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Angular dependence of magnetic properties of 2% silicon electrical steel

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Abstract

In this work, we studied the anisotropy of the magnetic properties of a 2% silicon steel. Permeability, core losses, remanence and coercivity were analyzed in Epstein strips cut at 0°, 15°, 30°, 45°, 60°, 75° and 90° from the rolling direction. Coercive force monotonically increased from 0° to 90°, accompanied with a remanence decrease. On the other hand, a minimum in B_{50} and B_{25} was observed between 45º and 60º. This behavior can be explained by the steel sheet crystallographic texture, that shows a strong (1 1 0) [0 0 1] component, which develops the best properties in rolling direction (0 0 1) and is worse at 54°, where ⟨1 1 1⟩ lies. Losses behavior is more complex.

Keywords: Electrical steel; Anisotropy; Magnetic loss; Permeability

Electrical steels are mainly applied as magnetic cores of electrical machines, such as transformers and motors, in which they are used to amplify the magnetic flux. Particularly in motors, higher magnetic flux implies in higher torque and higher efficiency. In this case, the magnetic flux flows in all in-plane directions inside the material and isotropy of the magnetic properties would be desirable. The commercial non-oriented steels partially satisfy this demand. However, the production of these materials evolves with many rolling and recrystallization steps, which cause anisotropy. Typically, lower core losses and higher permeability are obtained parallel to the rolling direction [1]. In this work, we studied the angular dependence of the magnetic properties of a fully processed non-oriented electrical steel with 2% Si and relate them to the crystallographic texture of the material. This material is the most used electrical steel in motors.

The studied steel presented a thickness of 0.48 mm, resistivity of 0.38 μΩ m and grain size of 60 μm. Epstein strips were cut at 0°, 15°, 30°, 45°, 60°, 75° and 90° from the rolling direction. No stress relief was applied after cutting. Magnetic characterization was performed at 60 Hz and in the quasi-static regime at a frequency of 5 mHz. Magnetization and hysteresis curves were measured. Orientation distribution functions (ODF) were determined from X-ray pole figures obtained with a Philips X' Pert MPD with a ATC-3 goniometer.

Fig. 1 shows the magnetic induction at applied field values of 2500 A/m (B_{25}) and 5000 A/m (B_{50}), as a function of the angle to the rolling direction. These magnetic fields are sufficiently high so that most of magnetization process is rotation controlled. Rotation processes are directly related to the crystallographic orientation and B_{25} or B_{50} can be used as parameters to evaluate the texture of the material. Fig. 1 shows a minimum between 45° and 60° indicating a texture more unfavorable to magnetization at this direction than parallel and perpendicular to rolling.

Texture data are presented in Fig. 2, which represents an ODF at sections $\varphi_2 = 45°$ and $\varphi_2 = 0°$. A high-intensity Goss texture component (1 1 0) [0 0 1] is observed, together with a {1 1 1} ⟨uvw⟩ fiber. These are typical recrystallization texture components in steels.

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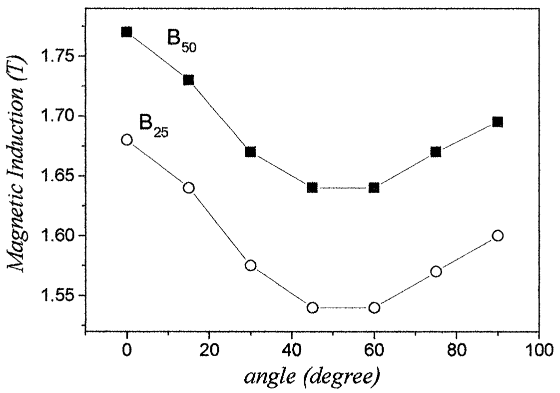

Fig. 1. B_{25} and B_{50} as a function of the angle to the rolling direction.

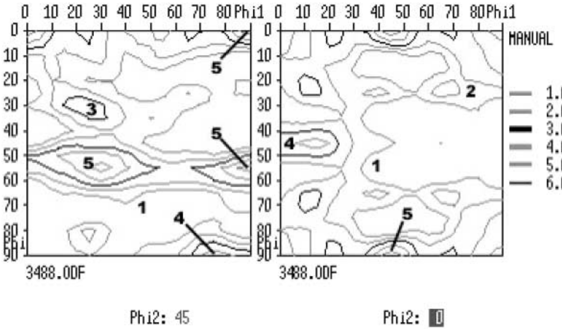

Fig. 2. ODF at sections $\varphi_2 = 45°$ $\varphi_2 = 0°$ (Bunge notation).

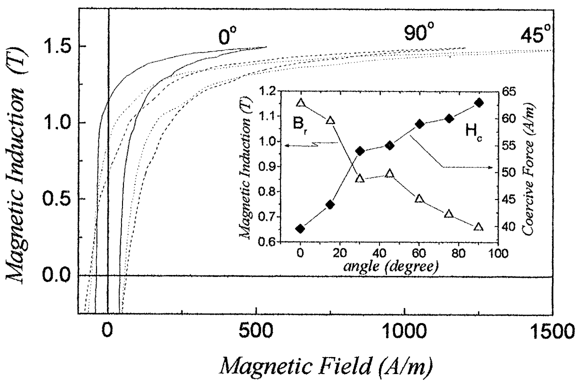

Fig. 3. Hysteresis curves at 0°, 45° and 90° to the rolling direction. Inset: Coercive force and remanence as a function of the angle to the rolling direction.

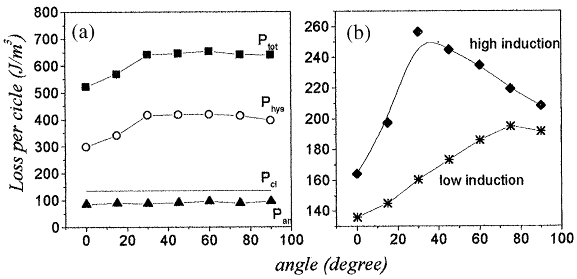

Fig. 4. (a) Hysteresis, classic and anomalous components of the total loss per cycle at 60 Hz as a function of the angle to the rolling direction and (b) high and low component of the hysteresis loss.

The B_{50} behavior on Fig. 1 can be related to the presence of the Goss component. At this orientation, the [0 0 1] easy axis coincides with the rolling direction allowing high B_{50} values. For Goss orientation, [1 1 0] lies at 90° to the rolling direction and [1 1 1] at 54°. Accordingly, the lowest B_{50} value lies between 45° and 60°.

Hysteresis curves for all the samples were measured with a maximum induction of 1.5 T (Fig. 3) and losses were determined as the internal area of these curves. Peak values of the applied field to trace these hysteresis curves are higher for 45° and 60°, indicating the crystallographic texture effects. Coercive force and remanence seemed to be less sensitive to texture as other processes instead of rotation predominate for low magnetic fields. Coercive force continuously increased as the angle varied from 0 to 90°, accompanied by the remanence decrease (Fig. 3-inset). Similar behavior is also observed in grain oriented electrical steels. Fig. 4a shows total losses determined at 1.5 T and 60 Hz and hysteresis, classic and anomalous components. Total losses rapidly increased from 520 J/m^3 to 640 J/m^3 as the angle is varied from 0 to 30° and slightly decreased to 75° and 90° (Fig. 4a). The same behavior was observed for the hysteresis losses, indicating that most part of anisotropy of total losses comes from quasi-static component. Anomalous losses remained almost constant as the angle is varied from 0° to 90°. This behavior is in contrast to that pointed by Bertotti [2] in which anomalous (excess) component should be proportional to the hysteresis loss.

Hysteresis losses were separated into high and low induction components, as previously proposed by the authors [3]. This analysis method is based on the fact that different magnetization/demagnetization processes must predominate at induction values higher and lower than that of the maximum permeability of the quasi-static hysteresis curve. Fig. 4b shows that the low induction component increases with angle, an effect of the coercive force increase observed in the inset of Fig. 3. On the other hand, the high induction component presents a maximum at 30° and then decreases. This effect may be related to the remanence decrease that reduces the high induction component more than texture effects increase loss between 45° and 60°.

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