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Tensile stress effect on magnetic Barkhausen noise of silicon steel single crystal (measurements and simulations)

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The Magnetic Barkhausen Noise (MBN) measurement can be used to evaluate non-destructively mechanical internal stress in electrical steel laminations. However such evaluation is complex as various factors can distort the MBN signal similarly. Internal stress is one of them, but an increase in dislocation density or other defects can be just as influential. This work focuses on single crystals with pre-determined crystallographic orientation to isolate basic mechanisms. The reconstructed MBN energy hysteresis cycles are compared to classical hysteresis loops, and to simulation obtained from a multiscale model. These comparisons provide new insights into the impact of tensile stress on the magnetization process and the magnetic domains kinetics and bring perspectives regarding the ideal way to perform MBN non-destructive evaluation of internal mechanical stress.

Index Terms—Magnetic Barkhausen Noise, magnetization mechanisms, non-destructive testing, multiscale model, tensile stress effect.

I. INTRODUCTION

THE MAGNETIC Barkhausen Noise (MBN) characterization technique is a valuable Non-Destructive Testing (NDT) of ferromagnetic steel components due to its sensitivity to microstructural changes, rapid inspection capabilities, subsurface defect detection, quantitative analysis, automation potential, and versatility. Its application ensures the integrity and reliability of ferromagnetic parts in critical sectors such as transportation, public structures, or energy. [1].

MBN is generated by the motion of magnetic domain walls encountering microstructural features like grain boundaries and dislocations under the influence of an external magnetic field. The resulting abrupt movements cause rapid changes in magnetic flux, producing the so-called Barkhausen noise.

Standardizing procedures and controlling experimental parameters are crucial for reproducibility in MBN NDT. The raw signal, containing undesired noise, is classically replaced with reproducible indicators like the amplitude of the MBN activity, frequency distribution, and energy content. For years, our group has privileged the Magnetic Barkhausen Noise energy (MBN_{energy}) for its physical meaning and specific link with the magnetic flux density. The computation of the MBN_{energy} involves the following successive steps [2]:

— Monitor the MBN signal under the form of an electrical voltage: $e(t)$

— Integrate the product of the sign of the magnetic excitation time-derivative and the square of the MBN signal:

$$MBN_{energy}(t) = \int_0^t \text{sign}\left(\frac{dH_{surf}}{ds}\right) e^2(s) ds \quad (1)$$

In parallel to the concept of the MBN_{energy} quantity arises the idea of $MBN_{energy}(H_{surf})$ hysteresis cycles, which depict how MBN_{energy} changes with respect to the external magnetizing field H_{surf} measured tangential to the specimen surface.

This graphical chart includes the MBN_{energy} on the y-axis and H_{surf} on the x-axis. The resulting cycles provide additional

information about the magnetization process, especially compared to classical magnetization loops ($B_a(H_{surf})$, where B_a is the flux density averaged through the specimen cross-section). More precisely, it helps establishing the respective weights of domain wall motion and rotation contribution during the magnetization process. Previous works, for instance, revealed similarities between MBN_{energy} and classical hysteresis loops for grain-oriented electrical steel (GOFesi) but significant differences for iron-cobalt (FeCo) laminations, meaning that the rotation contribution is limited for GOFesi and important for FeCo [3].

Still, most of these results are qualitative and based on experimental observations. They lack theoretical confirmation, especially considering that MBN is sensitive to many parameters (dislocation density, grain boundaries). In this work, we want to confirm these results by focusing MBN measurement on single crystals with pre-established crystallographic orientation. Hence, the number of parameters influencing MBN measurements will be limited. By combining experimental results (both MBN_{energy} and classical hysteresis cycles) and simulation predictions from a multiscale model [3][4], our objective is to define precisely the role of each of the magnetization mechanisms and to establish their order of appearance. The influence of uniaxial tensile stress σ will be studied too, with the objective to establish which magnetization mechanism is most sensitive to stress and what is the ideal solution for its assessment in NDT conditions.

II. SPECIMENS DESCRIPTION AND SINGLE CRYSTAL MBN CHARACTERIZATION

A. Tested specimens description

In this work, the tested specimens were GOFesi laminations submitted to specific thermal treatment to induce grains of exceptional size (of the order of centimeters). Fig. 1 depicts one of these specimens.

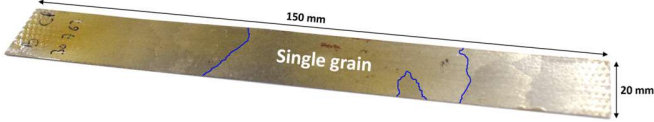


Fig. 1. Picture and dimensions of a tested specimen (thickness is 250 μm).

Laminations of GOFesi were used to obtain a series of samples cut at $\theta = 0, 30, 45, 54.7, 60,$ and 90° , where $\theta = 0^\circ$ and 90° are the rolling and the transverse directions, respectively (see Fig. 2). The cutting areas were chosen so that a large grain stands in the middle of the samples [5]. Two specimens were prepared for each angle.

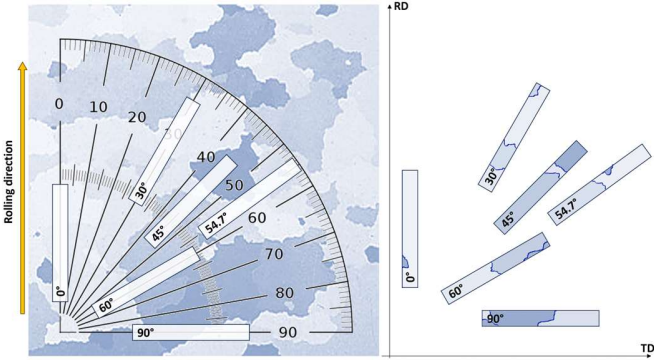


Fig. 2. Tested specimens and their orientations

B. Experimental setup

A dedicated experimental bench was set up to measure the $MBN_{energy}(H_{surf})$ and $B_a(H_{surf})$ under different uniaxial tensile stresses σ (elastic regime). A 2D sketch of this experimental setup is shown in Fig. 3. Two 200-turns wrapped coil sensors plugged in series opposition and positioned in the vicinity of the same grain (Fig. 3.B) are used for the MBN measurement.

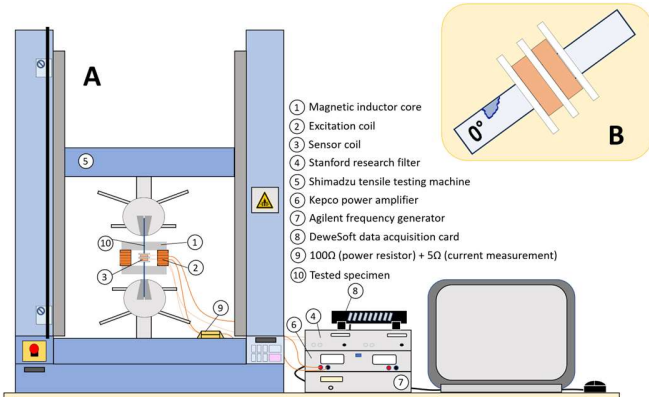


Fig. 3. A 2D sketch of the experimental setup. B. Close view of the double coil sensor positioned in the vicinity of the single-grain

III. MULTISCALE MODEL

The magnetic behavior under the influence of tensile stress is simulated thanks to the multiscale model described in [3] but in a single crystal configuration [6]. The multiscale simulation is used to predict the anhysteretic behavior of both classical and MBN_{energy} cycles. The latter are obtained by suppressing the magnetization rotation contribution.

IV. FIRST RESULTS

The first results shown in this abstract correspond to the comparisons between the $MBN_{energy}(H_{surf})$ and the $B_a(H_{surf})$ hysteresis cycles for applied tensile force $F = 0, 250, 500, 750,$ and 1000 N (corresponding to $\sigma = 0, 50, 100, 150,$ and 200 MPa, respectively). The maximum stress level was set to keep the material in the elastic regime.

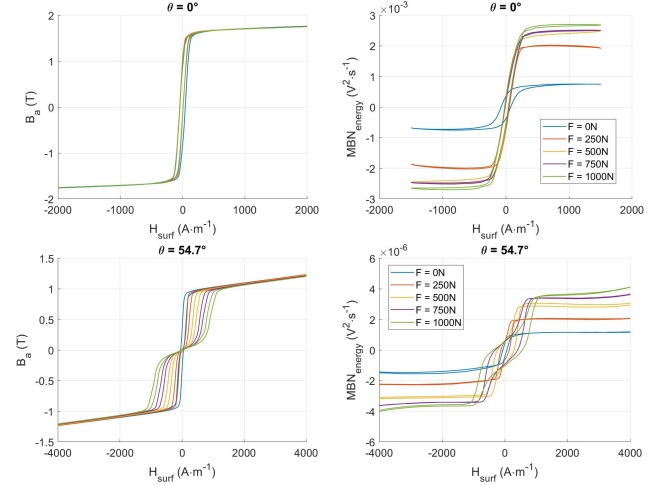


Fig. 4. Comparison $MBN_{energy}(H_{surf})$ and $B_a(H_{surf})$ hysteresis loop for different levels of σ and $\theta = 0$ and 54.7° .

In this abstract, only the results obtained for $\theta = 0$ and 54.7° are shown. These orientations are expected to be the easiest and the hardest magnetic angles. No rotation is expected at $\theta = 0^\circ$; the $MBN_{energy}(H_{surf})$ and $B_a(H_{surf})$ cycles have similar shapes. Oppositely, at $\theta = 54.7^\circ$, a significant rotation contribution is expected, which is confirmed by the evident difference between both types of cycles. Concerning the σ influence, almost no effect is visible on the $\theta = 0^\circ$ $B_a(H_{surf})$ loops, while the amplitude of the $MBN_{energy}(H_{surf})$ loops is highly affected.

V. CONCLUSION

MBN NDT is a promising route for the assessment of internal stresses in GOFesi. This preliminary work reduced the influent parameters by working with single crystals of pre-characterized crystallographic orientation.

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