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The effect of easy axis misorientation on the low induction hysteresis properties of non-oriented electrical steels

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ABSTRACT

The coercivity and hysteresis losses of non-oriented electrical steels (NOES) are determined by metallurgical parameters evolved during their manufacturing process. Although the links between grain size, inclusion content, orientation and these magnetic properties are well established, the effects of misorientation, especially with respect to the magnetic easy axis, are mostly unexplored. From this work examining NOES samples with "typical" grain size and inclusion distributions, but with texture variations induced by lab processing, the major factors determining the coercivity and hysteresis losses were limited to the magnetocrystalline anisotropy energy (E_a) and *EAM*, a newly created easy axis misorientation parameter. It is believed that E_a is a measure of the contribution of domain rotation processes, while *EAM* is a representation of the ability of the sample to nucleate reverse magnetic domains. The utilization of *EAM* allows for a better understanding of the influence of metallurgical parameters on the magnetic properties, especially for samples with large differences in processing and texture.

1. Introduction

Non-oriented electrical steels (NOES), with major alloying elements of silicon (~1–4 wt%) and aluminum (~0.5 wt%), are a key magnetic flux carrying material used in electric/hybrid vehicle motor cores. Due to the rotating magnetic fields in these cores, NOES is ideally intended to have isotropic magnetic properties in the plane of the sheet. However, due to its complex manufacturing process, this material has magnetic properties that vary in each direction due to variations in texture [1–8].

The reason for this strong influence of texture on the magnetic properties is the concept of magnetocrystalline anisotropy energy (E_a), as described in Eq. (1), where K_1 and K_2 are cubic anisotropy constants, and the α_i terms represent direction cosines of the magnetization vector with respect to the three crystal axes [9].

$$E_a = K_1(\alpha_1^2\alpha_2^2 + \alpha_2^2\alpha_3^2 + \alpha_3^2\alpha_1^2) + K_2(\alpha_1^2\alpha_2^2\alpha_3^2) + \cdots \tag{1}$$

The practical result of this equation, given the positive value for K_1 for NOES (and the negligible value of K_2), determines that the $\langle 100\rangle$ directions take less energy to magnetize, called the "easy" axes, while the $\langle 111\rangle$ directions take more energy to magnetize; the "hard" axes [9].

As a result, the key desired texture components for magnetic properties are in the cube or θ-fibre, which has two easy axis directions [7]. Similarly, the gamma or γ-fibre ({111}-fibre) is considered to be magnetically undesirable since it contains zero easy axes. These components, as well as other common texture fibres such as α^*, are typically presented in the $\varphi_2=45°$ section of the Orientation Distribution Function (ODF), as displayed in Fig. 1.

One of the magnetic properties that is used to study the magnetization process of NOES is coercivity, which is the *x*-axis intercept on the *B*–*H* magnetization curve, meaning that it is the applied field needed to fully demagnetize the sample. For NOES, it is desired that coercivity be as low as possible, in order to minimize the core loss, which is defined as the energy lost to heat during a complete magnetization cycle. Coercivity is linked to two main mechanisms, namely magnetic domain rotation processes, and domain nucleation and growth processes, which includes domain pinning effects [10,11].

Core loss (P_c), the chief evaluator of NOES quality, can be separated into the three components: classical eddy current loss (P_e), anomalous/excess loss (P_a), and eddy current loss (P_h) according to the equation [12,13]:

$$P_c = P_h + P_e + P_a, \tag{2}$$

which can be expanded to

$$P_c = k_h f B^n + k_e f^2 B^2 + k_a f^{1.5} B^{1.5}. \tag{3}$$

In terms of general material parameters, the hysteresis losses

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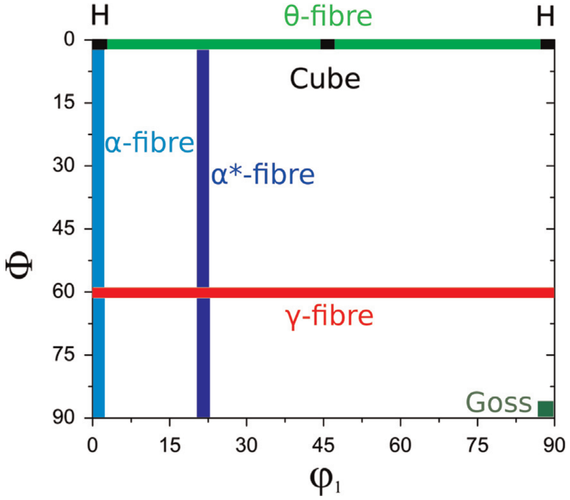

Fig. 1. $\varphi_2 = 45°$ ODF section showing the key NOES textures with respect to magnetic properties. In addition to the labelled fibres, cube indicates the cube component $\{001\}\langle 0\bar{1}0\rangle$, *H* indicates the rotated cube component $\{001\}\langle 1\bar{1}0\rangle$ or $\{001\}\langle \bar{1}\bar{1}0\rangle$, and Goss indicates the Goss component $\{110\}\langle 001\rangle$.

are typically associated with obstacles to domain wall movement such as grain boundaries and inclusions [14], while the eddy current losses are associated with properties such as sample thickness and resistivity [15]. In other words, both the coercivity and hysteresis losses are linked to metallurgical parameters such as grain size, inclusion content, and orientation.

An increasing grain size has been shown to reduce coercivity for grain sizes larger than roughly 10 μm [10,16,17]. Similarly, an increase in inclusion density has been shown to increase the coercivity in 47.5% NiFe [10], as well as NOES [18], with submicron inclusions around the same length scale of the domain walls in the material being particularly detrimental. Similarly, an increasing grain size and decreasing inclusion content has also been shown to reduce hysteresis losses in NOES [19].

Although a significant number of coercivity/hysteresis loss studies have involved barriers to domain wall movement in the form of grain boundaries or inclusions, texture related variable have also been considered. It has been shown that a better texture, characterized by more easy magnetic axes lying in the plane of the sheet, has been associated with decreased coercivity [20]. However, the texture related mechanisms have been shown to be made up of different contributions to domain rotation and domain movement processes, depending on the angle of deviation between the easy axis and the direction of the applied field [18]. With respect to magnetic properties, texture studies are typically compared to parameters such as magnetic flux density (ex. B_{50}) or total losses without loss separation, where more easy axes in the plane of the sheet, especially in the testing direction, have been linked to improved magnetic properties [1–5,8]. In some cases texture has been compared directly to hysteresis losses however, where more easy axes aligned in testing direction led to a reduction in hystersis losses [6,7].

Although orientation/texture has been studied, the effects of bulk misorientation, especially easy axis misorientation, on NOES coercivity/loss has not been previously examined in depth experimentally. The effects of easy axis misorientation are closely related to the magnetic free pole density ω (a term related to the amount of energy associated with stray magnetic fields from the sample) across a grain boundary, which is described by the following equation:

$$\omega = I_s(\cos\theta_1 - \cos\theta_2) \tag{4}$$

The angles θ_1 and θ_2 are the angles between the domain magnetizations (usually in the direction of the closest easy axis to the surface in static conditions) and the normal to the grain boundary (assuming that it lies in the plane of the sheet), and I_s is the material constant for spontaneous magnetization [9].

From theory and modelling, it has been shown that an increased easy axis misorientation (represented as an increased magnetic free pole density across a grain boundary) would increase the amount of reverse domain nucleation, decreasing the coercivity [21,22]. Experimentally, it has recently been demonstrated that an increase in a texture parameter describing easy axis misorientation led to an improvement in local magnetic properties [23]. Consequently, it is believed that easy axis misorientation can be linked to the bulk coercivity and hysteresis losses of NOES as well.

The purpose of this paper is to explore the influence of metallurgical parameters on coercivity and hysteresis losses, with a focus on easy axis misorientation. To facilitate this comparison, different NOES samples were subjected to additional processing in order to create a larger variation in crystallographic orientation and misorientation. It is believed that the utilization of a texture parameter describing the easy axis misorientation will lead to a more accurate understanding and prediction of the bulk magnetic properties of NOES.

2. Experimental methodology

2.1. Sample selection and preparation

Four grades of NOES were chosen for this study, identified as B1, B3, C3, and C4. These steels possessed differences in their metallurgical parameters, such as grain size and composition. In order to create a test sample population with significant variations in texture parameters (with a minimum of residual stress), the samples from each grade were split into two separate processing routes: (1) Samples that were subjected to the standard stress relief anneal (SRA) treatment from the manufacturer, also known as the fully processed condition and (2) Samples in the semi-processed or non-SRA condition (without the SRA treatment) that were subjected to additional cold rolling and annealing processes in the laboratory (CRA or cold rolled annealed samples).

For typically manufactured NOES, the final stage is a 2–5% cold roll, producing samples in the non-SRA condition. To create SRA samples, the NOES is annealed at approximately ~800–840 °C for 2 h. In this study, these SRA samples were studied in both the rolling direction (RD, "L" samples) and the transverse direction (TD, "C" samples) to provide more texture variability.

For the CRA samples, the laboratory processing applied to the non-SRA condition was an additional cold rolling by 20–30% followed by 1 h of annealing at 600 °C, 700 °C, or 800 °C. These samples were identified by the temperature of their annealing (ex. B3 600), and were only studied in the RD. In all cases, the annealing was performed in a $H_2 + Ar$ atmosphere, with a cooling rate of 1 °C/s.

2.2. Magnetic testing

Coercivity (H_c) and core loss (P_c) was measured at 40 Hz, 50 Hz, 60 Hz, and 400 Hz at 1.0 T. The low induction value was chosen to simplify the loss separation and to minimize the contribution of excess losses. The tests were performed under alternating current (AC) using a modular magnetic measurement instrument based on a data acquisition unit featuring a commercial software package for data analysis and a single strip test fixture (probe). The magnetic field was obtained by integrating the voltage pick up loop, while signal conditioning and analysis were performed