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

T. Kubota and T. Nagai

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) 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 W15/60 and 3000 Gauss/Oe in μ15/60, and those of NC-M4 (0.47-mm thickness) are 1.57 W/lb in W15/60 and 3000 Gauss/Oe in μ15/60. 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. 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.

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 ele-
ments 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 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 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. 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

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

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