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Electrical Steel for Motors of Electric and Hybrid Vehicles*

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Synopsis:

Kawasaki Steel has found that there exists suitable electrical steel sheets as core materials depending on motor types such as induction, brushless DC, and reluctance motors, through the evaluation of core materials conducted by using several motor test machines. RP and RMA series of high flux density are suitable to induction motors. RMHE series of excellent punchability, low iron loss and high density are suitable to brushless DC motors. B coating of self-adhesive type organic coating was found to be effective to reduce the iron loss and the noise of motors.

1 Introduction

Since the second half of 20th century, the effective use of energy and environmental protection have been considered as the most important issues in the world. The state of California has been especially advanced in dealing with these issues; for example it requires partial zero emission vehicles (PZEV) to account for at least 10% of all sales from 2003 onwards. This regulation by California has spurred the development of PZEV such as an electric and hybrid vehicles which offer less energy consumption and less pollution.

Motors used for driving or other purposes in an automobile, such as induction, brushless DC, and reluctance motors, are shown in **Fig. 1**. Electric vehicles made in Europe and USA generally use induction motors, because they are more reliable than DC motors with brushes and less expensive than brushless DC motors that use permanent magnets. In contrast in Japan, brushless DC motors have been mostly used in electric and hybrid vehicles, because of the advanced research and development of high quality and reliable magnets. Unlike the full size or large cars in USA, cars in Japan are more compact, and thus have smaller motors. This may be another reason for the use of brushless DC motors. Moreover, the recent development of control techniques has spurred the use of switched reluctance motors (SRM) and synchronous reluctance motors (SynRM) which had been restricted in automobile use due to their noise and vibration.[1)]

The properties of a motor are also greatly dependent on the electrical steel used as the core material. **Figure 2** shows the relationship between iron loss and magnetic flux density of non-oriented electrical steel produced by Kawasaki Steel.[2)] In addition to the RM series of conventional electrical steels ranging from high grades of high Si and low iron loss to low grades of low Si and high iron loss, we have developed several electrical steels which have higher magnetic flux density and the same iron loss as conventional steels.

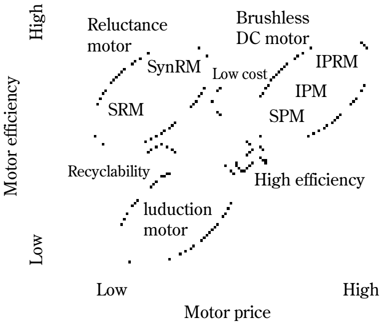

Fig. 1 Comparison of induction, reluctance and brushless DC motors

This article describes the effects of electrical steel used as a core material on the properties of motors of different kinds, and proposes an optimum core material for individual motors. It also introduces a newly developed electrical steel for reactors which is expected to come into widespread use in automobiles in future.

2 Effects of Core Materials on Motors

Kawasaki Steel evaluated the properties of several kinds of motors, namely 600 W single phase induction

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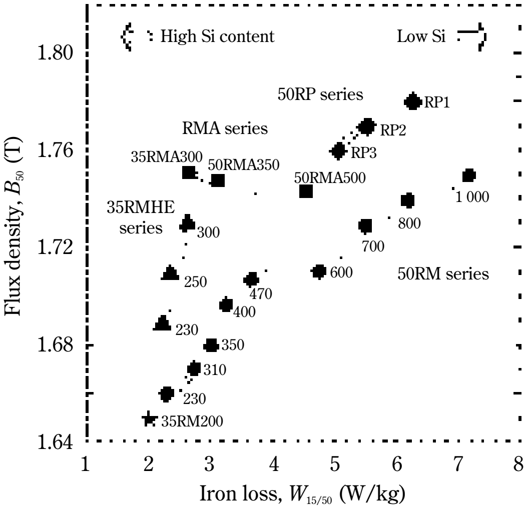


Fig. 2 Relation between iron loss and flux density of non-oriented electrical steel produced by Kawasaki Steel

motors, 400 W 3phase-6poles induction motors and 300 W 3phase-8poles brushless DC motors,[3–5] and has determined the effects of electrical steel on the properties. Presently we evaluate core material for SRM. We have also tried to evaluate core materials more precisely by using the magnetic field analysis software JMAG.

2.1 Effects of Core Materials on the Induction Motors

Figure 3 shows the measured losses for the single phase induction motor using some of electrical steels shown in Fig. 2 as the core material.[3)] The copper loss was more than twice as large as the iron loss in the induction motor. The use of high Si materials having low iron loss decreased motor iron loss, but increased motor copper loss. This was because the increase of Si content in the core material reduced iron loss and increased magnetizing current by reducing the magnetic flux density of the material in the saturation and high magnetic field regions.

The downsizing of motors requires them to have high operation flux density. In order to investigate the effects of operational flux density, motor losses were measured when the operating flux density was increased by increasing input voltage. **Figure 4** shows the results.[3)] A low Si material having high saturation flux density decreased total loss of the motor, while a high Si material caused severe deterioration in copper loss because the flux magnetic density nearly reached the saturation point.

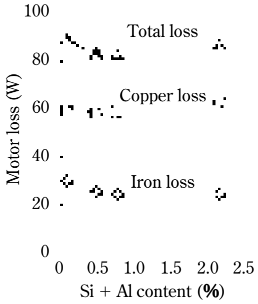


Fig. 3 Effect of Si + Al content of core material on iron loss, copper loss, and total loss of induction motor at rated input voltage of 100 V

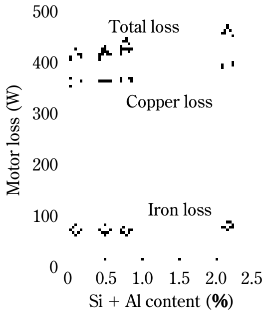


Fig. 4 Effect of Si + Al content of core material on iron loss, copper loss, and total loss of induction motor at high input voltage of 120 V

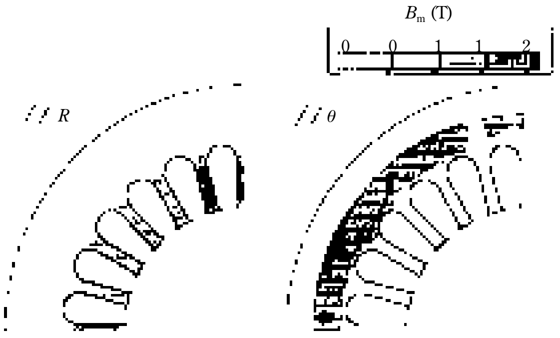


Fig. 5 Flux density distribution in induction motor stator core measured by the stylus probe method

Figure 5 shows an example of local flux density distribution in the induction motor measured by the stylus probe method.[6–8)] The flux densities of teeth and core back are both more than 1.5 T. Downsizing of the motor will make these areas approach the saturation point.

We concluded from these results that core materials with low Si content are suitable for induction motors having larger iron loss than copper loss.

2.2 Effect of Core Material on Brushless DC Motor Properties

Figure 6 shows the effects of core material on the maximum efficiencies of brushless DC motors.[5)] It was found that the maximum efficiency of motor depended mainly on iron loss at 400 Hz regardless of stress relief annealing of the material after punching. The brushless DC motor requires smaller primary current because it has powerful magnets such as those of rare earth metal

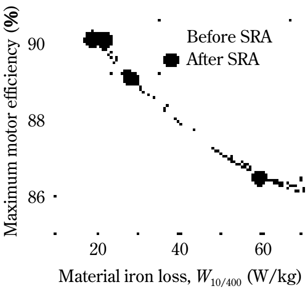


Fig. 6 Relation between material iron loss at high frequency before and after stress relief annealing (SRA) and maximum motor efficiency

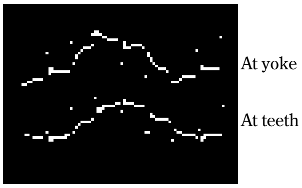


Fig. 7 Differential wave form of flux density in stator core

and it requires no secondary current because there are no conductors in the rotor. Therefore the brushless DC motor has less copper loss and more iron loss than the induction motor. This is the main reason the maximum efficiency of brushless DC motor shows a good correlation with material iron loss.

The maximum efficiency is correlated very well with material iron loss at 400 Hz despite the fact that the driving condition is at a basic frequency of 100 Hz. This is because the flux density waveform of the teeth and core back of the motors tested in this experiment included higher harmonics, as shown in **Fig. 7**. These higher harmonics would be due to the magnetizing waveform of PWM and the magnets in the rotor.

It can be suggested that materials having low iron loss at high frequency are suitable for brushless DC motors. It is also desirable to have high flux density because high flux density material has higher efficiency in the region over rated load shown in **Fig. 8**.

It is also well known that a rotational iron loss that is locally generated greatly influences the motor iron loss. **Figure 9** shows an example of rotational iron loss distribution of a brushless DC motor, which was calculated by analysis software JMAG. A large rotational flux density generated at the base of the teeth can be seen in the figure. In order to understand deeply the knowledges about the effect of core material on motor loss and further utilize these knowledge for motor design, it is necessary to improve techniques for simulating these local flux density changes. This makes it easier to find an optimum material for the motor which has a different flux density waveform from the motor tested here. Kawasaki Steel is conducting several studies on developing techniques to analyze local iron loss.

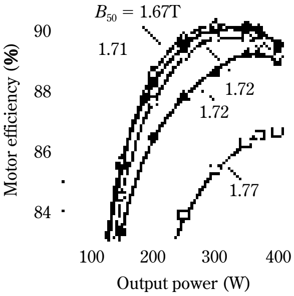


Fig. 8 Relationship between output power and motor efficiency

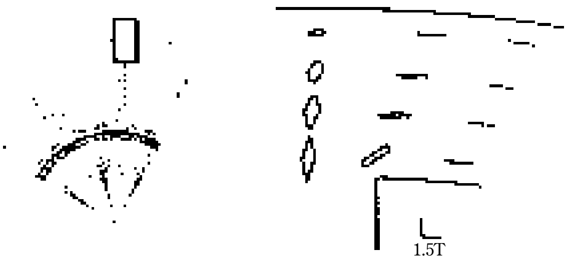


Fig. 9 Rotational flux distribution of brushless DC motor core calculated by JMAG

2.3 Effects of Core Materials on SRM

Unlike induction or brushless DC motors, SRM consisting of iron cores without conductors and magnets in rotor is inexpensive, tough, and superior in recyclability. Therefore it shows promise as a driving motor for cars.1) Several papers have reported on the effects of core materials on SRM properties.9,10) Nakamura et al.9) prepared SRMs using 50A1000 of low grade electrical steel and 35A290 of high grade low iron loss steel and tested them. They achieved more than 80% efficiency by using 35A290 and by progress magnetization controlling method, which is 10% more efficient than 50A1000. They concluded that the differences in motor efficiency were due to the differences in the iron loss of the core materials.

Thus low iron loss material are possibly effective for SRM. In addition, since high flux density of core materials makes the reluctance torque higher, the effect of core materials should be investigated in detail. Kawasaki Steel has already been testing it with SRM evaluation equipment.

3 Proposal of Optimum Materials for a Range of Motors

As already shown in Fig. 2, Kawasaki Steel has been developing various kinds of non-oriented electrical steels by applying techniques such as inclusion dispersion, grain size, and texture control and high purification technology.[11–15] Based on the effects of core material on the range of motors described in the previous chapter, we propose below the optimum core materials for induction, brushless DC, and SRM motors.

3.1 Core Materials for Induction Motor

(1) RMA Series[16,17]

Induction motors in which the copper loss is higher than iron loss, require a core material with high flux density rather than low iron loss. In order to meet this requirement, RMA series have been developed to spur high grain growth during stress relief annealing by the inclusion shape control. This technique has reduced iron loss by decreasing the hysteresis loss through grain growth control, and by maintaining high flux density through reducing Si content in the steel.

(2) RP Series[18]

The RP series of high flux density has been developed for induction motors and other small EI cores. As described earlier, the copper loss is dominant in downsized induction motors due to increased operational flux density. In order to reduce the cooper loss, it is important to use high flux density electrical steel in a high magnetic field having less Si content than the RMA series. The RP series is most suited to this application.

(3) Bonding Type B Coating[19,20]

B coat, which is an organic adhesive resin capable of heat bonding, was developed for applications in which clamping, welding, and other methods of joining cannot be applied, and for applications which require airtightness between stacked sheets. **Figure 10** shows the effect of bonding temperature on tensile shear strength of a 5 μm thick B coat at room temperature. High bonding strength was obtained at temperatures from 150~300°C. **Figure 11** shows a comparison of motor efficiency for clamped cores having ordinary insulating coating with that for adhesive cores having B coat. The adhesive types were more efficient, and showed a noise suppression effect of 2~5 dB. In contrast to the clamped type which gives partial strain in the core, the adhesive type with glued laminated sheets can reduce iron loss and vibration by dispersing strain.

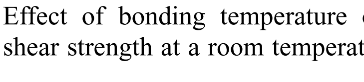


Fig. 10 Effect of bonding temperature on tensile shear strength at a room temperature

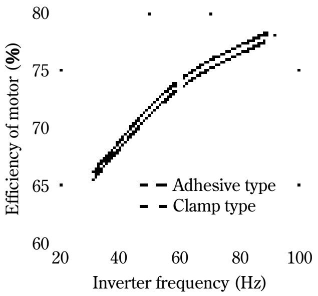


Fig. 11 Effect of core assembly method on efficiency of model motor using 50RM700*B as core material

This B coat can be applied not only to induction motors but also to brushless DC motors SRM, and other type of motors.

3.2 Proposal of a Core Material for Brushless DC Motors

(1) Highest Grade Non-Oriented Electrical Steel 35RM200[2]

The electrical steel 35RM200, which is presently one of the world's best electrical steels in its class, has been developed by using various sophisticated technologies, which include ultimately-advanced purification technology, technology for adding the elements Si and Al as much as possible to be allowed by cold rolling, inclusion dispersion control technology, and texture control technology. The magnetic properties and hardness for 35RM200 and other materials for brushless DC motors are shown in **Fig. 12**. It is clearly shown that 35RM200 has the lowest iron loss of all 0.35 mm thick materials and its hardness Hv is more than 220 owing to increased addition of Si and Al to reduce eddy current loss through increasing resistivity.

(2) RMHE Series of Superior Punchability[21]

Materials subjected to punching require a hardness Hv less than 200 due to the acceptable working conditions and abrasion of punching dies. RMHE provides high resistivity and low iron loss by optimizing the amount of Si, Al, and Mn, each of which contributes in its own way to electric resistivity and hardness. RMHE reduced (111) texture components which are unfavorable to the magnetic properties and increased favorable (100), (110) components, by adding a grain boundary segregation element and controlling the intermediate processes.

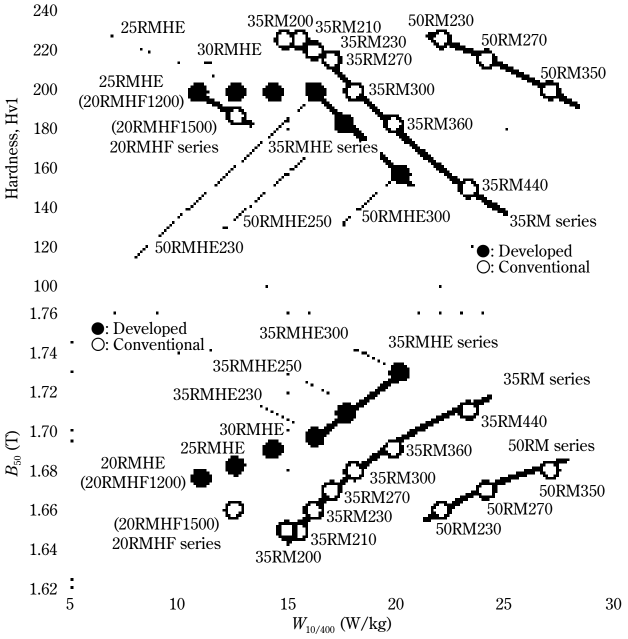
These improvements gave RMHE higher magnetic flux density and lower hardness than the RM series with the same iron loss. Iron loss was further reduced by developing 0.30 mm, 0.25 mm, and 0.20 mm thick RMHE which are not in conformity with JIS grade.

(3) Electrical Steel for Segmented Core Type motors

Concentrated winding type motors has been developed more aggressively than that of distributed wind-

Table 1 Magnetic properties of core materials for high frequency use

Material	Thickness (mm)	Resistivity ($\mu\Omega$m)	Saturation induction (T)	Iron loss (W/kg)		
				$W_{2/5k}$	$W_{1/10k}$	$W_{0.5/20k}$
HiFreqs	0.1	85	1.81	20	9.7	6.2
20RMHF1200	0.2	54	1.52	32	23	19



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

Fig. 12 Magnetic and mechanical properties of RMHE and RMHF series

ing type, to improve efficiency of winding and to reduce copper loss by reducing coil ends. Accordingly, a segmented type core has come to be used in hybrid cars, because it improves an efficiency of steel sheet use and affects the design of electrical steel. That is, the improvement of the magnetic properties of a material in only one direction can enhance the motor properties depending on the shape of the core. Therefore it may be possible to use grain-oriented electrical steel for this propose.

3.3 Proposal for Core Materials for SRM

Kawasaki Steel is now analyzing the SRM data and will soon propose the best material for SRM. We should note that the RMHE of high flux density and low iron loss would be effective for SRM since low iron loss material is effective for the motor efficiency, and high flux density is effective for improving high torque property which is a feature of SRM.

4 HiFreqs for Reactor Core for Inverter Drive Motor

Recently in Japan, many motors such as brushless DC motors are controlled by inverters. In order to improve

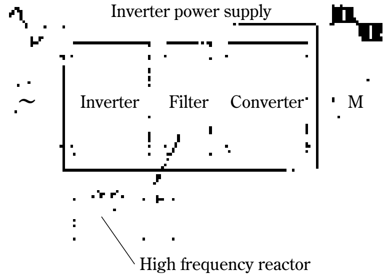


Fig. 13 Schematic diagram of reactor used in inverter circuit

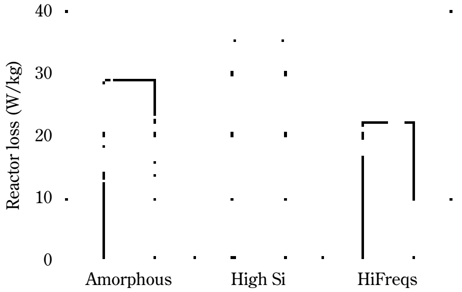


Fig. 14 Iron loss of reactors made by 3 kinds of core materials

the efficiency of inverter drive motors PAM control, which has been employed in some air conditioner motors (**Fig. 13**),[22] could also be applied to automobile motors.

PAM control requires a high frequency reactor operating at frequencies of 10~20 kHz where amorphous or high Si steel sheets are used as the core material. Since these materials have excellent properties at high frequency range but are not very workable, Kawasaki Steel developed new material HiFreqs with good properties at high frequencies and workability.[23–25] **Table 1** shows the properties of HiFreqs and other materials. By purifying steel and adding Si and Cr together, HiFreqs has achieved low hardness, low iron loss, and high corrosion resistivity.

Figure 14 shows the iron losses of the reactors used commercially available PAM air conditioner, using three kinds of core materials. Hifreqs shows the lowest iron loss of the three. The large iron loss of the amorphous reactor may be due to the strain induced by the manufacturing process including punching.

5 Conclusions

Kawasaki Steel has been developed new non-oriented

Si steel products for motor cores in cars.

The RP series of high flux density and RMA series of low iron loss and high flux density after stress relief annealing have been developed for induction motors. The electrical steel 35RM200 of low iron loss and the RMHE series of high punchability, low iron loss, and high flux density are suitable for brushless DC motors. Bonding type B coating, which reduces deterioration due to strain induced in the stacking process, can be used on each type of motor. HiFreqs with superior high frequency properties and workability has been developed as a high frequency reactor to improve inverter drive motors.

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