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Synopsis :
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In recent years, techniques of producing clean steel have progressed markedly. As a result, development of non-oriented silicon steel sheet with low core loss has been achieved in Kawasaki Steel Corporation, and the manufacture of RM7 (maximum core loss $W_{15/50}$; 2.50 W/kg at thickness 0.50 mm) has become possible. RM7 is suitable to core materials for large rotating machines, such as generators, and for various static induction apparatus, and meets the needs of energy saving. Qualitative effects on core loss are also presented of such factors as size and texture of crystal grains and amount of nonmetallic inclusions.

1 Introduction

The manufacturing techniques of silicon steel sheets in Japan are of the highest level. Core loss $W_{15/50}$ of type S09 non-oriented silicon steel sheets in JIS (Japan Industrial Standard) C2552 is specified to be lower than 2.90 W/kg for thickness 0.50 mm at 1.5 tesla of magnetic flux and 50 Hz of frequency, which is one of the most severe specification in the world. Kawasaki Steel Corporation has already manufactured type RM8 silicon steel sheet whose properties exceeds those of S09, that is, satisfies the specification of core loss $W_{15/50}$ lower than 2.70 W/kg for thickness 0.50 mm.

As a result of recent progress in clean steel production techniques, rolling ones and annealing ones, KSC has established the production technique making core loss further low, then the manufacture of type RM7 silicon steel sheet whose core loss $W_{15/50}$ is lower than 2.50 W/kg for thickness 0.50 mm has become possible. RM7 meets the needs of the energy-saving age as a suitable core material for large rotating machines such generators and for various static induction apparatus. In the following, a brief description is given about the technical background to the low core loss of non-oriented Si-steel sheets which permitted the manufacture of RM7.

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2 Factors Which Affect Core Loss

Specifications of electrical steel sheets are mainly determined by core loss values. Core loss is roughly divided into eddy current loss and hysteresis loss. As the higher the electrical resistivity of a steel sheet, the lower the eddy current loss, Si and Al are added into the non-oriented Si-steel sheet in accordance with its specification. The higher the steel grade, the higher the amount of addition. When too much is added, however, steel sheets become brittle; therefore, the sum of the Si and Al additions is limited to about 4%. The larger the grain diameter, the higher the eddy current loss, but the smaller the histeresis loss. Consequently, there is an optimum grain diameter which minimizes the core loss, that is, the sum of both the losses. Besides, hysteresis loss is affected by inclusions and the texture. These factors will be described below.

2.1 Grain Diameter

Non-oriented Si-steel consists of minute grains having a diameter of 50 to 200 μm. The grains are further divided into domains each of which has a respective magnetization in a single direction. This domain is called the "magnetic domain", and the boundary which surrounds the magnetic domain is called the "domain wall". When a steel sheet is magnetized, magnetization mainly occurs by displacing the domain wall. This displacement is frequently irreversible and generates core loss which is called "hysteresis loss". During the displacement, magnetization changes rapidly, which results in the occurrence of an eddy

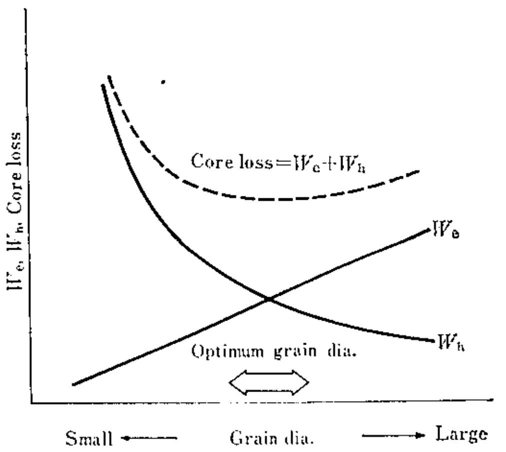

Fig. 1 Influence of grain diameter on hysteresis loss, eddy current loss and core loss

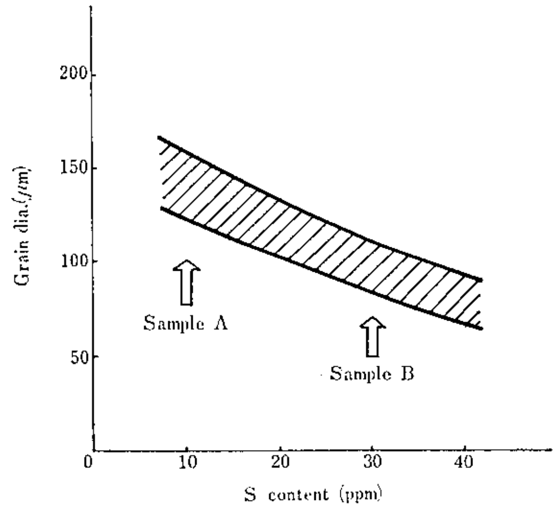

Fig. 2 Effect of S content on grain diameter

current flow at the changed portion and the generation of the eddy current loss. Now, it is known that as the grain diameter increases, the number of domain walls generally decreases. The decrease in the number of domain walls naturally decreases hysteresis loss, but the eddy current loss increases, because the velocity of the domain wall displacement increases. As shown in **Fig. 1**, therefore, hysteresis loss decreases and eddy current loss increases when grain diameter increases. The core loss, which is the sum of both the losses, has a minimum at the optimum grain diameter. The optimum grain diameter varies according to the chemical composition, etc., of steel sheets, but is about 150 μm, in high grade steels.

In order to produce low core loss materials commercially, it is necessary to cause grains to grow into the optimum grain size by short-time continuous annealing. For this purpose, it is necessary to decrease fine precipitates and inclusions such as S, O and N which obstruct the growth of grains. **Figure 2** shows the relationship between S content in steel and the grain diameter after continuous annealing. The figure indicates that grains can be made to reach the optimum grain diameters after a large decrease in S content as in the case of sample A. **Photo 1** shows transmission electron micrographs of sample A and sample B which has smaller grains, and the results of fine precipitate analyses (energy dispersive X-ray analysis, EDXA). In sample A, no precipitate and inclusion are observed, whereas in sample B, there are many fine MnS precipitates. As grain growing quality is improved by the decrease in impurities such as S, O and N, commercial production of the sheets with the optimum grain diameters has been made possible even in short-time continuous annealing process, and thereby the decrease of core loss has been achieved.

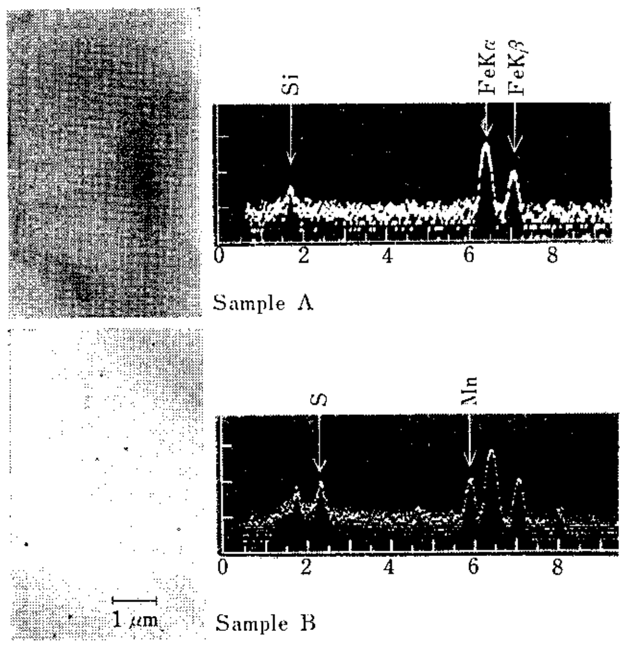

Photo 1 Fine precipitates observed with a TEM and its chemical composition analyzed by EDXA

2.2 Inclusions and Precipitates

Non-oriented Si-steel includes both precipitates and inclusions consisting of sulfides, oxides and nitrides. These impurities obstruct the growth of grains as described in Section 2.1, and directly give adverse effects on core loss. This is attributable to the

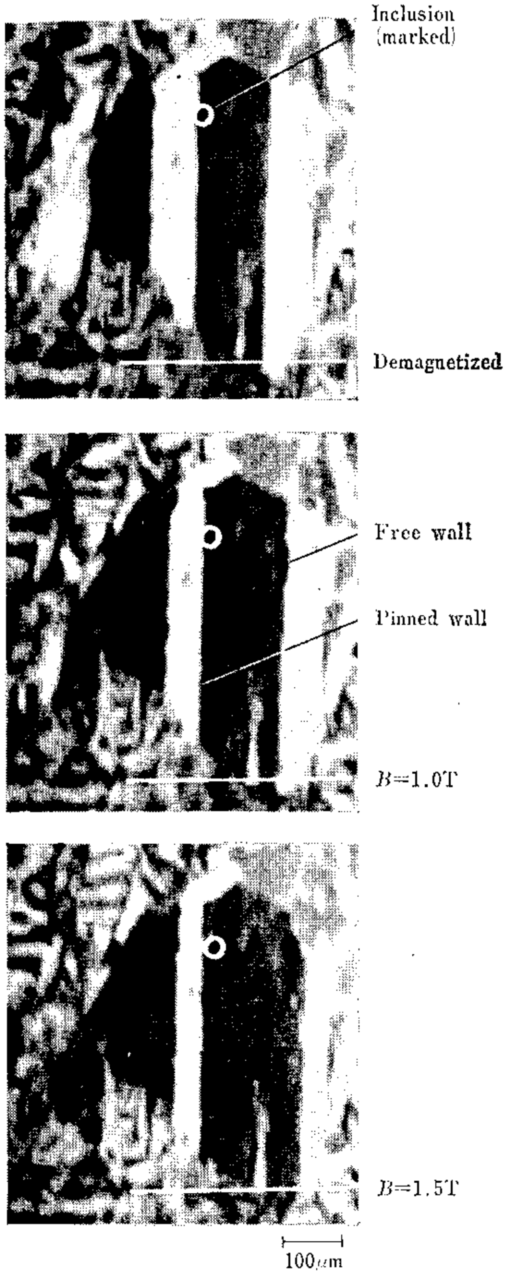

Photo 2 Domain wall pinned by inclusion during DC magnetization

fact that impurities obstruct domain wall displacement and form a new magnetic domain for decreasing magnetostatic energy in their periphery, thereby increasing the number of magnetic domains. As examples of inclusions obstructing the domain wall displacement, **Photos 2** and **3** show magnetic domains observed by the scanning electron microscope (SEM). These photos indicate how one of the 180° walls in a grain whose (110) plane is in parallel with the sheet surface is prevented from being displaced by inclusions, when the grain is magnetized by DC and AC.

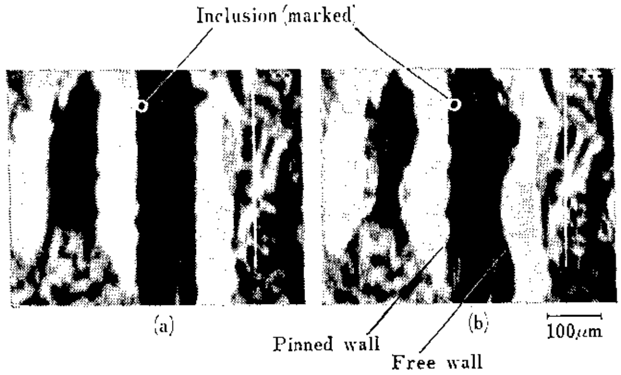

Photo 3 Domain wall pinned by inclusion during AC magnetization (a) demagnetized, (b) $B = 1.0$ T, 50 Hz

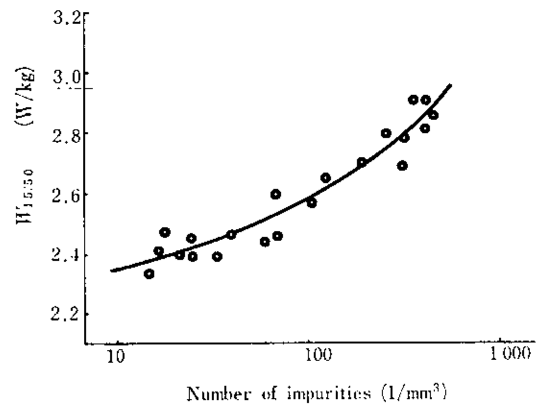

Fig. 3 Effect of impurities on core loss ($W_{15/50}$, 0.50 mm)

In the case of AC, the sinusoidal displacement of the domain wall with respect to time is viewed as sinusoidal changes with respect to the location, by synchronizing the scanning of electron beams with the exciting magnetic field. Sinusoidal undulation of the wall in the photo indicates that the wall moves sinusoidally with respect to time. **Photos 2** and **3** clearly indicate that inclusions are pinning the domain wall.

As shown above, impurities consisting of inclusions and precipitates directly affect the magnetic domain and deteriorate core loss. **Figure 3** shows the relation between the number of impurities in steel and core loss, and with the decrease in the number of impurities, core loss decreases.

2.3 Texture

When grains are arranged in a specified direction, i.e., when they have the so-called "preferred orientation", such a state is called the "texture", and the

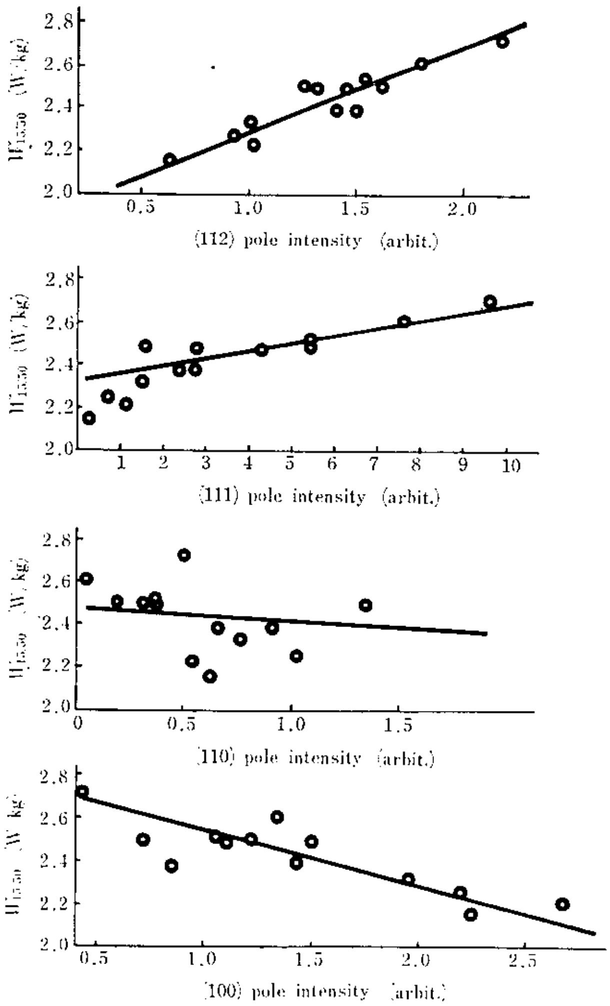

Fig. 4 Relationship between pole intensity and core loss ($W_{15/50}$, 0.50 mm)

magnetic properties of silicon steel is greatly dependent upon these textures. It is well known that silicon steel has a body-centered cubic structure, and the crystal is most easily magnetized along the ⟨001⟩ direction, followed by the ⟨011⟩ direction. The ⟨111⟩ direction is the most difficult to magnetize. Therefore, the texture in which the {100} plane is parallel to the sheet surface, i.e., the random cube texture is ideal because {100} plane includes the greatest numbers of ⟨001⟩ axes. Next, the texture with {110} plane, which includes a comparatively larger number of ⟨001⟩ axes and has ⟨110⟩ axes, is desirable in terms of magnetic characteristics, whereas the texture with {111} plane which includes no ⟨100⟩ axes and the texture with {112} plane which has ⟨111⟩ axes are undesirable. **Figure 4** shows the relation between core loss and the pole intensity of planes (100), (110), (111), and (112). The pole intensity is the X-ray reflection intensity of

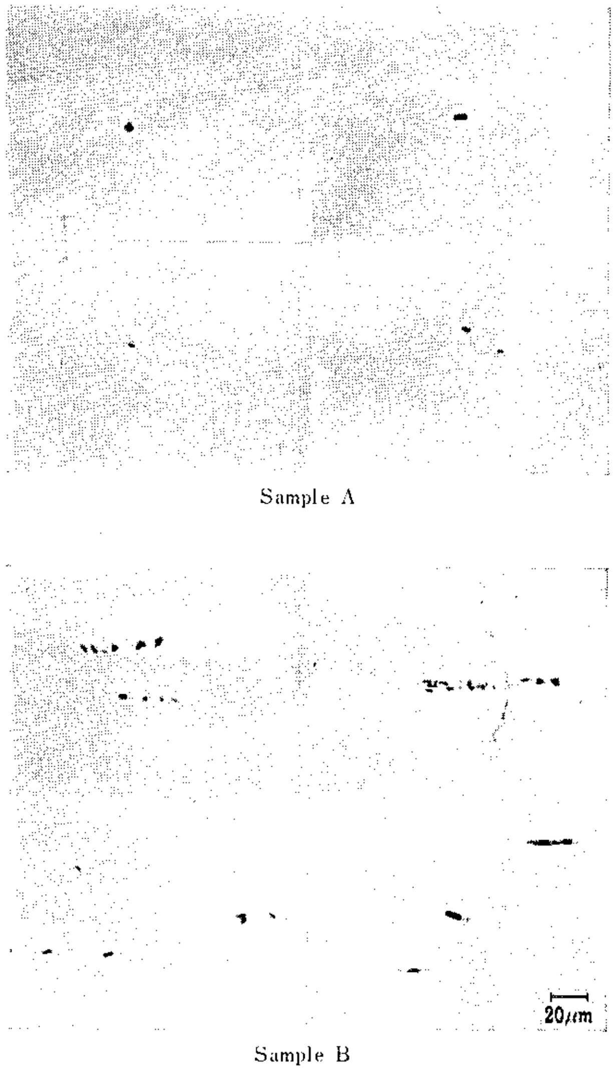

Photo 4 Inclusions in the specimen observed with an optical microscope

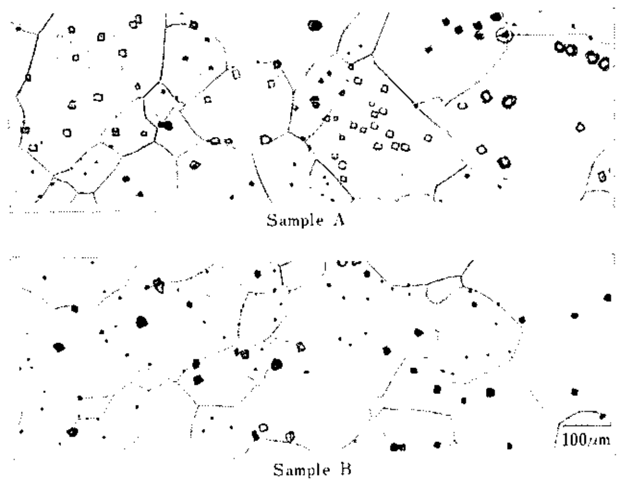

Photo 5 Facet pit of the specimen surface

each crystal plane with respect to a completely random structure, and becomes "1" for a random texture. It is found in the figure that the core loss is affected by the pole intensity of (100), (112) and (111) planes. When the pole intensity of (100) plane is stronger, core loss becomes lower, whereas when that of the (112) and (111) planes are stronger, core loss becomes higher.

The texture is greatly affected by the reduction in cold rolling and also by the quantity of inclusions in steel. For example, sample A includes a small quantity of inclusions and sample B includes a large quantity of them as shown in **Photo 4**. **Photo 5** shows these textures in which the difference of grain orientation are revealed as the difference of facet pit shapes in each grain surface by means of a special etchant technique. The shape of the facet pit varies with crystal planes. At this time, the {111} plane appears only as an unclear black shape and the {100} plane as a white square. Sample A having a small quantity of inclusions contains many grains each having a {100} plane parallel to the sheet surface, while sample B having a large quantity of inclusions contains many grains each having a {111} plane. This is considered to be attributable to the fact that inclusions in steel have become the generation sources of nuclei of grains each having a {111} plane. As described above, the decrease in inclusions in steel will decrease the number of grains having a {111} plane and increase those having a {100} thereby improving magnetic properties.

3 Refining of High Purity Steel

As described in Chapter 2 above, the decrease in impurities such as S, O and N in steel will eliminate their direct adverse effects on magnetic properties and improve both the grain growing quality and the texture, thereby greatly enhancing magnetic properties. Thus the refining of high purity steel owes a great deal to the recent noticeable progress in the steelmaking process.

Silicon steel is produced by the steelmaking process. Pig iron tapped from the blast furnace is decarburized and dephosphorized by oxygen and flux such as lime. Next, as the ladle refining—such as the vacuum degassing process—decarburization, deoxidation, and desulphurization are performed; at the same time, ferro-alloys such as Si, Al, and Mn are added to the molten steel to make adjustments for target chemical composition. Then this molten steel is made into a slab through the continuous casting process or cast into the ingot case, and finally hot rolled into strip.

As the chemical composition of molten steel is virtually determined by this steelmaking stage, refining of the molten steel in the converter and ladle

Table 1 An example of chemical composition

(%)

C	Si	Mn	S	Al	O	N
0.002	3.28	0.23	0.0003	0.608	0.0007	0.0014

is particularly important from the compositional point of view.

In regard to the converter operation, new converters such as Q-BOP, LD-KG and K-BOP are utilized to produce molten steel which is extremely low in C, O and N. In Q-BOP, the oxgen is directly blown into the molten steel from the bottom of the converter, and this bottom blowing method is applied to LD-KG and K-BOP. In the ladle refining operation, injection of rare earth and special flux, etc., has greatly improved the effects of desulphurization and floating removal of inclusions consisting of oxides, etc. Through these new facilities and processes, it has now become possible to produce high purity steel low in S, O and N contents and practically free of inclusions and precipitates. As an example, the chemical composition of silicon steel produced by the above described process is shown in **Table 1**.

4 Magnetic Properties

The hot rolled strip of high-purity composition, as described in Chapter 3, is cold rolled and finally annealed. The typical magnetic properties of the finally annealed sheet are shown in **Table 2**. In terms of core loss, the new product surpasses JIS S09 the highest conventional grade.

Kawasaki Steel sets up core loss grades lower than JIS, as shown in **Table 3**. The typical core loss in **Table 2** corresponds with RM7 according to the Kawasaki Steel specification.

The low core loss material like this will bring about energy saving of various electric apparatus.

Table 2 Typical magnetic properties

Grade	Thickness (mm)	Assumed density (g/cm^3)	Core loss (W/kg)		Magnetic induction (T)	
			$W_{10/50}$	$W_{15/50}$	B_{25}	B_{50}
RM7	0.50	7.65	1.03	2.43	1.59	1.68

Table 3 Specifications of RM high grade

Grade	Thickness (mm)	Assumed density (g/cm^3)	Max. core loss at 50 Hz (W/kg)		Min. induction at 5 000A/m (T)	Min. lamination factor (%)
			1.0 T	1.5 T		
RM7	0.50	7.65	1.05	2.50	1.58	95
RM8	0.50	7.65	1.10	2.70	1.58	95
RM9	0.50	7.65	1.15	2.90	1.58	95

5 Conclusion

The refining technique of high-purity steel was put to practical use for the non-oriented silicon steel production. Its effects are summarized below:

(1) The optimum grain size, which minimizes the core loss, is easily obtained by the reduction of impurities like S, O and N.

(2) It was directly observed by SEM that inclusions obstructed the domain wall displacement, and it became clear that core loss decreased with decrease in the number of inclusions.

(3) The (111) pole intensity, which is unfavorable for magnetic properties, becomes stronger with increase in the number of inclusions.

(4) Advance in the melting technology of high-purity steels resulted in extreme reduction of core loss. Then, the non-oriented silicon steel sheet RM7 (maximum core loss $W_{15/50}$; 2.50 W/kg for 0.50 mm thickness) has been developed.