Magnetoacoustic Emission during Deformation of Steel

Bohdan Klym [1,a], Valentyn Skalsky [1,b], Roman Basarab [2,c] and
Sviatoslav Hirnyj [1,d]

[1] Karpenko Physical-Mechanical Institute, National Academy of Sciences of Ukraine,
5 Naukova Street, Lviv, 79060, Ukraine

[2] Ukrtransnafta JSC, Oil-trunk pipelines Druzhba, 12 Lypynskoho Street, Lviv, 79000, Ukraine

klym@ipm.lviv.ua, skal@ipm.lviv.ua, mailbox@druzhba.lviv.ua, hirnyj@ipm.lviv.ua

Keywords: acoustic emission, magnetoacoustic emission, deformation, low-carbon steel, nondestructive evaluation.

Abstract. Preliminary results from the studies of the effect of elastic and plastic deformation of low-carbon steel on the intensity of magnetoacoustic emission (MAE) signal are presented. These studies employed a MAE measuring system MAE-1L, which was engineered at Karpenko Physical-Mechanical Institute. Generally, the observed tendencies of the reduction of the MAE signal intensity with deformation of iron-based alloys confirm those published in the literature. The reproducibility of measurements related to the elastic region was very high. Also, very high is the sensitivity of MAE parameters to elastic straining. As to the plastic region, it exhibited higher scatter of the MAE signal parameter with the sensitivity to the level of plastic deformation being rather low. The presented MAE measurements has demonstrated that the MAE method might bear a potential for nondestructive evaluation of plastically damaged parts of operated equipment or structures, but a more sensitive signal parameter should be found, or the method has to be accompanied with other technique in order to sense the difference between the safe elastic deformation and the dangerous plastic one. The engineered measuring system MAE-1L exhibited a reliable performance.

Introduction

As plastic deformation is the most important manifestation of the material’s overloading and the closeness to its ultimate stress, much effort has been dedicated for the quest of an effective method for nondestructive evaluation (NDE) of the level of stress and degree of straining in structural materials. Acoustic emission (AE) has an established record of detecting not only brittle fracture, but also plastic deformation or shear fracture of ductile materials. This method is practical when a structure is subjected to the levels of stresses that exceed the normal operational stresses. This is the case, for instance, in the so-called hydrostatic testing of pressure boundaries. The negative aspect of such testing is in additional overloading of the structure/equipment, which contributes to its ageing and makes closer its fatigue limit.

Another method that employs AE does not demand any overloading of the structure, but works similarly to other NDE methods, as far as excitation with external field is concerned. Magnetoacoustic emission (MAE), which is emission of acoustic waves from the bulk of a ferromagnetic material that undergoes magnetization change under the influence of externally applied alternating magnetic field, has long been known for its sensitivity to deformation, rooted either in magnetic anisotropy of materials, or in the increasing pinning of the domain walls.

Application of MAE in NDE. Before discussing the issues of plastic deformation and its measurements with magnetoacoustic instrumentation, a short note delineating the principles and issues related to MAE has to be given.

MAE – is a release of elastic acoustic waves in the bulk of a ferromagnetic material subjected to the influence of a variable magnetic field. MAE was experimentally discovered by Lord and coworkers during magnetization of nickel in the early 1970-s [1] and its potential in the area of NDE including aging and degradation of ferromagnetic structural materials has been continuously expanded ever since [2-4].

Though the nature of this phenomenon has not been clearly defined yet, the basic principles of MAE have been generally agreed upon by the scholars. It is believed that MAE reflects the dynamics (discontinuous movement, creation and annihilation) of the non-180° domain walls in the time-dependent field. The dynamics of 180° anti-parallel domain walls seemingly could not contribute to the generation of elastic waves since the movements of 180° walls do not affect magnetostrictive strain [5-7]. Also, it was suggested that in strong magnetic fields MAE could also originate from the irreversible rotations of the magnetization vectors through angles other than 180°, or reflect the dynamics of closure domains and island domains stabilized by inclusions or other microcrystalline imperfections [8,9]. The nature of MAE still raises questions mostly due to the presence of two maxima of the MAE intensity signal vs. magnetic field strength in the near-saturation region. A seemingly more simple method, known as Barkhausen noise, which is a magnetic analog to MAE, as commonly agreed, is originated solely from the 180° wall dynamics. However, its nature has also been questioned [10].

The basic advantage of the MAE method over the Barkhausen noise method is its informative depth, which practically depends only on the penetration ability of the excitation magnetic field. In case of MAE a depth of 10 mm or more could be easily achieved, while the Barkhausen noise signal is screened by subsurface eddy currents that limit the depth to 100-200 μm. The power of MAE seems to depend on magnetostriction coefficient λ, sweep frequency f, amplitude of the external magnetizing field H_a [2], although its relation to magnetostriction was questioned for some materials [11].

As to the disadvantages, MAE method suffers from its high sensitivity to the background acoustic and electric noises. Also, the MAE signal parameters reflect not only the properties of the generated elastic waves modified by the microstructure and stress field in the material, but also by the geometry of the studied object [12, 13], not to mention the properties of both the displacement-to-voltage transducers and the acquisition-processing systems. This makes the sets of MAE data obtained in different laboratories hardly comparable to each other since the influences of all the variables could not possibly be separated. Another issue is a uniqueness of every recorded MAE signal since the domain structure of the ferromagnetic material changes with every reversible magnetization cycle and, consequently, the arrays of waves generated in the bulk of the material are unique for every magnetization loop, which, consequently, demands averaging and statistical analysis of dozens of typical MAE signals rather then making a judgment from a single measurement.

Effect of plastic deformation on MAE – state of the art. Plastic deformation has been widely accepted as one of the most important manifestations of the material's overloading leading to the quest for an effective NDE method, which would be able to evaluate the level of stress and degree of straining in structural materials. MAE method has been one of the promising candidates for this task [2,14,15]. Stressing (straining) of a ferromagnetic material has a complex influence on the magnetic properties [16-19]. Elastic straining has an influence on magnetocrystalline anisotropy [2], while the plastic deformation increases the density of dislocations which serve as pinning points for domain walls. These changes have to be reflected not only in deviation of magnetic parameters, but also in acoustic emission that originates from the magnetization process, even solely for the reason of redistribution of the number of 180° and non-180° domain walls due to the influence of stress [2]. We will not touch here on the magneto-mechanical effect [20], which is also accompanied by acoustic emission [21] and reflect the changes in domain structure under the influence of stress.

Here we are concerned with quasistatic straining when acoustic waves are generated from the magnetization process alone.

From the early works of Kusanagi *et al* [14] and Ono and Shibata [8,9,22,23] followed by Burkhardt *et al* [24] it appeared that MAE could become the tool for measuring residual stresses and the amount of the prior cold work since its power decreases very significantly due to plastic deformation.

Moreover, the application of MAE for the NDE purposes appeared to be more practical than Barkhausen noise, since the dependency of the latter on the applied stress looked complicated [25]. Besides, it seemed that MAE was much more sensitive to stress than to microstructure. The subsequent experimentation of Buttle *et al* [26], who studied pure iron plastically deformed by 5 % followed by heat treatment at different temperatures for stress relief and dislocation density reduction, confirmed that MAE is sensitive to dislocation density even at weak magnetic fields. Eventually, Buttle and Hutchings presented two instruments that were developed for measurement of residual stress – one based on MAE and the other on the stress-induced magnetic anisotropy effect [27].

The most elegant analytical explanation of the decrease of MAE intensity with increased straining is given by Ng *et al* [28]. Since the magnetoelastic energy E_{me} (as taken from [29]) could be expressed as

$$E_{me} \sim \lambda\, \sigma \sin^2 \Theta, \qquad (1)$$

where λ – is the saturation magnetostriction (($\lambda_{100} > 0$ for Fe), σ – stress, and Θ – the angle between the directions of magnetization vector $\boldsymbol{M}$ and σ, the application of stress to steel would cause $\boldsymbol{M}$ to align along the σ direction so that E_{me} is minimized. This would increase the total area of 180° walls at the expense of 90° walls, consequently reducing the MAE intensity.

As phenomenologically analyzed by O'Sullivan *et al* [30], an increase of plastic deformation causes an increase in the density of dislocations together with an increase in the interaction between the domain walls and dislocations resulting in the hindered domain wall dynamics. The interaction between domain walls and dislocations seems stronger for 180° domain walls, than for non-180° domain walls.

The most recent series of experimental studies of the effect of plastic deformation on MAE belongs to Piotrowski *et al* [31-33]. Basically confirming the decay of MAE with plastic deformation, there had been observed a drop in MAE for the zero-strained sample. It could be questioned that the zero-strained sample exhibited the effects of machining operations, residual stresses or some artifacts of the experimental procedure. A definite value of this work is a clear presentation of the effect of plastic deformation on the position of the second MAE peak, which moves to the higher magnetic fields together with the knee of the magnetic hysteresis curve.

All these numerous experimental studies and industrial applications were not left without theoretical treatment. By combination of the Jiles-Atherton model [5,34,35] with Alessandro-Beatrice-Bertotti-Montorsi (ABBM) model [36] modified for non-180° domain walls, a treatment of the effect of plastic deformation on MAE became possible [37]. The most recent theoretical work belongs to an effort of extending the magnetoelastic theory [38], which previously could not explain the magnetic phenomena in ferromagnetic materials subjected to plastic deformation. In this development of magnetomechanical theory the following issues have been considered: i) field-induced magnetization, ii) elastic-deformation-induced field iii) plastic-deformation-induced field, and iv) magnetic–elastic-plastic model.

Objective. Having considered the above knowledge on the effects of mechanical deformation on MAE within the frame of application of MAE method for NDE of structural materials, as far as Ukrainian industry with its NDE instrumentation market is concerned, the developments of the MAE diagnostic instruments for practical implementation into the area of NDE of structural materials and their verification to the effects described above have been undertaken. Karpenko Physical-Mechanical Institute has engineered a sample of a PC-controlled MAE instrument, MAE-1L, shortly described in the other report submitted to this conference. Before this instrument becomes a prototype for massive industrial use for the in-service diagnostics, its detailed verification has to be conducted. Such verification had been the main goal of the presented study. Here we report the results of the employment of MAE-1L measuring system in studies of the MAE responses to deformation both elastic and plastic of commercial low-carbon steel, a typical structural material.

Experimental Approach

Before MAE measurements were conducted, the evaluation of the system for the most effective magnetizing frequency has been performed. Fig. 1 exhibits the optimization measurements from which the frequency of 6 Hz was selected for MAE study.

Initially two series of MAE measurements were conducted when a sample made of low carbon steel grade 15 (analog to SAE 1015 type) with gage sizes of 240x30x3 mm, surrounded by the solenoid was placed into the straining machine and stair-strained within elastic region to evaluate the effect of elastic deformation. During these studies, in order to evaluate the repeatability of measurements a second sample was strained in the order loading-unloading-reloading. In other series of experiments the samples with two different thicknesses were subjected to plastic strain and unloaded before MAE measurements were made so that the effect of plastic deformation could be evaluated. Magnetization in the strained sample was induced by the 6 Hz sinusoidal magnetic field with amplitude 7.1 kA/m, i.e. below the presaturation knee.

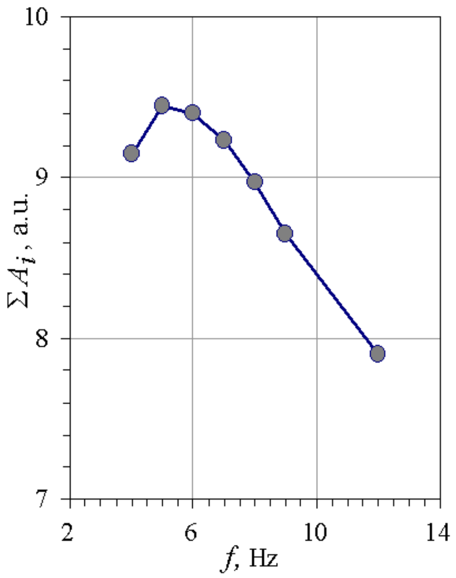


Fig. 1. The effect of the magnetizing current frequency on the sum of total amplitude for the impulses of MAE signal ΣA_i.

A wide-band piezoelectric transducer was acoustically attached to the surface of the sample near the upper grip of the tensile machine and was electrically connected to the system MAE-1L through a 40 dB preamplifier. Signal from the transducer was amplified to a total of about 100 dB and filtered within 200-1000 kHz. Ten data samples for each deformation step were recorded, MAE parameter ΣA_i (sum of the amplitudes of MAE impulses) was averaged for each step and the dependency of ΣA_i on deformation was plotted.

Results and discussion

The results from the first two series related to elastic deformation are presented in Fig. 2. From the dependency of MAE parameter ΣA_i (sum of the amplitudes of MAE impulses) on elastic deformation several conclusions could be made. The effect of strain on magnetocrystalline anisotropy is well manifested in agreement with the published reports. Moreover, the tendencies for both samples are very close to each other and the plots for two stair-straining runs of the second sample practically coincide with each other confirming high repeatability of the MAE measurements. This is encouraging information since the metrological issues, especially in the magnetic and even more so in the acoustic measurements are of serious concern.

Fig. 3 presents the results of the influence of plastic deformation on the 3 mm thick sample. In this case there is a scatter in ΣA_i, but the degree of scatter is very reasonable (for linear regression $R^2 = 0.86$) considering numerous acts of replacing of the sample, solenoid and transducer during this series of experiments.

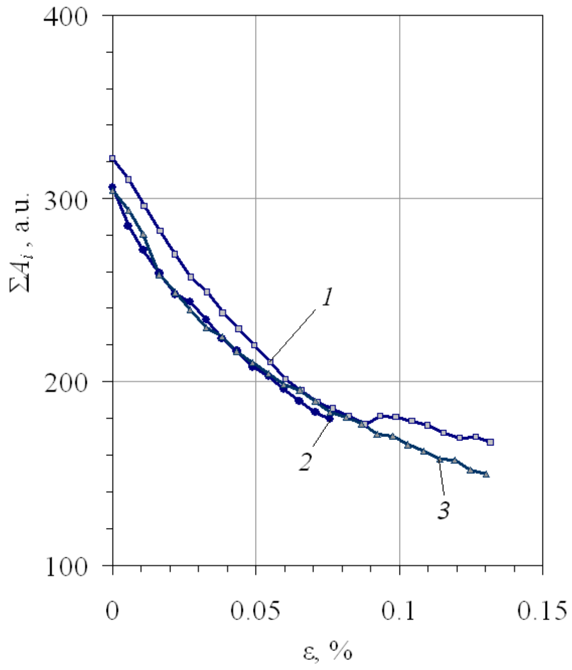


Fig. 2. The effect of elastic deformation on the sum of total amplitude for the impulses of MAE signal ΣA_i recorded for low carbon steel.

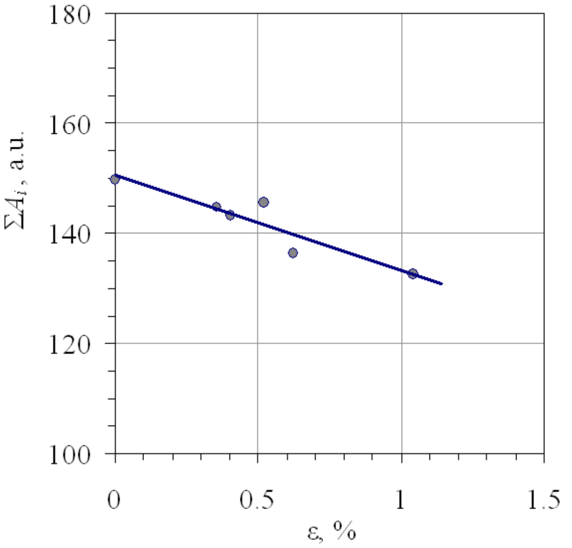
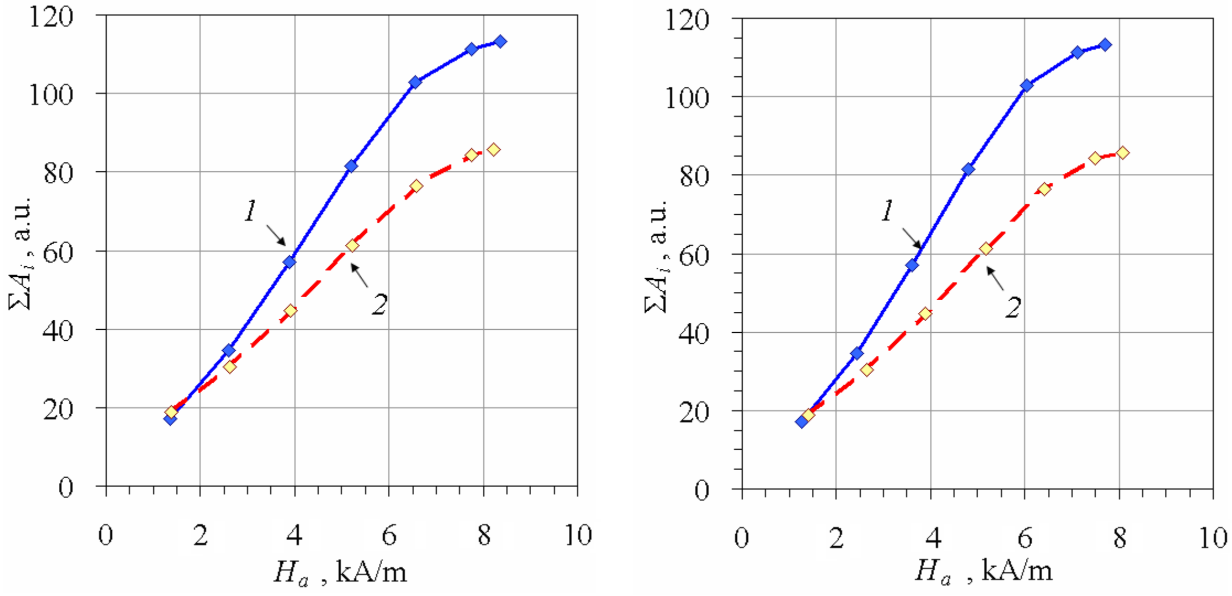


Fig. 3. The effect of plastic deformation on the sum of total amplitude for the impulses of MAE signal ΣA_i recorded for low carbon steel.

Fig. 4 exhibits the experiments conducted on two samples of different thicknesses – 2 mm and 3 mm – in order to observe how the dependency of ΣA_i on the amplitude of magnetic field strength H_a is influenced by plastic deformation. It is obvious that ΣA_i decreases for both differently plastically deformed samples of different thicknesses. Plastic deformation alone has a significant influence on ΣA_i, though this influence is obviously not as strong as for elastic deformation.



a

b

Fig. 4. The effect of the amplitude of magnetic field strength H_a on the MAE parameter ΣA_i for the samples 2 mm (a) and 3 mm (b) thick: *1* – non-deformed sample and *2* – the sample plastically deformed by $\varepsilon = 1.7$ % (2 mm thick) and $\varepsilon = 7$ % (3 mm thick).

It might be argued that small elastic deformation, which is of little concern to industrial operators, might have similar effect on MAE parameters as a significant plastic deformation, which could precede a catastrophic failure. As from the obtained results it is hard at this point to separate the effect of elastic deformation on the parameters of the MAE signal from the effect of plastic one. Further search into the differences in MAE signal parameters is needed to overcome this ambiguity. For instance, the spectral characteristics could be different for MAE signals induced by plastic and by elastic straining. If not, the other methods that can discriminate between elastic and plastic deformation should be employed. Besides, the routine verification of the presented dependencies on other ferromagnetic materials should be conducted.

Conclusions

Preliminary results from the studies of the effect of elastic and plastic deformation of low-carbon steel on the intensity of magnetoacoustic emission (MAE) signal are presented. These studies employed a MAE measuring system MAE-1L, which was engineered at Karpenko Physical-Mechanical Institute. Generally, the observed tendencies of the reduction of the MAE signal intensity with deformation of iron-based alloys confirm those published in the literature. The reproducibility of measurements related to the elastic region was very high. Also, very high is the sensitivity of MAE parameters to elastic straining. As to the plastic region, it exhibited higher scatter of the MAE signal parameter with the sensitivity to the level of plastic deformation being rather low. The presented MAE measurements has demonstrated that the MAE method might bear a potential for nondestructive evaluation of plastically damaged parts of operated equipment or structures, but a more sensitive signal parameter should be found, or the method has to be accompanied with other technique in order to sense the difference between the safe elastic deformation and the dangerous plastic one. The engineered measuring system MAE-1L exhibited a reliable performance.

References

[1] A.E. Lord, R. Usatchev and M. Robinson: Lett. Appl. Eng. Sci. Vol. 2 (1974), p. 1.
[2] D.C. Jiles: NDT Intern. Vol. 21 (1988), p. 311.
[3] B. Augustyniak, L. Piotrowski, M. Chmielewski and M.J. Sablik: J. Magnetism and Magnetic Mater. Vol. 304 (2006), p. e555.
[4] G. Sposito, C. Ward, P. Cawley, P.B. Nagy and C. Scruby: NDT&E Intern. Vol. 43 (2010), p. 555.
[5] D.C. Jiles and D.L. Atherton: J. Phys. D: Appl. Phys. Vol. 17 (1984), p. 1265.
[6] D.J. Buttle, G.A.D. Briggs, J.P. Jakubovics, E.A. Little and C.B. Scruby: Philos. Trans. Royal Soc. London. Vol. A320 (1986), p. 363.
[7] M. Guyot and V. Cagan: J. Magnetism and Magnetic Mater. Vol. 101 (1991), p. 256.
[8] K. Ono and M. Shibata, in: *Advances in Acoustic Emission*, edited by H.L. Dunegan and W.F. Hartman, Knoxville: Dunhart (1981), p. 154.
[9] M.M. Kwan, K. Ono and M. Shibata: J. Acoustic Emission. Vol. 3 (1984), p.190.
[10] B. Augustyniak: J. Magnetism and Magnetic Mater. ialsol. 196-197 (1999), p. 799.
[11] M. Guyot, T. Merceron and V. Cagan: J. Magnetism and Magnetic Mater. Vol. 83 (1990), p. 217.
[12] C. Edwards and S.B. Palmer: J. Acoust. Soc. Amer. Vol. 82 (1987), p. 534.
[13] A. Dhar, C. Jagadish and D.L. Atherton: NDT&E Intern. Vol. 24 (1991), p. 15.
[14] H. Kusanagi, H. Kimura and S. Sasaki: J. Appl. Phys. Vol. 50 (1979), p. 2985.
[15] E.S.Gorkunov, Yu.N. Dragoshanskii, V.A. Khamitov: Russ. J. Nondestr. Testing. Vol. 37 (2001), p. 835.
[16] D.L. Atherton and D.C. Jiles: NDT Intern. Vol. 19 (1986), p. 15.
[17] M.J. Sablik: NDT&E. Vol. 5 (1989), p. 49.
[18] R.A. Langman: IEEE Trans. Magn. Vol. 26 (1990), p. 1246.
[19] S.M. Thompson and B.K. Tanner: J. Magnetism and Magnetic Mater. Vol. 132 (1994), p. 71.
[20] D.C. Jiles: J. Phys. D: Appl. Phys. Vol. 28 (1995), p. 1537.
[21] F.P. Higgens and S.H. Carpenter: Acta Metall. Vol. 26 (1978), p. 133.
[22] K. Ono and M. Shibata: NDT Intern. Vol. 14 (1981), p. 227.
[23] K. Ono, M. Shibata and M.M. Kwan, in: *Residual Stress for Designers and Metallurgists*, edited by L.J. Van de Walls, Metals Park, OH: ASM (1981), p. 223.
[24] G.L. Burkhardt, R.E. Beissner, G.A. Matzkanin and J.D. King: Mater. Eval. Vol. 40 (1981), p. 669.
[25] D.J. Buttle, C.B. Scruby, G.A.D. Briggs and J.P. Jakubovics: Proc. Royal Soc. London A. Vol. 414 (1987), p. 469.
[26] D.J. Buttle, C.B. Scruby, J.P. Jakubovics and G.A.D. Briggs: Philos. Mag. A. Vol. 55 (1987), p. 717.
[27] D.J. Buttle and M.T. Hutchings: Brit. J. Non-Destr. Test. Vol. 34 (1992), p. 175.
[28] D.H.L. Ng, J.P. Jakubovics, C.B. Scruby and G.A.D. Briggs: J. Magnetism and Magnetic Mater. Vol. 104-107 (1992), p. 355.
[29] B.D. Cullity and C.D. Graham: *Introduction to Magnetic Materials*, Wiley-IEEE Press (2008), p. 258.

[30] D. O’Sullivan, M. Cotterell, S. Cassidy, D.A. Tanner and I. Meszaros: J. Magnetism and Magnetic Mater. Vol. 271 (2004), p. 381.

[31] L. Piotrowski, B. Augustyniak, M. Chmielewski and I. Tomas: J. Magnetism and Magnetic Mater. Vol. 321 (2009), p. 2331.

[32] L. Piotrowski, B. Augustyniak, M. Chmielewski, F.J.G. Landgraf and M.J. Sablik: NDT&E Intern. Vol. 42 (2009), p. 92.

[33] L. Piotrowski, B. Augustyniak, M. Chmielewski, E.V. Hristoforou and K. Kosmas: IEEE Trans. Magn. Vol. 46 (2010), p. 239.

[34] D.C. Jiles, D.L. Atherton: J. Magnetism and Magnetic Mater. Vol. 61 (1986), p. 48.

[35] D.C. Jiles and D.L. Atherton: J. Appl. Phys. Vol. 55 (1984), p. 2115.

[36] B. Allesandro, C. Beatrice, G. Bertotti and A. Montorsi: J. Appl. Phys. Vol. 68 (1990), p. 2901.

[37] M.J. Sablik, B. Augustyniak, M.F. De Campos and F. Landgraf: IEEE Trans. Magn. Vol. 44 (2008), p. 3221.

[38] Z.D. Wang, B. Deng and K. Yao: J. Appl. Phys. Vol. 109 (2011), 083928 (6 p).