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Magnetic domain structure and crystallographic orientation of electrical steels revealed by a forescatter detector and electron backscatter diffraction

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A B S T R A C T

The magnetic properties of non-oriented electrical steels (NOES) are an important factor in determining the efficiency of electric vehicle drivetrains. Due to the highly variable texture of NOES, the relationships between crystal orientation, the magnetic domain structure, and the final magnetic properties are complicated and not fully understood. In this study, a NOES sample was characterized with a method capable of imaging surface magnetic domains using scanning electron microscopy (SEM) with an electron backscatter diffraction (EBSD) system equipped with a forescatter detector. This method used type II magnetic contrast without a specialized SEM setup, and imaged with a resolution limit of approximately 250–300 nm. The domain structure of the NOES sample was successfully related to β, which was defined as the angle between the closest magnetic easy axis and the surface of the sample (the RD–TD plane). However, it was shown that if the easy axes were aligned between neighbouring grains with respect to the grain boundary normal, the domain structure could align with an easy axis that was not the closest to the surface, and complex domain structures could be become wider. This structure and width change of complex domain structures has not been previously observed from single crystal or large-grained material studies. The successful application of this method to reveal the influence of surrounding grains can be used to better understand the magnetic properties of NOES.

1. Introduction

Electrical steels, which contain silicon as their major alloying element at around 1–4 wt%, are important materials for magnetic flux carrying applications. Depending on their application, either for rotating magnetic fields or magnetic fields applied in a single direction, they come in different forms as non-oriented electrical steels (NOES) or grain oriented electrical steels (GOES), respectively [1,2]. NOES have a more random crystallographic texture than GOES, and typically have a smaller grain size. NOES have become a material of greater research focus recently with increased concentration on the optimization of electrical vehicle drivetrains [3,4]. While NOES are a relatively mature material, used for well over half a century, there is still a need for greater understanding of how their crystallographic orientation and the orientation of neighbouring grains influence the magnetic properties of the material.

One of the major influencing factors on the magnetic properties of electrical steels is the crystallographic texture. The crystal orientation of the grain, relative to the magnetization direction, determines the amount of energy needed to magnetize the steel. This concept is governed by the magnetocrystalline anisotropy energy (E_a), which is described by the formula for a cubic crystal,

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

where K_1 and K_2 are cubic anisotropy constants, and the other α_i terms are direction cosines of the magnetization vector with respect to the three crystal axes [5]. Given the values for the cubic anisotropy constants for iron, this equation determines that for NOES the $\langle 100\rangle$ directions take less energy to magnetize and are the "easy" axes, while the $\langle 111\rangle$ directions take more energy to magnetize and are the "hard" axes [5].

For GOES, where the easy axis direction $\langle 001\rangle$ lies in the rolling direction (RD) with the Goss texture $\{110\}\langle 001\rangle$, the steel has optimal magnetic properties in the RD of the sheet for single direction magnetic field applications. For rotating magnetic field applications, NOES are used, since they are designed to have optimal magnetic properties (and therefore as many easy axes as possible) in the plane of the steel sheet without a directional preference. The amount of easy axis directions in the plane of the sheet has most often been characterized and discussed by the use of a texture factor that describes the percentage of desirable $\{100\}$

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planes (that contain two easy axis directions, ⟨010⟩ and ⟨001⟩) parallel to the plane of the steel sheet (the RD–TD plane) divided by the percentage of undesirable {111} planes, which contain zero easy axis directions [6,7]. This texture factor, while useful, is not entirely accurate when describing magnetic properties, since it does not account for the {*hk*0} types of planes which contain one ⟨001⟩ easy axis direction. An accurate texture factor is important since in reality, the texture of NOES can vary significantly between samples, and any possible orientation can be present (unlike GOES, which consists of small variations of a single orientation).

This concept of magnetocrystalline anisotropy energy is important since it influences the local regions of magnetic alignment in the material known as magnetic domains. Under static conditions with no applied field, the magnetization of the magnetic domains will typically follow an easy axis direction, to minimize the magnetocrystalline anisotropy energy [8].

At the surface of the sample, if the easy axis deviates from the ideal alignment in the RD–TD plane, it produces a surface density of magnetic free poles (ω) that is proportional to the angle of deviation (β), as shown by the equation [5]

$$\omega = \pm I_s \sin\beta \tag{2}$$

where I_s is the material constant for spontaneous magnetization. This equation is significant because the density of magnetic free poles determined through this angle β, is closely related to the magnetostatic energy (E_m, the energy related to the stray magnetic fields from the sample) and magnetic domain width (W) by the relationship [5]

$$E_m = 5.40 \times 10^4 I_s^2 W \sin^2\beta \tag{3}$$

assuming a planar distribution of free poles. Considering only the magnetostatic energy influence on domain structure, as the angle β gets larger, the surface density of free poles will increase, leading to an increase in the magnetostatic energy. To minimize this energy, the width of the domains will be reduced, and for larger angles, the complexity of the domain structure will also increase. This β has been previously characterized for electrical steels with electron backscatter diffraction (EBSD) on GOES [9]. For NOES, this is a more complex concept because any crystal orientation is possible. All six easy axis directions must be considered for NOES in calculating β, where for GOES, only the deviation of the single easy axis associated with the GOES texture is significant.

In addition to the magnetostatic energy there is also the total domain wall energy, which is given by [5]

$$E_w = \frac{\gamma l}{W} \tag{4}$$

where γ is the wall energy, and l is the length of the domains. In other words, with no applied field, the drive to minimize the magnetostatic energy by shrinking the size of the domains is balanced by the amount of energy it takes to create the domain walls, and the domain structure is a result of the minimization of the total energy (the sum of the two terms).

In addition to just considering a single orientation/grain, another important factor in the surface domain structure, especially for NOES, is the minimization of free magnetic pole density at a grain boundary (GB) [5]. The free magnetic pole density ω across a grain boundary is described by the formula

$$\omega = I_s(\cos\theta_1 - \cos\theta_2), \tag{5}$$

where 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 it lies in the plane of the sheet) [5], as shown in Fig. 1. A small difference between the two angles will mean a minimum of the surface density of magnetic free poles, so the domain structure will be continuous across the grain boundary [5,8]. As the difference in the angles increases (and ω gets larger), compensating domains (a more complex domain structure to decrease the magnetostatic energy) at the grain boundary will be produced [8]. An increase in magnetic free poles will increase the magnetostatic energy across a grain boundary as well, but the equations are more complex than discussed above, and beyond the scope of this paper. Due to the smaller grain size and more random texture of NOES, and the limitations of current magnetic imaging techniques, the influence of neighbouring grains on magnetic domain structure of NOES has not been widely studied.

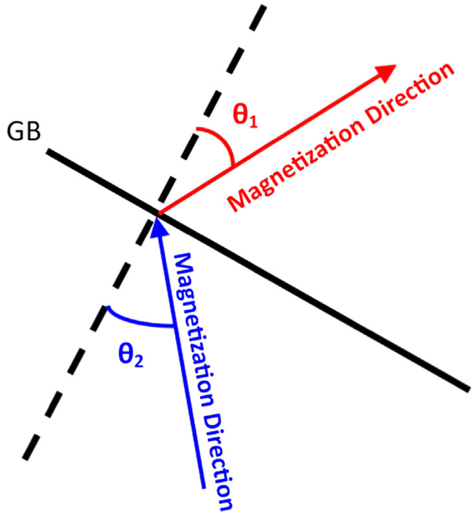

Fig. 1. Schematic showing how the orientation of the magnetization direction for adjacent grains is used to determine the free magnetic pole density ω across a grain boundary (GB). ω is proportional to the difference between the projection of the magnetization direction on the normal of the GB for each grain, as described in Eq. (5).

In order to image the magnetic domains at the surface, different methods are used, such as Bitter patterns (imaging a fine magnetic powder on the surface), magneto-optical (based on the rotation of the polarization plane of light), and electron microscopy [8]. Typically, magneto-optical imaging methods, also known as Kerr microscopy, have been applied to image the domains on both GOES and NOES [10–19], with most of these studies conducted on GOES. The reason most of these studies have been conducted on GOES is that Kerr microscopy has a spatial resolution limitation of roughly 300 nm [8], so resolving finer domain structure on smaller grains can be challenging. Additionally, magneto-optic methods do not provide texture information, which is not a significant problem for GOES since the grain structure consists of large grains that are slightly deviated from a single {110} < 001 > Goss texture, so the position of the closest easy axis to the surface can be inferred from the domain structure. For the more random textured NOES samples, an advanced understanding of the orientation is required since the combinations and relationships between the six easy axis positions and the domain structure are more complex.

Scanning electron microscopy (SEM) can provide local texture information with high spatial resolution when EBSD is utilized [20]. SEM can also be used to image magnetic domains [21], making it an ideal candidate for imaging magnetic domains of NOES along with capturing local texture information. In the SEM, magnetic contrast is classified into three types [21]. Type I magnetic contrast is produced by the deflection of emitted secondary electrons by stray magnetic fields above the specimen surface [21,22]. Since the contrast is related by the stray magnetic fields, this technique is typically only effective with hard magnetic