ISSN NO: 9726-001X
Volume 11 Issue 03 2023

JOURNAL OF CURRENT SCIENCE

USE OF THE ANHYSTERESIS RESIDUAL MAGNETIZATION TECHNIQUE TO ASSESS THE DISPERSION OF EXTRA PLASTIC DEFORMATION IN FERROMAGNETIC METALS HIROSHI KOTAKES

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Nondestructive testing using magnetic Barkhausen noise (MBN) was carried out on three steels that had a comparable microstructure but exhibited vastly divergent mechanical characteristics. A tensile test was performed on each of these steels, subjecting them to minute plastic deformations ranging from 0.5 to 4 percent. Even with a relatively little distortion of 0.5%, it becomes impossible to shift the domain wall 180 degrees. This is because plastic deformation causes grain fragmentation, which in turn causes the dislocation density to rise, leading to the creation of dislocation cells and tangles. After plastic deformation, the magnetostrictive process becomes more prominent, according to the changed structure of the MBN envelope. This is likely associated with the stress field around dislocations.

***Index Terms*—Hysteresis, magnetic Barkhausen noise (MBN), nondestructive testing, plastic deformation.**

I. Introduction

The effect of plastic deformation on magnetic properties still is a subject of considerable debate. As reviewed by Chen [1], there are several old theories for explaining the dependence of coercivity on the deformation. It was roughly suggested that the coercive field increases with the square root of the dislocation density [1]. As consequence, this simple law has been used in several models [2], [3].

Many theories summarized by Chen [1] go back to the 1950s. However, after electron back scattered diffraction (EBSD) has been used for studying the deformed structure of metals [4], [5], it is now clear that grain fragmentation is a very relevant consequence of the plastic deformations and not only the increase of dislocation density.

Due to the crystal discontinuity, the domain walls have to stop at the grain boundaries, and grain fragmentation thus avoids domain wall movement. When domain wall movement is difficult, the reversal of magnetization takes place by domain rotation. The coercivity is much larger when the crystal is small, with maximum coercivity near the single domain particle size [6]. As example, it is possible to mention the high coercivities found in nanocrystalline Sm_2Co_{17} magnets, near the single domain particle size [7]. It has also been observed that significant refinement of domain structure takes place after the plastic deformation [8], and this can be attributed to grain fragmentation. The low losses of grain oriented (GO) steels are explained by the very large grain size of these materials, where the domains can move freely [9].

As mentioned in the literature [10]–[12] magnetic Barkhausen noise (MBN) may provide helpful insights on understanding plastic deformation. It was pointed out that short range magnetostrictive effects [13], coupled with significant grain fragmentation [14], may increase sharply the coercivity (and decrease considerably the initial permeability) even with very small deformations. As MBN is able to detect 180° domain wall movement, and elimination of 90° closure domain walls [14], a detailed analysis of the MBN envelope of samples submitted to small deformation can help to reveal the mechanisms of magnetic hardening.

In the present paper, a very small deformation 0.5% up to 4.0% was applied to three steels with different chemical composition, and mechanical properties. However, the three steels present similar microstructure, basically ferrite (i.e., bcc alpha–iron) grains of 10 μm, as it will be discussed further.

The three compared steels are: 1) high resistance low alloy (HRLA) microalloyed with niobium; 2) titanium stabilized interstitial free (IF); and 3) carbon–manganese steel following specification SAE 1006–1008.

TABLE I
Chemical Composition for the Samples (Weight %)

sample	steel	%C	%Mn	%P	%S	%Ti	%Nb
M1	HRLA	<0.120	<1.00	<0.03	<0.03	-	<0.05
M2	IF-Ti	<0.005	<0.18	<0.03	<0.03	<0.08	-
M3	C-Mn	<0.080	<0.30	<0.03	<0.03	-	-

II. Experiment

The chemical composition of the three evaluated steels is given in Table I. The thickness of the samples is 1.0 mm for the HRLA and IF–Ti steels, and 0.95 mm for the C–Mn steel (it is designed to fit in the SAE 1006–1008 specification). These steels received previous skin-pass (i.e., cold rolling) of 0.8% for the HRLA, 1.2% for IF–Ti, and 1.4% for the C–Mn steel. Deformations of 0.5% and 4% were applied in the samples by means of the tensile test machine Instron model 5585H,

Manuscript received August 1, 2013; revised October 2, 2013; accepted October 24, 2013. Date of current version April 4, 2014. Corresponding author: M. F. de Campos (e-mail: mcampos@metal.eeimvr.uff.br).
Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.
Digital Object Identifier 10.1109/TMAG.2013.2288324

ISSN NO: 9726-001X
Volume 11 Issue 03 2023

TABLE II

GRAIN SIZE FOR THE SAMPLES

HRLA	IF-Ti	C-Mn
7.7 (μm)	12.9 (μm)	8.4 (μm)

TABLE III

MECHANICAL PROPERTIES OF THE SAMPLES

steel	Yielding strength superior (MPa)	Yielding strength $inferior_f$ (MPa)	Yielding strength 0.2% (MPa)	Tensile strength (MPa)	Elonga-tion (%)	n *
HRLA	377	371	-	448	31	0.17
IF-Ti	-	-	171	290	49	0.23
C-Mn	-	-	281	358	36	0.14

*) n is the hardening exponent.

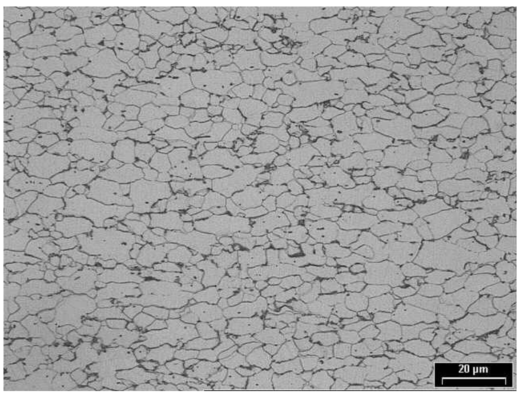

Fig. 1. Microstructure of HRLA steel.

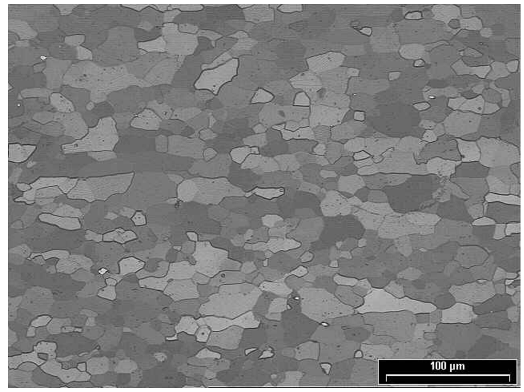

Fig. 2. Microstructure of IF–Ti steel.

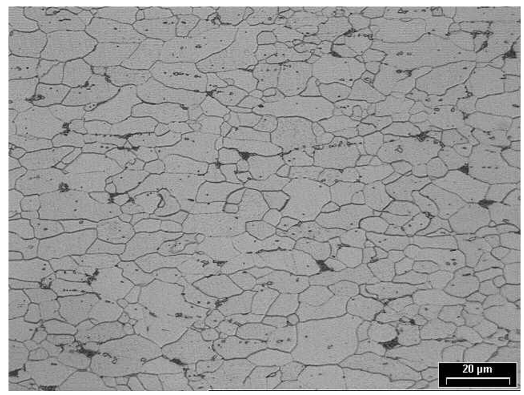

Fig. 3. Microstructure of C–Mn steel.

with advanced video extensometer (AVE) system. The speed of deformation was 1 mm/min. A Soken single sheet tester was used for measuring losses at 60 Hz, 1 T.

MBN data was acquired with Barktech equipment [14]. The parameters for MBN data acquisition were current $I = 1$ A, and frequency 10 Hz. A filter was used for elimination of frequencies below 2 kHz. The MBN envelope was calculated using Fourier Transform.

The HRLA and C–Mn samples were etched with Nital 3% for revealing grain boundaries after metallographic preparation. The IF–Ti steel was etched with Klemm's reagent. Microstructures were obtained in an optical microscope Zeiss Axiophot.

III. RESULTS AND DISCUSSION

The determined values for grain size are presented in Table II and the mechanical properties in Table III. Microstructures were presented in Figs. 1–3, and results of stress-strain test were presented in Figs. 4–6. As evidenced by the curves of Figs. 4–6, and Table III, the steels present considerable difference of mechanical properties and the HRLA steel shows discontinuous yielding (see Fig. 4). Magnetic properties presented at Fig. 7 show that losses (1T—60 Hz) increase significantly, even after small plastic deformation. For the IF–Ti steel, however, losses reduced slightly from 9.5 to 9.2 W/kg after 0.5% of deformation, but the shape of hysteresis curve changed and the field necessary for obtaining

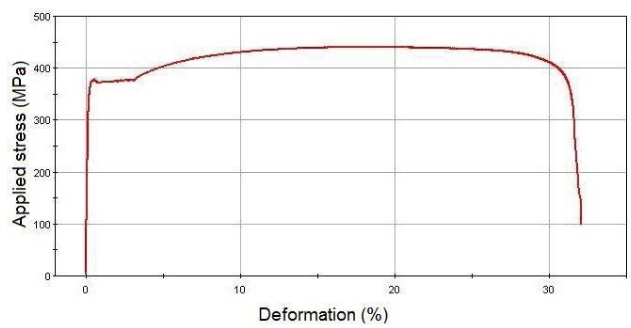

Fig. 4. Stress-strain test for the HRLA steel.

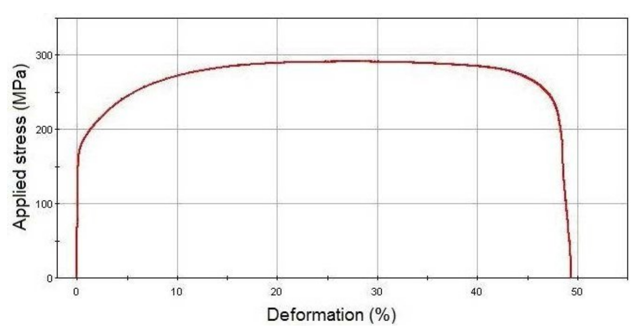

Fig. 5. Stress-strain test for the IF–Ti steel.

1 T is significantly higher, as can be seen in Table IV. This implies that the permeability reduced significantly after 0.5% of deformation.

ISSN NO: 9726-001X
Volume 11 Issue 03 2023
JOURNAL OF CURRENT SCIENCE

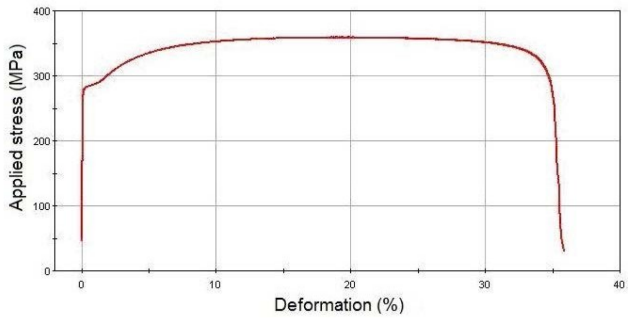

Fig. 6. Stress-strain test for the C–Mn steel.

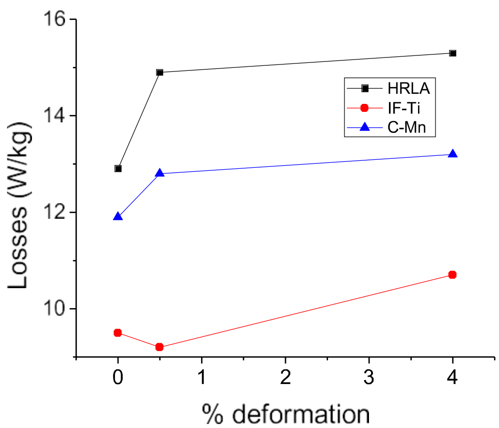

Fig. 7. Losses at 1 T, 60 Hz.

TABLE IV
FIELD APPLIED FOR THE LOSSES MEASUREMENT AT 1 T

steel	HRLA	IF-Ti	C-Mn
0	0.90	0.61	0.76
0.5%	1.20	0.86	1.15
4%	1.88	1.10	1.43

The softer material (from both mechanical and magnetic point-of-view) is the IF steel, and this happens because: 1) IF–Ti steel has larger grain size (see Table II) and 2) the other steels (HRLA and C–Mn) have solid solution mechanical hardening, due to carbon and manganese additions. In spite of the differences concerning mechanical and magnetic properties, the MBN as function of deformation, presented in Figs. 8–10, shows very similar behavior.

As can be seen in Fig. 7, in general the losses increase sharply after the very small deformation. The envelope of the MBN broadens and the intensity of the peak reduces (see Figs. 8–10). Previous studies have shown [3] that even with very small plastic deformation, there is significant increase of the dislocation density.

The results presented in Figs. 8–10 can be interpreted with the double Gaussian model. This model assumes two main bursts, the first usually occurring before the coercive field Hc (here it is assumed the Hc measured after it was applied an given H applied field sufficient for saturation), due to 180° domain wall moving and the second due to 90° closure domain walls elimination. The main idea comes from

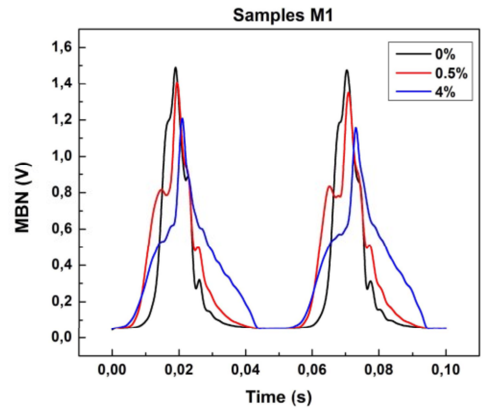

Fig. 8. MBN envelope for the HRLA steel.

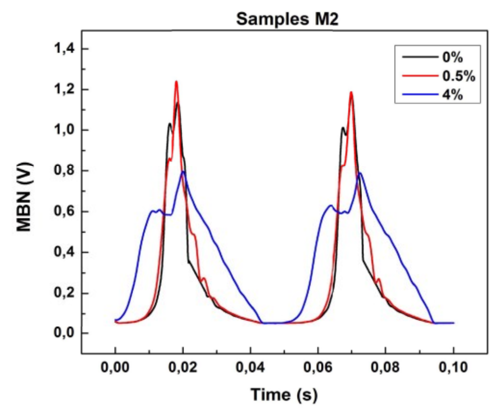

Fig. 9. MBN envelope for the IF–Ti steel.

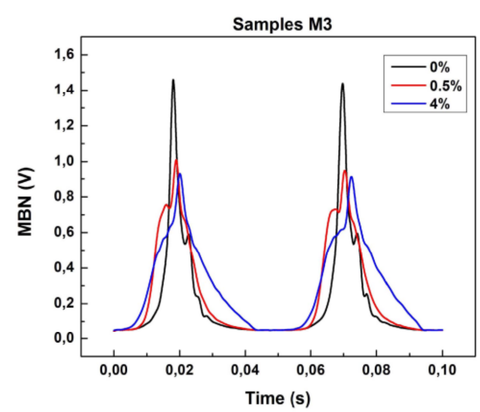

Fig. 10. MBN envelope for the C–Mn steel.

Williams *et al.* [15], which discussed the effect of applied field on domain wall movement and the eddy current dumping, and is the basis of the so-called ABBM model [16]. This basic idea was reworked by Perez-Benitez *et al.* [17], [18], as shown by

$$V_t = \frac{\rho}{G}\left[m_{90}\left(h_{90}\right)h_{90} + m_{180}\left(h_{180}\right)h_{180}\right] \quad (1)$$

where V_t is Voltage at a time (t), ρ is resistivity, G is the damping coefficient of one domain wall [15], [16], and $m_{90}(h_{90})h_{90}$ represents the 90° closure domain wall elimination and $m_{180}(h_{180})h_{180}$ represents 180° movement of domain walls. One of the most relevant results of this model is the prediction that the MBN signal increases with the number of active domain walls [14]: m_{90} is the number of MBN jumps produced by the 90° domain walls at an applied field h_{90}, m_{180} is the number of MBN jumps produced by 180° domain walls at an applied field h_{180}.

It has been pointed out that (1) represents two Gaussians [14], [18]. For example, for a Gaussian distribution of grain size, there is a Gaussian distribution of coercivity, since the coercive field is directly proportional to the inverse of grain size [13]. Thus, (1) can be modified to (2) [14], [18]

$$V(H) = k_{90} \cdot F_{90}\left(\frac{1}{H}, \bar{d}_{90}, \sigma_{90}^2\right) H^{3/4} + k_{180} \cdot F_{180}\left(\frac{1}{H'}, \bar{d}_{180}, \sigma_{180}^2\right) H \quad (2)$$

where k_{90}, k_{180} are experimental constants. $V(H)$ measures the intensity of the MBN signal, H is the applied field. The Gaussian $F(x, \bar{x}, \sigma_x^2) = 1/\sqrt{2\pi}\sigma_x \exp\left(-(x-\bar{x})^2/2\sigma_x^2\right)$ is defined as a function of three parameters, the applied field H, $\bar{d}_{90}$ (or $\bar{d}_{180}$), and its dispersion σ_{90} (or σ_{180}).

The results presented in Figs. 8–10 show that the intensity of the peak due to 180° movement decreases with plastic deformation, whereas the second peak—attributed to 90° closure domain wall elimination—increases. Plastic deformation should decrease the first peak, because after formation of dislocation tangles and dislocation cells the 180° domain wall movement becomes difficult and consequently domain rotation becomes relevant as reversal mechanism. As dislocations have stress fields of significant magnitude (∼1 GPa) [13], this should affect magnetostrictive process, changing the position and intensity of the 90° closure domain walls peak, which happen for higher applied fields.

In a previous study [19], it was found that the macroresidual stresses (along all samples) are less relevant when compared with the microresidual stresses (order of angstroms) around dislocations. These microstresses around dislocations can affect locally the anisotropy constant [13], decreasing the permeability [20], and increasing coercivity and losses [21].

IV. Conclusion

The MBN findings show that even a tiny amount of plastic deformation (0.5%) may cause the 180° domain wall to migrate. Nevertheless, there is an additional peak that appears at higher fields; this peak grows as the plastic deforms, and it could be a sign of magnetostrictive interactions, since magnetostriction plays a significant role in removing the domain walls that are 90° closed. This is a general outcome that was seen for all of the steels that were analysed.
Three steels with comparable microstructure but vastly differing mechanical characteristics shown that even little plastic deformation impacts MBN and iron losses.
As shown before, even a little deformation may cause significant grain fragmentation [14]. This prevents the domain walls from freely moving and promotes domain rotation as a magnetic reversal mechanism; as a result, hysteresis losses increase and the MBN peak decreases as a result of 180° domain wall movement. That is why even little plastic deformation results in a noticeable change to the microstructure, which in turn causes the MBN

Acknowledgment

M. F. de Campos and L. R. Padovese would like to thank CNPq.

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