

New Electrical Steel with High Permeability

J.C. Bavay and J. Verdun

This article describes the magnetic properties of a low-silicon-bearing nonoriented electrical steel, recently developed by UGINE S.A. as a core material for rotating machines. The new product is characterized by a high level of permeability related to a partial ideal texture {100}⟨0vw⟩. Typical properties are core losses of less than 5 W/kg at 1.5 T and 50 Hz and a magnetic polarization level greater than 1.78 T at 5000 A/m for a sheet thickness of 0.50 mm. The effects of sheet thickness and working induction on core loss at different frequencies are examined.

Keywords
high permeability, low-silicon, nonoriented electrical steel

1. Introduction

SPECIFICATIONS of electrical sheet steels are mainly expressed in terms of core loss values. The highest grades of nonoriented electrical steels with iron losses of less than 2.5 W/kg at 1.5 T magnetic flux and 50 Hz frequency for a 0.50-mm thickness are cleanly refined 3% silicon steels.[1] Core loss can be roughly divided into eddy current loss and hysteresis loss. The higher the silicon content, the higher the resistivity and the lower the crystalline anisotropy constant $K1$. Eddy current loss, which is inversely proportional to electrical resistivity, decreases with increasing silicon content. Hysteresis loss is roughly proportional to domain wall energy, which is proportional to $(K1)^{1/2}$. Therefore, hysteresis loss decreases with increasing silicon content. The effect of aluminum content is quite similar to that of silicon content. The higher the loss improvement, which results in the highest grades of nonoriented steels, the higher the amount of silicon and aluminum additions needed.

Silicon and aluminum additions to reduce iron loss of nonoriented electrical steel, however, deteriorate its permeability at high induction levels. In effect, increasing silicon and aluminum contents decrease the saturation magnetization of the steel sheet. Consequently, the working induction level that can be used in rotating machines tends to decrease. As a result, the volumetric power of the machine also decreases.

Electrical equipment manufacturers use core materials with the highest induction level, their choice being generally determined by the growth of losses when increasing the working induction. The peak value of the working induction greatly depends on the type of rotating machine. Local induction may reach a saturation level in certain places such as the stator teeth bases.

To improve the efficiency of a motor, it is necessary to reduce both iron and copper losses. Using nonoriented electrical steel with higher silicon content does not always result in higher motor efficiency.[2] This is because the copper loss of a motor is increased when steel sheet with high silicon content, which has a poor permeability at high induction, is used. Copper losses in the motor are generated in the stator and the rotor windings. Permeability of the core material is related to copper losses through magnetizing current, which is reciprocally proportional to the permeability. The copper loss due to exciting current is proportional to the square of the reciprocal of permeability.[3] For small- and medium-sized motors, high permeability is needed, and the proportion of copper loss is large. For large-capacity motors, however, although permeability of the material affects the copper loss, the magnitude of the effect is minimal because the ratio of copper loss due to exciting current to the total copper loss decreases. Large rotating machines are difficult to cool, and importance is placed on iron loss rather than permeability. Therefore, high-grade nonoriented silicon steel sheet is used.

Very low core loss at high magnetic induction and very high permeability are generally considered contradictory properties of nonoriented electrical steels. The new low-silicon steel that recently has been developed by UGINE S.A. exhibits both excellent permeability and low core loss. Improved magnetic properties are realized through control of chemistry and mill processing.

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2. Chemical Composition

Table 1 shows the base composition of the new electrical steel with low carbon, sulfur, and nitrogen contents. Phosphorus can be added to improve mechanical strength, punchability, and electrical resistivity.

Table 1 Chemical composition of the new material

Composition, wt%							
C	S	N	Si	Mn	P	Al	Fe
<0.003	<0.010	<0.010	<0.50	<0.50	<0.20	<0.05	bal

Table 2 Typical magnetic properties of the 0.5-mm thick new electrical steel

Direction	Core loss, W/kg *Wt* 1/50	Core loss, W/kg *Wt* 1.5/50	Induction, T *B*2500	Induction, T *B*5000	Induction, T *B*10000	Permeability, 1.5 T
L	2.11	4.68	1.744	1.825	1.937	2283
C	2.27	4.97	1.671	1.754	1.873	2127
L + C	2.17	4.82	1.706	1.789	1.903	2151

This low-carbon and nitrogen steel with low silicon and some manganese and phosphorus allows one to obtain a very high permeability via a special fabrication process while keeping the fabrication cost relatively low compared with top-grade high-purity high-aluminum and silicon nonoriented sheet.

3. Magnetic Properties

Typical magnetic properties of the newly developed electrical steel are shown in Table 2. Tests were conducted using the 25-cm Epstein frame in accordance with a standard mode of operation. As the typical parameters of magnetic properties, the magnetic inductions $B2500$, $B5000$, and $B10000$ (inductions at 2500, 5000, and 10000 A/m, respectively) and the total core losses $Wt1/50$ and $Wt1.5/50$ (core loss at 1 or 1.5 T, 50 Hz) were used. The magnetic properties of the stress relieved annealed sheet with 0.5-mm thickness were measured in the two directions of 0° and 90° from the rolling direction. The L samples were cut parallel to the rolling direction. C samples were taken in the transverse direction. The notation "L + C" means samples with half cut in the L direction and the rest cut in the C direction. The assumed density is 7.85 g/cm^3.

The designation "nonoriented" for an electrical sheet should not be considered as representative of a complete isotropy of magnetic properties. A relative gap between the longitudinal and transverse directions usually is observed. Hot rolling, cold rolling, and annealing produce a more or less marked texture.

4. Effect of Texture

It is well known that steel has a body-centered structure. 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 random cube texture, in which the {100} plane is parallel to the sheet surface, is ideal because it includes the greatest number (two) of ⟨001⟩ axes of easy magnetization in the sheet plane. The texture with the {111} plane, which has no ⟨001⟩ axes of easy magnetization, and the texture with the {112} plane, which has the ⟨111⟩ axes of hard magnetization, are undesirable.

The new product with low core loss and very high permeability has been developed via precise control of processing. The optimized process produces the formation of grains with the {100} ⟨0vw⟩ orientation and a significant decrease in the grains with the {111} orientation among the matrix having a random texture, thereby improving magnetic properties. The favorable effect of this desirable texture influences both permeability and iron loss of the fully processed new electrical steel.

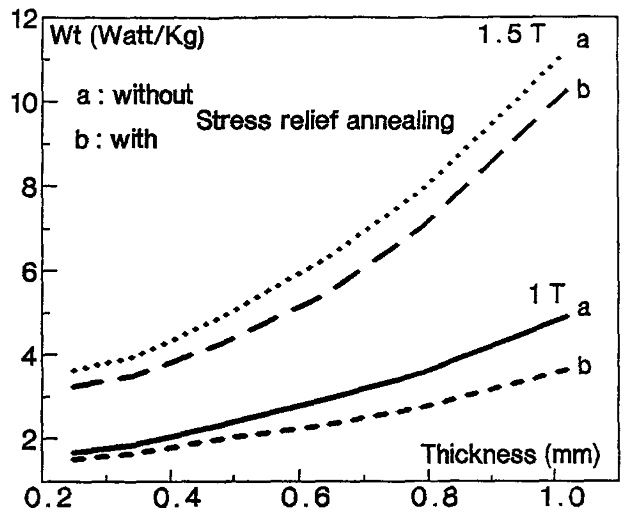

Fig. 1 Effect of sheet thickness t on total loss of the new electrical steel for $f = 50$ Hz. Dimensions of L + C Epstein samples: 160 × 20 mm. (a) Before stress relief annealing. (b) After stress relief annealing (730 °C, 3 h, $N_2 + 5\%\ H_2$).

5. Effect of Sheet Thickness

The total loss (Wt) can be written as the sum of hysteresis loss (Wh) and eddy current loss (We):

$$Wt = Wh + We$$

The classical eddy current loss We,c can be calculated with the assumption of a homogeneous polarization from Maxwell's law:

$$We,c = (\pi \cdot B \cdot f\,t)^2 / 6 \cdot d \cdot \rho \quad [1]$$

where B is the magnetic flux density; t the sheet thickness; f the frequency; d the density; and ρ the resistivity. The existence of magnetic domains and the dynamic behavior of the domain walls lead to a substantially higher eddy current loss than a classical one. The increase in eddy current loss usually is considered through the anomalous loss factor η:

$$We = We,c \times \eta \quad [2]$$

which depends on grain size, texture, and frequency.

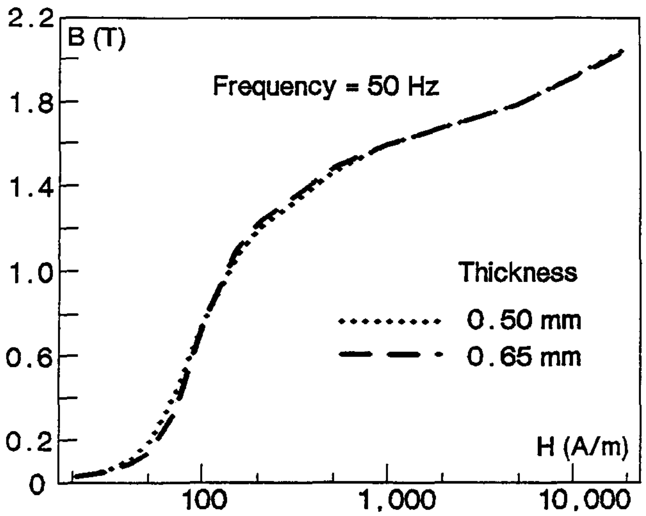

Fig. 2 (*B,H*) characteristics of the new electrical steel for sheet thickness of 0.50 and 0.65 mm.

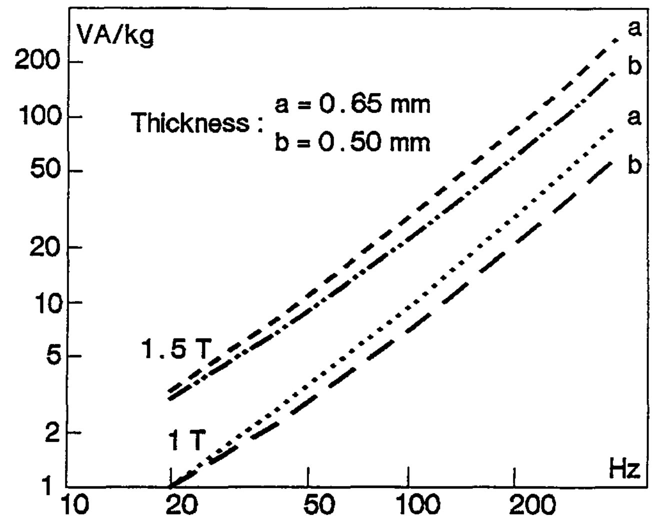

Fig. 4 Apparent power at 1 and 1.5 T versus frequency of the new electrical steel.

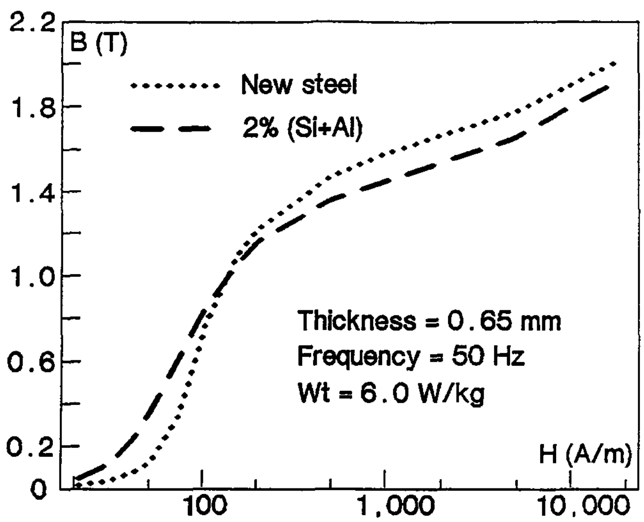

Fig. 3 (*B,H*) characteristics at 50 Hz of the low-silicon new electrical steel (a) and of a 2% (Si + Al) grade (b). (*Wt* = 6.0 W/kg at 1.5 T and 50 Hz for 0.65-mm thick materials.)

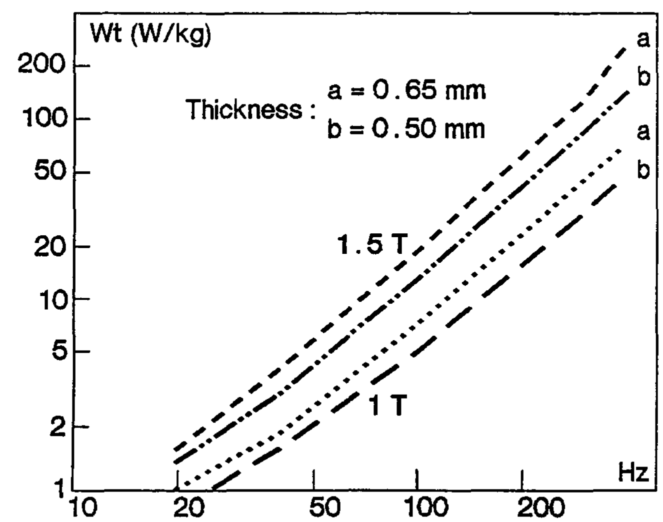

Fig. 5 Total loss at 1 and 1.5 T versus frequency of the new electrical steel.

Eq 1 shows that the sheet thickness t is one of the most important factors influencing the magnetic properties. Therefore, a decrease in the sheet thickness results in a lower eddy current loss and, consequently, in a lower total loss. Figure 1 shows the total loss Wt as a function of sheet thickness. For each final thickness, the induction B at 5000 A/m remains superior to 1.78 T. Figure 2 shows no significant effect of sheet thickness on the $B = f(H)$ curve at 50 Hz. The thickness of 0.65 mm is frequently used.

The magnetizing curves at a frequency of 50 Hz of the new electrical steel containing low silicon and a highly alloyed grade containing 2% (silicon + aluminum) of the same thickness may be compared (Fig. 3). The higher permeability at high field strength of the new electrical steel with low silicon is due to the higher saturation magnetization.

6. Effect of Frequency

The frequency dependence of total power loss and apparent power at 1 and 1.5 T is shown for frequencies up to 400 Hz for 0.50- and 0.65-mm sheet thickness (Fig. 4 and 5). In Fig. 6, the relationships between the hysteresis loss and the eddy current loss (in percentage of total loss) versus frequency are shown. The eddy current loss clearly predominates above 60 Hz for sheet thicknesses of 0.50 mm (40 Hz in the case of 0.65 mm thickness). A decrease in the sheet thickness results in a lower eddy current loss (in percentage of total loss), but simultaneously the hysteresis loss (in percentage of total loss) is increased and thus confirms the above indicated thickness dependence of the eddy current loss. The eddy current loss increases more than the hysteresis loss when increasing the fre-

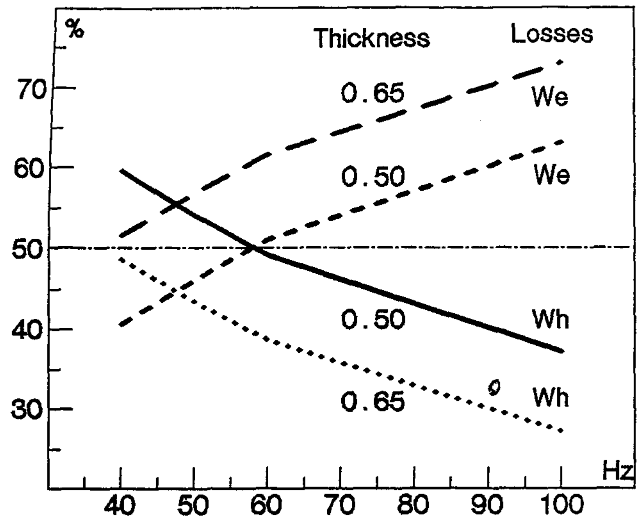

Fig. 6 Hysteresis and eddy current losses (in percentage of total loss) versus frequency of the new electrical steel (1.5 T).

quency according to the quadratic frequency dependence of the eddy current loss and the linear variation of the hysteresis loss with frequency.

7. Conclusion

To solve the problem of reducing electric energy loss, high-grade nonoriented silicon steel sheet can be used for large-capacity motors when importance is placed on iron loss rather than permeability. For small-capacity motors, more importance is attached to permeability, and low-cost, low-grade non-silicon-containing electrical sheet steels are used for economical reasons. A new nonoriented electrical steel containing low silicon has been developed with high permeability due to the presence of a favorable texture component {100} ⟨0vw⟩ and the control at a very low level of the undesirable planes {111}. This new material will attract attention for its advantages in the manufacturing of small-sized motors with high efficiency.

References

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