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Electrical Steel Sheet for Eco-Design of Electrical Equipment

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Abstract

An electrical steel sheet is a soft magnetic material used for cores of electrical equipments, such as generators, transformers and motors. It is also used for magnetic shielding materials. The progress not only in its material properties, but also in its performance when assembled into electrical eqiupment and magnetic shielding is remarkable. Electrical steel sheets are going to develop as eco-material for saving energy, for reducing noise, and as magnetic shielding.

1. Preface

Electrical steel sheets are indispensable magnetic materials for the electricity system because they are used for the cores of essential electrical equipment at various stages such as generators in the power generation stage, transformers in the transmission and distribution stage and motors in the consumption stage. Regarding electricity, energy conservation is an essential issue for the various stages mentioned above, and reduction of noise generated from that equipment has also become an important issue in view of the generally increasing consciousness for the environment. Another function of electrical steel sheet that is attracting attention is the magnetic shielding property which is also in relation to the general concern about the global environment.

Production and use of the electrical steel sheet can be traced back to the discovery in 1900 by Hadfield et al. of the fact that magnetic properties of steel is improved by addition of Si[1)]. Later, in 1926 magnetic anisotropy of iron crystal was discovered by Honda and Kaya[2)], and then in 1934 Goss invented grain-oriented silicon steel sheet[3)] having a {110}<001> crystalline texture, taking advantage of improving magnetic properties through control of crystalline orientation. The grain-oriented silicon steel sheet is used mainly for transformer cores and Nippon Steel began its production in 1953. From 1968, the energy loss of transformers began to be dramatically reduced thanks to new high permeability grain-oriented silicon steel (HI-B)[4)] developed by Nippon Steel. As for non-oriented silicon steel sheet mainly used for rotating machines, typically motors, its production in Japan was commenced in 1924 by Nippon Steel as hot rolled sheet, which was then replaced with the presently used cold rolled non-oriented silicon steel sheet from 1956.

This paper reports applications of the electrical steel sheet as a functional and environment-friendly material from the above-mentioned three aspects: energy saving, noise reduction and magnetic shielding.

2. Energy Saving of Electrical Equipment

It is required for transformers used in the power transmission and distribution stage to minimize energy loss as much as is possible. The cores of transformers is made of grain-oriented silicon steel sheets and the energy loss or the core loss occurring there has shown a remarkable decrease throughout the history of the efforts to reduce it[5)] ever since the above-mentioned discovery of Hadfield et al.

Reduction of core loss of the grain-oriented silicon steel sheet has developed mainly in three technical aspects: the production of a high permeability grain-oriented silicon steel sheet, the production of a thin gauge high permeability grain-oriented silicon steel sheet and the refining of a magnetic domain. **Fig.1** shows core loss reduction effects of these three factors[6)]. The technology for increasing the magnetic flux density (A) reduced the mean crystalline orientation angle deviation from {110}<001> orientation in the secondary recrystallized grain of the product from 7° to 3°, and the magnetic flux density B8 (flux density when magnetized at 800 A/m) was increased remarkably from 1.82 T to 1.92 T. This brought down, among several core loss factors, hysteresis loss at $W_{17/50}$ (core loss at flux density 1.7 Tesla and frequency 50 Hz) by 0.2 W/kg.

After that, another core-loss factor, eddy current loss, attracted attention and the thin gauge high permeability grain-oriented silicon

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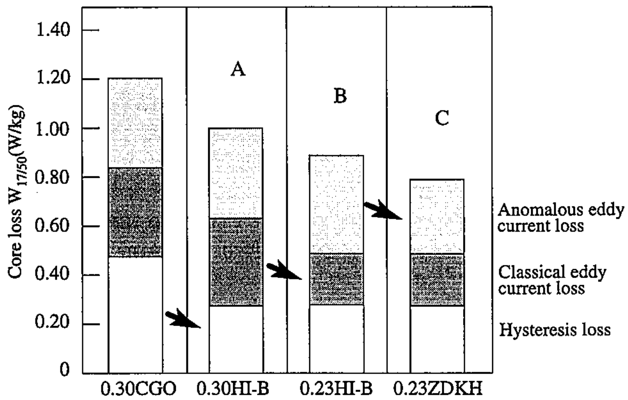

Fig.1 Change of core loss reduction of grain-oriented silicon steel sheet

steel sheet (B) was developed, and the eddy current loss at $W_{17/50}$ was reduced by approximately 0.15 W/kg by making the sheet thinner from 0.30 mm to 0.23 mm. Generally speaking, however, when the crystalline orientation angle deviation from {110}<001> orientation in the secondary re-crystallized grain is made smaller, magnetic domain width becomes larger which results in increased eddy current loss. To solve this problem, magnetic domain refining technology (C) was developed as a measure for controlling the increased magnetic domain width by physical methods. Laser irradiation[7] and grooving[8] on the sheet surface are examples of the technology, by which the eddy current loss at $W_{17/50}$ was further reduced by 0.1 W/kg.

An enormous amount of energy can be saved when the highest grade of thin gauge grain-oriented silicon steel sheet treated by the magnetic domain refining technology is used for the core of transformers. When all the transformers used in the power transmission and distribution grid of Japan are replaced with those made of the highest grade silicon steel sheet, for example, about 2.2 billion kWh of core loss will be reduced, an amount equivalent to the annual power consumption of the Shimane prefecture. Thus, the grain-oriented silicon steel largely contributes to energy conservation through reduction of the transformer core loss.

Control of magnetic domain wall movement is important as a new technology following the above A, B and C for further decreasing core loss of the grain-oriented silicon steel sheet. A ceramics film is formed on the surface of the grain-oriented silicon steel sheet, as shown in **Fig.2**, for the purpose of insulation and giving a tensile stress to the steel[5]. As the boundary between the ceramics film and the steel substrate is not smooth, movement of magnetic domain wall is hindered as a logical consequence. About 0.1 W/kg of core loss at $W_{17/50}$ can be reduced by making the steel surface smooth and eliminating the pinning sites of the magnetic domain wall[5] (See **Fig.3**). Besides the pinning effect of the ceramics film on the magnetic domain wall, sub-boundary structure[9] of the secondary crystallization grain has been confirmed to have an interactive relationship with the magnetic domain wall.

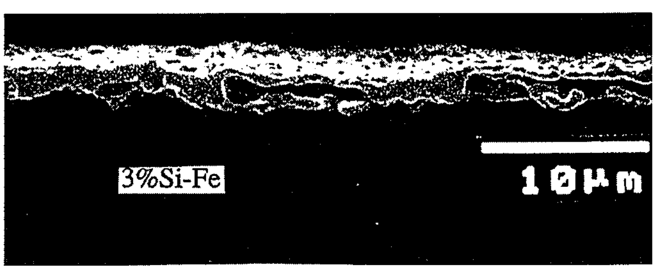

Fig.2 Surface oxidation layer (ceramics film) of grain-oriented silicon steel sheet

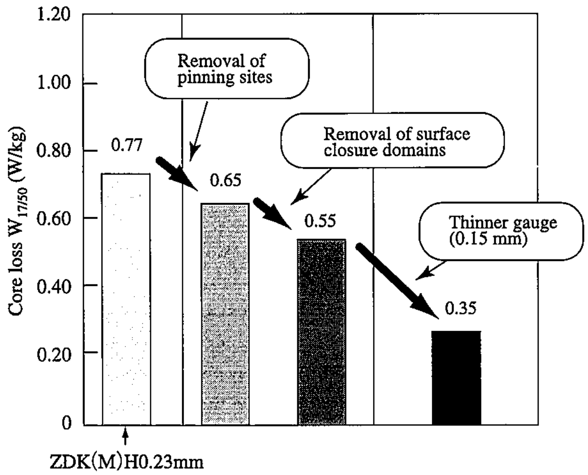

Fig.3 Prospected core loss reduction in grain-oriented silicon steel sheet

There is another phenomenon — the formation and the disappearance of lancet-shaped closure domain during the magnetization process — and this causes energy dissipation during the displacement of magnetic domain wall. It is effective for controlling the formation of the closure domain to align the {110}<001> orientation of the recrystallized grain as much as is possible. By raising the orientation alignment and enhancing the magnetic flux density B8 by 0.04 T (from 1.92 T to 1.96 T), the core loss can be improved by approximately 0.1 W/kg at $W_{17/50}$[5] (See Fig.3). If the sheet thickness is made thinner (from 0.23 mm to 0.15 mm), further reduction of core loss can be achieved and a core loss as small as approximately 0.35 W/kg at $W_{17/50}$ can be made a reality[5].

It is, of course, necessary to decrease energy loss as much as is possible in the generators at the power generation stage and the motors, etc., in the consumption stage of electric power. For reducing the core loss in these machines non-oriented silicon steel sheet has been mainly used for the cores. Control of crystalline orientation and consequent enhancement of magnetic property are important for decreasing core loss of the non-oriented silicon steel sheet, too, and utilization of these effects have actually lowered the core loss and raised the magnetic flux density of the product[10] compared with conventional products (See **Fig.4**).

Lower core loss and higher magnetic flux density, namely higher efficiency, of the non-oriented silicon steel sheet has brought about a marked improvement in the saving of energy, especially in motors. When the high efficiency non-oriented silicon steel sheet is used for motor cores and the efficiency of the motors, which are responsible for 60% of Japan's electricity consumption, is raised only by 1%, no less than 10 billion kWh of power is saved a year, offsetting the annual electric power consumption of Toyama or Kumamoto Prefectures. The significance of motor efficiency will no doubt become more stressed in the future because of changes such as wider use of electric vehicles, etc. This prospect is accelerating the efforts to improve the efficiency of non-oriented silicon steel sheet in a manner matched to the use of motors and other electrical machinery.

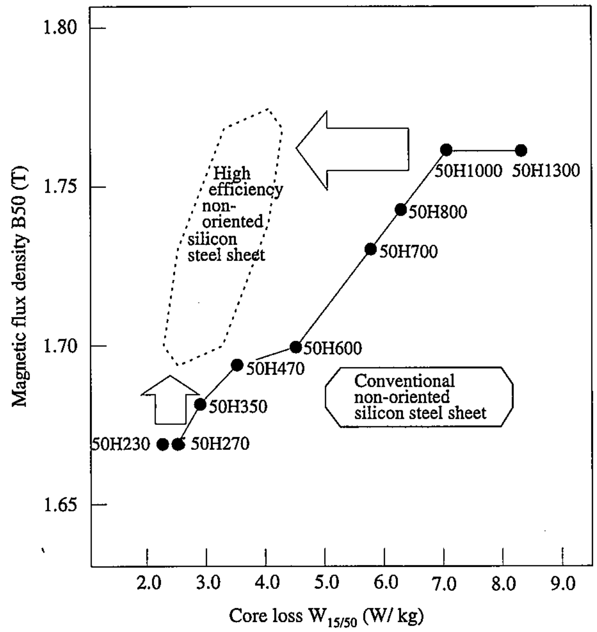

Fig.4 Reduction of core loss and increase of flux density (higher efficiency) of non-oriented silicon steel sheet

3. Noise Reduction of Transformers

Along with the energy saving, reduction of noises from the electrical machines has attracted increasing attention in the background of a general growing of environmental consciousness in general. The noise from transformers is caused by the vibration of the entire transformer, wherein cores and leading wires act as sources of the vibration.

One of the causes of the core vibration is magnetostriction of the grain-oriented silicon steel sheet. Magnetostriction is closely related to the magnetic domain structure as schematically illustrated in **Fig.5**[11]. When deviation from the {110}<001> orientation of the secondary recrystallized grain in the rolling direction is small, the magnetic domain structure will consist only of simple 180° domains and the magnetization process will comprise movement of the 180° domain walls only, and in such cases, no magnetostriction will not occur. Whereas, when the deviation from the {110}<001> orientation of the secondary recrystallized grain is large, the lancet magnetic domain is formed compensating an increase in magnetostatic energy generated by surface free magnetic poles. As the lancet domain has a magnetic domain sub-structure running normal to the rolling direction and the sub-structure forms and disappears during the magnetization process, magnetostriction is inevitably brought about.

For this reason, restriction of the 90° magnetic domain formation is the key to reduction of magnetostriction. Enhancement of alignment of the {110}<001> orientation of the secondary recrystallized grain and increase in tensile stress of the ceramics film are effective for this end. Reduction of residual stress as much as is possible during manufacturing of the silicon steel sheet or assembly of the transformer cores also helps. Making the sheet gauge thinner is effective for lowering magnetostriction, too, since the thinner that the sheet is, the stronger is the magnetostatic energy of the 90° magnetic domain and thus formation of the 90° magnetic domain is relatively restricted. It is additionally expected that the reduced sectional dimension in the thickness direction magnifies the effect of the tensile stress of the ceramics film.

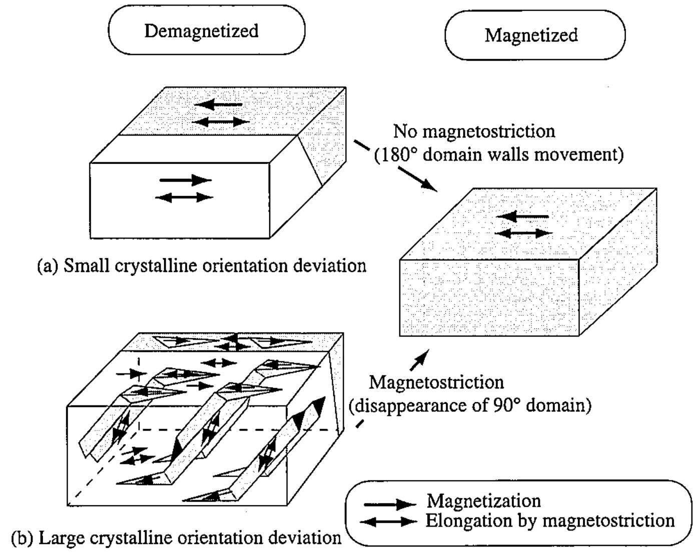

Fig.5 Magnetic domain structure and magnetostriction of grain-oriented silicon steel sheet

Waveform of magnetic flux in the core of actual transformers is distorted from time to time and from place to place, depending on construction of the core and characteristics of the material. As the distortion of the magnetic flux waveform affects the magnetostriction, analysis of magnetostriction behavior during magnetic exciting under non-sinusoidal waveform is important. In the case of excitation under PWM (pulse width modulation), for example, it has been observed that magnetostriction of the higher harmonic component increases in addition to that of the corresponding frequency component[11].

It has to be noted that, besides the magnetostriction discussed above, magnetic suction between the sheets is another cause of the core vibration. In this respect, it is essential for reducing the transformer noises to measure and analyze what kinds of vibration are actually taking place in the core and how they result in the noise. The authors developed a system for measuring and analyzing the transformer core vibration, which system made it possible to analyze the core vibration in detail[12]. **Fig.6** shows a result of vibration analysis on the core of a model 3-phase 3-leg transformer shown in

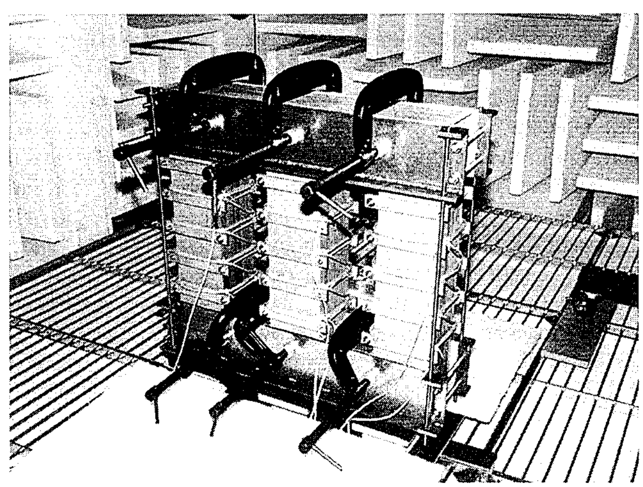

Fig.6 3-phase 3-limb model transformer core

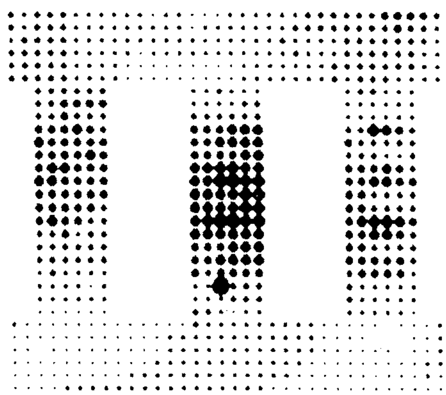

Fig.7 Analysis result of vibration displacement of model transformer core

Fig.7. The vibration of the core is found to be the largest in the leg portions and resonance is suspected to have occurred. It is therefore considered necessary to give due considerations to resonance in analyzing vibration and noise of transformer cores.

As discussed above, in parallel to the reduction of magnetostriction of the silicon steel sheet, analysis and study for optimization of the transformer construction is being advanced utilizing newly developed means such as the transformer core vibration analysis system.

4. Magnetic Shielding Using Silicon Steel Sheet

Electronic apparatuses and precision machines that emit electromagnetic waves but are themselves sensitive to the electromagnetic waves and easily affected by them became increasingly popular these days. Sources of low frequency magnetic noise are also rapidly increasing in number, such as electric trains, automobiles, elevators, power transmission cables and transformers. Shielding technology is one of the measures to prevent malfunction of the apparatuses and machinery from happening in such a complex electromagnetic environment. The magnetic shielding technology using ferromagnetic materials is employed especially against low frequency magnetic noise. The factors that determine the shielding performance are magnetic permeability and the thickness of the material, hence the electrical sheets and plates of high permeability and different thicknesses are used for magnetic shielding.

Magnetic shielding performance is usually evaluated by actually constructing a shield body of the selected material and measuring the performance of the entire shield body, but in this method, the design factor has more influence on the result than the material itself. For evaluating the material performance separately from the design factor, a device as shown in **Fig.8** is more effective[13]. First, the upper excitation core and the shielding body composed of the lower core and the specimen are thoroughly demagnetized by alternating magnetic field, then a magnetic field is applied to the shielding body by the excitation coil, and a magnetic field B1z parallel to the specimen and in the plate thickness direction is measured by a sensor placed near the specimen inside the shielding body. As the magnetic field in the plate thickness direction is attenuated by the shielding effect of the specimen, the shielding performance of the specimen can be evaluated by comparing B1z with the magnetic field without the specimen B0z. The shielding effect S is defined as S = B0z/B1z. Since the shielding body is not placed in a homogeneous

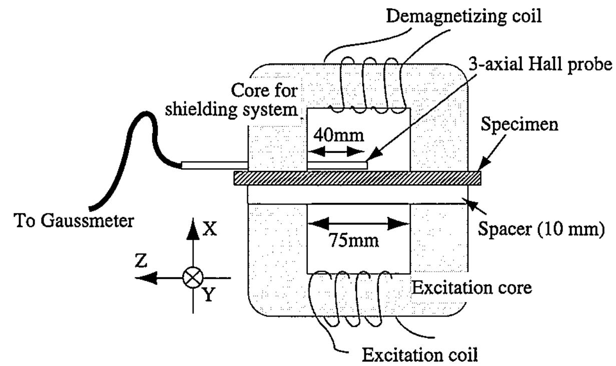

Fig.8 Measuring device of magnetic shielding performance

magnetic field, however, the evaluation thus made does not show the absolute value.

Fig.9 shows change of shielding effect of a non-oriented silicon steel sheet under magnetic exciting force against the flux density without the shielding body shown along the axis of abscissas. Here 50H250 is a high magnetic permeability non-oriented silicon steel sheet containing 3 wt% Si and 50H1000 is a low magnetic permeability non-oriented silicon steel sheet containing 0.3 wt% Si. It is clear from the figure that 50H250 has by far the better shielding

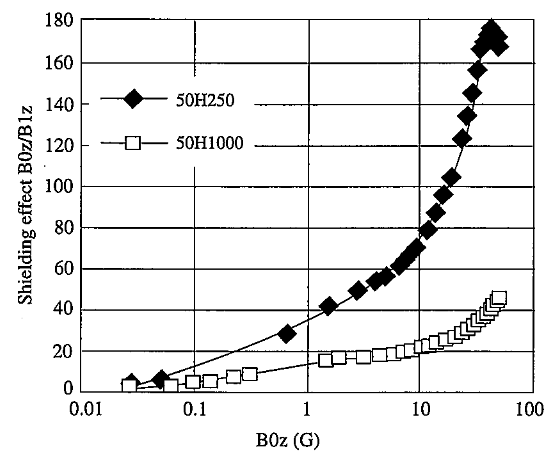

Fig.9 Shielding effects of non-oriented silicon steel sheets having different permeability

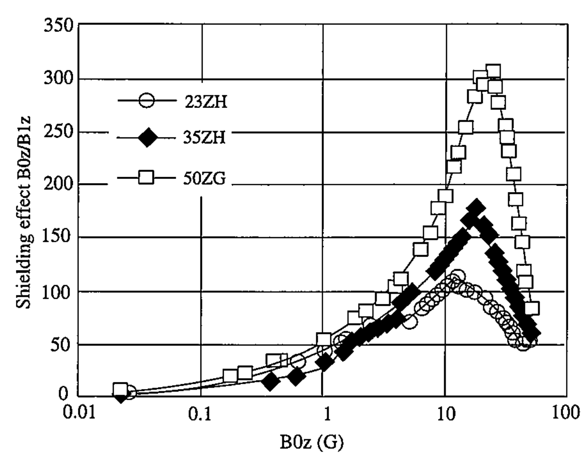

Fig.10 Shielding effects of grain-oriented silicon steel sheets of different thickness

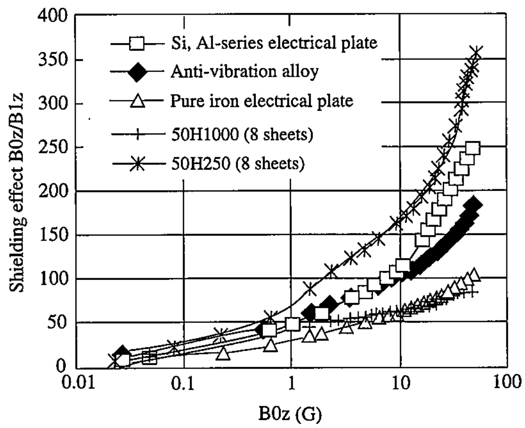

Fig.11 Shielding effects of electrical plates for shielding use (4 mm thick)

effect. The shielding effect curve of 50H250 stays low in the low excitation range and rises as the exciting force becomes larger and then falls after hitting a maximum value. This is because it reflects change of permeability of the material under excitation. **Fig.10** shows shielding effects of grain-oriented silicon steel sheets 0.23, 0.35 and 0.50 mm thick. The three DC magnetization curves have nearly the same shape and the difference in the shielding effects is accounted for mainly by the difference of thickness. The thicker the sheet the larger the shielding effect.

As discussed above, the larger the thickness and permeability the better the shielding performance, but the thickness of silicon steel sheet is usually 0.5 mm or less, and for this reason sometimes several sheets are used in lamination in order to obtain desired shielding performance. Electrical plates[14] which have shielding performance similar to laminated non-oriented silicon steel sheet 50H250 as shown in **Fig.11** are also available for the cases where the lamination has to be avoided.

5. Conclusions

Among various steel products having purposefully tailored functional characteristics, electrical sheets have an especially high functionality. Its application spans from cores of a variety of electrical machines used at various stages of the electricity-related industries to magnetic shielding, and its characteristics as an "eco-material" or an environment-friendly material have been attracting attention. Its application technologies have been vigorously developed aiming at becoming a state-of-the-art "eco-design" as well as its performance as an electrical material has become enhanced and it is hoped that it will be more widely used not only for environment-friendly purposes but, rather, for actively controlling the environment.

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