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Model for the correlation between magnetocrystalline energy and Barkhausen noise in ferromagnetic materials

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ABSTRACT

In the present work a model for the correlation between magnetocrystalline anisotropy energy and Barkhausen noise is proposed. The link between the magnetocrystalline anisotropy energy and the magnetic Barkhausen noise is due to the influence of the crystallographic texture on the domain nucleation process which produces the Barkhausen signal in the branch from saturation to remanence. The statistical distributions of magnetic free poles and local fields of nucleation and subsequent growth of reversed domains were obtained for a large number of grain boundaries and used to estimate the number and size of Barkhausen events at each angular position from 0 to 360° in ten degree-steps. The good agreement observed between the modeled magnetocrystalline energy and the prediction of this energy made from X-ray texture and Barkhausen noise measurements corroborates the validity of the proposed model.

1. Introduction

The Barkhausen effect is the discontinuous change of magnetization of ferromagnetic materials under the application of a variable magnetic field [1]. It is known [2,3] that Barkhausen noise (BHN) jumps are produced by two main sources: irreversible domain wall (DW) motion and irreversible domain rotation. The analysis and correlation of BHN signals with a given material's property are classified into two signal processing trends, which are related to the strong and low intensity of Barkhausen activities associated with the regions around coercivity [2] and the nucleation and growth of reverse domains [3] when the material leaves saturation, respectively. For the first one, it is commonly reported that the easy magnetic axis is along the direction for which the r. m. s. value of BHN signals is the highest [4,5]. This can be explained by considering the irreversible motion of 180° DW, which causes the highest peak of the BHN signal around coercivity. From this analysis, the correlations between the BHN signal and several physical parameters and properties have been extensively studied such as the stress-dependent anisotropy [6–8], carbon content and grain size [9–11], hardness [12], martensite phase [13], fatigue [14], and elastic-plastic deformation [15] in steels. For the second one, magnetic properties are associated with the small magnitude BHN peaks generated from the nucleation and growth processes of reversed domains. These signals are critical to the goals of the present study and are mainly produced in the branch from saturation to remanence (SR) of the hysteresis loop. The interest to explore this part of the hysteresis loop and the associated BHN has been increased due to the experimental evidence of the strong correlation of the angular dependence between the BHN and the magnetocrystalline energy (MCE) as reported in references [16,17]. In these works, the MCE predictions are made from X-ray macrotexture and microtexture texture measurements using electron backscatter diffraction (EBSD). However, there is a lack of a mathematical model capable of explaining the observed strong correlation between the angular dependence of BHN measurements in the SR branch and texture-derived MCE in ferromagnetic materials.

The general approach for modeling the BHN signal is based on the DW velocity theory [18], which can be described by analogy with a forced damped harmonic oscillation system, as shown by many researchers [3,19,20]. A large number of papers published on the BHN described this phenomenon through mathematical models, which focused on the DW motion through a ferromagnetic material [19–21]. In particular, a model was proposed by Alessandro, Beatrice, Bertotti, and Montosori (ABBM) [21], using a stochastic approach to describe the random character of BHN signals, although it is difficult to use this model to establish a correlation between the BHN and the microstructural features of the materials. Also, Perez-Benitez et al. [22] proposed a model based on the ABBM to describe the influence of the microstructural parameters

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such as carbon content and particle size on the BHN signal in plain steels. Nevertheless, this model did not consider the effect of magnetic free poles formed at grain boundaries neither the angular dependence of the BHN signal in the studied steels.

On the other hand, in the case of the correlation between MCE and BHN it could be explained using the model developed by Tu-Le et al. [23] in which the Barkhausen energy in the SR is considered to be proportional to the magnetic free poles density at grain boundaries in low carbon steels. However, the model in [23] only considers the nucleation of reversed domains due to the magnetic free poles at grain boundaries. The subsequent growth of these domains and the velocity of the domain growth from a nucleation site were not taken into account.

Therefore, in the present work a new model to explain the correlation between the MCE and the BHN is proposed, considering not only the nucleation and subsequent growth of reversed domains in terms of the number and size of BHN activities, but also the velocity that the reversed domains grow from a nucleation site at grain boundaries. It can be stressed that since current models are mainly focused on the strong Barkhausen activities in the region around coercivity, where the DW motion is dominated, they are not capable to explain the observed correlation between the MCE and the BHN signal. Otherwise, these models do not contain an angular variable that helps analyzing the magnetic anisotropy of the material. In this study, a generalized model is proposed to explain the observed correlation between MCE and BHN measurements. The proposed model describes, for the first time, the random nature of BHN signals in the SR branch from the knowledge of the microstructural parameters (grain size, grain size distribution, and carbon content through the pearlite volume fraction) and crystallographic texture (grain boundary distribution and misorientation angle distribution) in the six steel samples of different microstructures and textures, and their relationship to the nucleation and growth of reversed domains by means of a stochastic approach and also includes the angular variable to easily evaluate the angular dependence of the material's physical properties of interest. X-ray and Electron backscatter diffraction measurements are used to crystallo-graphically characterize six different steel samples. This characterization will be used to parameter the numerical simulations.

2. Materials and methods

Six API 5L steel samples (X52, X56, X60, sample A, sample B, and sample C) were obtained in the form of disks on the rolling plane containing the rolling (RD) and transverse (TD) directions, with a diameter of 1 cm and thickness of 2.5 mm (normal direction, ND). These samples were prepared with different textures and grain sizes to facilitate the comparison of the analysis from material to material. Indeed, the three samples (A, B, and C) were obtained by special heat treatments [24] in order to produce different type of textures with particular MCE shapes. The chemical composition of the studied steels can be seen elsewhere in a previous paper from the authors [24]. The microstructure of these steels was studied on the six steel samples by a JEOL JSM SEM 6300 equipment; and the resulting micrographs are shown in Fig. 1. The ferrite grain size and its volume fraction were determined by optical microscopy, for each one of these steels; and these microstructural parameters are given in Table 1.

The BHN signals were measured by means of the system depicted through the diagram shown in Fig. 2.

The U-core contains a magnetic field excitation coil of 1000 turns and a pick-up coil. A vertical set of sensors is used to measure the magnetic field H. The frequency and magnitude parameters of the excitation magnetic field are monitored by means of the Hall sensors array and set through an analog output of the DAQ PCI-6010. The BHN signal for each steel sample is detected by means of the pick-up coil. The output signal of the pick-up coil is fed to an amplifier with a gain of 60 dB and bandwidth of approximately 1 MHz, which is connected to an analog high-pass filter with a cut-off frequency of 1 kHz to remove possible low-frequency interferences from the excitation coil and the 60 Hz from the power line. A low-pass filter with cutoff frequency of 100 kHz is used to remove high frequency harmonics. The output signal of the amplifier is fed into the digital oscilloscope, which is coupled with a personal computer (PC) through a GPIB interface. Details of the experimental setup with a goniometer for the circular sample are given in previous papers [23,24].

For the BHN-derived MCE, ten BHN signals were obtained from 0 to 180°, in 10-degree steps and averaged at each angular position. The average MCE in each sample was determined through the angular dependence of the r. m. s. value of the BHN signal in the SR branch, applying the band selection criteria proposed by Perez-Benitez et al. [25]. The BHN measurements were obtained using a magnetization frequency of 1 Hz for the applied magnetic field H with a maximum of 12 kA/m during all excitation cycles. The r.m.s. values of the BHN signal were calculated with a band frequency in the range of 1–100 kHz and were integrated in all cases using the same ΔH interval (0.5 kA/m) of the SR branch. The methodology established for the determination of the MCE angular dependence from BHN measurements in the SR branch, for each steel, was explained in [17,24] and the predictions of this energy from X-ray texture measurements in [26].

The X-ray global texture measurements were carried out using a D8 Advance Brucker AXS diffractometer equipped with a compact Eulerian cradle. Three incomplete pole figures {1 1 0}, {2 0 0}, {1 1 2} were measured at the rolling plane for each steel sample. These experimental pole figures were processed using the ADC method [27] implemented in the LaboTex software for determining the orientation distribution function (ODF) of the studied steels. From the ODF, the MCE prediction of each steel was calculated for further comparison with the angular dependence of the MCE-derived from BHN measurements.

Fig. 3 shows the ODF triclinic representation calculated from X-ray texture measurements of the studied steels in the $\varphi_2 = 45°$ section of the Euler space. In general, the crystallographic textures of the studied steels are mainly dominant of the {1 1 1}ND, {1 1 2}ND, and {1 1 0}ND texture fibers [24]. These steels show markedly different textures from one sample to the other. From these ODFs, the pair of orientations for each studied steel was created using the LaboTex software.

For each steel, the grain size distribution obtained from the EBSD microtexture measurements using the OIM package software was used to simulate the dependence of the magnetic free pole density at grain boundaries with the texture and microstructural data. The grain size of each grain at both sides of each simulated grain boundary was introduced in the simulation by (randomly) sampling the grain size distribution. The grain size distribution used for the later simulation was determined from the EBSD measurements for each one of the investigated steels. For the sake of illustration, Fig. 4 only shows the grain size distribution obtained from the EBSD orientation map for the X56 steel sample.

3. Model for the correlation between MCE and BHN signal

Taking into account the ABBM model, Jiles [28] developed a model of BHN effect assuming that with a constant rate of change of the applied field, the time rate of change of magnetization is proportional to the BHN activities. These BHN events or jump sum M_{JS} in ferromagnetic materials can be expressed as [28]