JOURNAL OF MATERIALS SCIENCE 39 (2004) 1367–1370

Dependence of the magnetic Barkhausen emission with carbon content in commercial steels

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In this work, the dependence of the magnetic Barkhausen Effect (MBE) with carbon content in commercial steels has been studied. The dependence of the MBE amplitude, root mean square voltage and the parameters that characterize the form of the MBE Jumps with different carbon content were obtained. The cause of this dependence was analyzed on the base of domain walls theory.

1. Introduction

One of the most useful nondestructive evaluation methods is the magnetic method based on Barkhausen effect, attributed to the irreversible movement of magnetic domains walls, when they overcome the potential energy of the barriers, caused by the pinning sites during the magnetization process.

The MBE has been used to evaluate the microstructure and the level of residual strain in commercial steels [1, 2]. Furthermore the effect of crystalline microstructure features on MBE has been widely investigated in steels, and the influence of grain size [3–5], carbide precipitates [1, 3–6], ferrite pearlite and martensite phases and dislocations [7] can be found in literature. Specifically in plain steels are remarkable the studies of Clapham *et al.* [8] that have shown that fully pearlitic steels have an MBN pulse height distribution which is highly asymmetrical, exhibiting a tail which extends to large values of pulse height. However no wide description and understanding of the relation between the mean values of Barkhausen signals and the Barkhausen Jumps and their dependence on the carbon content for plain steels is available.

The more used magnitudes to establish these correlations between the microstructure parameters and the MBE are the MBE amplitude or peak voltage (V_p) and the root mean square voltage (V_{rms}). Recent works [9–12] has also verified the correlations between stress condition of the material and the Barkhausen jumps also known as Barkhausen effect elementary signals (MBEES) [13, 14]. The present work will show the dependence of V_{rms}, V_p on the carbon content, but also the dependence of new parameter of the MBEES on the carbon content.

2. Experiments and results

The samples were obtained from plain carbon steels: 1005, 1020, 1045 and 1070, with identical parallelepiped shape (200 mm × 15 mm × 2 mm). All the high temperature treatments were carried out with samples covered with a layer of special clay. Details of the heat treatment are summarized in Table I.

For metallographic examination the samples were polished using diamond paste (6 and 1 μm). The samples were etched in a 2% Nital solution to reveal the microstructure. The microstructure was observed with a Olympus microscope BX60M (see Fig. 1).

Experimental set-up consist of a function generator Tektronic CGF253, a power amplifier Kepco BOP20-20D and an U-shape ferrite. For the detection of the magnetic Barkhausen emission was used a commercial magnetic head, an instrumentation amplifier and a band-pass filter of fourth order from 4 to 100 KHz. A personal computer, a card of acquisition National Instrument PCI-MINE-16E-1 and a digital oscilloscopic Tektronic TDS-210 integrate the measurement system.

An alternative magnetic field with a frequency of 1 Hz, and current intensity of 2.5 A was applied to samples.

TABLE I Heat treatment steel samples

Sample	Heating temperature (C)	Holding time (min)	Cooling down (C)	Cooling
1005	925	10	–	Air
1020	925	10	–	Air
1045	860	10	670	Air
1070	830	10	690	Air

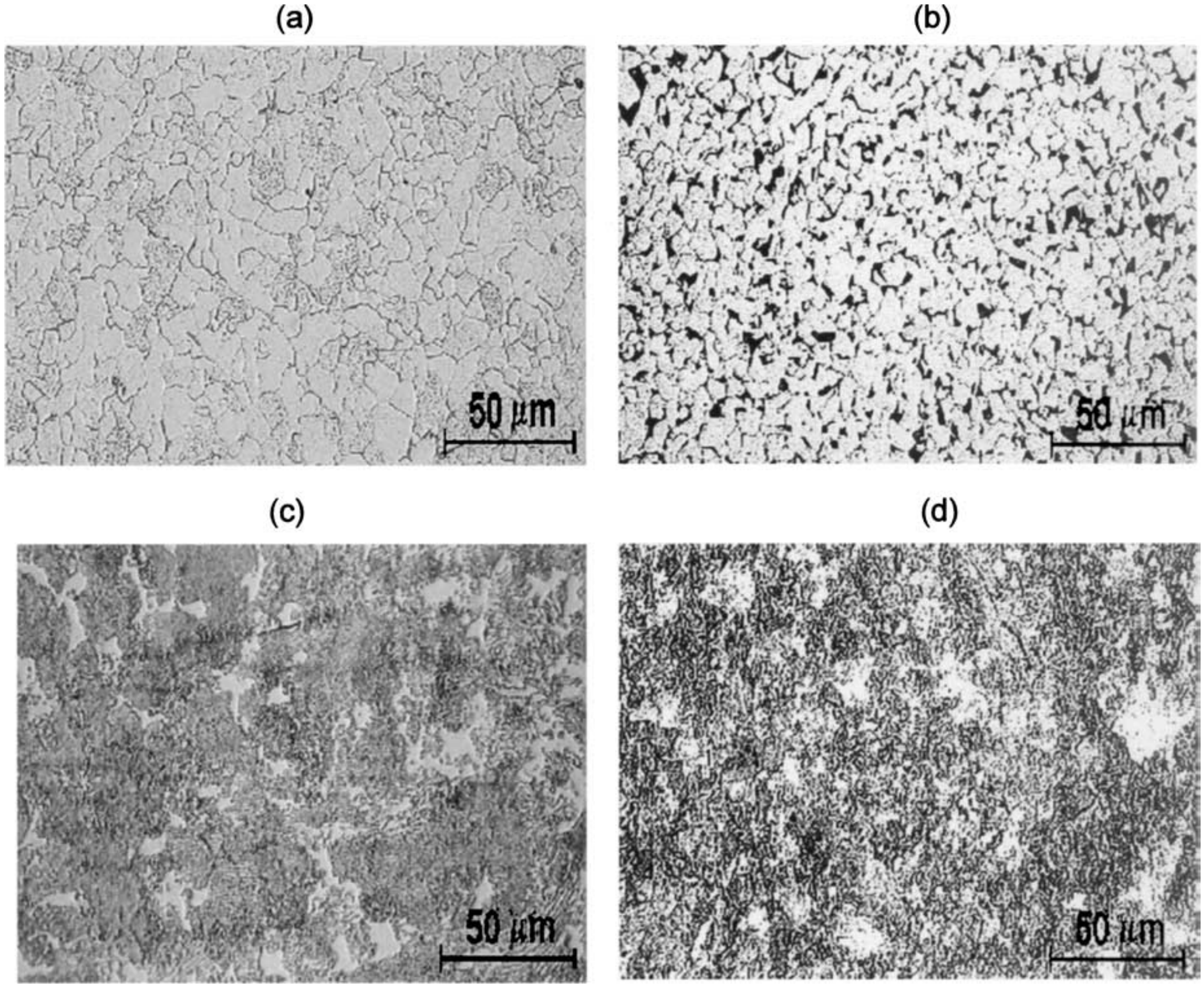

Figure 1 Microstructures obtained by optic microscope: (a) 1005, (b) 1020, (c) 1045, and (d) 1070 steel samples.

3. Discussions

3.1. Magnetic Barkhausen signal

The stochastic character of the MBE is consequence of the irregular jumps of the domain walls under the sweeping process of the magnetic field applied to the ferromagnetic material. The domain wall energy changes when the domain walls move through the material that arises from local defects, grain boundaries and small volume of second phase material.

The MBE amplitude (V_p) and the root mean square voltage (V_{rms}) are shown in Figs 1 and 2. This curve reveals a quadratic dependence of the V_{rms} with the carbon content until 0.45 wt%, and a decrease of V_{rms} for higher values of carbon content. This behaviour can be explained using the domain wall theory.

The qualitative explanation of this behaviour is related with the domain walls motion in the presence of energy barriers. In 1005 and 1020 steels with more ferrite content, the displacement of the domains walls present less difficulty because in this case the material have low density of pinning sites, and therefore less Barkhausen signals [15].

As the carbon content increases, also increases the quantity of pearlite in the material, and therefore the density of pinning sites that impede the free domains wall motion, until enough external energy is provided to overcome the local energy barriers created by the pinning sites. That is the reason for which we observe large Barkhausen jumps. Thus the Barkhausen signal increases, as can observed in 1045 steel. In 1070 steel high pearlite content exists, which increases the density of pinning site, but also, the potential energy of pinning sites. This potential energy cannot be easily overcome. Since the domain wall does not break away from the pinning site until the two surfaces of the domain wall coalesce due to the domain wall bending [15] in this case there will be a decrease of Barkhausen signal.

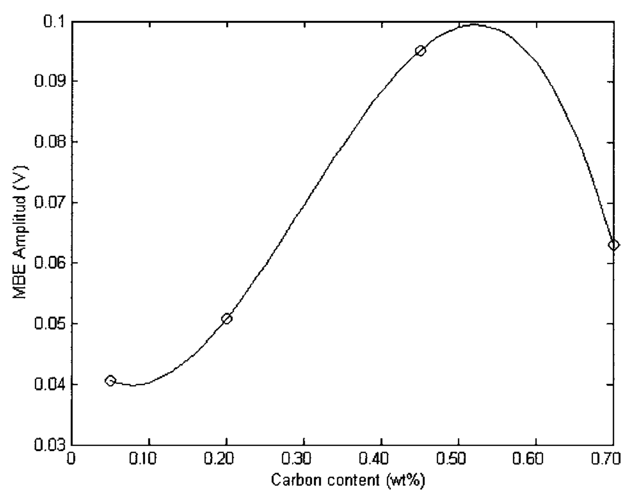

Figure 2 Dependence of MBE amplitude with carbon content.

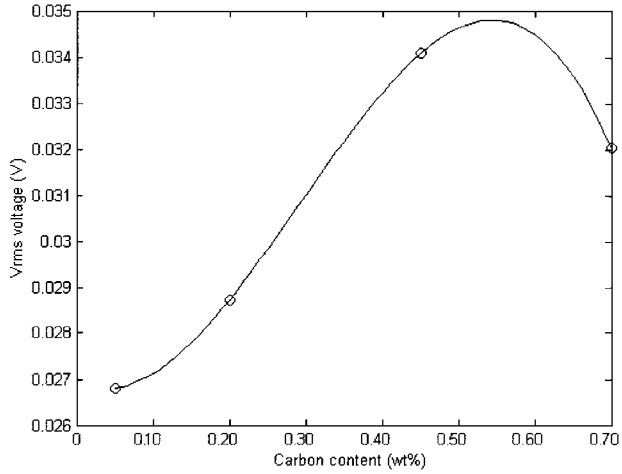

Figure 3 Dependence of V_{rms} with carbon content.

Furthermore the V_{rms} is given by [3]:

$$V_{rms} = \left\{ \frac{1}{T} \int_0^T \left[\mu n A \left(N \frac{d\langle M_{disc} \rangle}{dM_{irre}} + \left\langle M_{disc} \frac{dN}{dM_{irre}} \right\rangle \right) \frac{dM_{irre}}{dH} \frac{dH}{dt} \right]^2 dt \right\}^{\frac{1}{2}} \quad (1)$$

where n is the number of turns on the sensor coil, A is the cross sectional area, N is the number of Barkhausen events, $\langle M_{disc} \rangle$ is the average Barkhausen jump size, M_{irre} is the irreversible changes in magnetization and H is the intensity of the applied magnetic field. The Equation 1 can be approximated [15] to:

$$V_{rms} = \left\{ \frac{1}{T} \int_0^T \left[\mu n A \langle M_{disc} \rangle \frac{dN}{dM_{irre}} \frac{dM_{irre}}{dt} \right]^2 dt \right\}^{\frac{1}{2}} \quad (2)$$

This expression reveals [15] that the V_{rms} is proportional to the irreversible magnetization rate dM_{irre}/dt. Moreover according to Jiles [15], $dM_{irre}/dt \cong \beta(H - H_c)$, where β is a proportionality constant and H_c is the total coercive field of pinning sites. This coercive field can be expressed as $H_c = N \cdot h_c$, where N is number of pinning sites and h_c the local coercive field corresponding to each pinning site. Kersten [16] gave the pinning field (h_c) with diameter (D) and packing fraction(α) of the second phase particles (directly proportional to the carbon content) by the following equation:

$$h_c = 2.5(K/I_s) \cdot (\delta/D)\alpha^{2/3}, \quad (3)$$

where δ is the width of the domain wall, K is the magnetic anisotropy constant and I_s is the saturation

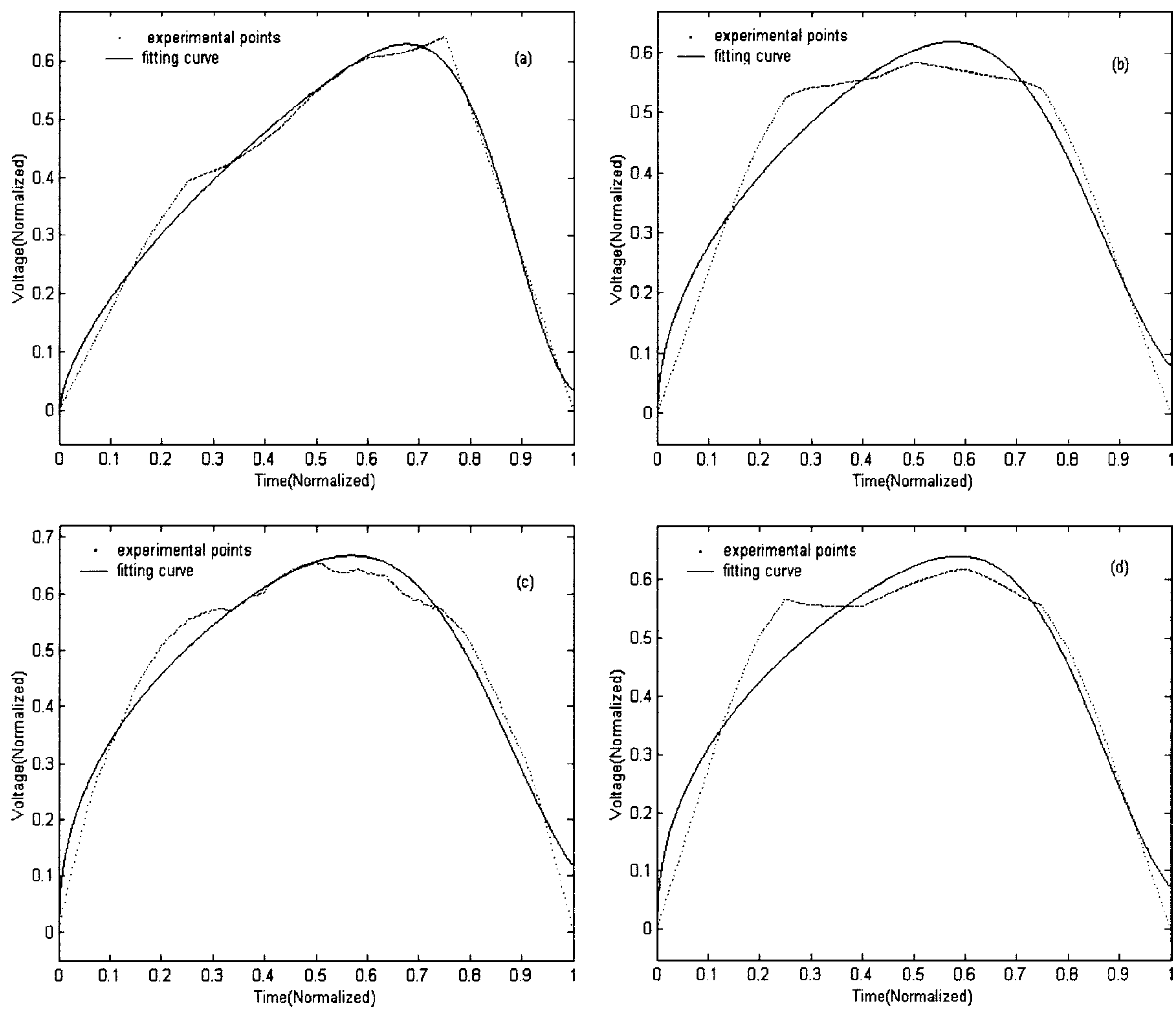

Figure 4 Average MBN elemental signal and the fitting curve for fourth different carbon contents $C = 0.8984$, $T = 0.8677$, $\alpha = 0.1835$ and (a) $\gamma = 0.5832$, (b) $\gamma = 0.5077$, (c) $\gamma = 0.3761$, and (d) $\gamma = 0.4933$.

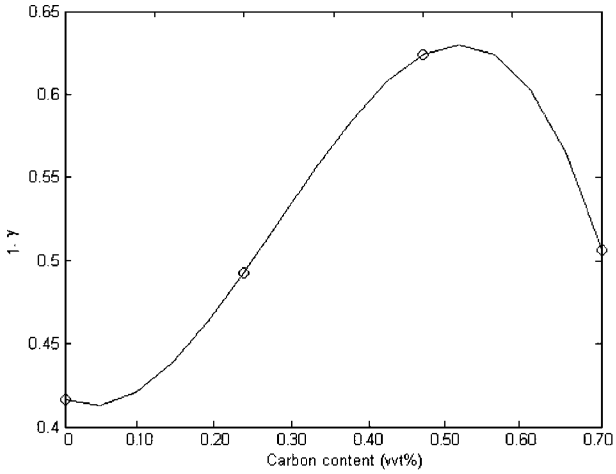

Figure 5 Dependence of 1-γ parameter with carbon content.

magnetization. Also H. Sakamoto [17] gave $N = 6\alpha/\pi d^3$. Finally results:

$$H_c = C\alpha^{5/3}, \quad (4)$$

where $C = 4.78 \cdot (K\delta)/(D^4 I_s)$, which gives:

$$dM_{irre}/dt \cong \beta[H - C \cdot \alpha^2] \quad (5)$$

Therefore, as the magnetizing conditions (H) are the same for all the samples, $V_{rms} \sim \alpha^2$. This dependence is valid for carbon contents equal or less than 0.45 wt%, for higher values of carbon appear strong pinning sites that are difficult to overcome and the MBE decreases, in agree with the present experimental results (Figs 2 and 3).

3.2. Analysis of the influence of the carbon on the MBE jumps form

In this section will be carried out a theoretical interpretation of the magnetic Barkhausen noise. If we consider that during the emission of MBE signals, domain walls avalanches occur; then using the formulations made in [13] and the hypothesis proposed in [14], the probability distribution function of the elementary signals can be expressed by:

$$f(t, C, \gamma, T, \alpha) = Ct^{\gamma-1} \exp\left(-\left(\frac{t}{T}\right)^{\frac{1}{\alpha}}\right), \quad (6)$$

where t is the time, measured from the beginning of the MBEES, C is the characteristic width, T is the characteristic time of duration of an elementary signal, α is an adjustment parameter and γ is the parameter that discriminates the form of MBEES.

Fig. 4 shows the average shape of the MBEES obtained for each steel sample. Can be observed from this figure that the biggest MBE signal corresponds to the 1045 steel.

In the expression (6), the term $t^{\gamma-1}$ represents the growing part of the avalanche front of Barkhausen signal [13]. Fig. 5 shows the dependence of the avalanche front growing with carbon content, which is similar to the V_p and V_{rms} dependence shown in Figs 2 and 3. This result reveals the influence of the microstructure of the material on the propagation of the avalanches through the material. In 1005, 1020 and 1045 steels with the increase of the carbon content, the pinning sites density also increases, which retard the movement of the walls until applied field overcomes the potential energy created by the local coercive field and avalanche occur. This avalanche will be much bigger when the force of the pinning sites is high. However as was previously referred in the 1070 steels the high pearlite content impedes the appearance of the avalanche.

4. Conclusions

This study shows the increase of the Barkhausen signals V_p and V_{rms} with carbon content until the 1045 steel, however a decrease is perceived for further contents (1070), which is due to the higher increase of pinning sites potential energy. On the other hand was obtained a dependence of the propagation of the avalanche on the carbon content, similar to those obtained for V_p and V_{rms}, which is related with the increase of the pinning sites density that augments the avalanches size, for higher carbon contents as in 1070 steel the increase of pinning sites potential energy decreases the velocity of propagation of the avalanches front.

Acknowledgements

This work was supported by FAPESP agency under the project 2001/04088-2.

References

1. A. P. PARAKKA and D. C. JILES, *J. Appl. Phys.* **81**(8) (1997) 5085.
2. V. MOORTHY, S. VAIDYANATHAN, T. JAYAKUMAR, BALDEV RAJ and B. P. KASHYAP, *Acta Mater.* **47**(6) (1999) 1869.
3. S. TIITTO, *Acta Pol. Scand* **119**(19) (1997) 39.
4. R. RAJAN, D. C. JILES and P. K. RASTOGI, *IEEE Trans. Magn.* **MAG-23** (1987) 1869.
5. C. GATELIER-ROTHEA, J. CHICOIS, R. FOUGÈRES and P. FLEISCHMANN, *Acta Mater.* **46** (1998) 4873.
6. J. KAMEDA and R. RANJAN, *Acta Metall.* **35** (1987) 1515.
7. *Idem., ibid.* **35** (1987) 1527.
8. L. CLAPHAM, C. JAGADISH and D. L. ATHERTHON, *ibid.* **39**(7) (1991) 1555.
9. B. ZHU, M. J. JOHNSON and D. C. JILES, *IEEE Trans. Magn.* **36**(5) (2000) 3602.
10. I. ALTPETER, *J. Nodest. Eval.* **15**(2) (1996) 45.
11. D. H. L. NG, K. CHENG, K. S. CHO, Z. Y. REN, X. Y. MA and S. L. I. CHAN, *IEEE Trans. Magn.* **37**(4) (2001) 2734.
12. A. MITRA and D. C. JILES, *ibid.* **31**(6) (1995) 4020.
13. D. SPASOJEVIC, S. BUKVIC, S. MILOSEVIC and H. E. STANLEY, *Phys. Rew.* E **54**(3) (1996) 2531.
14. H. J. JENSEN, K. CHRISTENSEN and H. C. FOGEDBY, *Phys. Rev.* B **40** (1989) 7425.
15. D. C. JILES, *Czechoslovak Journal of Physics* **50**(8) (2000) 893.
16. M. KERSTEN, "Ferromagnetische Hysterese u. Koerzitivikraft" (S. Hirsel, Leipzig, 1943).
17. H. SAKAMOTO, M. OKADA and M. HOMMA, *IEEE Trans. Magn.* **MAG-23**(5) (1987) 2236.

Received 11 September 2002
and accepted 22 July 2003