Micron 54–55 (2013) 43–51

Contents lists available at ScienceDirect

Micron

journal homepage: www.elsevier.com/locate/micron

EBSD study of angular deviations from the Goss component in grain-oriented electrical steels

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ARTICLE INFO

Article history:
Received 4 April 2013
Received in revised form 14 August 2013
Accepted 14 August 2013

Keywords:
Electron Backscatter Diffraction
Grain-oriented electrical steels
Magnetic properties
Texture

ABSTRACT

The magnetic properties of grain-oriented (GO) electrical steels strongly depend on the distribution of the α and β angles, i.e., the deviations of the easy magnetisation ⟨1 0 0⟩ from the rolling direction (RD) in the rolling plane and out of the rolling plane, respectively. However, most Electron Backscatter Diffraction (EBSD) studies consider the standard Goss deviation angle, which includes the rotation of the (1 1 0) plane about the RD. Therefore, in the present work, a new procedure is demonstrated for deriving the α and β angles from EBSD mappings to obtain a quantitative texture characterisation in line with the magnetic properties. This procedure is later applied to 37 GO steels after secondary recrystallisation that exhibit a wide range of permeability levels. The relation between the texture and the polarisation at 800 A/m (J800) that is measured in the present study by EBSD is compared to the one that has been determined in previous papers with optical goniometers and X-ray diffraction techniques, and this relation is subsequently used to define a relevant parameter to describe the orientation quality of the grains. The results indicate that the average angle of the α and β deviations is a relevant deviation parameter for the characterisation of grain orientations. Finally, it is demonstrated that the combination of the quantitative correlation between polarisation and texture with the orientation imaging of EBSD offers the possibilities of both studying the crystallographic environment of highly oriented grains in the primary recrystallised matrix for the production of high-permeability steels and evaluating the spatial distribution of the angular deviations in GO steels after secondary recrystallisation.

1. Introduction

Silicon steels, which are conventionally used for motors, transformers, generators, and similar electrical products, are processed to achieve low core loss and high permeability (Honma et al., 1985). These steels are produced to have either "oriented" grains or "non-oriented" grains. Grain-oriented (GO) electrical steels have superior magnetic properties along the rolling direction (RD) as a result of a so-called Goss texture, i.e., a {1 1 0} ⟨0 0 1⟩ orientation, as defined by the Miller crystallographic indexing system, in which the {1 1 0} planes are aligned in the rolling plane, and the ⟨0 0 1⟩ direction is parallel to the RD. The high induction or permeability level is related to the fact that the easy magnetisation direction ⟨0 0 1⟩ is parallel to the magnetisation direction of the sheet, i.e., the RD (Matsuo, 1989).

The dependence of the magnetic properties on the grain orientation has been thoroughly investigated over the past few decades (Craik and McIntyre, 1969; Foster and Kramer, 1960; Littmann, 1967; McCarty et al., 1967; Nozawa et al., 1978; Shilling, 1973; Swift et al., 1973; Yamamoto et al., 1983). All the results show that the polarisation at 800 A/m (J800) is inversely proportional to the spread of the α and β angles, i.e., the deviations of the ⟨1 0 0⟩ direction from the RD in the rolling plane and out of the rolling plane, respectively, whereas the rotation angle of the (1 1 0) plane about the RD, which is denoted by γ, that is measured in Goss-textured GO steels has very little impact on the polarisation. Therefore, the production of highly grain-oriented (HGO) steels with superior polarisation quality depends on the ability to achieve a sharp distribution of the in-plane and out-of-plane deviation angles, regardless of the γ distribution profile. This requirement implies that the Goss deviation angle, as it includes the grain rotation about the RD, should be replaced by a deviation angle more closely related to the in-plane and out-of-plane grain deviation angles. The latter angle may significantly contribute to the understanding of, e.g., the correlation between the texture and the magnetic properties or the influence of nuclei on the primary recrystallised matrix (e.g., Dorner et al., 2006; Homma and Hutchinson, 2003; Homma et al., 2003; Rajmohan and Szpunar, 2001; Shin et al., 2008).

To the best of our knowledge, no such quantitative grain characterisation has yet been implemented in EBSD studies, and the optimised methodology is briefly explained in Section 3 of the

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http://dx.doi.org/10.1016/j.micron.2013.08.003

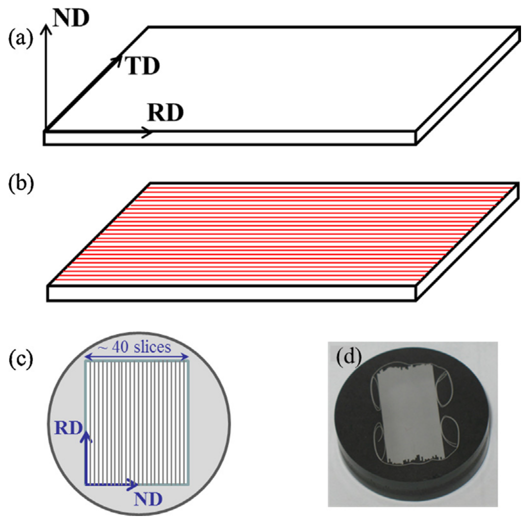

Fig. 1. EBSD sample preparation: (a) slices cut from the steel sheet, (b) embedded slices with the investigated (RD,ND) plane, and (c) a view of the pastille with rings to vertically support the slices during the embedding process.

present work. Furthermore, the deviation angles in previous studies have been measured using either optical goniometers or X-ray diffraction (XRD) techniques, which exhibit lower angular resolutions than EBSD. XRD results in particular are based on a restricted number of incompletely measured pole figures, whereas the implementation of other texture representations from EBSD data is possible, as the full orientation at each position is accessible (e.g., via the measurement of Euler angles). Therefore, it is of particular interest to compare the J800-texture correlation measured by EBSD with those that have been determined in previous papers and, in turn, to derive a relevant deviation angle to describe the correlation between the grain orientation and the final magnetic properties. For this purpose, a statistical polarisation analysis based on the measurement of 37 GO steels is presented in Section 4. Finally, examples of applications are shown in Section 5, including, on one hand, the study of the crystallographic environment of highly oriented grains in the primary recrystallised matrix for the production of HGO steels and, on the other hand, the spatial distribution of the grain-polarisation efficiency in the final products.

2. Experimental procedure

The materials studied in the present work to determine the correlation between the J800 value and the deviation angles from the Goss component (Section 4) are commercially produced GO steels after secondary recrystallisation. They exhibit either conventional grain-oriented (CGO, J800 > 1.84 T) or highly grain-oriented (HGO, J800 > 1.88 T) properties according to the European standard EN 10-107. In Section 5, decarburised materials are analysed for the characterisation of the environment of highly oriented nuclei.

Electron Backscatter Diffraction (EBSD) experiments were carried out on a JEOL JSM-7001F FEG-SEM equipped with an HKL Nordlys camera. One of the main characteristics of final GO-steel products is their large grain size, which is typically in the centimetre range. As standard cross sections (or plane views) would cover a very limited number of grains, a different sample preparation, which was similar to the one used by Frommert et al. (2008), was used; it is illustrated in Fig. 1. It consists of cutting the sample into approximately 40 slices (great care to ensure straight cutting is of the utmost importance to avoid errors in the measured deviations). These slices are then placed next to each other such

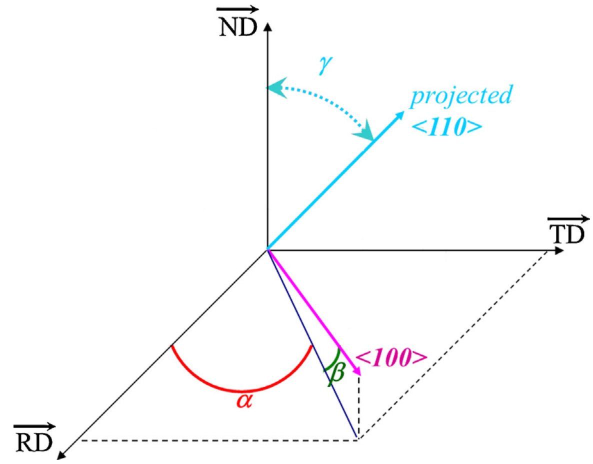

Fig. 2. Definition of the α, β and γ angles.

that the transverse direction (TD) is normal to the resin surface. This sample preparation allows more than 80 grains to be probed by EBSD in the same pastille.

The control of the sample preparation is critical to ensure that the measured grain orientations are accurate. For that purpose, the "instrumental deviation" was measured by acquiring the EBSD mappings of several $\langle 0\,0\,1\rangle$ Si wafers that were prepared using the sample preparation method shown in Fig. 1. The intensity profile across the central peak in the $\langle 0\,0\,1\rangle$ pole figure (not shown here) indicated an instrumental accuracy of ~1.3°, including all experimental uncertainties, e.g., the sample preparation, the tilt accuracy of the SEM stage, and the mounting of the pastille in the sample holder. Because this deviation is lower than the 3° usually found in HGO, the sample preparation is not regarded as a limiting factor for the measurement of the grain orientations by EBSD.

3. EBSD data treatment

The procedure for the determination of the α, β, and γ deviation angles (depicted in Fig. 2) from the Goss component is briefly explained below. The orientation is defined as the position of the crystal coordinate system with respect to that of the specimen (Engler and Randle, 2009), i.e., $M_{\text{crystal}} = gM_{\text{specimen}}$, where M_{crystal} and M_{specimen} are directions in the crystal and specimen coordinate systems, respectively, and g is the orientation matrix in terms of Euler angles (φ_1, Φ, φ_2):

$$g = \begin{pmatrix} g_{11}(\varphi_1, \Phi, \varphi_2) & g_{12}(\varphi_1, \Phi, \varphi_2) & g_{13}(\varphi_1, \Phi, \varphi_2) \\ g_{21}(\varphi_1, \Phi, \varphi_2) & g_{22}(\varphi_1, \Phi, \varphi_2) & g_{23}(\varphi_1, \Phi, \varphi_2) \\ g_{31}(\varphi_1, \Phi, \varphi_2) & g_{32}(\varphi_1, \Phi, \varphi_2) & g_{33}(\varphi_1, \Phi, \varphi_2) \end{pmatrix} \quad (1)$$

The expression of the g_{ij} elements as a function of Euler angles can be found elsewhere (e.g., Engler and Randle, 2009). As g is a rotation matrix with $\det^2(g) = 1$, the transpose matrix g^t is equivalent to the inverse, which leads to $g^t M_{\text{crystal}} = M_{\text{specimen}}$. Therefore, any [$xyz$] direction in the crystal coordinate system can be written as M_{XYZ} in the specimen frame as follows:

$$M_{XYZ} = \begin{pmatrix} g_{11}x + g_{21}y + g_{31}z \\ g_{12}x + g_{22}y + g_{23}z \\ g_{13}x + g_{23}y + g_{33}z \end{pmatrix} \quad (2)$$