SOME CONSIDERATIONS ON THE MAGNETOACOUSTIC EFFECT OF FERROMAGNETIC ELASTIC CARBON STEEL RODS

Nicolae Cretu

Department of Physics, "Transilvania" University, B-dul Eroilor 29, Brasov, Romania
e-mail: cretu.c@unitbv.ro

Abstract
The present paper contains a lot of experimental measurements on the magnetoacoustic effect in carbon steel rods and an analysis of the shape of the line of the effect, obtained in the standing wave case. The analysis suggest a possible application in nondestructive evaluation of ferromagnetic samples.

Keywords: magnetoacoustic effect, line shape analysis, nondestructive evaluation.

1. INTRODUCTION

A bulk ferromagnetic sample is usually divided into a number of magnetic domains, within each of which the magnetization has some direction. The domains are separated by domain walls, in which the magnetization gradually turns from the magnetization in one domain to the magnetization direction in the other. The magnetization process in a ferromagnet usually consists of domain wall motion and magnetization rotation [1]. Although the concept of domain wall motion and magnetization rotation is not new, the study of these processes and related phenomena continues to be an important topic in the understanding of the behavior of magnetic materials. The properties of the domain walls provide a key to understand the magnetic microstructure. There are some high resolution methods to observe the domain wall motion such as Lorentz microscopy [2], photoemission microscopy using magnetic circular dicroism [3], spin- polarized scanning tunneling microscopy [4], or combined methods [5]. Because magnetoelastic interaction is the primary factor governing the width, internal structure and interaction between walls, the study of the magnetoacoustic emission can give complementary information near the above mentioned methods about the magnetization processes in the samples. In the same time this phenomenon can be used in nondestructive testing (NDT) of ferromagnetic materials.

The magnetoacoustic emission (MAE) means the generation of the elastic waves in ferromagnetic materials being magnetized in an alternating magnetic field. Another method based on magnetoelastic interaction between domain walls is the Barkhausen noise (BN). The

Barkhausen noise is detected only from near surface of the sample, whereas the MAE signals originate from the bulk. The MAE is sensitive to the 90^0 domain wall motion but is not for 180^0 domain wall motion, for which there is no magnetostrictive strain. BN is sensitive to 180^0 domain wall motion because this is connected to the largest change in magnetic moment [6,8]. The maximum effect of MAE is obtained when the time-varying magnetic field has the same frequency as the eigenfrequencies of the sample. In this case the oscillations of magnetic field are correlated with the standing elastic waves from the sample, and the domain wall motion become a forced oscillation. The exploration of the line shape, give information about the magnetoelastic interactions between the magnetic walls and the magnetization processes in the sample.

The existence of internal mechanical stresses, crystal dislocations, defects or defect clusters, which have the size of several nanometers, and the change of magnetic properties is attributed to the domain wall pining associated with these defects This explain the possibility to use the MAE in the nondestructive evaluation of ferromagnetic materials [6,7]. The present paper contain investigations on MAE in the standing wave state of ferromagnetic carbon steel rods. The influence of the artificial defects on the shape of the velocity line is investigated.

2. EXPERIMENTAL SETUP AND MEASUREMENTS

The alternating signal was obtained from a calibrated sinusoidal signal generator coupled to a linear power amplifier. The amplifier was able to provide an 100 W adjustable sinusoidal signal in a magnetization coil having inside the ferromagnetic sample. The ferromagnetic sample consists from uniform carbon steel rods with the same length and various cross-sections. The material of the ferromagnetic rod is a polycrystalline steel sample, with the first magnetization curve given in Figure 1.

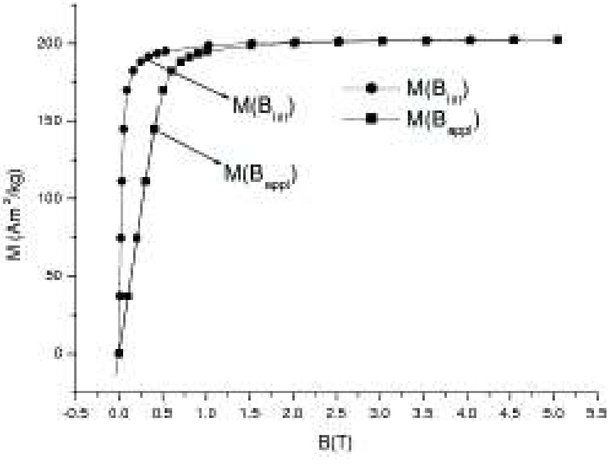

Fig. 1. The first magnetization curve of the ferromagnetic sample

The samples were central placed inside the coil using hairline yarns so we could consider having a free rod behavior. The magnetoelastic signal was detected by a noncontact method using a Bruel & Kjaer Laser Velocity Transducer Type 3544 (with excellent results in velocity measurements) attached to a linear preamplifier RFT Type 20027 connected to a

USB acquisition board NI DAQPad6015. The spectral decomposition of the signals, the filtering and other, were obtained using the signal processing formalism.

In all cases was necessary to take into consideration that the magnetic field inside the sample was nonuniform because of the shape and because of the inhomogeneity of the external field at the ends of the solenoidal coil. A simple measurement of the magnetic induction along the cylindrical sample, central placed in the solenoidal coil with a constant current in the winding, made with a magnetic fluxmetter , reveal the profile from Figure 2.

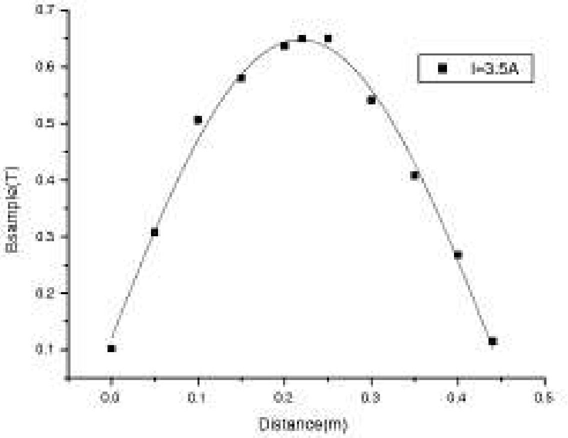

Fig. 2. The inhomogeneity of the magnetic field along the ferromagnetic rod.

The MAE effect is an indubitable proof of the existence of magnetic domains. In connection with, there are two kinds of magnetic wall 180^0 and 90^0. For the sample placed axial with the solenoidal coil, an alternating signal will favor the increasing during a half of time period of corresponding magnetic domain, like in Figure 3.

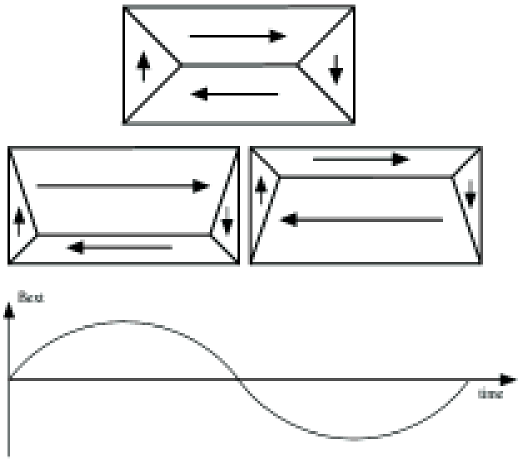

Fig. 3. The alternative increasing of magnetic domains in alternative magnetic field in the magnetic coil.

As a consequence, the appearance of the 90^0 domain walls motion leads to axial magnetostriction, which can be measured. The wall motion is a forced oscillation in the reversible magnetic region. In Figure 4 we plotted the amplitude of the velocity of MAE effect for a carbon steel rod for the first 4-th standing wave eigenfrequencies.

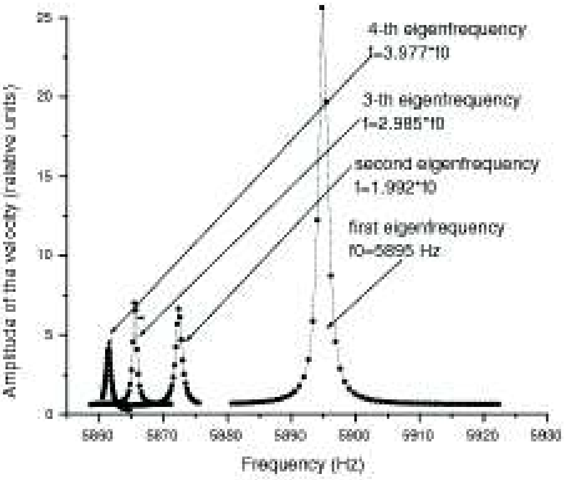

Fig. 4. The shape of the amplitude of the velocity of MAE effect obtained by axial magnetostriction measurements.

The square of the amplitude of domain wall vibrations in this case depends on frequency according to a Lorentzian shape formula:

$$|\mathrm{A}(\omega)|^2 = |\mathrm{A}(\omega_0)|^2 \frac{\Gamma^2 \omega_0^{\ 2}}{(\omega_0 - \omega)^2 + \Gamma^2 \omega^2} = |\mathrm{A}(\omega_0)|^2 \frac{(\Gamma/2)^2}{(\omega_0 - \omega)^2 + (\Gamma/2)^2} \qquad (1)$$

where Γ is the line width of the square amplitude spectrum. In Figure 5 is plotted the line width obtained by experiment corresponding to plots from Figure 4. The plot indicates an increase of the line width with frequency and certainly a decrease of the time constant of corresponding free oscillations. The increase of the line width is approximately exponential.

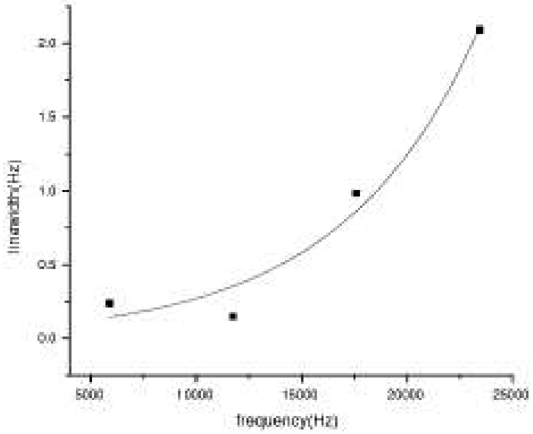

Fig. 5. Linewidth of MAE in standing wave case for the first four eigenfrequencies of the ferromagnetic rod

The square of the amplitude is the sum of two terms describing the dispersion and absobtion phenomena:

$$|A(\omega)|^2 = |A_{dispersive}(\omega)|^2 + |A_{absorbtive}(\omega)|^2 \tag{2}$$

When $\omega = \omega_0$, $A_{dispersive}(\omega_0) = 0$ and $A_{absorbtive}(\omega)$ has a maximum value. If we accept the equation of motion for a 90^0 domain wall given by:

$$m\ddot{x} + m\Gamma\dot{x} + m\omega_0{}^2 x = aM_s B_z e^{i\omega t} \tag{3}$$

where m is the mass per surface unit of the wall, M_s the magnetization, a a number which can be obtained by averaging the magnetization over the thickness d of the wall, the maximum value of absorbtive amplitude will be given by:

$$A_{absorbtive}(\omega_0) = \frac{aM_s B_z}{m} \tag{4}$$

Therefore, the maximum and the area of the resonance plot of the amplitude of MAE will provide information about magnetization of the sample, and the mass of the surface unit of the involved walls. In Figure 6 is represented the change of the area of resonance plot of MAE for the first four natural frequencies of a cylindrical ferromagnetic bar with length $L = 0.44\,m$ and uniform diameter $D = 19 \cdot 10^{-3}\,m$. The decrease of the corresponding areas of the resonance plots follows an exponential first order decay.

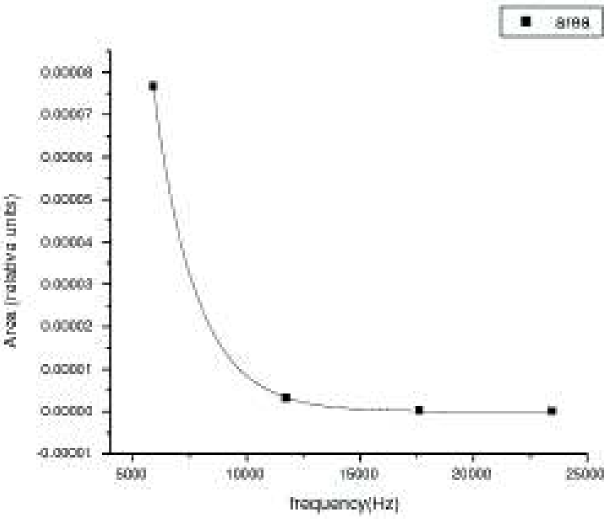

Fig. 6. Area of the resonance curve for the first four eigenfrequencies

The fact that the MAE is very sensitive to internal stress, defects, or clusters of defects, is illustrated in Figure 7. This figure shows the plot of MAE obtained in the standing wave case for the first natural frequency of a ferromagnetic rod with the length $L = 0.44\,m$ and diameter $D = 0.02\,m$ from carbon steel, in which we created artificial defects consisting of small holes obtained by drilling.

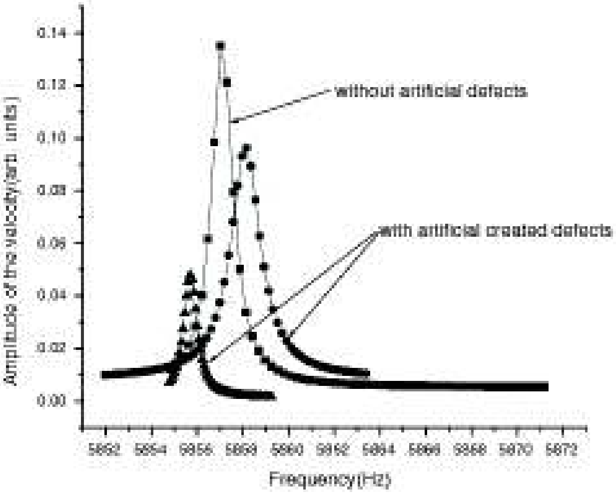

Fig. 7. The influence of artificial defects on the height and the shape of the MAE in the standing wave method.

3. CONCLUSIONS

The magnetoacoustic emission is a consequence of the existance of magnetic domains in ferromagnetic samples. This effect is driven by an alternating magnetic field, which engages the increase or decrease of the favourized magnetic domains and thereby the domain wall movement. In the standing wave case, the domain wall motion is correlated with the displacements of portions of the elastic ferromagnetic medium from the elastic standing wave in the sample. In this case, the MAE effect becomes maximum, the domain walls perform a forced oscillation, and we can obtain information about the evolution of the magnetic domains in the sample by the analysis of the resonance curve. Certainly, in the case of standing wave method, the maximum effect is obtained for the natural frequencies of the sample. In the sample, in the case of longitudinal wave, on both sides of the nodes, the medium is subject of alternative compressions and dilatations, such as the interaction between the magnetic wall motion and the elastic wave will have the maximum effect.

By comparing the effect for natural frequencies of the sample, the maximum effect is obtained for the first eigenfrequency of the ferromagnetic rod. This can be explained by the fact that in this case, in the whole sample, the wave oscillations and the magnetic wall motion are in phase. For the second natural frequency, with an antinode at the middle of the bar, only for half of the sample the two oscillations are in phase. This explain why the effect is approximately fifty percent lower as the effect for the first natural frequency, and the analogism can be extended to the next natural frequencies. On the other hand, placing the sample in a constant magnetic field, and transmitting an ultrasonic wave into the sample at the node locations, where the standing wave stress is maximum, a high frequency magnetic field is generated by the reciprocal effect of magnetostriction [9].

Due to the fact that the magnetoacoustic effect is very sensitive to the internal stress or to magnetic modifications, this method can be used in the nondestructive evaluation of ferromagnetic materials.

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