Magnetic Barkhausen measurements to evaluate formation of heterogeneous plastic deformation zones in carbon steel

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Abstract

Localized inhomogeneous plastic deformation phenomenon was experimentally investigated in a structural steel through the analysis of the Magnetic Barkhausen Noise (MBN). The MBN signal of steel plates ANSI 1050 samples, oriented throughout rolling (RD) and transversal direction (TD) with different strain was analyzed. The scan of the samples shown that the MBN activity increases in the region presenting Lüder bands-like formation and displacement in specific zones of the RD samples. A strong magnetic anisotropy was also observed in these regions with the generation of dual magnetic easy axis in the MBN energy angular dependency, as well as a quite different behavior of the magnetic anisotropy coefficient with strain, between RD and TD samples. Losses measurements and Permeability calculations corroborate those results.

1. Introduction

After being plastically deformed, small localized discontinuous zones, denominated Lüder bands, commonly appear in the deformed region, for several types of structural steels[(1)]. In general, Lüder bands are due to the presence of strong interstitial atom interaction, like that in carbon or nitrogen atoms, the dislocations in the material being under the effect of a monotonic applied stress[(2)]. During the propagation of Lüder bands, local deformations experience two successive states of deformation: an abrupt step plastic deformation, characterized by a high density dislocation, followed by a slower process practically deformation-free.

One of the main microscopic theories that explain the occurrence of Lüder bands was proposed by Cottrell and Bilby[(3)]. They attribute the upper yield stress to the pinning of dislocations by carbon and nitrogen atoms which naturally tends to form atmospheres around these dislocations. The authors postulate that initial yielding requires high stresses in order to pull the dislocations out of these “atmospheres”. Once released, the dislocations can be moved by lower stresses. Another microscopic model, proposed by Johnston and Gilman, attributes the load drop in the stress-strain curve to a mechanism of multiplication of dislocations[(4)].

The macroscopic and microscopic properties associated with the propagation of Lüder bands under a monotonic applied stress have been extensively studied. The appearance of Lüder bands depends not only on the experimental variables but also on the heat treatment and on micro structural parameters[5-8].

Different techniques have been developed to observe the propagation of Lüder bands and to characterize the strain profile near the Lüder front [9-11]. On the other hand, few works have been published regarding the possibility of applying non-destructive magnetic evaluation of materials on the study of Lüder bands[12,13]. This is the context of the present investigation that aims to understand the effect of Lüder bands on the magnetic Barkhausen noise in ANSI 1050 steel, a phenomenon that is being increasingly used in the area of non- destructive testing.

2. Experimental setup

A cold laminated annealed steel ANSI 1050 plate was selected for the investigation. Its chemical composition appears in Table 1.

Table 1. Steel composition (wt. 10^{-3} %)

C	Mn	P	S	Si	Al	Cu	Cr	Ni	Mo	Ti	Nb
517	686	15,7	4	195	42,2	13	15,1	8,7	1,3	1,8	1,9

For all the experimental measurements, the used samples (25 mm x 250 mm x 0.98 mm) were made of commercial ASTM 1050 steel. The samples were cut along the transverse and rolling direction of the annealed cold rolling sheet.

The samples were subject to a uniaxial testing machine at a strain rate of approximately 0.5 mm/min. The present work studied samples "as received", that is, not subjected to this deformation process, and samples with additional relative deformations of 0.2%; 0.4%; 1.0%; 3.0% and 5.0 %, produced by the mentioned stress-strain machine.

The measurement arrangement is schematically shown in Figure 1. A Personal Computer (PC) with a data acquisition device (with A/D, D/A and D/D channels) supplies a sinusoidal wave of 10 Hz, which is amplified by a bipolar source Kepco BOP20-20D that feeds the magnetic circuit in order to magnetize the sample with a magnetic field of $\pm$ 1.4 x 10^4 A/m, producing magnetic saturation in the samples. The MBN sensor output is amplified and band pass filtered (1 - 100 kHz). The MBN signals were visualized using a digital oscilloscope and a data acquisition device performed the digital acquisition with a sampling frequency of 200 kHz.

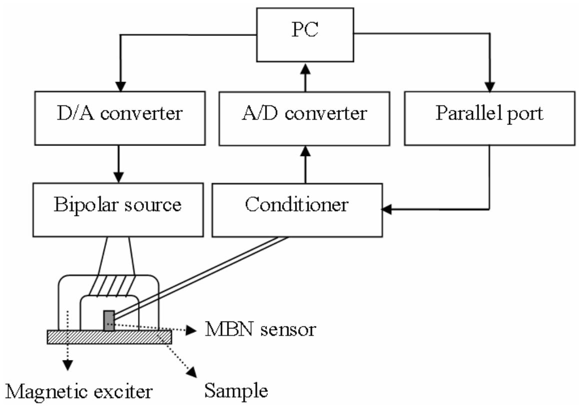

Figure 1. Experimental setup for measurement of the MBN signal.

The integral of the voltage square of all MBN events represents the parameter known as the MBN energy (MBN_{energy}). This magnitude is first calculated for all the MBN measurements of each sample and then averaged. By the use of a bottom voltage level, the noise not belonging to the Barkhausen signal was eliminated from the MBN measurements. The experimental MBN data for different angles of magnetic excitation were obtained through a rotational excitation-sensor system with angular increment of 15º. The resulting curves are plotted by means of polar graphs. The measurements over the gauge zone were made using a PC controlled xy coordinates table.

Magnetic losses at 0.65T, 1.0T and 1.5 T, 60Hz were measured for 1.0% strain sample, in three regions, where angular MBN_{energy} identified the region presenting Lüder bands-like formation (see Figure 2), and at the left and right side of this region. Measurements were made using a single-sheet feature with a SOKEN steel sheet tester; model DAC-BHW-5.

3. Results and discussion

3.1 MBN behaviour under plastic deformation

The behavior of the MBN_{energy} throughout the gauge zone was studied for several samples under different plastic strains. The measurements were made in the rolling and transversal directions of the sample, at each 1 mm along the gauge zone.

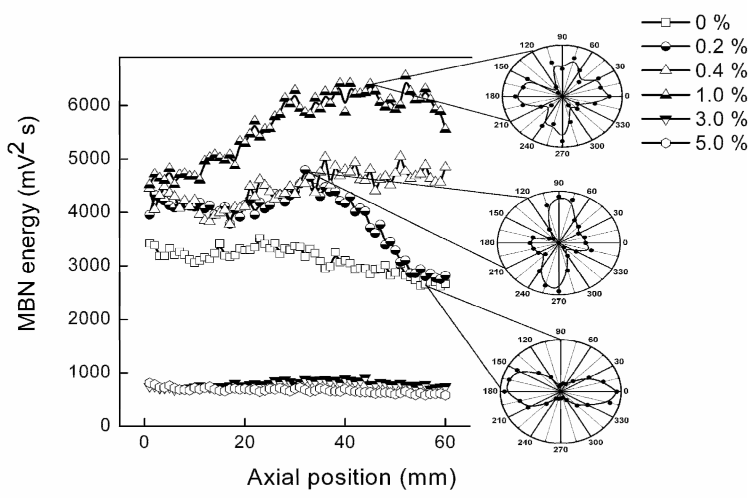

Figure 2. MBN$_{energy}$ variation over the half-gauge zone for different strains in the Rolling Direction sample.

Figure 2. shows the MBN$_{energy}$ variations throughout the sample gauge zone for samples oriented in the rolling direction, the magnetic field being applied in the same direction. In the curve corresponding to the 0.2% deformation, the MBN$_{energy}$ values pass through a maximum before decreasing to the values corresponding to the 0% deformation. As the plastic deformation increases, this maximum evolves to a plateau which level depends on the plastic deformation. This behavior is likely to be related to the formation of Lüder bands. For high plastic deformations, the MBN$_{energy}$ values drop as shown, for deformation of 3% and 5%. For these high deformations, the growth of the MBN$_{energy}$ with strain disappears in all the gauge length, the curves showing a uniform behavior and presenting an appreciable decrease of the MBN$_{energy}$ values when compared to those for the smaller plastic deformations. A similar behavior has been observed by Mitra et al.[14] in stainless steels.

In this figure is also presented the three polar graphics showing the angular variation of the MBN$_{energy}$ for three cases of plastic deformation. It is possible to note that the behavior of the polar curve changes as the deformation increases. For the non-deformed case, the polar curve presents the expected form of an "8", aligned with the rolling direction. For the 0.2% deformation case, a second axes appears, its configuration evolving gradually to the configuration of the 1% deformation polar curve. This second axes is associated with the formation of Lüder bands. It is important to point out that the measurements, shown in the polar graphics, where made in positions that correspond to the maximum of the MBN$_{energy}$, in order to maximize the detection of the Lüder band. For high plastic deformation, the polar curve returns to the initial configuration, since the Lüder bands disappear.

In contrast for sample in the transverse direction the MBN$_{energy}$ values decrease with the rise of the strain from 0 to 5%, since no Lüder bands occurs in this case.

3.2 MBN behaviour under tensile stress

Figure 3 shows the angular dependence of the MBN$_{energy}$ for different applied tensile stresses. In this case, a sample obtained from a steel sheet was subject to 10 levels of tensile stresses in strain-stress equipment, in the range of 0 to 490 MPa. For each tensile stress value, the Barkhausen noise was measured at different angular directions in a given position of the gauge zone. In this figure, only 5 levels are plotted, in order to turn the graphic visually clear. The direction of the applied tensile stress, the same as the rolling direction, corresponds to 0^o in the polar curve.

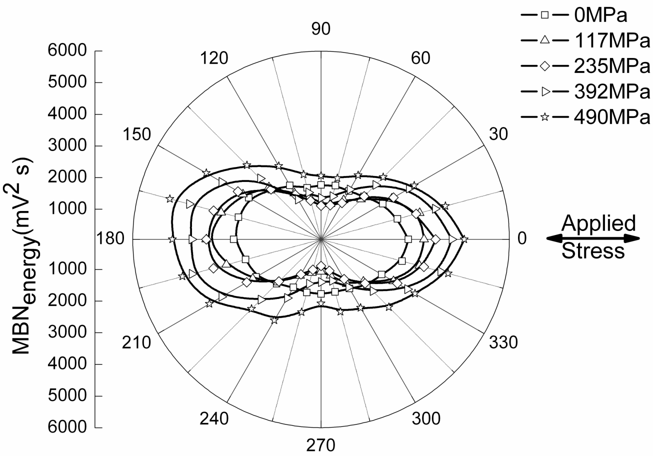

Figure 3. Polar plots of MBN_{energy} for sample oriented along the Rolling Direction at different stress value

Figure 4 presents details of Figure 3, that is, the variation of MBN_{energy} with applied stress only in the rolling direction (RD, 0^o) and in the transversal direction (TD, 90^o).

Regarding both, figures, one can observe, that there is an increase of the MBN_{energy} with the stress rise, in the $MBN_{energy}(0^o)$ direction, while in the transversal direction ($MBN_{energy}(90^o)$) the value decreases until approximately 150 MPa, and then increases again up to 490 MPa.

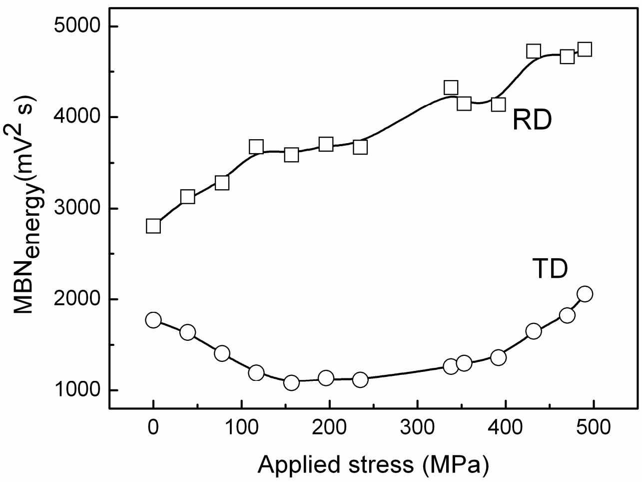

Figure 4. Dependence of the MBN energy on the applied stress, for rolling (RD) and transversal (TD) directions

By combining the two curves of Figure 4, it is possible to calculate a useful parameter, the anisotropy coefficient, which describes the angular behavior of the MBN_{energy}:

$k = MBN_{energy}(0^o) / MBN_{energy}(90^o)$..(1)

where $MBN_{energy}(0^o)$ is the MBN energy in the direction of easy axis (maximum MBN_{energy}) and $MBN_{energy}(90^o)$ the energy of MBN signal in a direction perpendicular to the easy axis (minimum MBN_{energy}). The dependence of parameter k on the applied tensile stress is shown in Figure 5.

In Figure 5, it is possible to distinguish three regions in the curve of the anisotropy coefficient k. Initially the coefficient k increases linearly with the applied tension up to 150 MPa, which corresponds to the elastic region, and then reach an almost flat region until 350 MPa, that corresponds to the formation of Lüder band, and finally has a sharp fall, which corresponds to the full development of the material plastic deformation.

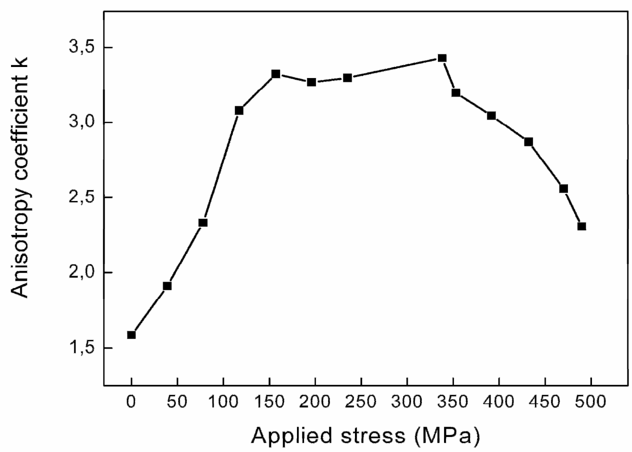

Fig. 5 Dependency of coefficient de anisotropic with applied stress

3.3 Magnetic properties analysis

The behavior of the relative permeability measured on the RD sample with 1% of plastic deformation, at the right, left side of the region where the cuadripolar behavior appears (see Figure 2), and over this region, is shown in the Figure 6.

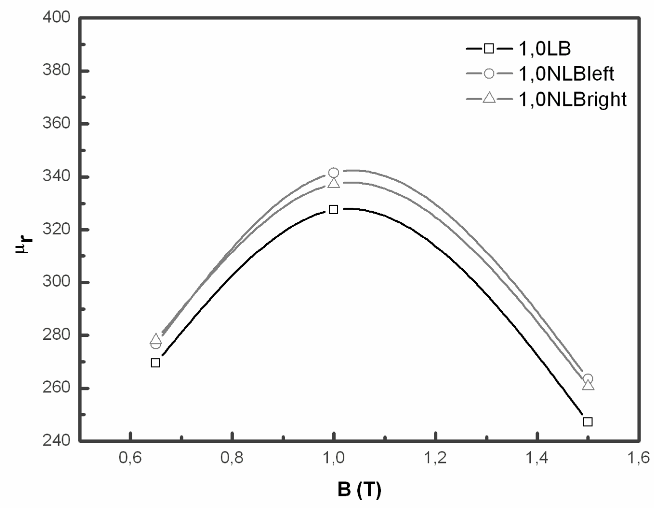

Figure 6. Relative Permeability of the 1% deformation in the R D sample.

The reason of this behavior is that in the region where residual tensile strain increase the coercitive field and the Hysteresis losses increase too, as shown in Figure 7, and because of this, decreases the relative permeability[15].

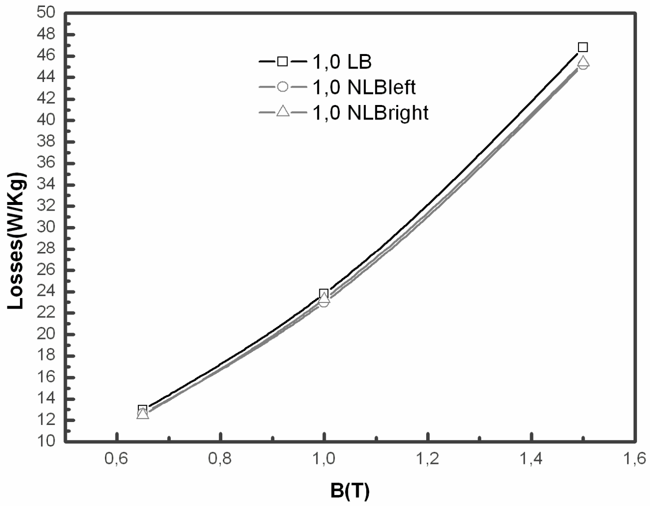

Figure 7. Losses of the 1% deformation in the R D sample.

4. Conclusions

The present work shows the angular dependence of the MBN_{energy} in ASTM 1050 steel. These results provide a tool, based on the MBN_{energy} that allows establishing a methodology for the study of the elastic-plastic behavior of ferromagnetic materials.
Particularly, it is shown that it is possible to detect the formation of Lüder bands (plastic heterogeneity) by MBN_{energy} mapping of the steel samples. This plastic heterogeneity occurs only in the rolling direction and not in the transversal direction. It is also shown that a coefficient, named coefficient of anisotropy, can be calculate in order to characterize the elastic, the elastic-plastic and full developed plastic regions.
Finally, by using an angular MBN_{energy} mapping, it is possible to evaluate the structural changes of the material under stress variation. Behavior of magnetic properties as losses and permeability were in agreement with these results.
Therefore, this nondestructive method opens a wide range of possibilities in the study and understanding of deformation processes in ferromagnetic materials.

Acknowledgements

The authors wish to thank Brazilian agencies, CAPES (Process No 084-15/06) and FAPESP (Process N^{o} 2006/02741-4) for the financial support.

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