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Investigation of magnetic and magnetomechanical hysteresis properties of Fe–Si alloys with classical and mechanical Barkhausen effects and magnetoacoustic emission

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Grain oriented Fe 3.5% Si sheet samples with a Goss (GO) microstructure and Fe 3.5% samples with nonoriented (NO) grains were tested using two Barkhausen effects, the classical Barkhausen effect (HBE) and the mechanical Barkhausen effect (MBE), as well as the magnetoacoustic emission (MAE). The aim of the work was to present further evidence that the $B(H)$ hysteresis with effects like HBE and MAE, and magnetomechanical hysteresis with MBE are correlated via internal stress barriers pinning domain walls (DWs). In the case of a GO alloy, the long axis of the sample was parallel to the [100], [110], and [111] directions with respect to the rolling direction. The HBE and MAE were measured using a C-core electromagnet supplied with a triangular wave form of current intensity. The MBE intensity was recorded during a monotonous increase of shear stress using a torque machine. The maxima of MBE intensity for the ''first load'' mode for a NO sample and for three GO samples indicate an internal stress distribution pinning 90° DWs. The MAE plots reveal at least two maxima which are well correlated with H strength values where creation and annihilation of magnetic domains appears. Since the MBE and MAE are associated with abrupt jumps of 90° DW, the existence of MBE and MAE reinforces the fact that such DWs are present in the tested samples. These walls belong mainly to the secondary closure domains at GO alloys and to closure domains at NO alloy.
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I. INTRODUCTION

The questions about the source of the magnetoacoustic emission (MAE) source seems to be quite important when this effect is used in practice. The MAE intensity envelope reveals mostly two maximums in the knee region of the hysteresis curve, therefore the interpretation of the MAE source is not obvious. It is argued that MAE is caused by microscopic changes in local strain induced magnetoelastically,[1] but various mechanisms are still discussed. Two main mechanisms were proposed in the mid-1980's: The discontinuous motion of non-180° domain walls (DWs) for low magnetic field strengths,[1] and the creation and annihilation of DWs for high magnetic field strengths.[2] The last process was subsequently postulated by Ref. 3. The hypothesis that the movement of 180° DWs provides a MAE signal was proposed in Ref. 4, and was recently reinforced in Ref. 5. However, it seems that insight into the MAE source can be achieved through a multiparameter study. In Ref. 6, it was revealed that MAE peak positions correlate well with positions of maxima of the magnetostriction derivative, indicating that MAE is related to movement of 90°, and not 180°, DWs. Furthermore, a comparative study of the mechanical Barkhausen effect (MBE) and of the acoustic emission of dynamically stressed samples[7] revealed results in support of the hypothesis, that both effects are due to the abrupt movement of 90° DWs. The aim of the present work is to provide additional evidence that magnetic hysteresis with HBE, as well as MAE and MBE, are correlated via internal stress barriers pinning DWs, and that MAE is due mainly to the movement of 90° DWs. This is made using model-like materials: Grain oriented Fe 3.5% Si sheet samples with a Goss (GO) microstructure and Fe 3.5% samples with nonoriented (NO) grains.

II. EXPERIMENT

Grain oriented Fe 3.5% Si sheet samples with a GO microstructure and Fe 3.5% samples with NO grains were tested using two Barkhausen effects (BEs), HBE and MBE, and MAE. The samples were in the form of stripes with length $\ell = 150$ mm and with widths: $d = 30$ mm for HBE and $d = 10$ mm for MBE experiments. In the case of a GO alloy, the long axis of the sample was parallel to the [100], [110] and [111] directions with respect to the rolling direction. The HBE and MAE were measured using a C-core electromagnet supplied with a triangular wave form of current intensity with frequency $f = 1$ Hz and magnetic field strength amplitude $H_0 = 1$ kA/m. Details of the experimental setup are given in Ref. 6. The HBE intensity as well as the $B(H)$ hysteresis loop were obtained from the voltage signal (U_i) induced at the pick-up coil wound on the sample. This voltage was analyzed by electronic instrumentation described in

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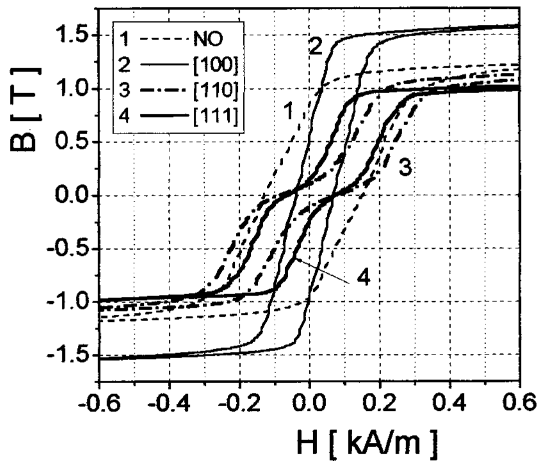

FIG. 1. Magnetic hysteresis loops of tested samples.

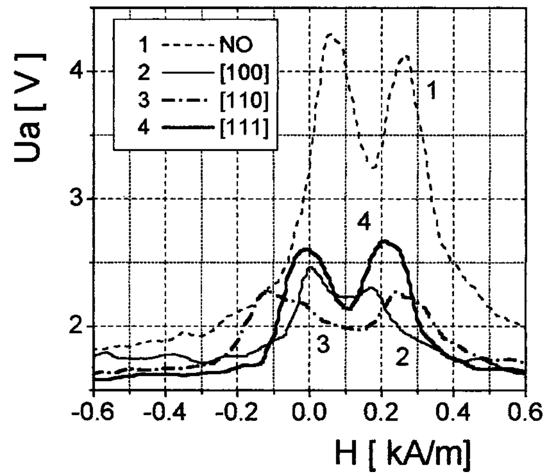

FIG. 2. The MAE intensity for a half loop for tested samples.

Ref. 8. The output HBE intensity voltage (U_b) is proportional to the integral of rectified BE pulses. The MAE signal was produced by a piezoelectric transducer with a resonant frequency of about 200 kHz. This voltage was amplified (110 dB), filtered (frequency band 4 kHz to 1 MHz) and transformed to dc-like signal (U_a) using a root-mean-square integral circuit. The MBE intensity was recorded during the monotonous increase of shear stress using a torque machine.[9] The shear strain γ of the sample was determined using a light spot and a photocell transducer.[10] The MBE voltage was induced at pick-up coil wound on the sample, and the MBE intensity was given by the voltage (U_m) obtained from the same analyzer used for HBE signal.

III. RESULTS AND DISCUSSION

Figure 1 shows the part of $B(H)$ hysteresis loops within a ''window'' of H strength from -0.6 kA/m to 0.6 kA/m. These plots reveal the typical features of the hysteresis loop, as expected for such samples.[11] In comparison with results obtained using the Epstain frame method, our coercivity values are apparently higher. This is due to the demagnetization effect caused by applying the C-core method. This fact, however, does not disturb the comparative study of the MAE and MBE intensities. The hysteresis loop of the NO sample (plot 1 in Fig. 1) reveals the material with the highest level of coercive force. The lowest level of H_c is obtained for the GO sample when the magnetization is parallel to the [100] direction (plot 2 in Fig. 1). Distortion of the $B(H)$ loops for the [110] direction (plot 3) and the [111] direction (plot 4 in Fig. 1) is due to a two-steplike magnetization process when the magnetic field is not parallel to the rolling direction of the sheet. The field dependencies of the MAE and HBE intensities are shown in Figs. 2 and 3, respectively. The MAE intensity plot reveals a two-peaklike behavior. These peaks can be labeled ''P1''—for low-field—and ''P2''—for higher-field strength. The plot with the highest intensity indicates a NO sample, while the intensity of the MAE for a GO is highest when the sample is magnetized along the [111] direction (plot 4, in Fig. 2). A comparison of the MAE plots with the $B(H)$ curve for an increasing field strength allows one to conclude that the MAE peak positions can be related to ''knees'' in the $B(H)$ curve: Peak P1 appears at the ''first'' knee and P2—at the ''last'' knee. On the other hand, the HBE intensity field dependence differs from the MAE dependence. Figure 3 shows that the field dependence of the HBE intensity measured for the NO sample (plot 1) and for the GO sample along the [100] direction (plot 2) is characterized by two peaks. Their positions seem to be well correlated with MAE peaks position. However, the HBE intensity of the GO samples for directions [110] (plot 3) and [111] (plot 4 in Fig. 3) is generally lower than for the [100] case and displays three peaks. Nevertheless, that position of the first and last peak are close to the positions of MAE peaks.

The MBE results are summarized in Fig. 4. Four plots of the MBE intensity for ''first load'' mode indicate an internal stress distribution pinning 90° DWs.[12] The MBE intensity level denotes the intensity of the DWs just depinned when the external stress is equal or higher than the internal pinning stress. The maximum of MBE appears when the highest number of 90° DWs is depinned from their pinning centers. One can find that maximum of MBE for a NO sample appears at strain values much higher than for GO samples. The difference in MBE intensity for GO samples is also evident. The maximums appear nearly at the same strain level, but the

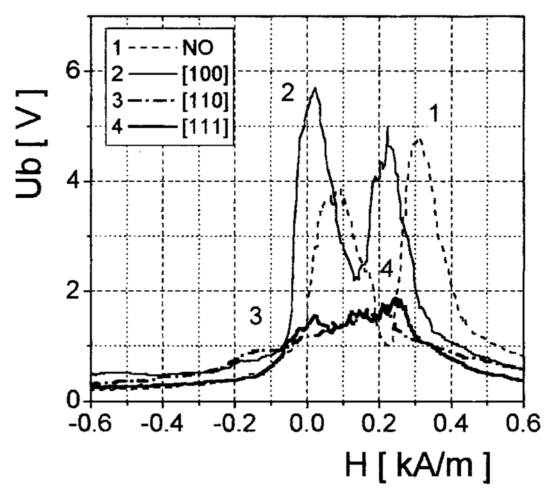

FIG. 3. The MBE intensity for a half loop for tested samples.

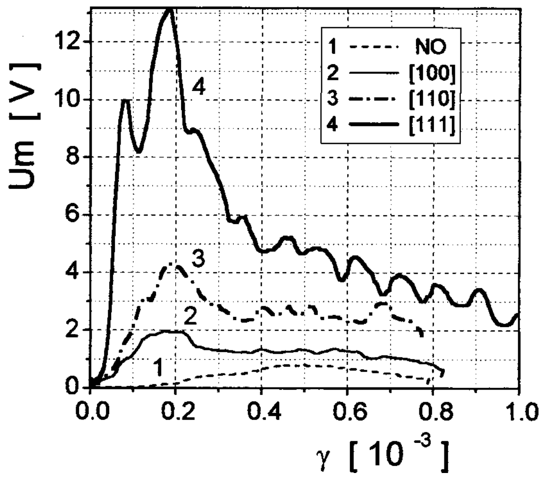

FIG. 4. The MBE intensity for tested samples.

highest intensity is obtained for the sample with the magnetization direction in the [111] direction, and the lowest for the direction [100]. It should be noted that this difference in MBE intensity sample is due to difference of the main axis of stress applied during loading against rolling direction. One can find that the tensile and compressive stresses are close to the [100] direction as in the case of the sample type [111]—plot 4 (Fig. 4).[13] It means that for this sample the external stress is the most ''effective'' for magnetomechanical effect. The mean value of the internal stress can be evaluated using the position of the MBE maximum shear strain γ. This shear strain γ can be converted to an effective normal stress level σ using standard von Mises' criterion: $\sigma=\sqrt{3}\tau$, where τ is the applied shear stress. One can find that for a shear modulus G of the order of 80 GPa, the internal stress level is approximately 20 MPa for GO samples and about 60 MPa for the NO samples. The existence of a MBE signal for Fe–Si samples denotes that both alloys contain active 90° DWs. These walls are part of ''closure domains'' inside the grains of the NO Fe–Si alloy, and part of ''secondary'' closure domains present in the GO Fe–Si alloy. Secondary closure domains are illustrated in Ref. 4. It means that MAE activity in GO and NO alloys is likely due to the movement of this type of DW. The position of MAE peaks at the knee region of the $B(H)$ loop can lead to the argument that only ''creation–annihilation'' processes are responsible for MAE. However to our knowledge this last hypothesis has never been proven through dynamic detection of DW movement with simultaneous MAE signal measurement. The correlation between MAE activity and magnetostriction rate for low carbon steel and iron, suggests that MAE maximum at the knee region is due mostly to movement of non-180° DWs because this type of movement leads to the greatest change in magnetostriction. This process seems to be the most important after ''creation'' and 'before ''annihilation'' of reverse domains.

IV. CONCLUSIONS

Multiparameter analysis of magnetomechanical properties of GO and NO Fe–Si reveal that the MAE maximums, well correlated with H strength values at which creation and annihilation of magnetic domains is assumed to appear, can be attributed to 90° DW activity. The existence of such type of DWs is reinforced through MBE measurements. This further indicates that $B(H)$ hysteresis with effects like HBE, MAE, and magnetomechanical hysteresis with MBE are well correlated via internal stress barriers pinning DWs.

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