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Directional magnetic Barkhausen noise measurement using the magnetic needle probe method

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Abstract

A directional local magnetic measurement technique as example of measuring the angular dependence of the magnetic Barkhausen noise in electrical and construction steels at typical quasi-static frequency by the magnetic needle probe (MNP) method is presented. The directional measurement configuration of the MNP method is typical of a half-turn search coil sensor coupled to high gain analogue amplification and high order filtration stages, owing to its very weak induced electromotive force. The method exploits the $MBN_{energy}(H)$ hysteresis cycle (time integration of the square of the MBN voltage signal as a function of the tangent excitation field H) and brings forth stable indicators possibly related to the Magnetocrystalline Anisotropy Energy (MAE). Experimental tests performed on grain-oriented Fe-Si and low carbon steel specimens, and comparison with the conventional search coil measurement results were worth the validation of the MNP method. These results put to the front the good directional selectivity of the MNP method over the conventional MBN sensors adversely affected by the transverse fields at the material surface. Eventually, the printed magnetic needle probe (PMNP) sensor was relatedly described to provide non-invasive directional measurements for continuous structural health monitoring.

Keywords

Barkhausen noise, directional magnetic measurement, magnetic needle probe method.

1 - Introduction

Magnetic monitoring techniques for the non-destructive testing and evaluation (NDT & E) of steel-based manufactured products are widely spread because of the predominant production and use of steel products and related ferromagnetic materials in the industry. Exploiting the evolution of the magnetic behavior in line with material properties' fluctuations of steel products for a correct correlation between the sensing techniques and observable microstructural conditions/anomalies of the materials explains the diversity in magnetic NDT methods. These methods range from surface cracks and defects detections (magnetic Flux Leakages – MFL [1]-[3] and Magnetic Particle Testing – MPT [4]) to microstructural changes (magnetic Incremental Permeability – MIP [5]-[7] and B(H) measurement [8]-[10]), and eventually, investigation of mechanical stress of diverse origin (magnetic Barkhausen noise MBN [11]-[13]).

Magnetic Barkhausen noise (MBN) has been used for decades to evaluate microstructural properties in ferromagnetic materials [14]. The observable material anomalies such as: precipitates, inclusions, defects, dislocations, micro-strains etc., translate into microstructural impediments, generally referred to as materials pinning sites, whose interaction with magnetic domain walls' motion forms the "*raison d'être*" of the Barkhausen effect [15]. It is the characteristic result of irregular magnetization or demagnetization processes of a ferromagnetic material submitted to one or more external excitations (magnetic [16], thermal [17] and even mechanical [18]). Over the magnetization or demagnetization processes, the magnetic domain sizes' fluctuations result in natural energy minimization due to energy spent in overcoming the pinning sites, consequence of the domain walls jerky's motion [19]. Every domain wall motion generates local flux variations which, in turn, trigger discontinuous magnetic flux density displayed as series of electrical pulses induced in the magnetic sensor.

Hence, the dependence of MBN measurement accuracy on the quality and sensitivity of the sensing device [20][21].

The Barkhausen emissions typically draw from magnetic flux variations at the material's surfaces as can be captured using inductive sensors. A number of factors however affect the MBN measurement, among which are the sensor design parameters [14][20][21]. Besides, the absence of a common standard design, size and specification for conventional MBN probes may, in one way or the other, impact the research interest for such sensors [22]. In fact, of the existing variety of magnetic sensors for MBN measurement, the pickup coil stands out as the most popular in use. Generally referred to as the pickup unit – in reference to the magnetization unit which generates the excitation field – the coil configuration and geometry have long been at the core of the MBN method optimization perspectives [21]. Several design modifications, running from the earlier surrounding and search coil (Fig. 1a to the common air/ferrite core pickup coil (Fig. 1b and d) set-up (also called pancake-type coil) led to an improved sensitivity of the probes [20][23]. One can cite, for instance, the experimental investigation by Stupakov et al. [20] on the effects of different pickup core material types (from mild steels to cast irons), size and number of turns, on the sensitivity and quality of the pickup coil sensor for different experimental configurations. The results showed that the addition of a core material to the air core pickup led to 3–5 times the amplification of the MBN responses depending on the core material type. As for the various magnetic core materials, their MBN responses were yet alike for equivalent probes' configuration. This investigation equally pointed out the ineluctable necessity for magnetic core for measurements at typical quasi-static magnetization (about 1Hz) and its improved effect on the measurement stability with respect to the coil lift-off [20].

Such a dependence on the magnetic core material for measurable MBN responses raises the issues of quality, sensitivity and directional selectivity of the pickup coil sensor, generally relinquished to MBN leakages measurements from unpredictable directions yet not strong enough to create a measurable electromotive force. While the surrounding coil and search coil sensors give access to well-defined directional information, they are both limited by the unidirectional measurements; parallel to the longitudinal axis. Moreover, the surrounding coil (Fig. 1c) is further restricted to the specimen's geometry on which it is enwrapped while the search coil sensor is destructive in nature [24]. A later MBN sensor based on an anti-series connection of two similar coils in close proximity can also be used to cancel out the magnetizing frequency component and offers a much better signal to noise ratio (Fig. 1c) [25].

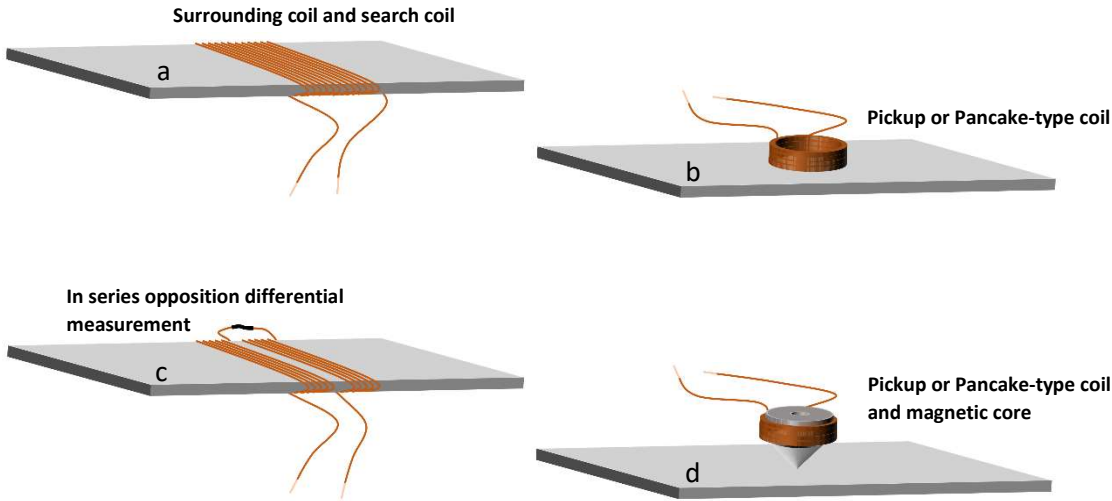


Fig. 1a Wounded coil MBN sensor, 1b Pancake coil MBN sensor, 1c In series opposition differential measurement, 1d Pancake coil and magnetic core MBN sensor.

The current research trend of alternative and/or self-made magnetic sensors for MBN measurements are perceptible in the literature [20] [26]-[29]. These MBN sensors, usually for research purposes, lay emphasis on either upgrading existing probes or rolling out new probe design while taking into account the design parameters, crucial for the operation of the measurement system as a whole. These innovations, while interesting in terms of sensor

reproducibility and stability, fail to accurately showcase the claim for directional selectivity of the MBN sensor as applied in angular dependent measurements. One running counter to such innovation is exemplified by the magnetic needle probe (MNP) sensor herein studied. A significant advantage of the latest MBN sensor over the others is the directional selectivity of the measurement long-awaited in MBN measurements. By coupling the magnetic needle probe (MNP) method to a highly performing signal processing, we propose a local Barkhausen noise sensor easy to move and which provide accurate directional measurements. To validate this new sensing method, comparison with search coil measurements was carried out on anisotropic FeSi 3% Grain-Oriented steel and low carbon steel specimens under typical quasi-static magnetic field. The MBN_{energy} was calculated and plotted to provide stable and reproducible magnetic information. Remarkable connections between the MBN_{energy} and the Magnetocrystalline Anisotropy Energy (MAE) can be highlighted.

The structure of the manuscript can be resumed as follows: the fundamentals of the MBN_{energy} will be described in the first section of this manuscript. Then, the second section reviews the state-of-the-art of directional MBN measurements. The theoretical basis of the magnetic needle probe and its directional selectivity dependence will ensue in the next section. The MBN sensing process will be described after. Large number of comparison with search coil measurements will be used in the experimental validation. Discussion over the relation between MBN_{energy} and MAE are equally provided. In the last section, perspectives will be given including the possibility of printing the MNP for providing a non-intrusive MBN directional sensor solution.

2 – Methods

2.1 The MBN Energy

The Barkhausen noise signal is linearly connected to the domain wall speed. The speed, density and timing of the Barkhausen noise events have strong bonds with the tested specimen micro-structure alongside; the precipitations, micro-residual stresses, cracks and defects of diverse origin, which are in some way influencing the domain walls motion. By analyzing the magnetic Barkhausen noise, precise information on the micro-structural content and materials properties can be obtained. In bulk specimen, the Barkhausen noise is a stochastic phenomenon and the voltage observed from a magnetization cycle to another will always be fundamentally different. The domain distribution is unpredictable; it depends on so many parameters such that identical Barkhausen values never happen.

Since the first magnetic Barkhausen noise (MBN) non-destructive testing devices, researchers and users have always striven to replace the erratic raw signal with stable parameters (the raw signal RMS value, the MBN envelope, the sum of the MBN peaks amplitudes [30]-[32] ...).

Unfortunately, most of these parameters lack physical meaning.

More recently, in [13][33]-[36] authors proposed another stable indicator called Magnetic Barkhausen Noise energy (MBN_{energy}) which can be calculated thanks to Eq. 1 below:

$$MBN_{energy} = \int_0^T \text{sign}\left(\frac{dH(t)}{dt}\right) (V_{Barkhausen}(t))^2 dt \quad (1)$$

By plotting the MBN_{energy} as a function of H, a hysteresis cycle $MBN_{energy}(H)$ can be observed.

After rescaling, the MBN_{energy} comparison with the classic B(H) hysteresis cycles lead to very profitable information. Assuming the domain walls motion as the only source of hysteresis losses, the rescaling factor is set when the areas of the $MBN_{energy}(H)$ and the B(H) hysteresis cycles are similar.

Although the so-called MBN_{energy} is not, strictly speaking, an energy, it is connected to the domain wall kinetic energy. During the magnetization process, the abrupt displacement of a domain wall gives rise to a flux variation over time, which in turn induces a voltage in the dedicated sensor coil. Considering the Faraday's law of induction, the induced voltage V is proportional to the magnetization rate of change dM/dt (Eq. 2):

$$V \propto \frac{dM}{dt} \quad (2)$$

This average magnetization rate of change can be interpreted as the sum of local magnetization rates of change dm/dt within a volume Ω :

$$\frac{dM}{dt} = \frac{1}{\Omega} \int \frac{dm}{dt} d\Omega \quad (3)$$

This time differential dm/dt can be decomposed as:

$$\frac{dm}{dt} = \frac{dm}{dx} \frac{dx}{dt} \quad (4)$$

dx and $d\Omega$ are respectively an infinitesimal change of displacement and volume. In most of the materials, inside magnetic domains, the term dm/dx is zero since there is no spatial variation of the magnetization. The term is nonzero only in magnetic walls. If we assume that the spatial variation of magnetization is constant (with its value depending on the domain wall width) in the domain walls, the time differential of the local magnetization is proportional to dx/dt ; interpreted as the domain wall velocity. As a result, the sensor voltage V is proportional to the domain wall velocity.

$$V \propto \int \frac{dx}{dt} d\Omega \quad (5)$$

In a practical situation, where multitude of domain walls are displayed quasi simultaneously and over different locations within the material, the resulting signal is made out of microsecond pulses, which are the superposition (whether constructive or destructive) of these induced pulses. By integrating the square of the signal (Eq. 1), the resulting area of the $MBN_{energy}(H)$ cycle is an image of the kinetic energy spent by the magnetization process. The

stochastic, unpredictable MBN raw signal is clearly a limitation for the industrial development of MBN as a NDT method but MBN_{energy} indicator constitutes an elegant alternative solution. Now, for an even larger development, the improvement of the dedicated sensors and measurement processes is the second issue which needs to be addressed.

2.2 Directional MBN measurement: the conventional approach

The sensor sensitivity and reproducibility are fundamental in magnetic monitoring and control; a high quality signal is the sine qua none condition to a fine correlation with the microstructural properties. Moreover, the polycrystalline aggregated structures of ferromagnetic steels in industrial applications are expedient for natural intrinsic anisotropic properties whose directional dependence with the applied magnetic field shapes the MBN energy behavior and further evokes the directional measurements concerns [37][38]. The directional selectivity of magnetic sensors is fundamental, more especially in the angular dependent measurements of the Magnetic Barkhausen noise (MBN) [20][29]. It is therefore evident the dependence of magnetic properties on a preferred direction of magnetization, generally referred to as magnetic anisotropy. The magnetic anisotropic behavior of ferromagnetic materials as observed by $B(H)$ measurements [39]-[41], depends on the Magnetocrystalline Anisotropy Energy (MAE); intrinsic characteristic of the crystal structure, grain shape and stress induced anisotropies [40][42]. The resultant orientation of the magnetic moments in magnetic material is mainly governed by combined influence of magnetocrystalline and magnetostatic energies [19]. The crystallographic configuration of most steel materials are suitable for direct correlation between the angular dependence of the MBN energy and MAE. This correlation, while illustrative of the dependence on the texture [42], microstructures or residual stresses of the material [43], may draw to no end difficulties

[44]. Torque curves, magnetization curves, and crystallographic textures [45][46] (commonly from X-ray global texture) are used to precisely characterize MAE, but these methods are not easy to handle and impossible to carry out in a non-destructive context. Nonetheless, the reputability of the MBN methods in assessing the angular anisotropic properties of ferromagnetic steel objects is highly questionable [29][42][47].

Two experimental configurations are common for these directional MBN measurements. The most popular method generally implements manual or motor-operated rotation of the magnetic dipole probes as shown in Fig. 2a. Its experimental setup generally consists of a standard yoke carrying the excitation coil to ensure the magnetization process, suspended over a flat, rotational platform on which stands the wide test specimen with negligible fringing effect. A goniometer can be used to estimate precisely the angular position. A stepper motor ensures the rotational movement and a pickup/pancake coil, the MBN measurement. In this experimental situation, the directionality factor is due to the magnetization process (supposed to be in the yoke direction), however the pancake coil signal is affected by flux variations of every direction which limits the accuracy of the method. However, the energy penalty that characterizes MAE when a magnetic moment is magnetized away from the magnetization easy axis is expected to be smaller in rotating devices, in order to ease magnetization. This consequently argues on the strong correlation between the measured angular dependent MBN response and MAE.

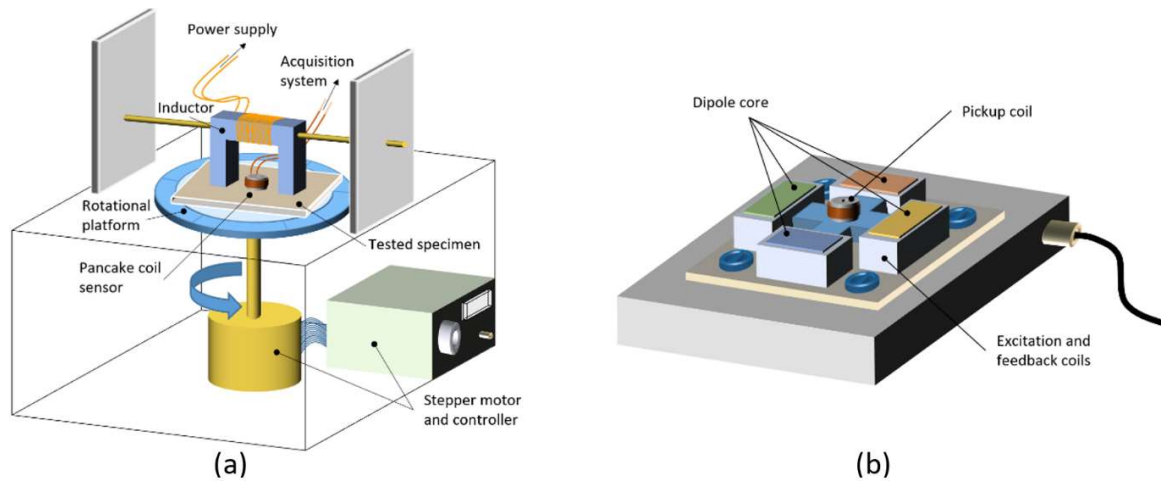


Fig. 2a Directional magnetic Barkhausen noise characterization setup; one-plane goniometer, 2b tetra-pole probe design.

The tetra-pole MBN system designs were recently developed for rapid angular measurement and to eliminate the induced effects due to mechanical rotation of the platform [27][42][48].

The Queen's University's system spring-loaded 4-pole (SL4P) (tetra-pole) probe design is shown in Fig. 2b. It is fundamentally made up of magnetic dipoles pair aimed at generating a superposition field at its center; where the pickup/pancake coil is positioned. The magnetic dipoles produce orthogonal magnetic fields whose magnitude is monitored accordingly via implemented flux control at the four poles of the tetra-pole probe [29]. The flux control is a four-channel analogue feedback circuit coupled to a digital error correction algorithm. This configuration results in an electronically rotated, uniform and stable superposition field, thus generating an angular MBN measurement. The Queen's tetra-pole configuration was found less susceptible to the effects of probe-specimen lift-off, when compared to traditional voltage control algorithm common in MBN system designs [29][49].

But notwithstanding, it is worth noting the defective tangential context of the magnetic sensor and its repercussions on the angular dependence of the MBN measurement, for no significant upgrades on the directional selectivity of the MBN sensors were yet observed albeit the noticeable progress in the measurement configurations. Besides, the measurement dependence on near surface to inbuilt specimen flux equivalence – case at the boundaries

between two media of different magnetic permeabilities (case of air μ_{air} and the material steel μ_{steel} under test), the tangential component B_{steel} just inside the specimen is equal to B_{air} just at the immediate surface outside leans on several assumptions which weakens the accuracy of the measurements [50]. Among them are; the lack of surface currents – if a superconductor material or influenced by the magnetizing coil – and the effects of the sensor lift-off above the material surface [51]. The next section describes how the MNP method goes about the above directional selectivity limits of the current MBN sensors technology.

2.3 Directional MBN measurement by the magnetic needle probe method

2.3.1 The classic magnetic needle probe method

The possibility to record magnetic flux variations in ferromagnetic conductive materials using MNP is quite old, as it was first proposed by Werner [52] in 1949. A few years later, Stauffer in [53] described the first magnetic characterization setup based on this method. At that time, even if the idea of directional measurements for the anisotropy characterization was already attractive, instrumentation limitations forced the researchers to abandon this technique. Almost 50 years later, encouraged by the rise of new technologies, Japanese teams revisited Werner's method for the local characterization of a ferromagnetic lamination [54]-[58].

Anisotropic behavior is complex to observe with the usual electromagnetic NDT sensors but MNP tackles this issue by using two needle contacts to build a half-cross sectional search coil of equivalent contact spacing which can be easily oriented at the 360° over the surface of a tested specimen. It provides a directional measurement set by the geometrical position of the two electrical contacts (see Fig. 3). Based on the potential difference produced by eddy

currents generated by ac magnetization or by domain wall motions, it is possible to measure the flux density in the surrounding area using points 1-2-3-4 as depicted in Fig. 3.

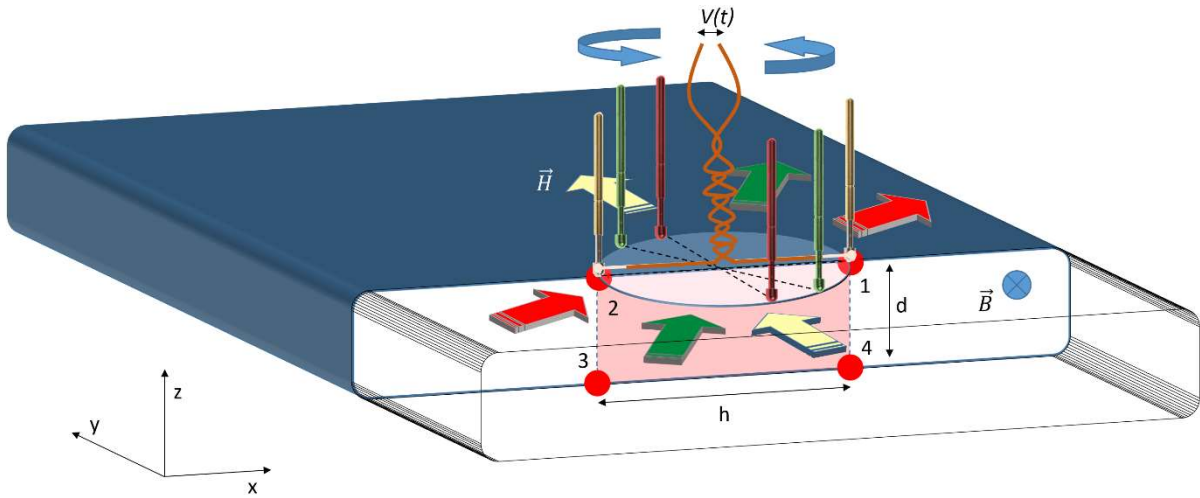


Fig. 3 – Directional MNP, explanation scheme.

As described in detail in [54], the induced voltage (V_{12}) between position 1 and 2 can be approximated to:

$$V_{12} \approx \frac{1}{2} \int_{S_{1234}} \frac{\partial \vec{B}_{1234}}{\partial t} d\vec{S}_{1234} \quad (6)$$

Where B_{1234} and S_{1234} are respectively the homogeneous magnetic field and the cross section through the position 1234. The MNP method, however, to guarantee accuracy and reproducibility in measurements has to mean certain measurement conditions: (1) a minimum probe spacing $h=10$ mm is required [54], while at a significant distance (usually half the specimen thickness ($d/2$)) away from the specimen edges; (2) negligible leakage flux in the enclosed near surface magnetized air [54][55][56]; (3) huge probe spacing to specimen thickness ratio (h/d) to go about the z-component of the induced electric field [57]. Meeting these conditions makes the MNP method a legitimate local magnetic NDT method. Today's applications of the MNP method range from local non-uniform electromagnetic field investigations [59][60], cutting-edge stress [61][62], stress-induced peening processes [63] and homogenization analysis in lamination stack [64].

2.3.1 The magnetic needle probe method as a magnetic Barkhausen noise sensor

As far as we have investigated, even if MNP offers an easy way to obtain local magnetic directional information it has never been used to observe anisotropic MBN behavior. The reason is obvious: the maximum amplitude of the electromotive forces created by the Barkhausen activity in a wounded 200 turns Barkhausen sensor coil is approximately a few millivolts, a simple linear interpolation leads to a few μV for the half a turn MNP sensor. Highly performing acquisition set-up combined to special analogue signal treatment is the only way to isolate and detect such extremely low electromotive force. Fig. 4 below depicts the acquisition process we have been using to observe MBN using MNP sensor:

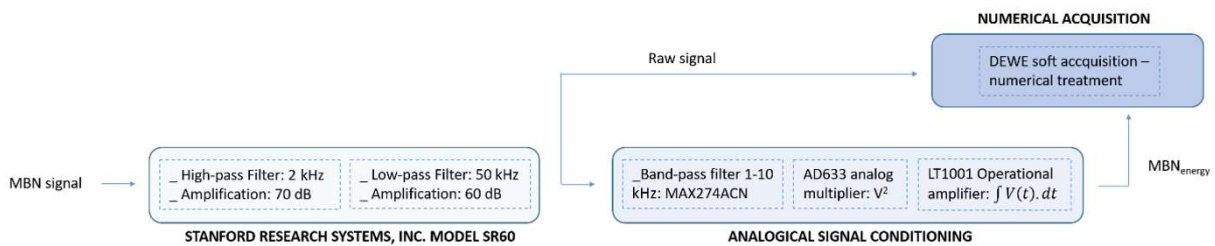


Fig. 4 – MBN signal processing and acquisition description.

The acquisition chain can be decomposed in two stages, a pre-filtering and pre-amplification stage and an analogue signal treatment stage leading to the $\text{MBN}_{\text{energy}}$ quantity. Both stages are described in details in the experimental setup section below.

Despite the relatively weak measurable MBN voltage amplitude, the MNP method transcends all existing sensors by its complete directional selectivity for tangential measurements. The sensor is equally free from lift-off effects since it is in constant electrical contact with the specimen. Its electrical wiring further lessens the induced effects of leakage flux and surrounding noise for an optimal sensor performance and efficiency.

3 – Results

3.1 Experimental setup

Fig. 5 below depicts an overall 3D view of the experimental setup developed for the MBN directional measurement using MNP.

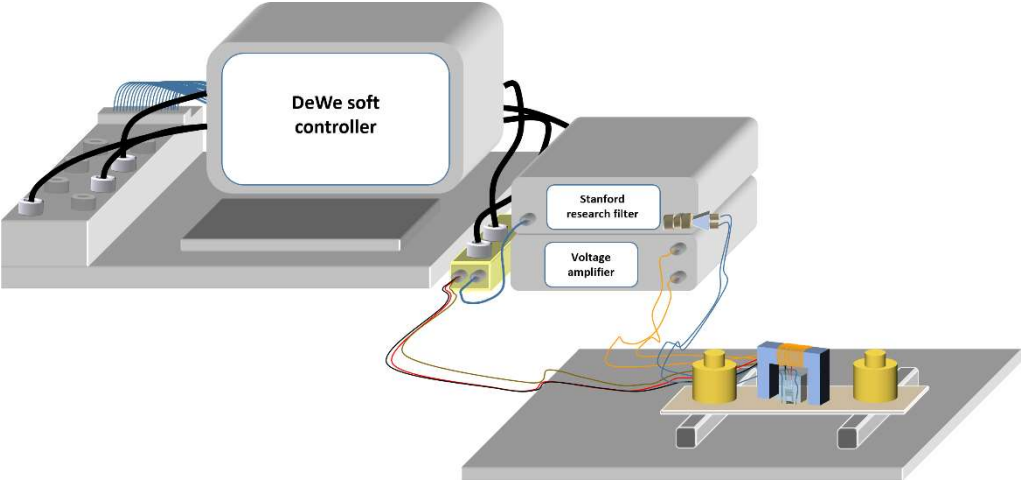


Fig. 5 – 3D overview of the experimental setup.

The magnetic excitation is ensured by a reduced size U-shape yoke (see Fig. 6 below), made out of Fe-Si oriented grains laminated magnetic core. This yoke is wound by a 500 turns excitation coil. A power amplifier Kepco BOP 100-4M in its imposed current configuration and driven by a frequency generator Agilent 32220A ensures the coils' electrical energy supply.



Fig. 6 – Magnetic Inductor; core dimensions (left), magnetic Inductor unit (middle) and magnetic sensors (right)

Two 1.27 mm pitch spring test probes with point tip are used for the needle probe measurement. A noise shielded radiometric linear Hall probe (SS94A from Honeywell)

positioned ideally just in the middle of the needle probes measures the surface magnetic field H_{surf} over the probe area.

The MNP signal is filtered through a dual channel filter Stanford research systems model SR650. The cut-off frequencies were set to 2 and 50 kHz. The high pass stage comes first with an input and output amplification gains set to 50 dB and 10 dB, respectively, then the low-pass stage with a gain amplification of 50 dB and 10 dB. The data-acquisition of both the filtered signal and the hall sensor voltages is ensured from a DEWESoftX2 data acquisition software associated to a SIRIUSif 8×CAN data acquisition. An analogue treatment including the square calculus (AD633 analog multiplier) and the integration steps (low noise operational amplifier LT1001) is performed to obtain the MBN_{energy} waveform. Finally, before each new acquisition, the reproducibility of the results is ensured by a complete demagnetization of the tested sample. The single sheet tester described in [64]-[67] is used for this demagnetization. The excitation coil is subjected to an exponentially decreasing periodic triangular voltage signal. The frequency of the triangular voltage is 50 Hz and a complete demagnetization lasts approximately 2 minutes.

3.2 Experimental results

3.2.1 MNP for the MBN characterization

All the experimental tests have been achieved using the experimental setup and procedure described in the previous section. Two types of materials have been tested; each specimen is coming from the same batch of material type. As our objective is to develop a MBN directional sensor, the first nature of material selected are FeSi oriented grain laminations with a 3wt% silicon content. These laminations are characterized by a strong magnetic anisotropic behavior. Tab. 1 below reveals the FeSi GO typical properties observed at room temperature.

Tab. 1 – FeSi GO (3wt %) and low carbon steel typical magnetic properties.

	Composition	Max. relative permeability (μ_{max})	Coercive field H_c (A/m)	polarization J_s (T)	Curie temperature T_c (°C)	magnetostriction $\lambda_s=(\Delta l/l)_s$
FeSi GO	$Fe_{97} - Si_3$	$15 - 80 \times 10^3$	4 - 15	2.02	750	$1 - 3 \times 10^{-6}$
Low carbon steel	$Fe_{98,81 - 99,26} - C_{0,14 - 0,2} - Mn_{0,6 - 0,9} - P_{<0,04}$	1.1×10^3	800	2.01	770	4.6×10^{-6}

These laminations exhibit a varnish coating (electrical isolation) applied during the stack manufacturing and their thickness is 0.35 mm. These varnish has to be removed locally to ensure the electrical contact required by the PMNP. We never measured the microstructural details of the FeSi GO laminations tested in this study, however some information can be found in [68]. The second type of material selected are low carbon steel, 0.5 mm thick laminations. The magnetic properties of this type of material are proposed in Tab. 1 as well. The first experimental results exposed below (Fig. 7, 8) have been obtained with the FeSiGo laminations. For comparison purposes, the search coil was wound round the 1-2-3-4 area (Fig. 3), after holes had been drilled through the lamination to allow the 30 turns search coils deployment. As we can see in Fig. 6 below, four directions for both the needle probe and the search coil have been tested. 0° and 90° are respectively the rolling and the transverse directions.

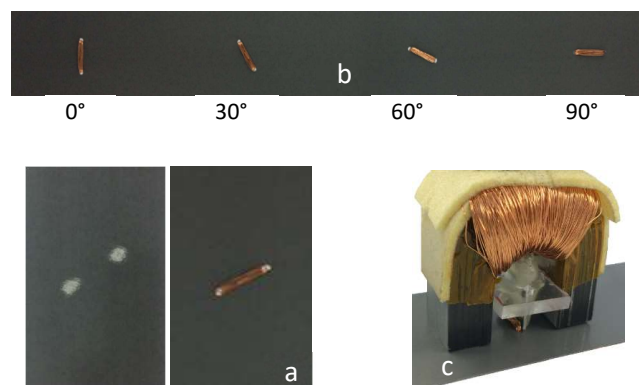


Fig. 7a Varnish coating removal and search coil sensor, 7b Search coil setup at different measured angles, 7c Inductor and search coil.

Fig. 8 below depicts the raw signals obtained for both the search coil and the needle probe sensors. On a one hand and as expected, the needle probe measurements are a little noisier,

on the other hand, the $MBN_{energy}(H)$ hysteresis cycles in Fig. 9 reveal relatively good agreement. It is worth noting the two MBN peaks for the transverse direction excitation, each peak is related to a high permeability zone as observed on the $B(H)$ hysteresis envelope.

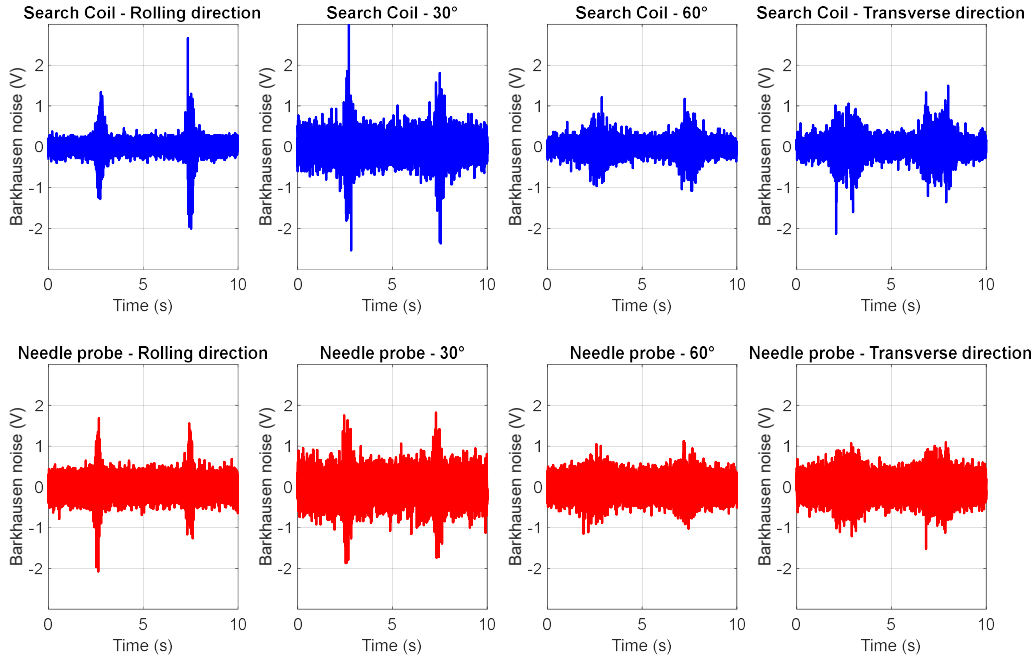


Fig. 8 – Comparisons MNP/search coil measurements, for MBN raw signal at different angles.

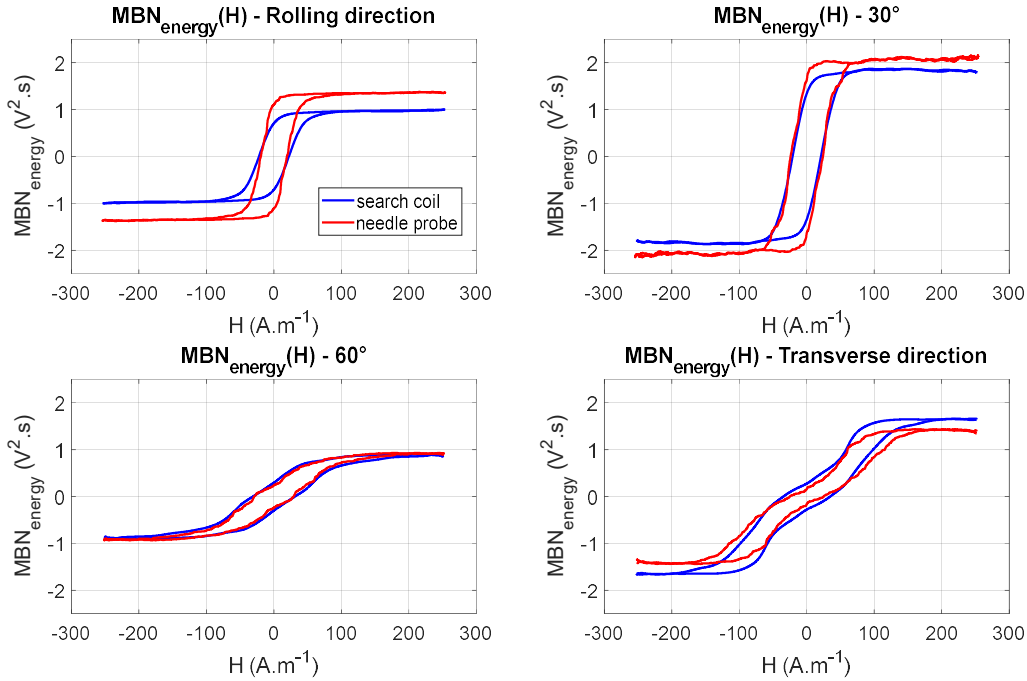


Fig. 9 – Comparisons MNP/search coil measurements, for $MBN_{energy}(H)$ hysteresis cycle at different angles.

Fig. 10 depicted raw signals and MBN_{energy} hysteresis cycles again, low carbon steel specimens are tested here. The experimental $MBN_{energy}(H)$ hysteresis cycles plotted in Fig. 9 and 10 have been obtained using the experimental setup described in section 3.1. Good fits are observed. Even though not plotted here tests on varying direction show no significant anisotropic behavior.

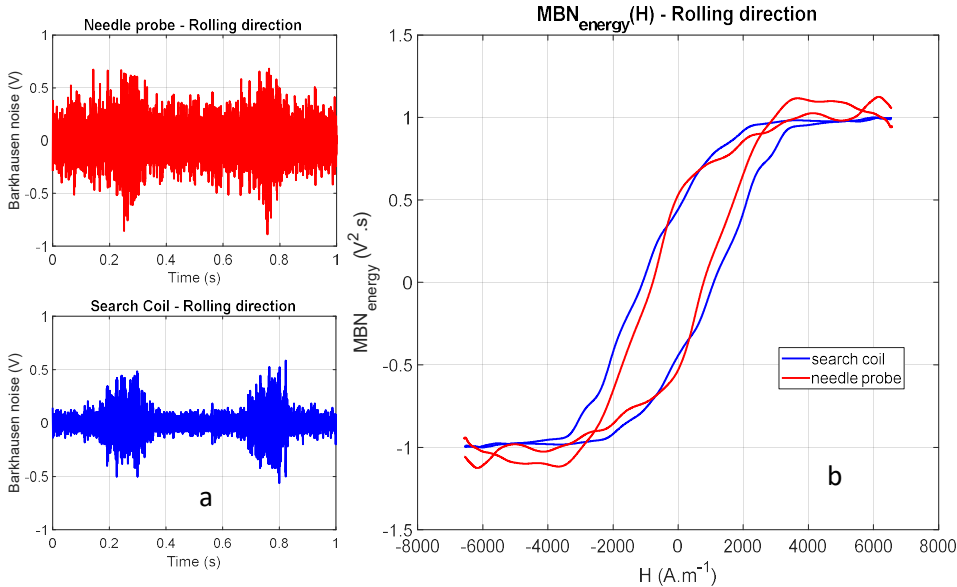


Fig. 10a, Low carbon steel, comparisons MNP/search coil measurements for MBN raw signal, 10b for $MBN_{energy}(H)$ hysteresis cycle.

The signal crossing in the needle probe plot (Fig. 10) close to the saturation state has no physical sense and is probably due to some undesired noise incorrectly filtered.

3.2.2 MAE observation from $MBN_{energy}(H)$ cycles

Magnetic controls/treatments are performed all along the ferromagnetic steel fabrication and lifetime. Ferromagnetic steel is intrinsically anisotropic, mostly due to MAE. Once a magnetic process/treatment is over, remanent magnetic states are observed. Their amplitudes depend on the magnetic excitation direction. High remanent induction levels are undesired since they generate stresses, mechanical interactions and early stage degradations. MAE is therefore a fundamental property which needs to be characterized precisely to assess these issues. MAE

evaluation requires complex, fixed experimental setups [69]. MBN could constitute an elegant alternative solution to evaluate MAE. The sensitivity of the MBN raw signal to MAE has already been demonstrated especially in the saturation remanence branch [70]. In this study, PMNP and $MBN_{energy}(H)$ hysteresis cycles have been combined to establish the MAE sensitivity of four indicators, directly read on the $MBN_{energy}(H)$ hysteresis cycles:

- _ The remanent MBN_{energy} (Fig. 11, blue dot)
- _ The coercive field (Fig. 11, red dot)
- _ The $MBN_{energy}(H)$ hysteresis area (Fig. 11, yellow zone)
- _ The $MBN_{energy}(H)$ average slope (Fig. 11, black line)

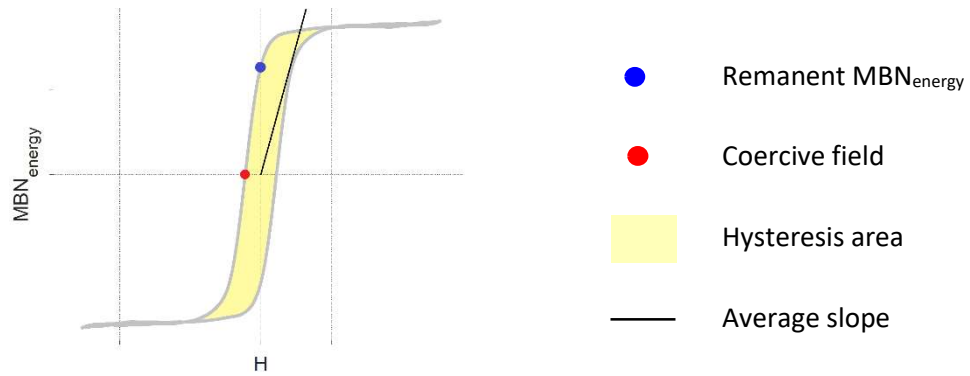


Fig. 11, $MBN_{energy}(H)$ hysteresis cycle indicators.

MAE is well established in FeSi 3% GO specimens, and therefore this nature of material is convenient for this study. In a single crystal MAE is ruled by eq. 7 below (for details see, [68]):

$$W_{\alpha}^K = K_1(\gamma_1^2\gamma_2^2 + \gamma_2^2\gamma_3^2 + \gamma_3^2\gamma_1^2) + K_2(\gamma_1^2\gamma_2^2\gamma_3^2) \quad (7)$$

According to [69], K_1 and K_2 are respectively $3.4 \cdot 10^4 \text{ J}\cdot\text{m}^{-3}$ and 0 for the FeSi 3% GO; solving eq. 7 leads to the MAE surface depicted on the left hand plot of Fig. 11 below. On Fig. 12, right hand side polar plot corresponds to the theoretical MAE through the cross section of the FeSi 3% GO lamination. Twenty four $MBN_{energy}(H)$ hysteresis cycles have been plotted and analyzed (The angular orientation is varying from 0 to 360 ° and the angle step is 15°, where 0° and 90° are respectively the rolling and the transverse direction).

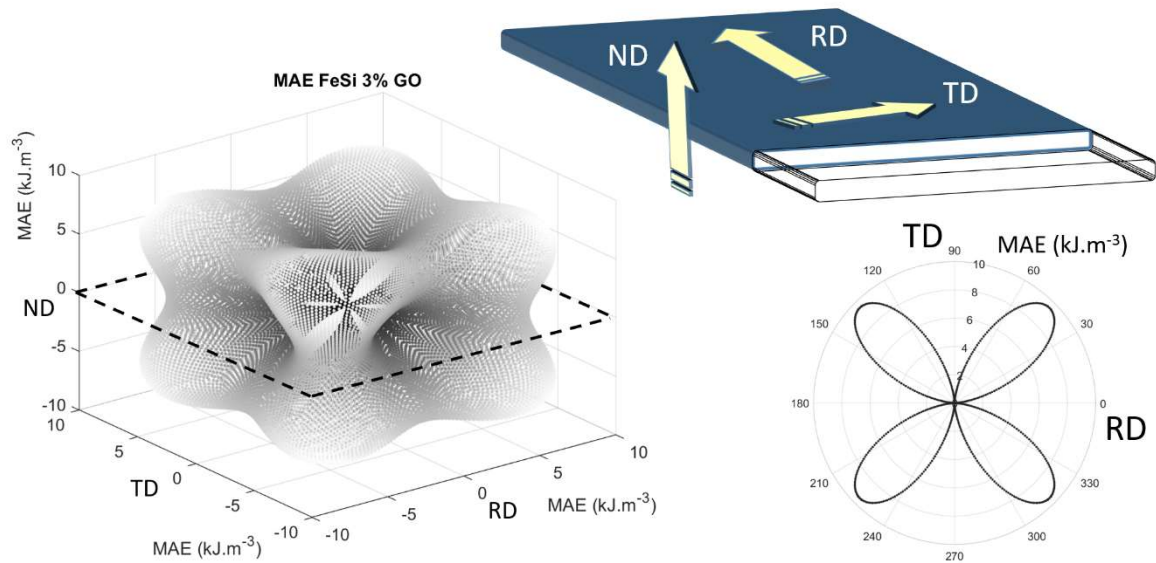


Fig. 12, Theoretical MAE distribution in a FeSi 3% GO.

The angle dependences of the 4 $MBN_{energy}(H)$ indicators are shown in Fig. 13.

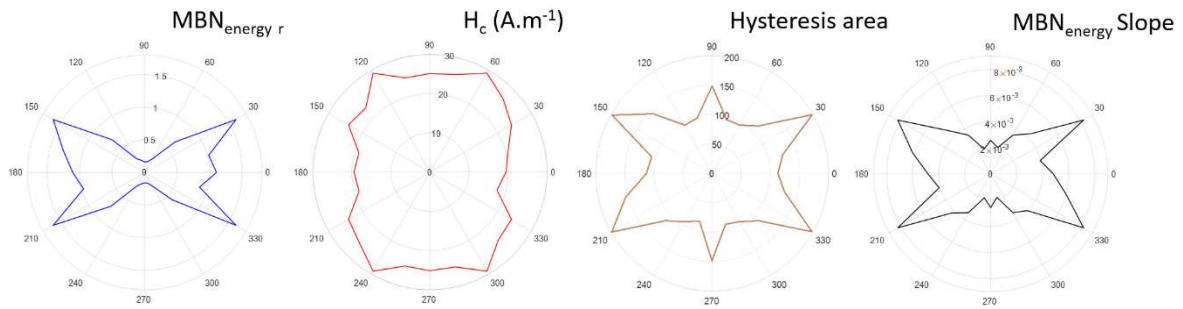


Fig. 13, Angular dependence of the 4 $MBN_{energy}(H)$ hysteresis cycle indicators.

The evaluation of the most MAE sensitive, MBN_{energy} indicator is not accurate since none of the four tested parameters are reproducing closely the shape of Fig. 12 right hand side plot.

However, the remanent MBN_{energy} and the average slope plots happen to be the closest. Many reasons can be proposed to justify the inaccuracy of the four parameters, including:

- _The texture has a strong influence on the FeSi GO macroscopic anisotropy, and is probably influencing MBN as well.

- _ The theoretical distribution of MAE is given for a single crystal, even if the MBN measurement is local, we are probably dealing with a polycrystalline area where the MAE distribution can be slightly different.

This prospective work constitutes a first stage of further researches, even if the first results look interesting the emergence of a given indicator is not established. In a close future, additional research will be done focusing particularly on the remanent to saturation branch of the MBN_{energy} hysteresis cycle.

3.2.3 Printed magnetic needle probe method: a non-intrusive way to sensor Barkhausen noise

Recent progress in printing technologies via improved miniaturized printed electronics as well as the development of non-magnetic conductive inks has paved the way for surface-printed conductive tracks in an authentic replica of a classic needle probe method [64]. Thus, its name, printed magnetic needle probe (PMNP) method. Its conception substitutes the traditional needle electrodes by a non-magnetic guided track of conductive varnish that runs from the measurement points on the specimen to the copper connective straps at its edge for signal acquisition. For specimen treated with surface insulation coating, this coating needs to be locally scrapped off beforehand so as to guarantee electric continuity between the specimen and the later deployed conductive track. For the specimens free of insulation coating, a non-conductive layer has to be printed first to isolate the PMNP conductive ink from the tested specimen. Implementation of the PMNP method is twofold; the mask or manual printing method and the computer aided design (CAD) printing method. These two design methods are detailed in [64]. PMNP sensor takes advantage of its miniaturized geometry to further extend its scope of application to an embedded magnetic sensor inside a stack of laminations for homogenization testing/evaluation in magnetic cores. As a permanent sensor, it reduces the reproducibility issues due to the human factor (lift-off, electrical connections ...). In this study PMNP have been tested on the RD and TD direction of the FeSi 3% GO laminations (Fig.

14 below). Well defined MBN signals have been measured confirming our expectation and the feasibility of PMNP as a MBN sensor.

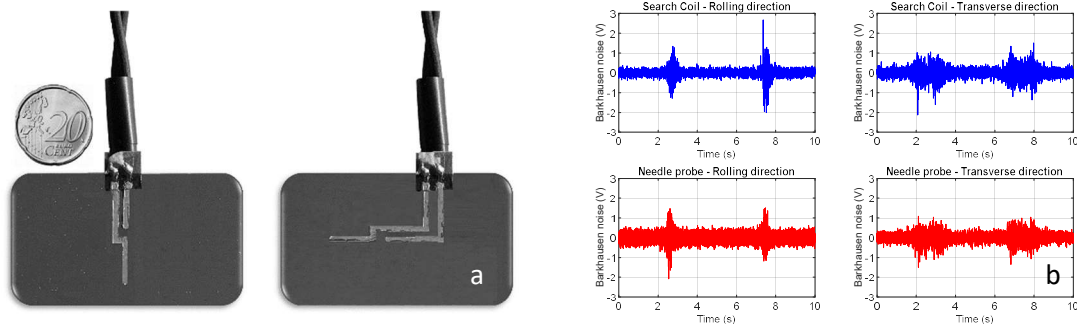


Fig. 14a, PMNP RD and TD configuration, 14b Comparisons PMNP/search coil measurements, raw signals.

4 – Conclusion

Magnetic Barkhausen noise (MBN) controls are performed daily by the steel producers and steel users companies. MBN conveys precious information about the integrity of tested specimens. Different sensor designs and signal processing methods have already been proposed to observe MBN but progress in this domain are still expected. In this research, the magnetic needle probe method (MNP) has been used to observe MBN. Although MNP electromotive force amplitudes coming from MBN activities range in the microvolts level, by combining a dedicated signal processing to the MBN_{energy} stability, we succeeded in reconstructing a reproducible directional MBN signature. Good fits were obtained by comparing the PMNP measurement to a 30 turns search coil, confirming PMNP as an authenticate MBN directional sensor. The strong bond between MBN and MAE has already been commented in the scientific literature. In this research, we used PMN and its access to directional information to check on four different $MBN_{energy}(H)$ hysteresis cycle indicators and it figured out that the remanent MBN_{energy} and the average slope are the most significant MAE indicators. Finally, conductive ink and printing methods have been used to print PMN and get

access to MBN directional permanent sensors useful in a long term structural health monitoring purpose.

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