Non-destructive testing of ferromagnetic steel components based on their magnetic response

Benjamin Ducharne

Nondestructive Testing of ferromagnetic steel components based on their magnetic answer

B. Ducharne[1,2]

[1] Laboratoire de Génie Electrique et Ferroélectricité – INSA de Lyon, Villeurbanne, France.

[2] ELyTMaX UMI 3757, CNRS – Université de Lyon – Tohoku University, International Joint Unit, Tohoku University, Sendai Japan.

ABSTRACT

The magnetization processes have been used for years to observe mechanical or microstructural properties in ferromagnetic steel. The usual techniques rely on standard specimens, time-consuming experimental campaigns, and rejection thresholds. These demanding methods give limited satisfaction, and controllers are looking for alternative solutions.

For physical reasons, every magnetization mechanism (domain walls bulging, domain walls irreversible motions, etc.) is characterized by its specific sensitivity to a given property to be evaluated. An ideal way to monitor this property is to develop an experimental situation where the most responsive magnetization mechanism can be isolated and easily monitored.

This chapter introduces first the nondestructive testing methods based on the magnetization mechanisms. Then, the targeted properties, i.e., the specific information required by the industrials or nondestructive testing end-users, are described (internal stress, microstructural properties, to name a few). It is followed by the magnetization mechanisms definition and some associated experimental situations. Finally, discussions and conclusions are provided.

1 – Introduction

Magnetism entails many facets in contemporary Nondestructive Testing (NDT):

- A way to convey and transmit information like in eddy current testing [1].
- A source of a mechanical force like in magnetic particle inspection [2].
- The natural earth field being distorted by defects or properties to be assessed like in metal magnetic memory [3].
- An induced magnetic field distorted by surface or sub-surface defects like in magnetic flux leakages [4].

A new trend consists in exploiting magnetism differently, still for an NDT purpose, but the focus is set on the magnetization mechanisms of ferromagnetic components and their capability to indirectly convey information about targeted properties (mechanical, microstructural, etc.) [5].

Steel production is by far more extensive than any other metal production. Steel is used in domains as diverse as transportation (railway track, boat tanks, etc.), construction (concrete re-enforcing bars, bridges, etc.)[6], and energy (pipelines, turbines, etc.). In the steel industry, the demand for NDT is immense. Historically, surface defects (porosity, corrosion, cracks, etc.) were first targeted, but internal properties like residual stresses, plastic strains, internal dislocations, and the likelihood of failure due to creep or fatigue have grown in interest recently.

Every NDT method (ultrasound, magnetic particle inspection, X-Ray diffraction, etc.) can be applied to steel. Still, the techniques relying on magnetization mechanisms are unique to ferromagnetic materials, including steel [7].

The idea of developing NDT from the magnetization response is not new, and the first scientific publications on this topic can be found in the sixties [8][9]. Firstly, developed at the academic level, it soon grew significant interest among steel companies. The first industrial machines dedicated to this topic were commercialized in the eighties and found relative success [10]. Nowadays, devices like the Fraünofer IZFP 3MA or the Stresstech® rollscan are relatively common [11]-[13].

The implementation and configuration of these devices are all based on the same protocols [14][15]. A large amount of experimental data is collected, then specific indicators evaluated on this data are defined. Eventually, complex mathematical correlations are established with targeted properties predetermined on well-known specimens. This method relies on meticulous experimental campaigns and leads to rejection thresholds setting acceptance limits. This configuration process is tedious, and not always reliable, and manufacturers are looking for alternatives.

Unfortunately, the configuration issue is not the only one mentioned by the end-users; the signal interpretation, indicators selection, and physical meaning are also recurrently stated as holding back this technological development [16].

Recently, researchers have proposed a new, fundamentally different approach. They are convinced that the sensitivity to the targeted properties differs from one magnetization mechanism to the other [5][17]. Progress in this domain comes from developing experimental

situations where those mechanisms are separated. Once the targeted property is well defined, the final step consists of exploiting the most sensitive magnetization mechanism.

In this book chapter, we will introduce in the first section what is nowadays considered in this domain as a targeted property. Then, the magnetization mechanisms will be described, such as the experimental situations where these mechanisms can be ideally observed. In the third section, correlations between the targeted properties and the magnetization mechanisms will be shown, and the last paragraph will include conclusions and perspectives.

2 – Nondestructive Testing based on the magnetization mechanisms: the targeted properties

In the domain of NDT based on the magnetization mechanisms, the targeted properties to be assessed can be classified into three categories:

- Internal mechanical stress
- Surface and sub-surface heterogeneities
- Aging, creep, and microstructural variations vs. time

2.1 The internal mechanical stress

In continuum mechanics, stress is defined as a physical quantity that expresses the internal forces that neighboring particles of a continuous material exert on each other. Internal mechanical stress is a critical factor in material performance, structural reliability, and the lifetime of industrial systems. Many techniques have been developed for their assessment

[18][19]. The hole-drilling method [20], the contour method [21], the crack compliance method [22], and the stripping method [23] are mechanical techniques [19]. Chemical methods exist, too [24]. These techniques are destructive. NDT methods have also been developed [25], like diffraction methods (X-ray, Neutron), ultrasonic, or acoustic [26]. All these techniques can be applied independently from the tested specimens' nature. For ferromagnetic steel, methods based on the magnetization processes can be used as well. Eddy currents testing [27], magneto-acoustic emission [28][29], electromagnetic acoustic transducer [19], and Magnetic Barkhausen Noise (MBN) [30]-[32] are some of the most used magnetic methods, alone or in combination with other NDT techniques [33].

2.2 Surface and sub-surface heterogeneities

Every metallic material contains heterogeneities. Inherent to the elaboration process, they spread all over the materials. These defects may be inclusions (metallic or non-metallic), segregated or plastically deformed areas, cracks, precipitates of a second phase (iron carbide in steel), etc. [23][34]. These heterogeneities not only affect the mechanical properties. They are detrimental to the surface aspect and facilitate corrosion [35][36]. Furthermore, they can induce stress concentrations and thus cause premature failure of in-service components. The traditional NDT methods currently used to analyze the quality of new and in-service materials are mainly dedicated to detecting the heterogeneities. These methods include ultrasound [37], X-ray [38], eddy current [1], or electrostatic conductivity [39]. Successful results have been obtained using these techniques for non-metallic inclusions. However, metallic inclusions or heterogeneities are more complex to detect due to their similar physical properties to the host metal.

Surface defects are relatively easy to detect, and many existing techniques such as optical scanning can be used for this [40]. Subsurface damage observation is much more challenging. Subsurface damages are highly detrimental. They directly determine the performance and lifetime of a mechanical part, and their assessment is a priority [41].

2.3 Aging, creep, and microstructural variations vs. time

In thermal power plants, ferromagnetic steels used in turbines and boilers are permanently exposed to high temperatures and pressures [42][43]. Similarly, in aeronautics, steel materials are exposed to extreme external conditions [44]. This continuous exposure can lead to irreversible microstructural changes. If not monitored on time, they can be followed by severe damages or even catastrophic incidents. Classical NDT techniques aim to identify material flaws at a later stage. Once a crack is initiated, it grows exponentially, and at the detection time, it is often too late to avoid irreversible harm. However, it has already been experimentally verified that a specimen undergoes local microstructural changes before crack initiation. If monitored on time, such microstructural clues can help anticipate failures. The concept of crack length versus time is shown in Fig. 1 below. Microscopic imaging methods can be used to observe microstructural variations. These methods include scanning electron microscopy (SEM) [45] and electron backscatter diffraction (EBSD) [46]. The tested specimens must undergo specific shape and size and require extensive sample preparation effort beyond the NDT's scope to obtain reliable data.

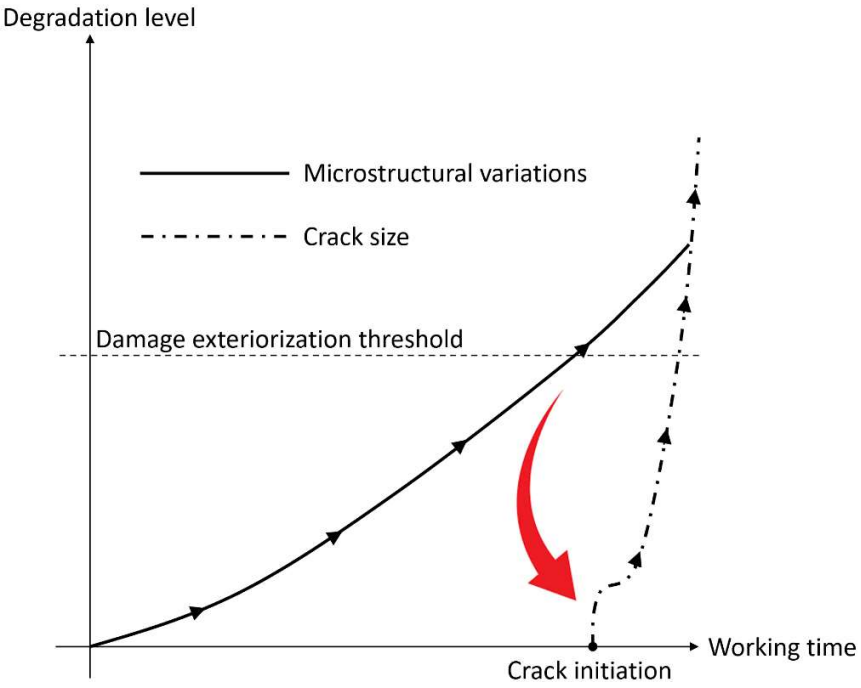

Fig. 1 – Comparison of crack size vs. time, microstructural variation vs. time

These methods find application at the laboratory scale, but in-situ applications are definitively unimaginable. Fig. 2 shows the microstructural evolution of creep on a strain vs. time curve [47]. Initially, isolated cavities are created, eventually growing and forming larger oriented cavities. Under higher strain, oriented cavities result in crack formation and, finally, material rupture.

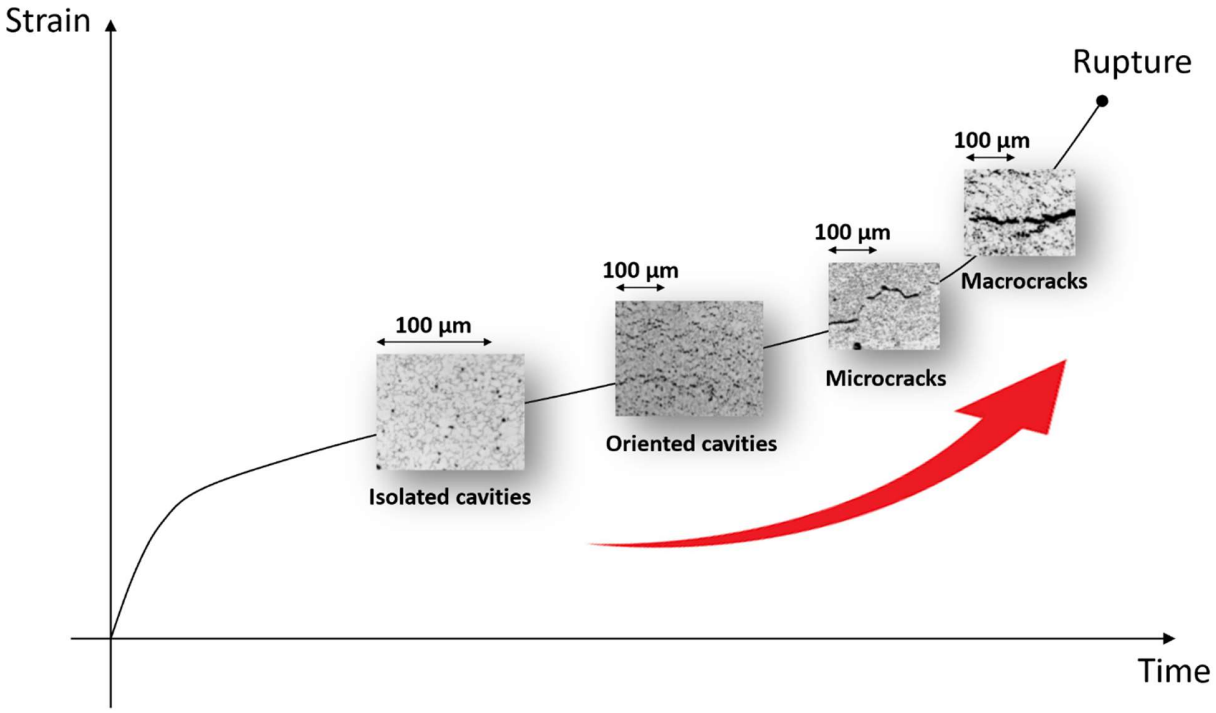

Fig. 2 – Strain vs. time, illustration of the creep effect

To replace SEM or EBSD in an industrial context, one promising solution is to use the magnetization signature and correlate it to the material microstructure. The magnetic response is strongly dependent on the microstructural properties and distribution, and contemporary magnetic sensors can easily detect local information. Magnetic techniques have already been tried to identify creep, mostly on low-alloy steel, and a relatively poor correlation was found, as illustrated in Table 1 below [42]. In this table, selectivity means the choice and effectiveness of the method. Quite surprisingly, opposite conclusions can be found in the literature about the selectivity of magnetic methods where Sposito et al. [42] rank it as poor, Tomas et al. result [48] in reliable applicability to detect early-stage fatigue and foresee lifespan.

Table. 1 – Comparison of NDT methods for creep detection

Technique	Sensitivity	Selectivity	Damage type
Replication [42]	Surface only	++	Localized
Ultrasonic [49]	Average over thickness	++ (later stages) Surface sensitive	Localized / Volumetric
Magnetic properties [50]	Bulk	-/+	Volumetric
Barkhausen emission [51]	Thin sub-surface layers	+ (Surface sensitive)	Localized
Eddy current [52]	Decays rapidily with depth	--	Volumetric

++ Good

-- Poor

3 – The magnetization mechanisms

3.1 Ferromagnetism

Ferromagnetism occurs from atomic magnetic moments of electronic origin becoming ordered into small regions known as magnetic domains [53]. Each magnetic domain is typically composed of 10^{12} to 10^{18} magnetic moments aligned in the same direction and orientation. The size of the magnetic domains can vary from 10^{-4} to 10^{-6} m. At the domain boundaries, the atomic magnetic moments change their direction. These boundaries are called domain walls. As illustrated in Fig. 3, inside a domain wall, the change in direction progressively takes place over several hundred atoms (the exact number depends on energy minimization).

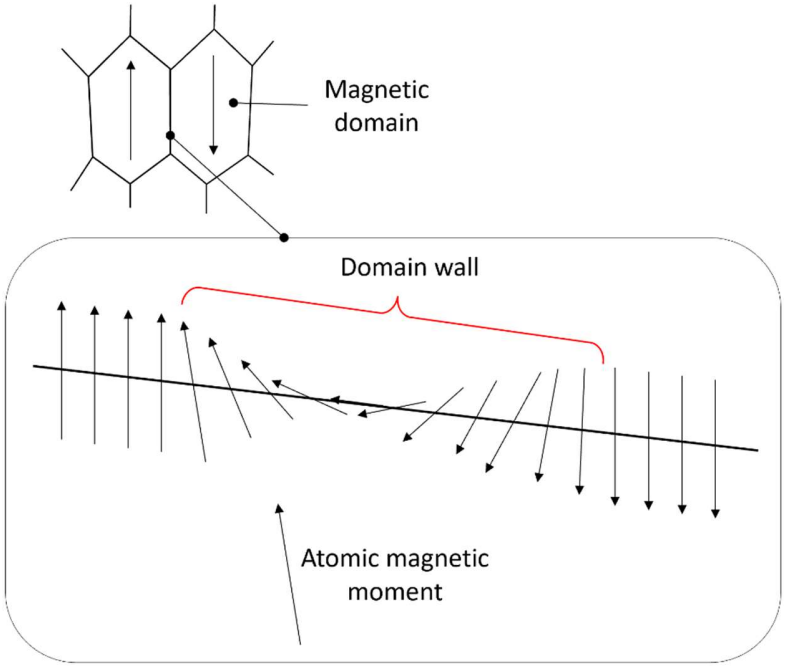

Fig. 3 – Orientation change of atomic magnetic moment in a Bloch type domain wall

A fully saturated magnetic state characterizes every domain. Unless most of them are aligned in a given direction, the vector sum of all the domains is zero in a macroscopic demagnetized state. The domain direction of alignment typically follows the crystallographic axes. Due to the minimization of the magnetocrystalline anisotropy, some axes called “easy axes” are favored. The single-domain state being highly energetically unfavorable, an unmagnetized ferromagnetic material contains a large number of domains. The domain's energy (known as magnetostatic) increases following an increase of the magnetic moments number. Under a magnetic field stimulus, domains favorably aligned with the magnetic excitation grow at the expense of the unfavorable ones. The growth of a magnetic domain generates irreversible domain wall motions. The domain extension and the amount of domain wall motions depend on the intensity of the applied excitation, but microstructural, composition and intern stresses are also highly influential.

As already discussed, the microstructural inhomogeneities include voids, cracks, non-ferromagnetic inclusions, or impurities. These defects affect the mobility of the domain walls during the magnetization process. More specifically, two reasons can be listed:

- The reduction of the domain wall energy due to nonmagnetic regions.
- The generation of unusual domains called spike domains close to the nonmagnetic areas and the resulting reduction of the magnetostatic energy.

By reducing the domain wall area, an inclusion reduces the domain wall energy. It inhibits any motion, up to an applied field strong enough to push it through the following hooking defect. The creation of unconventional domains around inclusions was firstly suggested by Neel [54]. Inclusions produce a significant returning force. As a domain wall crosses a defect, spike domains are generated in parallel to a reduction of the magnetostatic energy. Later, Neel's concept was experimentally confirmed by Williams [55][56], who studied iron-silicon crystals and checked the presence of spike domains.

The impending power of inclusions on the domain wall motion depends on their size. A large defect (≈ 1μm, approximately the domain wall thickness) primarily hinders walls through spike domain formation and growth. More minor inclusions impede a wall mainly by reducing the domain wall energy. From the macroscopic point of view, a ferromagnetic material is constituted of multiple inclusions of randomly distributed sizes and shapes. On the first hand, this complex density makes it quasi impossible to foresee the evolution of the magnetic parameters.

On the other hand, the effects of specific inclusions on the magnetization mechanisms can be studied and lead to conclusions. Significant nonmagnetic defects will increase the coercivity and

decrease the initial differential permeability (larger magnetostatic energy). Minor nonmagnetic flaws (second-phase precipitates or carbide inclusions) will also increase the coercivity and the initial differential permeability. Still, the reason is, in that case, linked to the reduction of the domain walls' surface energy [53].

The magnetization process in a ferromagnetic material is illustrated in a simplified way in Fig. 4. It can be summarized as follows: the magnetic domains with a magnetization oriented favorably to the applied magnetic field grow, while the domains unfavorably oriented decline in proportion. Then the magnetization of a magnetic domain, initially oriented along an easy axis, coherently rotates towards the direction of the applied magnetic field [57].

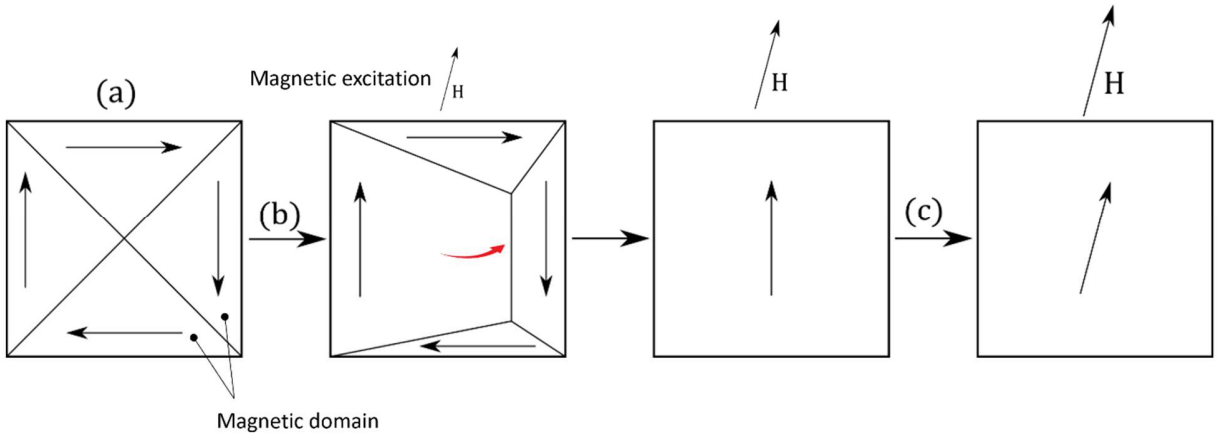

Fig. 4 – Schematic illustration of the magnetization process. (a) Demagnetised state (b) Domain wall motion (c) Magnetisation rotation. In practice, the two mechanisms can occur simultaneously.

3.2 The magnetization mechanisms and their associated experimental situations

Each magnetization mechanism is characterized by Its own time constant, its own sensitivity to the magnetic excitation, and the targeted properties listed in the second section of this

chapter. It is complex to establish a list of magnetization mechanisms, most of which overlap or even happen simultaneously. Five of them can, however, clearly be distinguished:

- The domain wall bulging:

The domain wall bulging is a high time constant, reversible local distortion of the magnetic domain walls, happening in the low magnetic field amplitude excitation range [57][58]. The so-called magnetic incremental permeability is the best way to observe domain wall bulging and its variations vs. the targeted properties (For a practical example, refer to Fig. 7). Magnetic incremental permeability is defined as the magnetic response of a ferromagnetic specimen exposed to a steady, high amplitude quasi-static magnetic field (0.1 Hz, $H_{max} > 5 \cdot H_c$) superimposed to a small amplitude alternative magnetic excitation (50 kHz, $H > H_c/2$). The mathematical expression of magnetic incremental permeability μ_Δ is:

$$\mu_\Delta = \frac{1}{\mu_0} \cdot \frac{\Delta B}{\Delta H} \quad (1)$$

Two options can be used to measure the magnetic incremental permeability:

_ The flat coil solution, where the coil impedance is monitored along the whole magnetization process [59].

_ The transmitter/receiver coil solution see [60].

- The domain wall irreversible motions:

The magnetic domain wall's irreversible motions is a middle-range time constant and amplitude magnetization mechanism. It is due to the irreversible motions of the magnetic domain walls when they break away from pinning sites under the influence of a magnetic

excitation. The best way to observe the domain wall's irreversible motions and its variations vs. the targeted properties is through the so-called magnetic Barkhausen noise technique [61][62]. Every domain wall motion generates local flux variations that trigger discontinuous magnetic flux density displayed as a series of electrical pulses induced in an inductive magnetic sensor [63]. Among the large variety of magnetic sensors for MBN measurement, the pickup coil is the most popular in use.

Inside a material, the domain number being vast, the wall motions can be assimilated to a stochastic process, and the MBN raw signal is erratic and not reproducible. To overcome this issue and to obtain repeatable results, time average indicators are used for the MBN analysis. This includes by instant the Magnetic Barkhausen Noise energy (MBN_{energy}) [63]-[66] (For illustration, refer to Fig.8 top right-hand side corner):

$$\mathrm{MBN_{energy}}(t) = \int_0^t \mathrm{sign}\left[\frac{dH}{dt}(s)\right] V_{BK}^2(s)\, ds \qquad (2)$$

Where V_{BK} is the sensor coil electromotive force, MBN_{energy} is not strictly energy but can be assimilated into an image of the kinetic energy of the domain walls [63][66].

- The magnetization rotation:

The magnetization rotation is a high time constant and amplitude magnetization mechanism. It corresponds to the rotation of the magnetic moment in a magnetic domain under the influence of very strong excitations. Among the magnetization mechanisms, the magnetization rotation has barely been studied and even less in an NDT context. Usually, this mechanism starts once the saturation elbow is reached and continues up to the magnetization saturation. Magnetization rotation can be observed experimentally when a tested specimen is excited with a high amplitude

rotating magnetic field [57]. At sufficiently high excitation, the domains begin to merge and annihilate. Ideally, the domain structure converges toward a single domain structure under an extremely high magnetic field. The disappearing of the magnetic domains and their kinetic reduces the hysteresis losses and the influence of the structural properties (dislocations, precipitates, etc.).

- The domain wall frequency dependence, ripples, and avalanches phenomena:

The magnetic energy losses in a ferromagnetic core have been studied for many years. It is a critical aspect of the definition of a new prototype as these losses affect the conversion efficiency and the temperature distribution highly. In this domain, Bertotti's statistical theory of losses [67][68] is still the most used method to evaluate the ferromagnetic losses in electromagnetic conversions. The statistical theory of losses is based on the concept of loss separation. It works under sinusoidal magnetization and assumes the absence of skin effect. The total loss per cycle W_{tot} is supposed to be the sum of three contributions (Eq. 3):

$$W_{tot} = W_{hyst} + W_{clas} + W_{exc} \tag{3}$$

W_{hyst} is the frequency-independent hysteresis loss contribution. W_{clas} (Eq. 4) is the classical eddy current loss term:

$$W_{cl} = \frac{\sigma d^2}{12} \int_0^{1/f} \left(\frac{dB_a}{dt}\right)^2 dt \tag{4}$$

W_{clas} is derived from Maxwell's equations. It is due to the macroscopic eddy currents. B_a is the projection of induction field $\mathbf{B}_a$ averaged through the sheet cross-section in the thickness direction. σ is the electrical conductivity and d the lamination thickness.

The last term W_{exc} is the excess eddy current loss (Eq. 5), it is a direct image of the domain wall frequency dependence, ripples, and avalanches phenomena (magnetic domains kinetic) as observed during the magnetization process.

$$W_{ex} = \sqrt{\sigma S G V_0} \int_0^{1/f} \left|\frac{dB_a}{dt}\right|^{1.5} dt \quad (5)$$

S is the cross-section, G = 0.1356 a dimensionless coefficient, and V_0 a max(B_a) dependent statistical parameter linked to the microstructure [69].

This magnetization mechanism is frequency dependent and is happening under middle-range field amplitude. An illustration of the relationship between this mechanism and plastic strain is available in Fig. 4 of [70].

- The macroscopic eddy currents:

This magnetization mechanism is well identified in the NDT community, it is the fundament of the eddy current testing method [1], and it is observable through the W_{clas} term in the statistical theory of losses [68] (an example is given in Fig. 6). This mechanism is frequency-dependent and happens whatever the amplitude of the magnetic excitation. It is worth mentioning the skin effect associated with this mechanism [71]-[73] (diffusion equation, Eq. 6) which reduces the volume of the magnetized mater as the frequency increases.

Table 2 summarizes the different magnetization mechanisms' properties (time constant, excitation level, geometrical scale).

Table. 2 – The magnetization mechanisms and properties

Magnetization mechanism	Time constant	Magnetic excitation level	geometrical scale
domain wall bulging	long	low	magnetic domain scale
domain wall irreversible motions	medium	medium	magnetic domain scale
magnetization rotation	short	high	atomic scale
domain wall frequency dependence	medium	medium	magnetic domain scale
macroscopic eddy currents	medium	medium	macroscopic scale

Fig. 5 below provides pictures of sensors (on the top), specimens, and examples of experimental setups (on the bottom) used at the academic scale to observe and isolate the magnetization mechanisms.

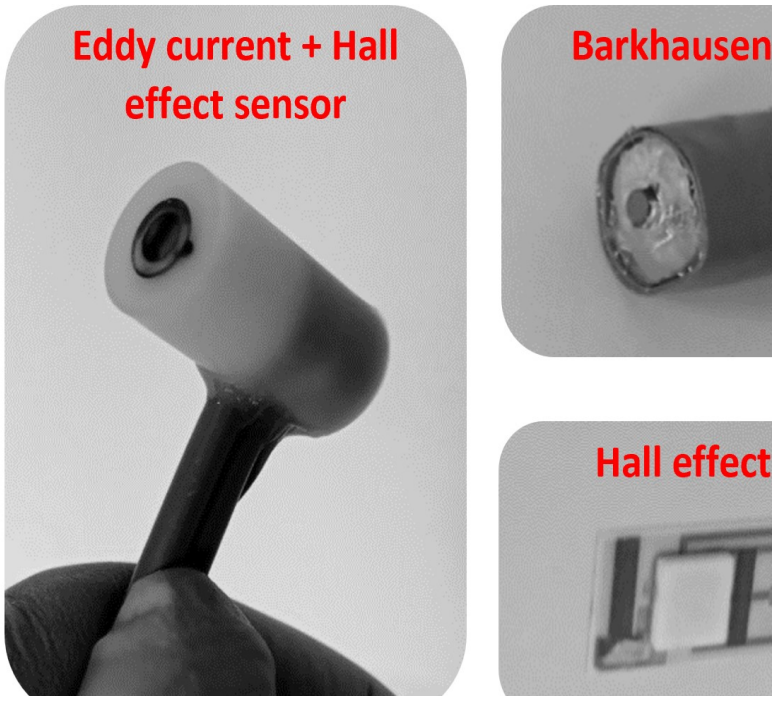

Fig. 5 – Illustration of sensors, specimens, and experimental setups used to observe the magnetization mechanisms at a laboratory scale.

4 – Some examples of the link between the targeted properties and the magnetization mechanisms

Strong correlations have already been emphasized between the targeted properties described in the second section of this chapter and the magnetization mechanisms. The influence of uniaxial compressive stresses on an eddy current testing measurement is, for instance, illustrated in Fig. 6 below. In ferritic steel, compression diminishes the magnetic permeability, which increases the penetration depth and reduces the sensor coil impedance for a given frequency. In this example, the coil characteristics are 3.3 mm inner diameter, 3.95 mm outer diameter, 3.0 mm height, 275 turns, and 0.05 mm wire thickness. The lift-off is 0.39 mm.

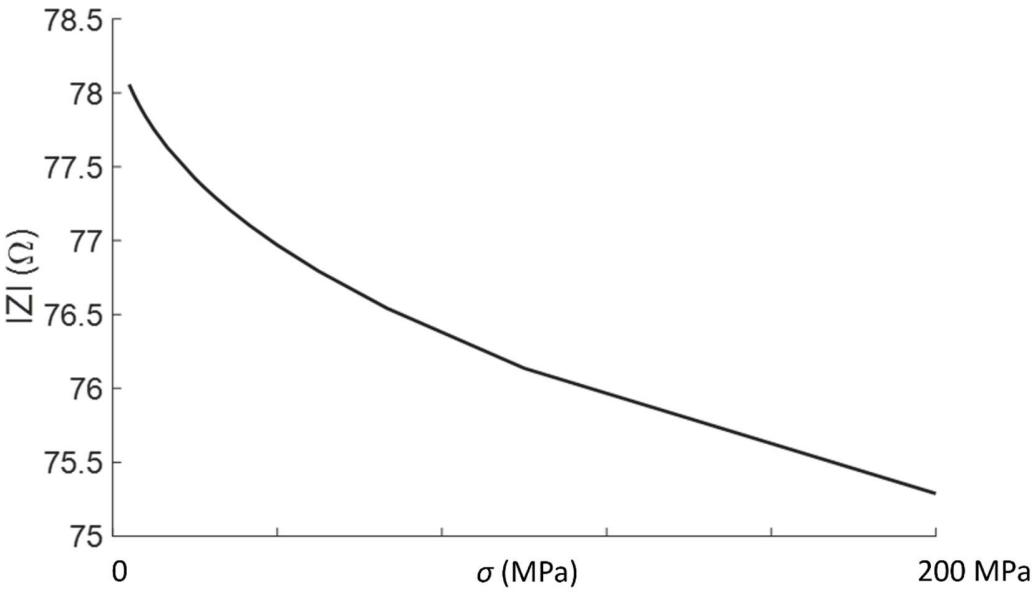

Fig. 6 – Illustration of a uniaxial homogeneous stress influence on the impedance modulus of an eddy current sensor.

Similarly, the domain wall bulging observed from magnetic incremental permeability has already been demonstrated to be intensely dependent on the microstructural creep variations (see Fig. 7 below for illustration) in high-chromium steel [17].

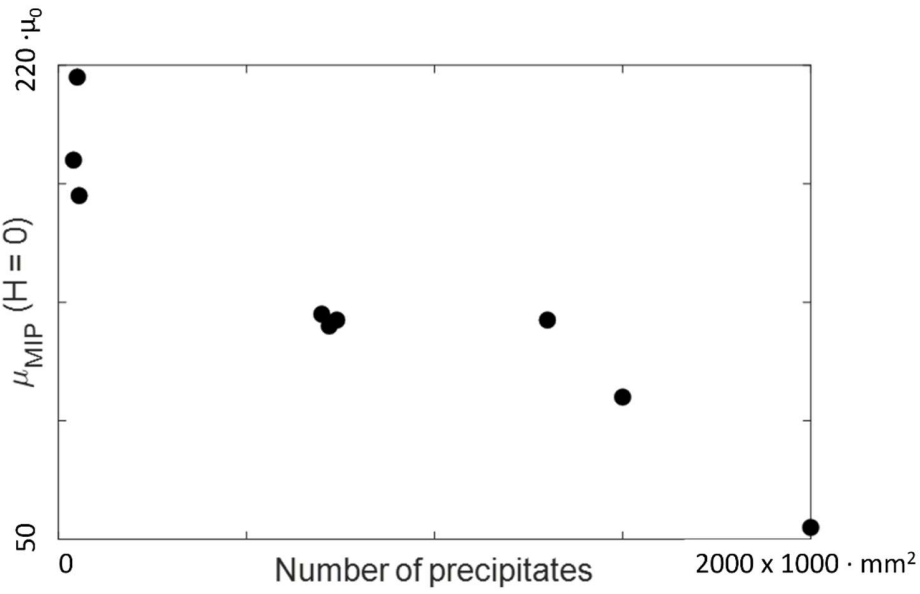

Fig. 7 – Typical evolution of the magnetic incremental permeability at H = 0 as a function of the number of precipitates.

Also, the irreversible domain wall motion and the magnetic Barkhausen noise measurement have been studied as a function of the three targeted properties [74]. Here again, as illustrated in Fig. 8, strong correlations were observed.

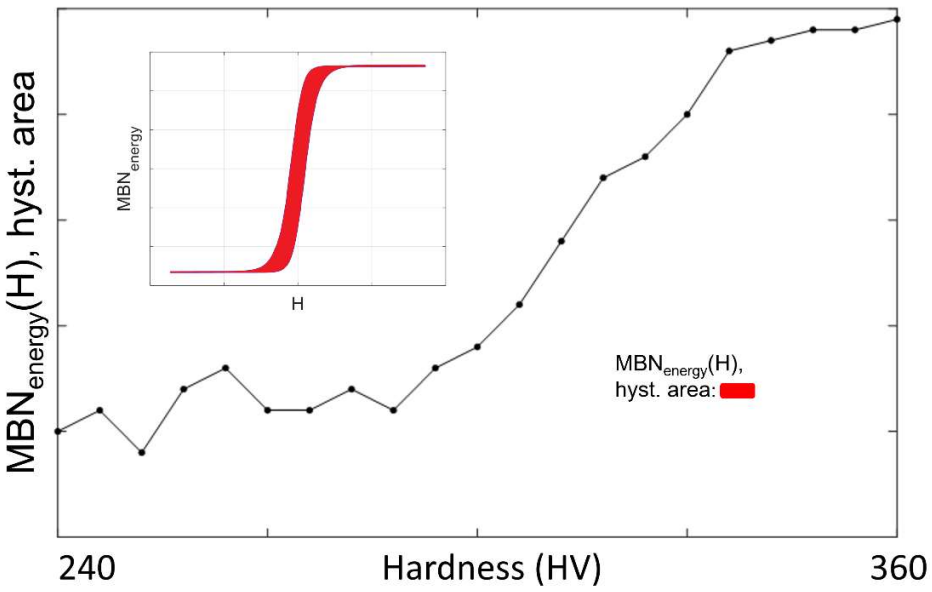

Fig. 8 – Typical evolution of the $MBN_{energy}(H)$ hysteresis loop area as a function of hardness.

For the spontaneous rotation, since this magnetization mechanism is definitively more complex to isolate and observe, no study can be found in the scientific literature. Eventually, the influence of the targeted properties on the magnetic domain wall frequency dependence, ripples, and avalanches phenomena have been studied through the evolution of the magnetic losses and, more specifically, the excess losses. A good example can be seen in [75].

The experimental situations described in the third section of this chapter provide specific magnetic signatures ($MBN_{energy}(H)$ hysteresis cycles, MIP butterfly loops, etc.). However, it is essential to specify that even if those signatures were obtained in ideal configuration, some indicators read on them can still be associated with multiple mechanisms. Let's mention coercivity, which depends on multiple magnetization mechanisms and in every experimental situation tested.

Another interesting fact comes from the combination of these signatures, which can reveal rich information on a given magnetization mechanism. By instant, the magnetization rotation can be observed from the difference of slopes at a saturated state of the usual $B_a(H)$ and $MBN_{energy}(H)$ hysteresis cycles.

5 – Conclusion

Improvement in steel component quality controls has triggered strong efforts in developing consistent nondestructive testing methods. The final objective is reliability. Well-defined targeted properties can be scanned as precursors in developing undesired cracks and potentially catastrophic failures. Those properties include internal stress, microstructural variations, etc. Unfortunately, there is no direct method to measure internal stress, and optical microstructural observations are unimaginable beyond the laboratory environment. Magnetization is the solution promoted in this chapter to reach the targeted properties indirectly.

The magnetization mechanisms are dependent on the targeted properties. These dependencies are not constant, and for physical reasons, a given targeted property will affect a given magnetization mechanism more.

Most of the magnetization mechanisms overlapped. One of the main challenges is to define experimental situations where the best magnetization mechanism can be isolated.

The future of this discipline relies upon the capability of developing magnetic sensors and experimental contexts able to provide reliable and reproducible images of the magnetization mechanisms. Printed electronics and sensors is an exciting solution [76][77]. By designing advanced parts, including permanent monitoring instruments, issues due to the positioning and the lift-off are overcome, and the reproducibility in the measurement is ensured.

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