduction of Plate Thickness for High Frequency Use

In order to achieve higher efficiency of machinery such as brushless DC motors and high rpm motors, it is necessary to lower the iron loss in the high frequency range. Iron loss consists of eddy current and hysteresis losses, and the eddy current loss portion is relatively large in the high frequency range. Therefore, reduction of eddy current loss by reducing the plate thickness becomes an extremely effective means. The targets of plate thickness of the developed materials were set at 0.30, 0.20 mm, values thinner than the standard 0.35 mm.

4.4 Stress Relief Annealing Properties

An inactive atmosphere is preferable during stress relief annealing in order to suppress oxidization and nitriding of the surface layer. Various gasses are used, however, DX gas or N_2 is ordinarily used at a temperature condition of 750~800°C. Under these conditions, oxidization and nitriding are apt to progress with high-grade electrical steel having a large Si and Al content, and consequently, iron loss after stress relief annealing is not necessarily enhanced and problems of materials deterioration might even occur. Sb, which is added to improve the texture, is known to suppress oxidization and nitriding and the developed materials are also advantageous from this point. **Table 1** shows changes in iron loss in 3% Si steel with and without Sb content before and after stress relief annealing in an N_2 atmosphere. SEM photographs taken of the surface of these materials are shown in **Photo 1**. The table indicates that the iron loss of Sb added steel is always steadily enhanced. Therefore, this material can be regarded to be an ideal stress relief annealed material for high-efficiency motors.

Table 1 Effect of Sb additon on enhancement of iron loss after stress relief annealing (SRA)

Si 3%

	Iron loss $W_{15/50}$ (W/kg)		
	As sheared A	After SRA B	Improvement of iron loss A−B
Sb free	2.71	2.45	0.26
Sb added	2.65	2.32	0.33

Iron loss: measured by the Epstein method
SRA condition: 2 h duration at 750°C in N_2

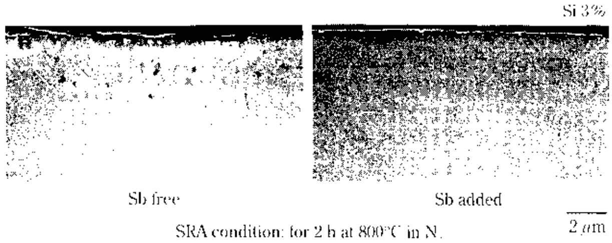
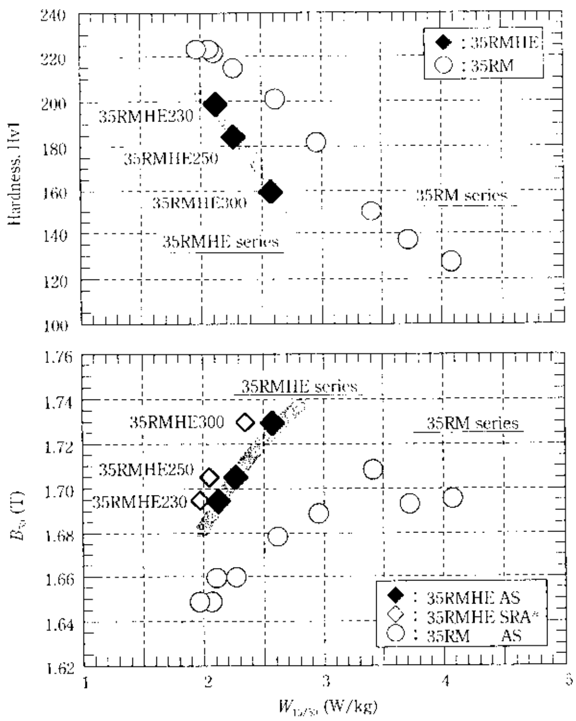


Photo 1 Cross sectional SEM observation of nitride precipitation in the vicinity of surface after SRA

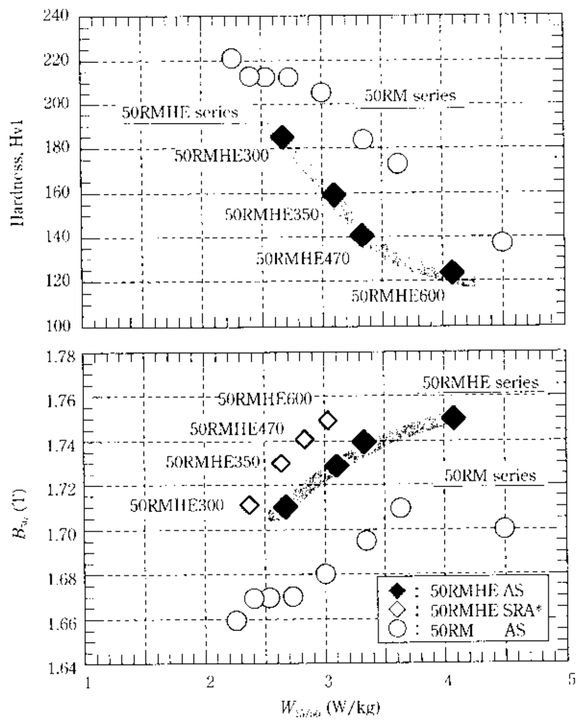
5 Properties of Developed Materials

Figures 7 and **8** show relationships between the iron loss and the hardness and between the iron loss and the magnetic flux density for the developed materials of the RMHE series with a thickness of 0.35 mm and 0.50 mm respectively in comparison with the conventional materials of the RM series. The RMHE series materials have a lower hardness than the RM series materials having the same iron loss, yet the properties of low iron loss and excellent punchability are maintained. At the same time, the magnetic flux density is enhanced by more than 0.03 T in B_{50}. Improved efficiency by lowering the iron loss and at the same time, improved torque by increasing the magnetic flux density can be expected and the degree of freedom in motor design will increase. Furthermore, because of the increased compactness of the motors, the material quantities for various parts including copper wires, core materials, motor covers, etc. can be reduced, and a contribution to environmental protection can be expected. **Table 2** shows the iron loss of the materials after shearing and after stress relief annealing (750°C × 2 h under an N_2 atmosphere) with respect to 35RMHE230 (developed material) and 35RM210 (conventional material). The iron loss ($W_{15/50}$) of 35RMHE230 is less than 2.0 W/kg after stress relief



Note: Relation between hardness (Hv1) and iron loss at 50 Hz
Relation between magnetic flux density and iron loss at 50 Hz

Fig. 7 Magnetic and mechanical properties of RMHE series in 0.35 mm in thickness



Note: Relation between hardness (Hv1) and iron loss at 50 Hz
Relation between magnetic flux density and iron loss at 50 Hz

Fig. 8 Magnetic and mechanical properties of RMHE series in 0.50 mm in thickness

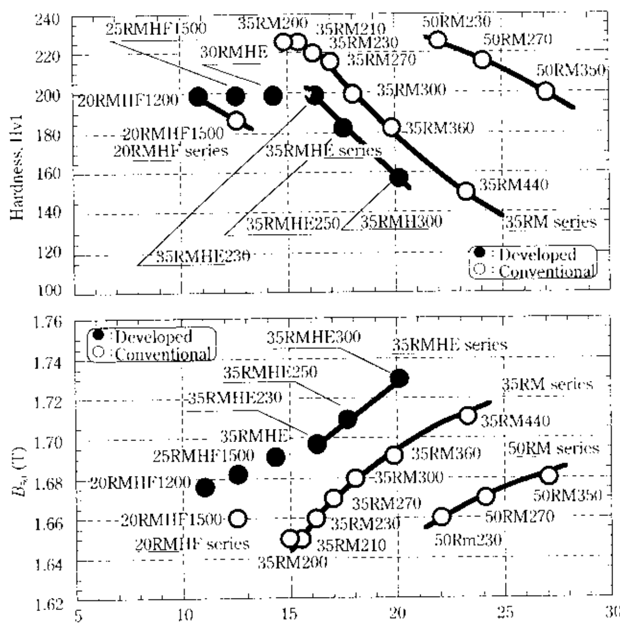
Table 2 Typical magnetic properties of 35RMHE230 and 35RM210

	Density (g/cm³)	$W_{15/50}$ (W/kg) As sheared	After SRA*
35RMHE230 (Developed)	7.65	2.15	1.98
35RM210	7.60	2.05	2.00

Iron loss : measured by the Epstein method
*SRA condition: 2 h duration at 750°C in N_2

annealing. The lower limit of the iron loss with a 0.35 mm thick plate had been considered to be 2.0 W/kg, therefore, the above means produced a further improvement.

Figure 9 shows the relationships between the high frequency iron loss ($W_{10/400}$) and the hardness and magnetic flux density for the developed materials of the RMHF and RMHE series. Like the materials of the RMHE series, the RMHF series is designed to have a low hardness, and in particular, importance is attached to the punchability, even for motors used in the high frequency range. Comparing materials having the same hardness, iron loss $W_{100/400}$ is 17.9 W/kg (corresponding to 35A300) in the case of conventional material 35RM300, whereas, it is 16.3 W/kg, 12.4 W/kg and 11.0 W/kg with the developed materials 35RMHE230, 25RMHF1500 and 20RMHF1200 respectively. This means that it has become possible to use materials with extremely low iron loss. According to an efficiency formula obtained through experiments using model motors of the company,[9] it has been estimated that those devel-



Note: Relation between hardness (Hv1) and iron loss at 400 Hz
Relation between magnetic flux density and iron loss at 400 Hz

Fig. 9 Magnetic and mechanical properties of RMHE and RMHF series

Table 3 Magnetic properties and motor efficiency of brushless DC motor

Material	Grade	Magnetic properties			Hardness Hv1	Maximum motor efficiency (%)
		$W_{15/50}$ (W/kg)	$W_{10/400}$ (W/kg)	B_{50} (T)		
RMHE	35RMHE250	2.25	17.5	1.71	185	91.7
RM	50RM230	2.20	21.0	1.66	220	90.2

oped materials contribute toward an efficiency improvement by 0.4% with 35RMHE230, 1.5% with 25RMHF1500 and 2.0% with 20RMHF1200 when used for brushless DC motors.

6 Evaluation of Motor Characteristics Using the RMHE by Means of Model Motors

Stator cores were made for PWM controlled inverter driven brushless DC model motors using the conventional highest grade electrical steel, 50RM230 of 0.5 mm thickness, and using the developed materials, 35RMHE250 of 0.35 mm thickness. These motors were then subjected to motor efficiency measurement tests. The results of these tests are shown in **Table 3** together with the material properties. The $W_{10/400}$ property of the new material 35RMHE250 is superior and achieved a higher efficiency with lower hardness than the conventional highest grade material, 50RM230.

Based on the results explained above, it can be understood that the RMHE series materials and thin plates made of these materials are most suitable for improving the punchability and motor efficiency of brushless DC motors.

7 Improvement of Punchability Using RMHE

Motor cores are usually made by shearing 0.2~0.7 mm thick electrical steel into predetermined shapes by punching and then layering them. The number or layers per unit core is usually from several tens to several hundreds except for micromotors and the proportion of the punching processes in the entire production process is high. **Table 4** shows an example of the relationship between the material hardness and the punching cost. For cores made by layering 200 sheets of 0.35 mm thick plates to a height of 70 mm, the cost was compared by trial and error calculations taking into consideration the cost of metallic molds and the repair cycle. The cost for punching one core made of electrical steel with a hardness Hv1 of 220 is double that of one with 185. Using an electrical steel of the RMHE series having an Hv1 lower than 200 decreases the cost.

8 Conclusions

(1) The newly developed RMHE and RMHF series electrical steel has the best grade low iron loss properties of the various non-oriented electrical steels and has an improved punchability. Accordingly, it has

Table 4 Relation between punching cost and material hardness (Hv1)

Hardness, Hv1	Cycle for repair (punches)	Repetition (cycle)	Capacity of product	Cost of core (yen/one)
185	1 000 000	20	100 000	300
220	500 000	20	50 000	600

Thickness : 0.35 mm
Height of core : 70 mm (200 sheets lam.)
Cost of new die: 30 million yen per 1 unit

become possible for motor core manufacturers to use low iron loss materials, even those makers who previously had not been able to work on electrical steel because of its high hardness.

(2) The iron loss, $W_{15/50}$, of the 35RMHE250 RMHE series steel, after stress relief annealing, is lower than 2.0 W/kg. This means that a value below 2.0 W/kg, which had been regarded as the limit with 0.35 mm thick materials, has been achieved.

(3) Compared with the conventional materials of the RM series with a similar iron loss, the new materials have a magnetic flux density (B_{50}) higher by 0.03 T contributing to an efficiency improvement for motors, which are the final products of the materials. At the same time, the quantity of materials used for the products can be reduced by designing them to be more compact.

(4) The newly developed electrical steel plates of the RMHE and RMHF series have the special features that they are non-oriented electrical steels having excellent punchability for use in high-efficiency motors. In this respect, the new materials will contribute to a widened use of high-efficiency motors as well as to promoting environmental protection in the following respects:

(a) Lower hardness
Improved productivity → Wider use of high-efficiency motors

(b) Lower iron loss
Reduced energy loss due to heat generation

(c) Higher magnetic flux density
More compact design by virtue of torque enhancement → Reduction of materials required for products

References

1) Agency of Natural Resources and Energy ed.: "Denryoku Jukyu no Gaiyo", (2000), 167, [Chuwa Insatsu]

2) Japan Electric Power Information Center ed.: "Kaigaishokoku no Denryoku Jigyo Dai I hen" (1998), 1, [Shoueisha]

3) Y. Obata: *Tekkokai*, **49**(1999)11, 14
4) A. Honda, K. Sato, and I. Oyama: *Kawasaki Steel Giho*, **29**(1997)3, 163
5) M. Ishida, N. Shiga, M. Kawano, A. Honda, M. Komatsubara, and I. Oyama: *J. AEM*, **7**(1999), 248
6) T. Obara: 155th Nishiyama Memorial Lecture, (1995), 151
7) H. Shimanaka, Y. Ito, T. Irie, K. Matsumura, H. Nakamura, and Y. Shono: "Energy Efficient Electrical Steels", (1980), 193, [TMS-AIME]
8) M. Takashima, T. Obara, and T. Kan: *J. Mater. Eng. Perform.*, **2**(1993), 249
9) M. Komatsubara: *Kawasaki Steel Giho*, **32**(2000)3, 69