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Modelling the angular dependence of magnetic properties of a fully processed non-oriented electrical steel

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Abstract

Two different ways to approach the anisotropy of magnetic losses are compared, one of them based on texture and particles distribution and the other on a graphical subdivision of the hysteresis loss in two components. We have found an excellent quantitative correlation between the anisotropy of the ''particles'' and ''low-induction'' components, and a good qualitative correlation between the anisotropy of ''texture'' and the ''high-induction'' components.

Keywords: Electrical steel; Anisotropy—magnetic; Magnetic loss; Energy dissipation

The anisotropy of magnetic properties of steel sheets for electromagnetic purposes is well known in literature [1–3]. Despite their name, the non-oriented steels have relatively strong texture components and that is the most obvious source of anisotropy.

Authors have shown that the magnetic properties of commercial electrical steels cut in different angles with respect to the rolling direction follow a behaviour that can be associated to the presence of a Goss component among the overall texture [3]. Although the induction B50 angular behavior confirmed its good relation to the crystallographic texture, showing the worst properties at 45–60°, magnetic loss showed a weaker dependence. Previous results on 2%Si fully processed steel [4] showed that the coercive force increased monotonically with the angle, suggesting that other variables besides texture are also affecting it. Furthermore, applying a graphical subdivision technique on the hysteresis curve (4), it was clear that the ''high-induction component'' followed the texture behaviour, while the ''low-induction component'' increased monotonically with the angle from the rolling direction. Independently addressing similar angular behaviour in industrial practice, Cunha [5] proposed to consider another source of anisotropy, the distance between inclusions. Having shown that this distance increases monotonically with the angle, his model assumes that the angular dependence of the total magnetic losses is a function of two factors, one directly associated to magnetocrystalline anisotropy energy (E_A), [6] and the other related to the variation of distance between inclusions.

To compare results of both approaches, Epstein strips of Fe–3.25%Si of thickness 0.5 mm were cut in different directions, from 0° to 90° (10° step), with respect to rolling direction. The samples were annealed for 1 h at 700°C under argon for stress relief before measurements. Total magnetic loss measurements were made at 60 Hz and 1.5 T in a standard Epstein frame. The induction at 5000 A/m (B50) and quasi-static hysteresis loss were also measured.

The texture/inclusion distance model is based on a fitting that takes into account the anisotropy energy E_A of the sample, depending on the material texture and the applied field angle. The material texture is determined by means of electron backscattering diffraction (EBSD) identification of the orientation of at least 600 grains. The average anisotropy energy due to magnetic field applied in a specific direction is calculated taking into

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account the anisotropy energy value for each grain orientation identified by means of EBSD. On the other hand, the variation of distance between inclusions is based on previous experimental results [5] where it was observed that the distances on the rolling direction are 1.2 times larger than on the transversal direction. The equation describing the variation of d_θ, the distance between inclusions as a function of angle (θ) with respect to the rolling direction, is given by

$$d_\theta = d_{90} f_\theta = d_{90} \frac{a}{\sqrt{\cos^2\theta + a^2 \sin^2\theta}}, \quad (1)$$

where $a = d_0/d_{90}$.

Measuring the space distribution of inclusion distances, Cunha found that $a = 1.2$ is a good value for these materials and processing [5]. Assuming that losses vary with the inverse of the distance between inclusions (d_θ) (as coercive force varies with the inverse of grain size [7]), the total magnetic losses (W_{total}) may be written as

$$W_{\text{total}} = A + B/f_\theta + CE_{A\theta}. \quad (2)$$

The values of A, B and C can be obtained by linear regression from total magnetic losses data determined for each sample's cut direction (W_{total}), which is associated with the specific values of factor f_θ and anisotropy energy $E_{A\theta}$.

The hysteresis loss subdivision method is based on different principles. Its starting point is that total magnetic losses can be divided into hysteresis, eddy and anomalous components. It is experimentally observed that anisotropy of the total losses is strongly concentrated (more than 90%) on hysteresis losses. The hysteresis loop is divided into two regions limited by the value of induction at maximum permeability ($\mu_{\max}$). It is supposed that there are different energy dissipation mechanisms acting on these two different regions of hysteresis loop: in the low-induction region (below $\mu_{\max}$), it is well accepted that domain wall motion is the major source of loss, but in high-induction region (above $\mu_{\max}$) the main energy dissipation mechanism is not clear, whether irreversible domain rotation, domain annihilation and nucleation or simply more domain wall movement.

Fig. 1 shows the angular variation of total losses and its hysteresis, eddy and anomalous components. Fig. 2 compares the anisotropy of the two components of the texture/inclusion model (W_{f_θ} and W_{E_A}) with the anisotropy of the high induction and the low induction of the graphical subdivision of hysteresis loss calculated for 60 Hz (W_{HI} and W_{LI}). Just to understand the logic, note that Fig. 1 shows the experimental result that hysteresis loss at 90° is 0.47 W/kg higher than hysteresis loss at RD (which means 30% higher). Fig. 2 shows that, applying the graphical subdivision of the hysteresis loop, the low-induction component of hysteresis loss at 90° is 0.21 W/kg higher than at RD, while high-induction component is 0.26 W/kg higher than at RD, summing up 0.47 W/kg. Detailed information on the calculations is given in [8]. The most striking features of Fig. 2 are the quantitative correlation between the angular dependence of the inclusion distribution component (W_{f_θ}) and of the low-induction component (W_{LI}) and the general behaviour of the other two components. The fitting of latter is not perfect because, as shown in Fig. 1, the anomalous loss component also showed some anisotropy.

Concluding, the anisotropy of total losses originates mostly from the anisotropy of hysteresis loss, but there

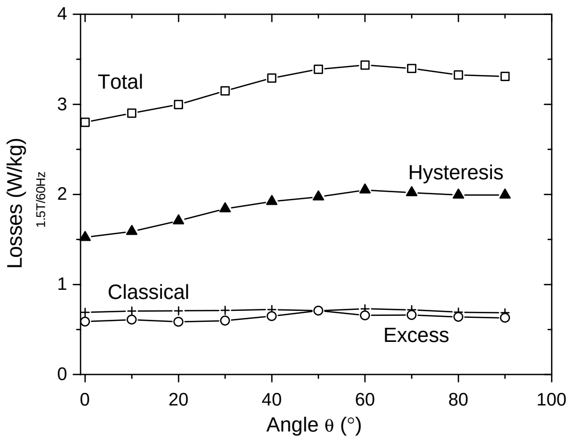

Fig. 1. Angular variation of total loss and its hysteresis, eddy and anomalous loss components of a 3.2%Si steel, measured at 1.5 T, 60 Hz.

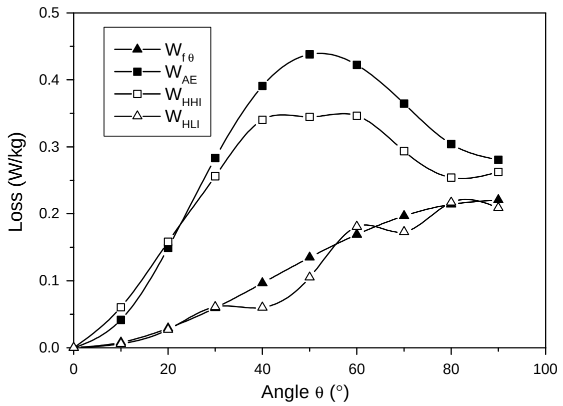

Fig. 2. Angular behaviour of the anisotropic part of the inclusion (W_{f_θ}) and texture (W_{E_A}) component of the total losses, as determined by the inclusion/texture model, compared to the high-induction (W_{HHI}) and low-induction (W_{HLI}) components of the hysteresis loss, as determined by the graphical separation of hysteresis loss.

is a contribution of the anomalous loss. The anisotropy is not only due to texture but also due to other effects. The angular behaviour of low-induction component of the hysteresis loss fits very well with the $1/f_0$ dependence of the inclusion component, while the high-induction fraction showed a good relation to the texture component.

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References

[1] M. Shiozaki, Y. Kurosaki, Texture Microstruct. 11 (1989) 159.
[2] G. Bertotti, G. Ban, G. Abbruzzese, J. Appl. Phys. 73 (1993) 6612.
[3] A. Honda, I. Ohyama, Y. Mine, J. Mater. Eng. 12 (1990) 41.
[4] M. Emura, M.F. de Campos, F.J.G. Landgraf, J.C. Teixeira, J. Magn. Magn. Mater. 226–230 (2001) 1524.
[5] M.A. Cunha, P.C. Luna, Acta Microsc. 8 (Suppl. A) (1999) 289.
[6] W.B. Hutchinson, J.G. Swift, Texture 1 (1982) 117.
[7] E. Adler, H. Pfeiffer, IEEE Trans. Magn. 10 (1974) 172.
[8] F.J.G. Landgraf, T. Yonamine, M. Emura, M.A. Cunha, Proc. 56 Congresso Anual ABM, CD-ROM (2001) 1612–1620.