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Magnetic Properties of High-Efficiency Core Materials NC-M3 and NC-M4

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High-efficiency core materials—New Core NC-M3 and NC-M4—with very low core loss and high permeability have been developed to improve the magnetic properties of conventional magnetic lamination steels. The magnetically favorable crystalline textures are enhanced through the addition of Mn and Sn to low-silicon steel. By adding Mn, particularly more than ~ 1.0 wt.%, to low-silicon steel, a decrease in (111) plane crystals and an increase in (110) and (100) plane crystals are achieved. Moreover, by adding Sn to low-silicon steel containing Mn, the decrease in (111) plane crystals and the increase in (110) plane crystals are more significant. The most suitable amount for the addition of Sn is ~ 0.1 wt.%, because excessive Sn content prevents normal grain growth in steels and makes magnetic properties, particularly core loss, inferior. Typical magnetic properties of NC-M3 (0.47-mm thickness) are 1.70 W/lb in $W_{15/60}$ and 3000 Gauss/Oe in $\mu_{15/60}$, and those of NC-M4 (0.47-mm thickness) are 1.57 W/lb in $W_{15/60}$ and 3000 Gauss/Oe in $\mu_{15/60}$. The lower core losses are attained mainly by reducing hysteresis loss. The superior magnetic properties of NC-M4 compared to NC-M3 are due to the fact that the steel is cleaner and has undergone sufficient hot band annealing during manufacturing.

1 Introduction

As an aspect of the worldwide trend toward energy consumption and preservation of the natural environment, the reduction of electrical consumption has recently become a crucial matter. Consequently, demand has grown for nonoriented electrical steels and magnetic lamination steels used for small motor cores and ballast cores to have very low core loss and high permeability. These materials are known as high-efficiency core materials.

Usually, silicon and aluminum have been used to reduce core loss by reducing the eddy current loss through an increase in electrical resistivity of the steel provided by the presence of silicon and aluminum. However, because this method is also accompanied by a decrease in magnetic flux density and permeability, it is not suitable for manufacturing high-efficiency core materials, which have very low core loss and high permeability.

A study was made to improve the crystalline texture in an effort to reduce hysteresis loss and increase magnetic flux density and permeability. Through the development of special process techniques to produce clean refined steel, such as desulfurizing, decarburizing, and vacuum degassing, it is now possible to use any element to improve the crystalline texture of the steel without producing harmful effects.[1,2] This article discusses the crystalline texture control of steel through the addition of manganese and tin, as well as the magnetic properties of the high-efficiency core materials New Core NC-M3 and NC-M4, which have been developed by adding manganese and tin to steel.

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2 Experiment

Vacuum-melted steels produced in the laboratory and commercially produced steel sheet were used in this study. The main alloying element was silicon, and its content was about 0.5 wt.%. Resulting ingots made at the laboratory were hot rolled into 2.5 to ~ 2.7-mm-thick strip. Hot rolled pieces were annealed according to the magnetic properties of the final steel sheet. After pickling, hot rolled pieces were cold rolled to the final thickness of 0.47 mm, then annealed for recrystallization. In the case of skin pass rolling, cold rolled pieces were annealed for recrystallization and skin pass rolled to the final thickness of 0.47 mm. The final steel sheet was sheared into strip for the purpose of measuring magnetic properties, followed by stress relief annealing.

Alternating core loss was measured according to JIS C 2550 and was conducted on Epstein specimens at 50 and 60 Hz. Hysteresis loss and eddy current loss were obtained by calculation. Single sheet specimens of 55 by 55 mm were also used for measuring alternating core loss. Core loss at high frequencies was measured using a modified Hay-Bridge method with the same specimens as the Epstein specimens.

Crystalline texture was measured using a Shimadzu X-ray Diffractometer XD-3A. (200) pole figures and the pole intensity parallel to normal direction were analyzed for the evolution of crystalline texture. Microstructures of specimens were also measured by optical microscopy to analyze grain size.

3 Results and Discussion

3.1 *Crystalline Texture Control*

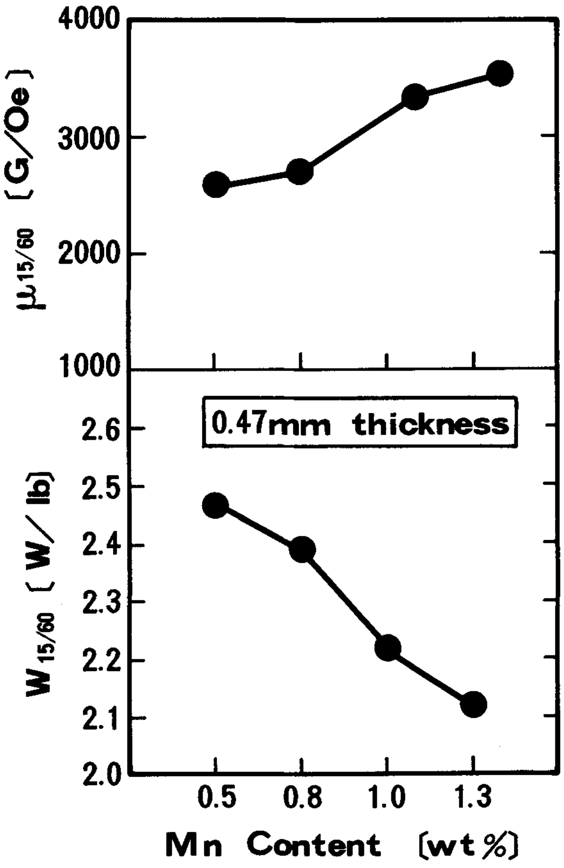
Higher silicon and aluminum contents are not feasible, because they cause deterioration of magnetic flux density and permeability. Therefore, low-silicon steel is the basis for the development of high-efficiency core materials. A number of elements were carefully examined for their influence on improving the crystalline texture of the steel in terms of both reduction of hysteresis loss and an increase in magnetic flux density and permeability. As a result, it was found that very clean, low-silicon steel with above ~1 wt.% Mn can be significantly improved in terms of crystalline texture by hot rolling, cold rolling, and annealing under the proper processing conditions.

It is known that excessive Mn content has a harmful effect on magnetic properties, because it generally forms undesirable precipitates such as MnS. However, when very clean steels are used and processed properly, Mn content can have a beneficial effect on magnetic properties through an improvement in crystalline texture. Figure 1 illustrates the improvement in magnetic properties induced by the addition of Mn. By adding more than, ~1.0 wt.% Mn, both reduced core loss and increased permeability are attained. As shown in this figure, low-silicon steel (0.5 wt.% Si) was used for the experiment to prevent a decrease in magnetic flux density and permeability.

Figure 2 shows the improvement in crystalline texture provided by the addition of Mn. The specimens in Fig. 2 are the same as those used in Fig. 1. By adding Mn, particularly more than ~1.0 wt.% Mn, (111) plane crystals decrease, whereas (110) and (100) plane crystals increase. These improvements in crystalline texture with the addition of Mn correspond to the improvement in magnetic properties shown in Fig. 1. The improvement in crystalline texture provided by the addition of Mn is due to a change in the recrystallization site after cold rolling induced by Mn content.

By practical application of the beneficial effect of Mn for the improvement in crystalline texture mentioned above, high-efficiency core materials called NC-M1 and NC-B1 had been developed.[1-3] Figure 3 shows the magnetic characteristics of nonoriented electrical steels and magnetic lamination steels. It can be seen that NC-M1 and NC-B1 have lower core losses and higher magnetic flux density than ordinary nonoriented electrical steels and magnetic lamination steels.

The crystalline texture of NC-M1 is shown in Fig. 4 which is an example of a steel that has improved crystalline texture via the addition of Mn. The crystalline texture of conventional magnetic lamination steel (CRMQ) is also shown in Fig. 4 for comparison with NC-M1. It can be seen that NC-M1 has more favorable crystalline texture for magnetic properties, that is, reduced crystalline texture (111) <011> and increased crystalline



*Basic Composition

Si	Aℓ	P	C	S	N
0.5	0.2	0.05	0.002	0.001	0.002

[wt%]

Fig. 1 Improvement in magnetic properties due to addition of Mn.

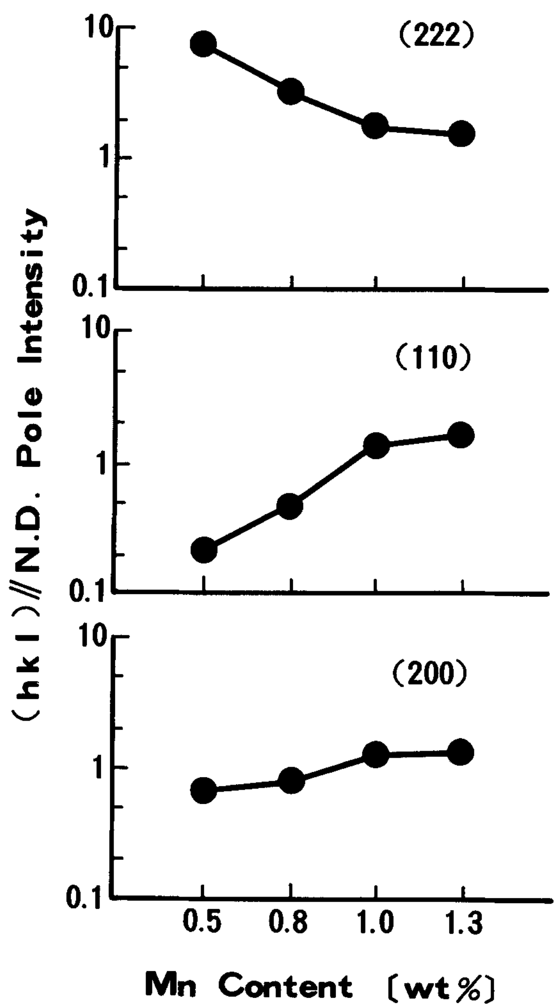


Fig. 2 Improvement in crystalline texture due to addition of Mn.

texture (110) <001>, which are attained more in NC-M1 compared with conventional magnetic lamination steel (CRMQ).

A study was made to improve the crystalline texture further to reduce hysteresis loss and increase magnetic flux density and permeability. As a result, it was found that low-silicon steel containing Mn can be improved in terms of crystalline texture even more by adding Sn. Figure 5 shows the improvement in crystalline texture gained by the addition of Sn. By adding Sn, (111) plane crystals decrease, whereas (110) plane crystals increase during any non-skin pass or skin pass processes. Low-silicon steel (0.5 wt.% Si) was also used for experiment to prevent the decrease in magnetic flux density and permeability. Mn content was more than 1.0 wt.% according to above experimental results for improving crystalline texture via addition of Mn.

Contrary to the beneficial effect of Sn in improving crystalline texture as mentioned above, Sn content tends to prevent normal grain growth in steel because of its segregation to grain boundaries. Figure 6 shows the microstructures of specimens after hot rolling. By adding Sn, the grain size of specimens after hot rolling becomes smaller than that of Sn-free specimen. It is

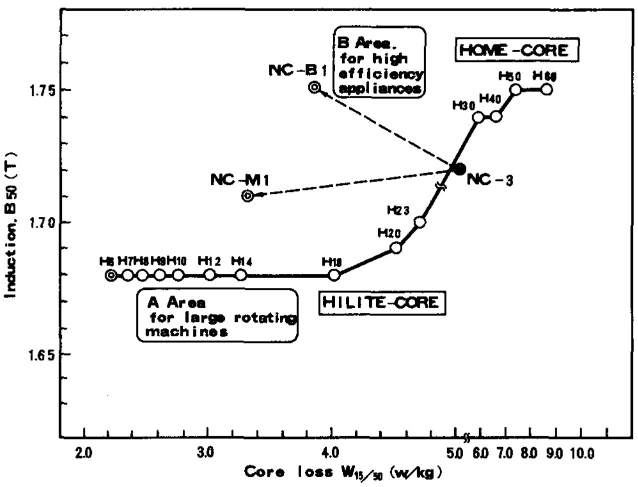


Fig. 3 Magnetic characteristics of nonoriented electrical steels and magnetic lamination steels.

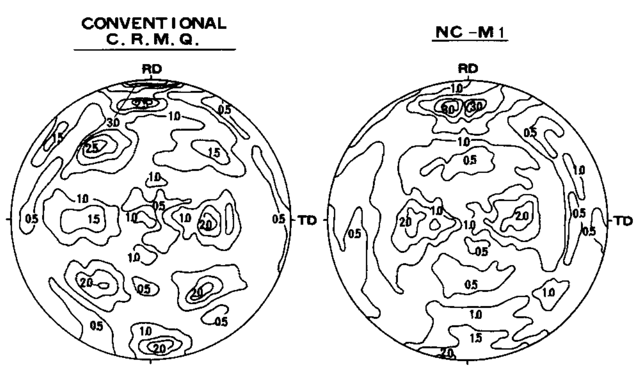


Fig. 4 Crystalline textures of NC-M1 and conventional CRMQ.

well known that the crystalline texture found from recrystallization after cold rolling depends largely on the grain size of hot rolled sheet. The larger grain size of hot rolled sheet causes a favorable crystalline texture for magnetic properties, that is, (111) plane crystals tend to decrease. Consequently, it is predicted that excessive Sn content leads to a smaller grain size in hot rolled sheet and has a harmful effect on magnetic properties.

Similarly, the grain size of annealed sheet after cold rolling is also affected by the addition of Sn. Figure 7 shows the microstructures of specimens after final annealing. By adding Sn, the grain size of specimens after final annealing becomes smaller than those of the Sn-free specimen. Consequently, it is estimated that excessive Sn content leads to smaller grain size in final annealed sheet and increases hysteresis loss.

Figure 8 shows the improvement in magnetic properties induced by the addition of Sn. By adding Sn, both reduced core loss and increased magnetic flux density are attained. However, by adding more than, ~ 0.1 wt.% Sn, core loss begins to increase, which is the contrary effect obtained by adding less than ~ 0.1 wt.% Sn. These improvements in magnetic properties induced by the addition of Sn correspond to the improvement in crystalline texture provided by the addition of Sn shown in Fig. 5. The addition of Sn prevents the nucleation of recrystallization with (111) orientation grains near original grain boundaries of hot rolled sheet, because Sn content tends to promote the nucleation of recrystallization with (110) orientation grains near the deformation band of hot rolled sheet. On the other hand, excessive Sn content prevents normal grain growth dur-

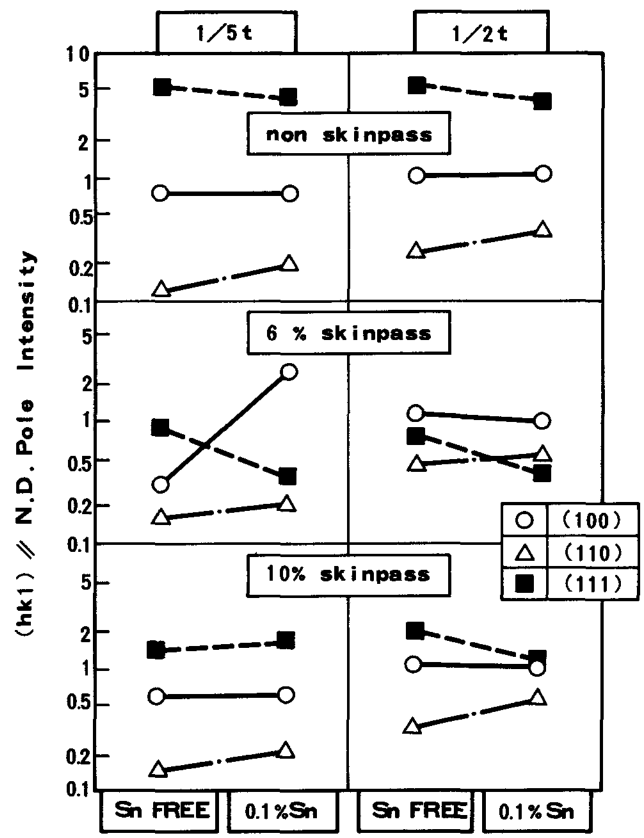


Fig. 5 Improvement in crystalline texture due to addition of Sn.

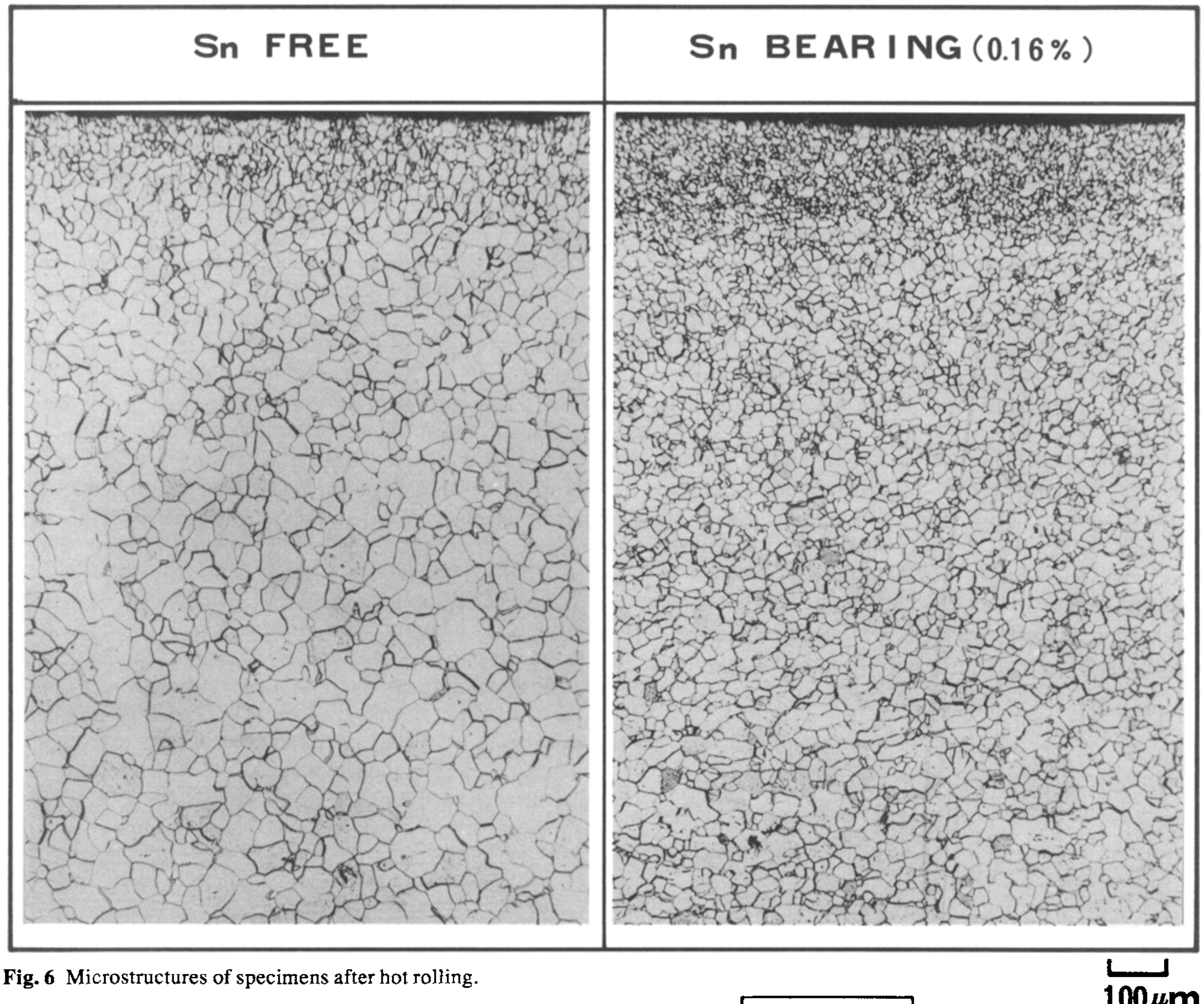


Fig. 6 Microstructures of specimens after hot rolling.

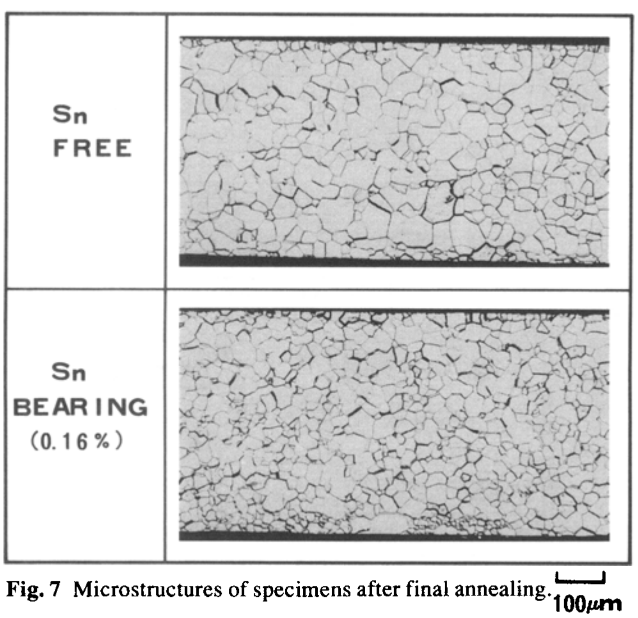


Fig. 7 Microstructures of specimens after final annealing.

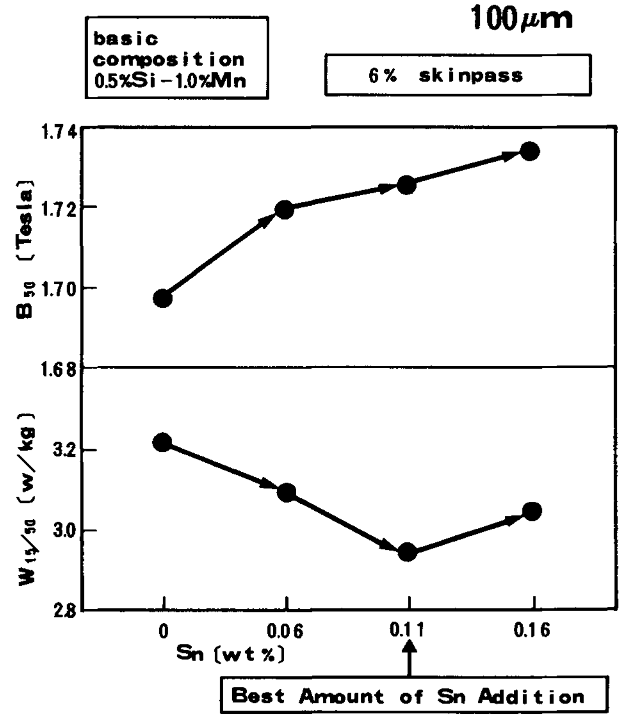


Fig. 8 Improvement in magnetic properties due to addition of Sn.

Table 1 Typical Magnetic Properties of NC-M3, NC-M4, NC-M1, and Conventional CRMQ

Grade	Thickness, mm	Assumed density, g/cm^3	Core loss, W/lb $W_{10/50}$	$W_{15/50}$	$W_{10/60}$	$W_{15/60}$	Peak permeability, Gauss/Oe
New Core NC-M4	0.47	7.80	0.51	1.20	0.66	1.57	3000
New Core NC-M3	0.47	7.80	0.54	1.30	0.70	1.70	3000
NC-M1	0.47	7.80	0.62	1.54	0.81	2.00	2540
Conventional CRMQ	0.47	7.85	0.69	1.70	0.91	2.20	2530

Notes: The values were measured according to JIS C 2550 conducted on Epstein specimens consisting of strip, half of which are sheared parallel and half transverse to the rolling direction. The specimens were tested as stress relief annealed.

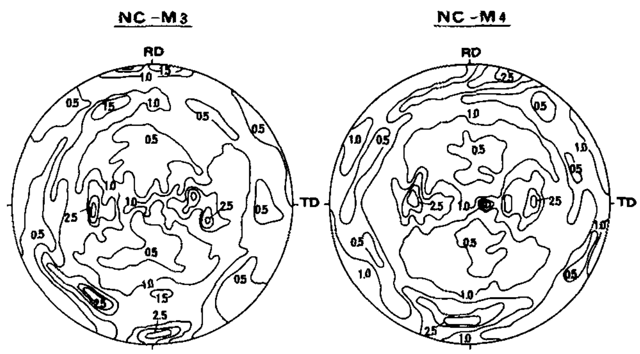


Fig. 9 Crystalline textures of NC-M3 and NC-M4.

ing final annealing, because Sn segregates to grain boundaries. As the smaller grain size makes hysteresis loss increase, excessive Sn content has a detrimental effect on magnetic properties. Consequently, the most suitable amount of the Sn addition is ~ 0.1 wt.%, as shown in Fig. 8.

The beneficial effect of Sn in improving crystalline texture mentioned above has been practically used to develop the high-efficiency core materials New Core NC-M3 and NC-M4, which have lower core loss and higher permeability. The crystalline texture of NC-M3 and NC-M4 are shown in Fig. 9. It can be seen that NC-M3 and NC-M4 have much more favorable crystalline texture for magnetic properties compared with previous versions of NC-M1 and conventional magnetic lamination steel (CRMQ) shown in Fig. 4. In particular, NC-M4 has more favorable crystalline texture for magnetic properties, that is, the increase in and clearness of crystalline texture (110)<001> compared to NC-M3, because NC-M4 is made from a cleaner steel and is given sufficient hot band annealing compared to NC-M3.

3.2 *Magnetic Properties*

Typical magnetic properties of NC-M3 and NC-M4 are shown in Table 1 in the form of a comparison of NC-M1 and conventional magnetic lamination steel (CRMQ). The core loss of NC-M3 and NC-M4 are lower than that of NC-M1 and conventional CRMQ and correspond to M27S. Moreover, the permeability of NC-M3 and NC-M4 are sufficiently high due to their improved crystalline texture. Table 2 shows the core loss separation of NC-M3 and NC-M4, also in the form of a comparison with NC-M1 and conventional CRMQ. It can be seen that the lower core loss of NC-M3 and NC-M4 are attained mainly by reducing hysteresis loss. The lower hysteresis loss is caused by an improvement in crystalline texture, as mentioned above. The ratio of hysteresis loss and eddy current loss of NC-M3 and NC-M4 are almost 1:1; although in the case of NC-M1 and conventional CRMQ, hysteresis loss is more than eddy current loss.

Table 2 Core Loss Separation of NC-M3, NC-M4, NC-M1, and Conventional CRMQ

Grade	Hysteresis loss ($Wh_{15/60}$) (a), W/lb	Eddy current loss ($We_{15/60}$) (b), W/lb	Total core loss ($W_{15/60}$), W/lb
New Core NC-M4	0.79	0.78	1.57
New Core NC-M3	0.86	0.84	1.70
NC-M1	1.09	0.91	2.00
Conventional CRMQ	1.24	0.96	2.20

(a) $Wh_{15/60}$ = Hysteresis loss measured at 1.5T, 60 Hz. (b) $We_{15/60}$ = Eddy current measured at 1.5T, 60 Hz.

Core loss at high frequencies accounts for a rather high percentage (46 to ~52%) of the total core loss of small motor cores.[3,4] This is due to harmonic components of alternating magnetic field, which yield at the tooth at the top of the stator core. Figure 10 shows the core loss at high frequencies of NC-M3 and NC-M4 compared with conventional CRMQ. From low frequencies (50 Hz) to high frequencies (2000 Hz), NC-M3 and NC-M4 exhibit lower core loss than conventional CRMQ at every level of magnetic flux density. This superiority at high frequencies is shown more clearly in Fig. 11. Figure 11 shows the core loss per 1 cycle of NC-M3 and NC-M4 compared with conventional CRMQ. It can be seen that the core loss per cycle of NC-M3 and NC-M4 is lower than that of conventional CRMQ throughout the whole range of frequencies, especially at higher frequencies. This superiority at high frequencies below ~2000 Hz observed in NC-M3 and NC-M4 is also due to their improved crystalline texture mentioned above.

Based on these experimental results, NC-M3 and NC-M4 have excellent magnetic properties, that is, very low core loss and high permeability due to their improved crystalline texture. Figure 12 shows the typical magnetic properties of high-effi-

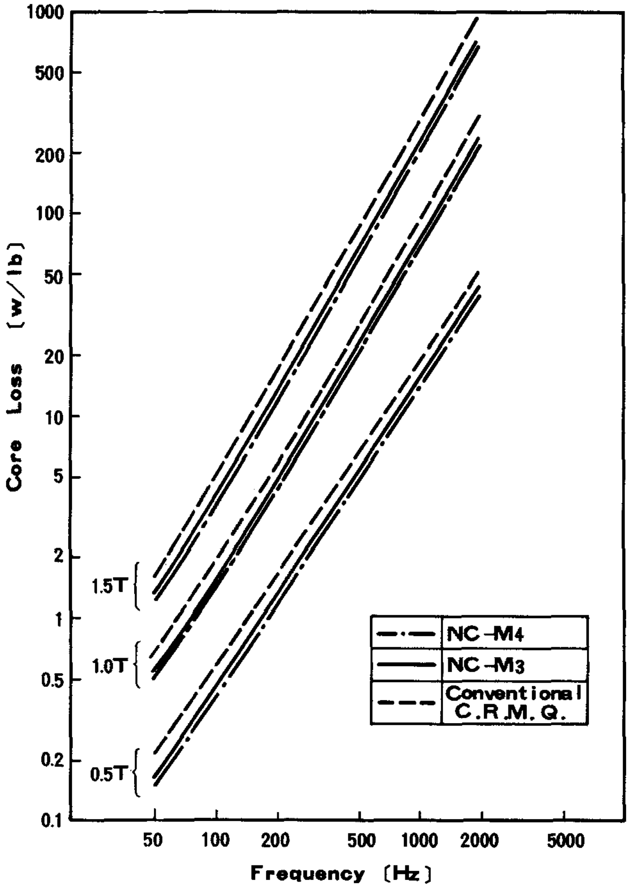


Fig. 10 Core loss at high frequencies in NC-M3, NC-M4, and conventional CRMQ.

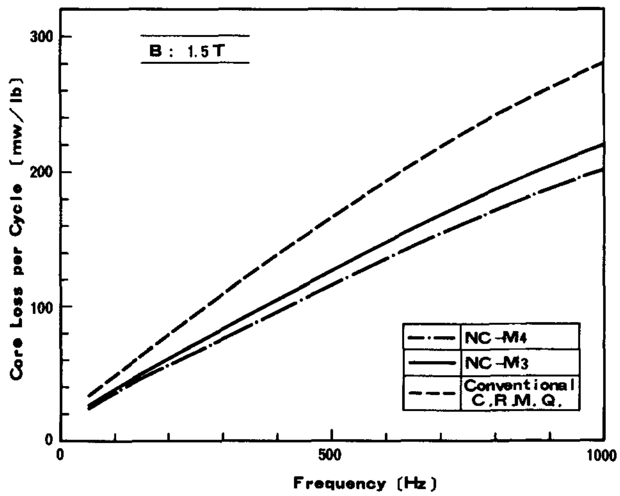


Fig. 11 Core loss per 1 cycle in NC-M3, NC-M4, and conventional CRMQ.

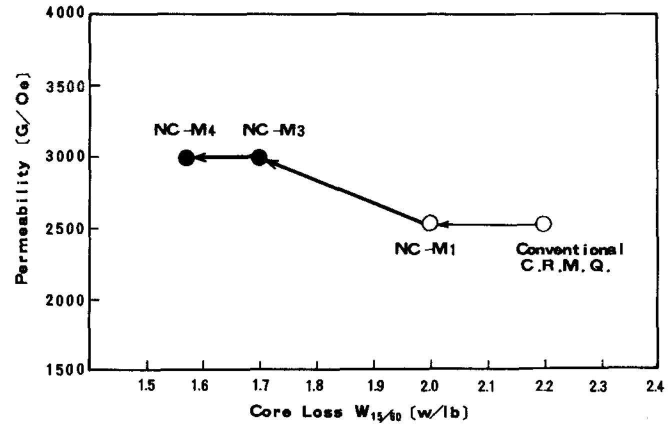


Fig. 12 Magnetic characteristics of NC-M3, NC-M4, NC-M1, and conventional CRMQ.

ciency core materials NC-M3 and NC-M4 compared with previous versions of NC-M1 and conventional CRMQ. It can be seen that the core loss, $W_{15/60}$, of NC-M3 and NC-M4 are below 1.7 W/lb. In particular, that of NC-M4 is below 1.6 W/lb, and the permeability, $\mu_{15/60}$, is 3000 Gauss/Oe, that is, they have very low core loss and high permeability compared with NC-M1 and conventional CRMQ. These improvements in magnetic properties sufficiently contribute to the recent demand for nonoriented electrical steels and magnetic lamination steels used for small motor cores and ballast cores.

4 Summary

High-efficiency core materials, called New Core NC-M3 and NC-M4, with very low core loss and high permeability have been developed. Their excellent magnetic properties are due to the improvement in crystalline texture provided by the addition of Mn and Sn. By adding Mn, particularly more than ~ 1.0 wt.% Mn, to the low-silicon steel, (111) plane crystals decrease, whereas (110) and (100) plane crystals increase. Moreover, by adding Sn to low-silicon steel containing Mn, the decrease of (111) plane crystals and the increase of (110) plane crystals are promoted further more. The most suitable additive amount of Sn is ~ 0.1 wt.% for the improvement in magnetic properties.

The lower core loss of NC-M3 and NC-M4 are attained mainly by reducing hysteresis loss. The lower hysteresis loss is obviously caused by the improvement in crystalline texture provided by the addition of Mn and Sn. The higher permeability is also due to the improvement in crystalline texture by adding Mn and Sn to low-silicon steel. In addition to the lower core loss at ordinary low frequencies (50 to ~60Hz), the core loss at high frequencies below ~2000 Hz is also lower than that of conventional CRMQ. This superiority at high frequencies is considered to be caused by the improvement in crystalline texture.

Typical magnetic properties of NC-M3 (0.47-mm thickness) are 1.70 W/lb in $W_{15/60}$ and 3000 Gauss/Oe in $\mu_{15/60}$, and those of NC-M4 (0.47-mm thickness) are 1.57 W/lb in $W_{15/60}$ and 3000 Gauss/Oe in $\mu_{15/60}$, respectively. The superior magnetic properties of NC-M4 are due to the cleaner steel and sufficient hot band annealing during manufacturing compared to NC-M3.

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