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# ON THE CORRELATION OF MAGNETOCRYSTALLINE ENERGY AND BARKHAUSEN NOISE IN API 5L STEELS: A STOCHASTIC MODEL

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A stochastic model has been developed to explore the experimental correlation between magnetocrystalline energy and Barkhausen noise in the region from saturation to remanence in low-carbon steels. The proposed model helps evaluate the angular dependence of magnetocrystalline energy in API 5L steel samples from their crystallographic texture, grain orientation, and grain boundary misorientation distribution. These microstructural characteristics are used to model the distribution of free magnetic charges at grain boundaries in the steel. The statistical distribution of magnetic free poles leading to the nucleation and growth of reverse domains is computed for a large number of grain boundaries from the material's texture, considering the magnitude and direction of the applied field; this is used to estimate the Barkhausen activity at each angular position of interest. The model is validated against magnetocrystalline energy predictions made from X-ray texture and Barkhausen noise measurements.

Keywords: Barkhausen noise, magnetocrystalline energy, non-destructive method, stochastic modelling

## 1 INTRODUCTION

Among the non-destructive methods based on the magnetic properties of materials, Barkhausen noise (BN) is effective for the determination of easy magnetic axes and stress induced-anisotropy evaluation [1, 2, 3]. BN has been found dependent on microstructural features such as grain size [4], carbon content [5], and grain boundary distribution [6]. These features make BN suitable for pipeline inspection for detection of macro defects like pitting corrosion [7].

Previous works have reported experimental evidence of the strong correlation between magnetocrystalline energy (MCE) and BN in the band from saturation to remanence (SR) in API 5L steels [8,9]. In these materials, the average MCE estimated from the BN measurements was found in close agreement with MCE predictions made from X-ray global texture and Electron Backscatter Diffraction (EBSD) microtexture measurements. Although MCE has been obtained from BN measurements, the origin of the correlation between MCE and BN signals has not been clearly explained yet.

A large number of models have been developed from the theory of domain wall in order to interpret the BN signals. It seems to be that the model proposed by Alessandro, Beatrice, Bertotti, and Montosori (ABBM) is the most general one [10,11]. These authors use a stochastic approach to describe the random character of BN signals. However, this model only focuses on the region around coercivity point in the hysteresis curve, where the main Barkhausen activity takes place [12]. Therefore, the information required to explain the nucleation and growth of reverse domains in the SR band is not provided by this model.

Besides the ABBM model, one can also consider Jiles' model [11,13,14]. The idea of Barkhausen events was introduced in the ABBM model for the correlation of the number of events in each time interval with the strength of the BN signal. Jiles' model is able to stochastically describe the Barkhausen spectrum for the entire hysteresis loop, subjected to the conditions that the rate of change of the applied field is constant and the rate of change of magnetization with time is proportional to the Barkhausen activity. Therefore, the magnetization discontinuity in a bulk material is expressed as [14]

$$M_{JS} = \sum_{i=1}^{N} m_i = N\langle M_{disc}\rangle , \tag{1}$$

where $m_i$ is the individual change of magnetization and $\langle M_{disc}\rangle$ is the average magnitude or size of the BN events, while the number of events N is determined by the correlation between the number of events in two successive time intervals $N_{t-1}$ and $N_t$

$$N_t = N_{t-1} + \delta_{rand}\sqrt{N_{t-1}} \quad , \tag{2}$$

where $\delta_{rand}$ is a random number within ±1.47.

It is important to note that the Jiles' model fits well to the experimental BN signal and shows its connection with the hysteresis phenomenon of the material [14]. However, it does not explore the angular dependence of the BN signal and its dependence on MCE, which is the key to assess this latter from BN measurements in the SR band.

In summary, the review of Barkhausen effect models shows that the current models are not suitable to explain the observed correlation between the MCE and BN signal in the SR part of the hysteresis loop. The Jiles' model can be assessed appropriate to describe the correlation between MCE and BN measurements by introducing a new

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stochastic component that makes possible the evaluation of the angular dependence of the BN signal, and this is the main idea proposed in this paper.

## 2 MATERIALS AND METHODS

Three API 5L steel samples (X52, X56, and X60) were obtained in the form of disks on the rolling plane, with a diameter of 1 cm and thickness of 2.5 mm. The chemical composition and other microstructural characteristics of these steels were given in previous works by the authors [8, 9, 20].

The global texture measurements were carried out in a D8 Advance Brucker AXS X-ray equipment, using an Eulerian cradle. Three incomplete pole figures {110}, {200}, and {112} were measured at the rolling plane for each steel sample. The experimental pole figures were processed using the ADC method, implemented in the LaboTex software [19], in order to determine the orientation distribution function (ODF) of the studied steels. From the ODF, the MCE of each steel was calculated for further correlation with the BN-derived MCE. The details concerning the determination of the MCE from crystallographic texture measurements can be found in references [8, 9], which follows the methodology given in [15]. From the ODF data of each steel, $2 \times 10^6$ individual orientations were created in LaboTex for the simulation of free magnetic charges in the steel as explained later.

The angular dependence of MCE in the studied steels was determined from BN measurements using the following method.

The BN signals were obtained with a magnetization frequency of 1 Hz for the applied magnetic field H, which reached a maximum of 12 kA/m during all excitation cycles. The band frequency for the calculation of the *rms* of the BN signal was in the range of 1– 100 kHz. The BN was integrated in all cases using the same ΔH interval of the SR band.

The angular BN measurements were obtained from 0 to 180 degrees, in 10-degree steps. Ten signals were obtained and averaged at each angular position. The average MCE in each steel at each angular position was determined as the *rms* value of the BN signal in the SR band of the hysteresis loop for this position.

## 3 STOCHASTIC MODEL

In a polycrystal, the presence of grain boundaries leads to the formation of magnetic free poles at them. The general expression for the determination of free charge poles density $\omega$ at a (*i-th*) grain boundary is [16, 17]

$$\omega_i = J_s(\cos\theta_1 - \cos\theta_2)\ , \tag{3}$$

$$\omega_i^* = \omega_i / J_s\,, \tag{3a}$$

where $\theta_1$ and $\theta_2$ are the angles between the magnetization vectors on the two sides of the grain boundary and the normal to the boundary, and $J_s = \mu_0 M_s$ is the saturation polarization.

As has been previously proposed [9], when the material is at remanence the average free poles density in a polycrystal for a given angular position $\eta$ along which the field is oriented with respect to a given sample direction (for example: the rolling direction, RD), can be determined as

$$\overline{\omega}(\eta) = \frac{1}{N_{GB}} \sum_{i=1}^{N_{GB}} \left|\omega_i^*(\eta, \theta_1, \theta_2)\right|, \tag{4}$$

where $N_{GB}$ is the number of grain boundaries in the polycrystal.

At remanence, the value of $\theta$ at both sides of the grain boundary can be determined from the orientation of the boundary plane, the crystallographic orientation of the two grains that share the boundary, and the direction of the magnetic field at saturation [16, 17].

In the general case, (4) must be expressed in terms of the applied field $H$. When the material goes from saturation to remanence, this can be expressed as

$$\overline{\omega}(\eta|H_\eta) = \frac{1}{N_{GB}} \sum_{i=1}^{N_{GB}} \left|\omega_i^*(\eta|H_\eta, g_{GB}, \theta_1, \theta_2)\right|, \tag{5}$$

where $H_\eta$ is the value of applied field at each angular position $\eta$, and $g_{GB}$ is the orientation of the grain boundary plane.

The determination of $\theta$ for a given value and direction of applied field is carried out by minimizing the total magnetic energy at each side of the grain boundary [18]

$$E(\eta,\varphi) = \frac{K_1}{K_d} \sin^2\varphi \cos^2\varphi - h\cos(\varphi - \eta)\,, \tag{6}$$

$$h = \frac{H}{2J_s K_d}\,,$$

where $h$ is the reduced field, $K_1$ the anisotropy constant, $K_d$ the stray magnetic field energy, and φ indicates the angular position of the magnetization in the grain with respect to the closest [100] crystal easy axis.

The relationship between a Barkhausen event (as measured by the induction voltage $V_i$ produced in the magnetic pickup coil) and the rate of change of the magnetic flux is

$$V_i = -f_p \frac{\mathrm{d}\varphi'}{\mathrm{d}t}\,, \tag{7}$$

where $f_p$ is a proportionality factor.

The magnetic flux $\phi'$ in (8) is defined by the magnetic flux density, B crossing the ferromagnetic material through an area A

$$\phi' = BA\ . \tag{8}$$

On the other hand, the magnetic energy associated with the BN signal in the SR band is determined by [1]

$$E_{BN} = \sum_{i=1}^{N_{event}} \int V_i^2 dt \, , \tag{9}$$

where the time integral is over each event time duration, while the summation is taken over all events $N_{\mathrm{event}}$ observed in SR. By substituting (8) and (9) in (10), and considering that in a ferromagnetic material B can be approximated by the magnetization of the sample, $\mu_0 M$

$$E_{BN} = n\sum_{i=1}^{N_{event}} \int (\frac{\mathrm{d}M_i}{\mathrm{d}t})^2 \mathrm{d}t \quad , \tag{10}$$

where $n = \mu_0^2 f^2 A^2$ is an experimental constant.

The relationship between the rate change of magnetization, d$M$/d$t$, and the rate change of applied field is [11, 14]

$$\frac{\mathrm{d}M}{\mathrm{d}t} = \frac{\mathrm{d}M}{\mathrm{d}H}\frac{\mathrm{d}H}{\mathrm{d}t} = \chi \frac{\mathrm{d}H}{\mathrm{d}t} \, , \tag{11}$$

where $\chi$ is the magnetic susceptibility.

According to reference [14], the rate of change of Barkhausen jump sum (1) d$M_{JS}$/d$t$ can be assumed to be proportional to d$M$/d$t$

$$\frac{\mathrm{d}M_{JS}}{\mathrm{d}t} \propto \chi \frac{\mathrm{d}H}{\mathrm{d}t} \, , \tag{12}$$

By introducing a proportionality constant, $\xi$, the substitution of (12) in (10) gives

$$E_{BN} = \xi n \chi \frac{\mathrm{d}H}{\mathrm{d}t} \int \mathrm{d}M_{JS} \; , \tag{13}$$

In this paper, the change of Barkhausen jump $dM_{JS}$ is assumed to be proportional to the discontinuity of magnetization due to the magnetic free charges at both sides of the grain boundary. Therefore, (13) can be written as

$$E_{BN}(\eta | H_\eta) = \xi n \chi \frac{\mathrm{d}H}{\mathrm{d}t} \frac{1}{N_{GB}} \sum_{i=1}^{N_{GB}} \left| \omega_i (\eta | H_\eta , g_{GB}, \theta_1, \theta_2) \right| \; . \tag{14}$$

It can be noted that if the model only evaluates what happens in the SR band; thus, the magnetic susceptibility $\chi$ and the rate change of the applied field in (12) can be assumed to be constant.

Taking into account (5), the final expression for the Barkhausen energy per volume is reduced to

$$e_{BN}(\eta | H_\eta) = E_{BN}(\eta | H_\eta) / J_s \xi n \chi \frac{\mathrm{d}H}{\mathrm{d}t} = \bar{\omega}(\eta | H_\eta) \; . \tag{15}$$

As the average charge density is expressed as a function of the value of the applied field and its angular position $\eta$ with respect to RD, the proposed model can be used to analyse the angular dependence of the BN in SR.

Equation (15) can be validated by comparing the results of the stochastic simulation of $e_{BN}(\eta | H_\eta)$ with the MCE derived from the experimental BN and texture measurements of the studied steels.

In order to carry out the stochastic modelling based on (15), a data set of 2 × $10^6$ orientation pairs was created for each studied steel from its X-ray-determined crystallographic texture using the LaboTex software. These pairs were then sampled at random to simulate $10^6$ grain boundaries whose orientation with respect to the sample reference system was also set at random (within ±15 deg. from RD). For each angular position of the applied field with a magnitude of 1 kA/m, $\bar{\omega}(\eta | H_\eta)$ was computed, from 0 to 360 degrees, in 10-degree steps to produce the angular dependence of the free magnetic pole density in each sample.

## RESULTS

The results of the stochastic simulation of the reduced BN energy described by (15) are shown in Fig. 1(a). The number of events was accounted for using the density of free poles formed at each grain boundary created by a pair of individual grains. The number of simulations at each angular position was the same as the number of grain boundaries considered ($10^6$). Figures 1(b) and 1(c) show the angular dependence of the MCE estimated from the crystallographic texture and BN measurements of the studied samples.

As the stochastic simulation is time consuming due to the large number of calculations required, parallel programming was used for the determination of $e_{BN}(\eta | H_\eta)$ in order to increase the computation speed.

On the one hand, figures 1(a) and 1(b) evidence the similarity of the MCE, both in shape and relative magnitude (from one steel to the next), in the three investigated steels in comparison with the prediction made from X-rays texture measurements. On the other hand, Figs. 1(a) and 1(c) show that the modelled MCE also agrees, both qualitatively in shape, and quantitatively in relative magnitude, with the observed behaviour of MCE as obtained from the BN measurements in the SR band.

The close agreement between the BN- and texture-derived MCE and the simulation of $e_{BN}(\eta | H_\eta)$ evidences that there exists a strong physical correlation between the MCE and the BN signals in the SR band. This comparison validates the practical use of the proposed stochastic model for the explanation of the correlation between MCE and BN signals in this band.

## 5 DISCUSSION

The strong correlation between the MCE and the BN signal in the SR band can be explained by considering the dependence of the Barkhausen activity on the number of magnetic free poles created at the grain boundary during the magnetization reversal process and, ultimately, by taking into consideration the role that the MCE energy plays in the formation of these charges.

The formation of magnetic free poles at a grain boundary leads to the nucleation and growth of domains of reversed magnetization as the applied field is reduced and the material goes from saturation to remanence [16]. As a new domain is formed, the magnetization follows the direction of the easy axis in the volume occupied by this new domain.

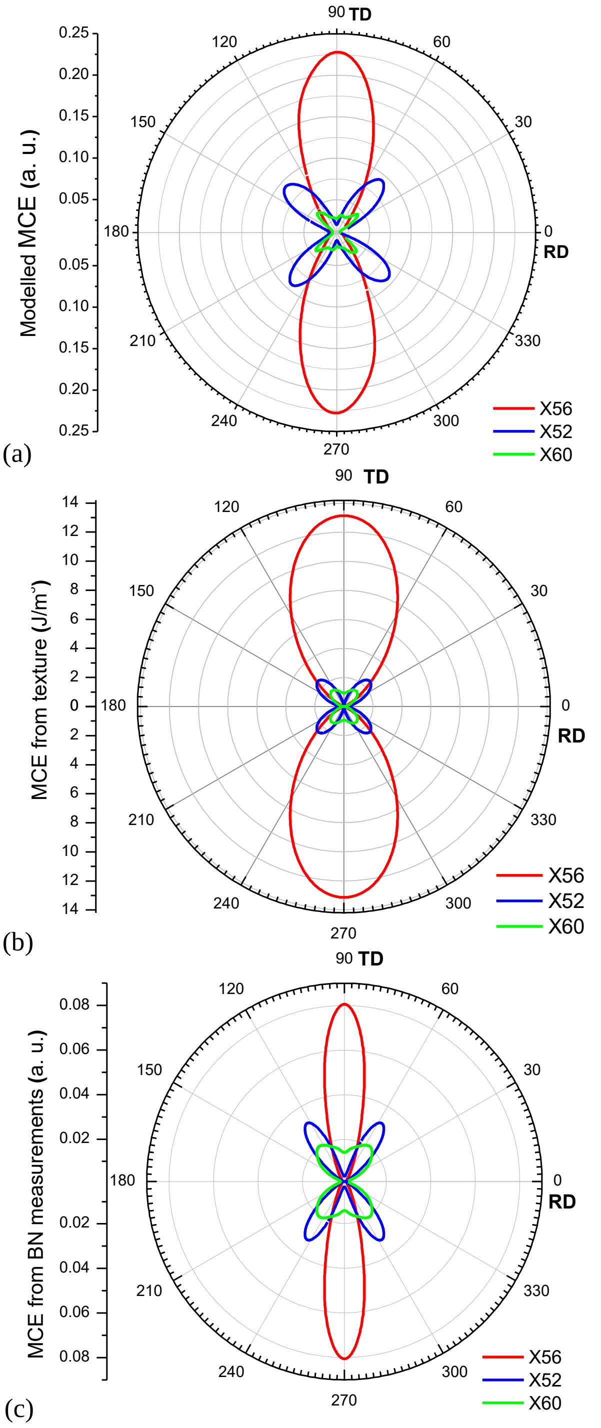

**Fig. 1.** (a) - MCE obtained from the simulation of magnetic free pole at grain boundaries, (b) - MCE predicted from crystallographic texture measurements, and (c) - MCE estimated from Barkhausen noise measurements in the SR band

As shown by the simulation results, the creation of free poles and the subsequent nucleation and growth of the domains of reversed magnetization depends intimately on the microstructural characteristics of the material such as the crystallographic texture, grain orientation and grain boundary misorientation. These are the factors that mainly define the behaviour of MCE in the investigated steels as they determine the angular proximity between the grain boundary normal and the magnetization of reverse domains. This can explain the good correlation in Fig. 1 between the modelled and measured angular dependence of the MCE and BN energy.

It can be observed in Fig. 1 that the MCE obtained from the simulation is broader than the experimental MCE from BN measurements. This points out to the fact that the proposed model needs to include the effect of other microstructural parameters such as grain size and carbon content, which are not considered in the present approach in order to simplify the mathematical modelling.

The influence of grain size and carbon content on the statistical distribution of magnetic free poles and its impact on the modelled BN angular dependence will be thoroughly discussed in a future paper, which is under development by the authors. Although some assumptions were made, the proposed model is able to reproduce the experimental observation and explain using sound physical arguments the strong correlation between MCE and BN signals for the three pipeline steels.

## 6 CONCLUSIONS

The stochastically modelled angular dependence of the average MCE in the studied API pipeline steels is in good agreement, both in shape and magnitude, with the average MCE derived from BN measurements and predicted from crystallographic texture. This points out to the fact that the strong correlation between the BN signal and the MCE in the SR band is due to the role that the MCE plays in the formation of magnetic free poles at grain boundaries. The results obtained in this work show that the proposed model is capable of reproducing experimental measurements and explaining the relationship between the MCE and BN signal, from the microstructural and texture characteristics of these steels.

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