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Magnetostriction in non-oriented electrical steels

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Abstract

The magnetostriction in non-oriented electrical steels $FeSi_{3.2\%}$ E110 grade samples produced by ACESITA as a function of the magnetic induction for several angles between the applied field and the rolling direction is investigated. The results are discussed in terms of the domain wall motion, magnetization rotation, nucleation and annihilation of domains and evolution of the complex magnetic domain structure present in these steels.

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In contrast with the case of grain-oriented (GO) electrical steels, the magnetization process of non-oriented (NO) electrical steels is much less known. NO electrical steels are commonly used in applications that demand isotropy of magnetic properties along the plane of the sheet such as transformers and rotating electrical machines in home appliances. Recently, one of the authors [1] has suggested that the magnetic losses in these materials could be separated in two components: low induction losses, associated to the magnetization processes in $B < B(\mu_{max})$, usually related to domain wall (DW) motion, and high induction losses, $B > B(\mu_{max})$, usually associated to magnetization rotation. However, experimental results show that the high induction loss component represents approximately 50% of total losses in NO electrical steels, a result that is not consistent with the usual assumption of magnetization processes dominated by magnetization rotation. Therefore, the study of the magnetization process in NO steels is important not only to solve the question raised by the scheme of loss separation proposed in Ref. [1], but also to provide a further insight in these steel magnetization processes and to help NO producers to get a decrease in the magnetic losses by making appropriate changes in the fabrication process.

Magnetostriction λ corresponds to the dimensional variation of a sample under different induction levels. Details of the $\lambda(B)$ curve can be associated with peculiar changes of the domain structure [2]. In particular, 180° DW motion does not produce any dimensional change. The reverse is true for domain nucleation, 90° DW motion and magnetization rotation [2]. In general, the analysis of the magnetostriction curve starts from the λ value corresponding to that inside a domain:

$$\frac{\Delta l}{l} = \left(\frac{3}{2}\right)\lambda_{100}\left(\alpha_1^2\beta_1^2 + \alpha_2^2\beta_2^2 + \alpha_3^2\beta_3^2 - \frac{1}{3}\right) + 3\lambda_{111}(\alpha_1\alpha_2\beta_1\beta_2 + \alpha_1\alpha_3\beta_1\beta_3 + \alpha_2\alpha_3\beta_2\beta_3), \quad (1)$$

where the α_i and β_i are the direction cosines of the magnetization and strain measurement direction with respect to the cube axis, respectively; λ_{100} is the saturation magnetostriction (λ_S) in the [1 0 0] direction and λ_{111} is the λ_S in the [1 1 1] direction [3]. In the case of NO steels, the measured λ corresponds to an average of 1 over the contributions of many domains of different grains.

The aim of the present work is to study the static $\lambda(B)$ curves as a function of the angle θ between the applied magnetic field H and the rolling direction (RD) in the range

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0–90° in NO steels E110 grade samples produced by ACESITA in order to understand the magnetization process and magnetic losses when H is applied in different directions than the RD.

The samples were cut by photocorrosion with the principal axis oriented at angles θ from 0° to 90° (step 10°) with respect to the RD, defined during the fabrication process, as shown in Fig. 1, with dimensions $30 \times 3 \times 0.5\,mm^3$. Texture measurements established that this steel shows a component (1 1 0)[0 0 1] texture in the RD, while the saturation induction, $B_m \sim 1.5\,T$.

Longitudinal and transverse $\lambda(B)$ curves were measured using strain gauge extensometers produced by Excel Sensores Ind. Com. e Exportação Ltda., with resistance of 350 Ω and gauge factor 2.1. The relevant sample directions are shown in Fig. 1a and b. The voltage signal proportional to the change of resistance of the strain gauge and strain was measured using a Wheatstone bridge connected to an amplifier lock-in Stanford model SR830. The same lock-in controls the magnetic field provided by GMW model 5403 electromagnet ($H_{max} = \pm 2\,kOe$), measured by a Hall sensor. The magnetic field was applied along the principal axis of the sample.

The induction and Barkhausen noise measurements, not shown here, were performed using a fluxmeter. In order to quantify the Barkhausen activity, the root-mean-square (RMS) voltage of the time series as a function of the induction was obtained. The RMS value can be related to DW motion, domain nucleation, growth and annihilation [4].

It is important to keep in mind that these samples show a component (1 1 0)[0 0 1] texture in the RD to discuss the results. In NO electrical steels, in contrast with GO steels, a differentiation between main and supplementary domains is not possible because the fraction of supplementary structure is large. Consequently, the domain structure is very complex. For samples cut at an angle θ, the fractions of the domains and the magnetic behavior change, depending on θ. Fig. 2 shows the longitudinal λ as a function of the induction. The curves correspond to half cycle of the hysteresis loop. Measurements in the other half cycle are similar. The reference value to zero λ was taken at −1.5 T. Starting from B_m, the magnetization process is initially due to rotation of the magnetization that can be observed through the increase of the λ value. The sample emerges through magnetization rotation from the saturation to a state where the magnetization vectors are parallel with axes [1 0 0], [0 1 0] and [0 0 1] of the crystals. At approximately −1.2 T, the maximum λ value corresponds to the magnetic state that the magnetization is oriented along these easy directions. Between approximately −1.2 and −1 T, the λ value decreases significantly and it can be associated with 90° DW motion. At this B level, this wall movement is a consequence of the nucleation and growth of new domains and this is connected to the first peak in the RMS value [4]. From B approximately equal to −1 T until 0 T, as the λ does not change significantly, magnetization process proceeds by 180° DW motion. For B 0–1.2 T, there is the rearrangement of the domain structure through the 180° and 90° DW motion. At approximately 1 T, this DW motion can be related to the annihilation of domains as an impression of the second peak in the RMS value [4]. At 1.2 T, λ reaches the second peak and the domains have the magnetization oriented along the axes [1 0 0], [0 1 0] and [0 0 1] of the crystals. At higher B levels, the λ decreases and the few changes in magnetization occur due to the magnetization rotation.

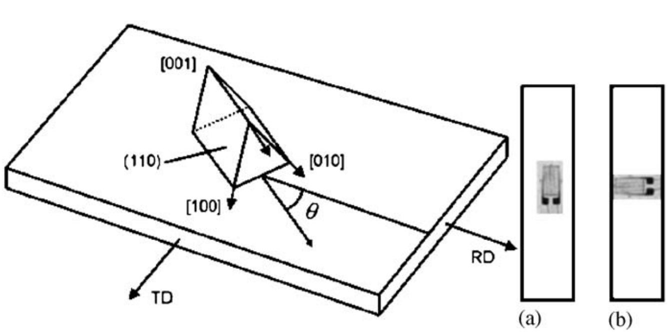

Fig. 1. Sample dimensions and the intermediary directions with respect to the RD and (a) longitudinal and (b) transverse strain gauge configuration.

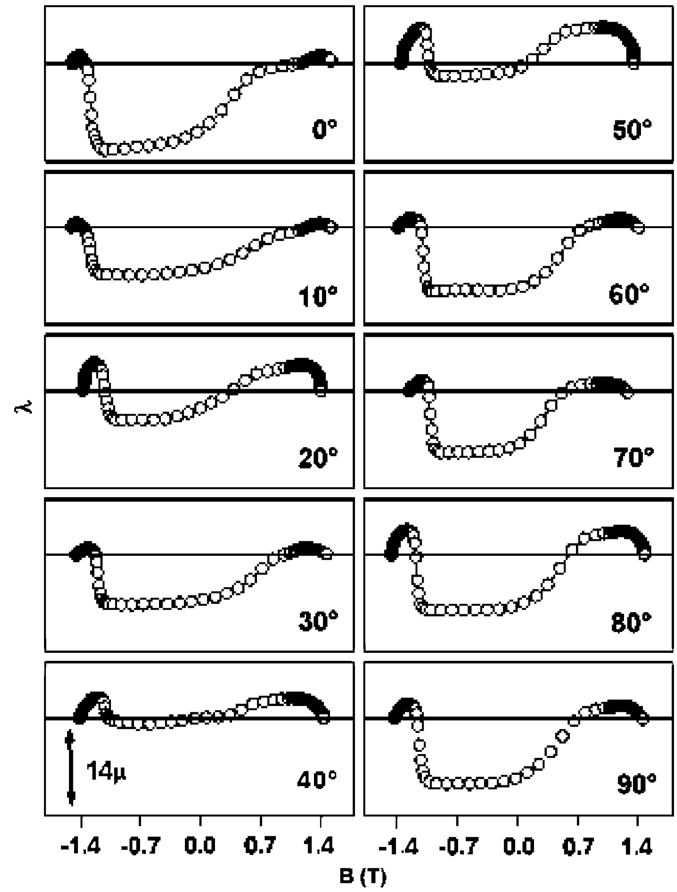

Fig. 2. Longitudinal $\lambda(B)$ curves for angle between 0° and 90° (step 10°).

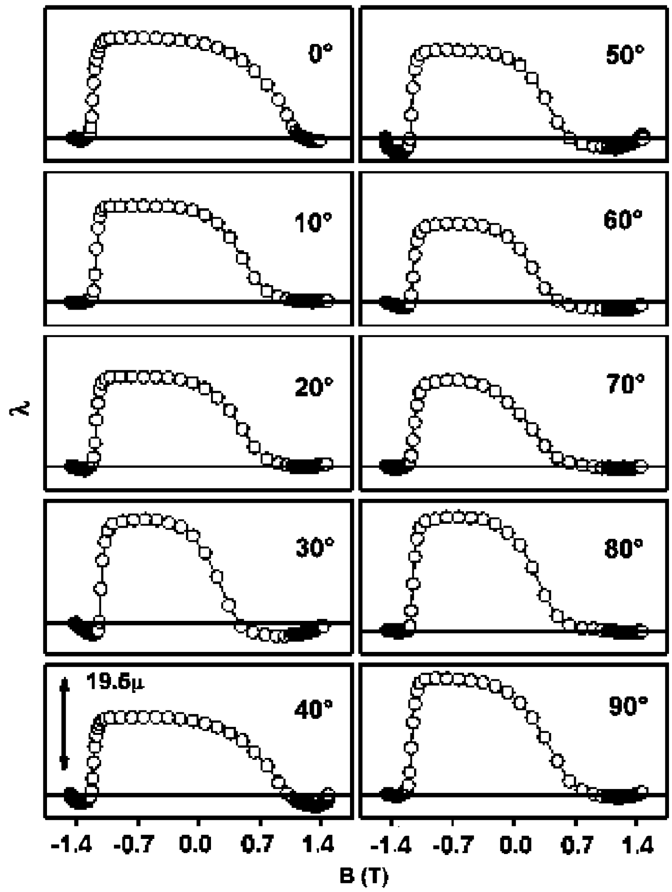

Fig. 3. Transverse $\lambda(B)$ curves for the same angles of Fig. 2.

It can be seen that $\lambda(B)$ have similar forms but different amplitudes. This feature reflects the fact that the magnetization mechanisms depend on the angle θ. In the literature two ranges of angles are, in general, considered [5]. For $0^\circ < \theta < 55^\circ$, the [0 0 1] axis is favored. Starting at B_m, the magnetization process is initially due to domain nucleation and the subsequent 90° DW motion. The contraction of the material is connected to the nucleation of transverse domains. At lower induction levels, the structure evolves by 180° DW motion until the reversion of the field, after what the nucleation of magnetic domains occurs and the 90° DW motion is again present [4]. For $55^\circ < \theta < 90^\circ$, the [1 0 0] and [0 1 0] axes are favored and the λ increases. There are small differences from sample to sample depending on θ. As in GO steels, the nucleation, annihilation and DW motion in NO electrical steels can be related to significant changes of the supplementary domain in order to close the magnetic flux in the sample.

Fig. 3 shows the transverse $\lambda(B)$ curves. It can be seen that the changes on the value happen at the same B point as that in longitudinal λ, but the longitudinal and transverse changes in the sample dimensions are opposite.

In summary, the measured $\lambda(B)$ curves in NO electrical steels indicate that a reasonable part of the magnetic losses at high induction levels can be associated to the irreversible motion of 90° DWs and also to irreversible magnetization rotation, as well as to nucleation and annihilation of domain structures during the magnetization process [4,5].

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