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THE EFFECT OF DEFORMATION ON THE PARAMETERS OF MAGNETOACOUSTIC SIGNALS

The summary. *This paper presents results on the study of the effect of elastic and plastic deformation of low-carbon steel on magnetoacoustic emission (MAE) performed with the measuring system MAE-1L. Generally, the observed tendencies of reduction of MAE with deformation of iron-based alloys confirm those published in the literature. The reproducibility of measurements in the ealstic region is very high. As to the plastic region it demands further investigations. These measurements confirmed the perspectiveness of the method MAE for nondestructive evaluation (NDE) of plastically damaged parts of operated equipment or structures. MAE-1L system exhibited an appropriate service performance.*

***Key words**: low-carbon steel, plastic deformation, elastic deformation, nondestructive evaluation, magnetic field, ferromagnetic materials, magnetoacoustic emission, Barkhausen jumps.*

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ВПЛИВ ДЕФОРМАЦІЇ НА ПАРАМЕТРИ МАГНЕТОАКУСТИЧНИХ СИГНАЛІВ

Резюме. *Наведено результати досліджень впливу пружної та пластичної деформацій низьковуглецевої сталі на мегнетоакустичну емісію (МАЕ) із використанням вимірювальної системи МАЕ-1L. Виявлені тенденції зниження МАЕ із деформуванням сплавів на основі заліза загалом збігаються із опублікованими даними. Відтворюваність вимірювань на ділянці пружних деформацій є дуже висока. Щодо пластичної ділянки, необхідні подальші дослідження. Наведені результати підтверджують перспективність методу МАЕ для неруйнівного контролю ділянок діючого обладнання та споруд, які зазнали пластичного деформування. Система МАЕ-1L продемонструвала належну працездатність.*

***Ключові слова**: низьковуглецева сталь, пластична деформація, пружна деформація, неруйнівний контроль, магнетне поле, феромагнетні матеріали, магнетоакустична емісія, стрибки Баркгаузена.*

Introduction: 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 magnetoacoustic emission has to be given.

A phenomenon of magnetoacoustic emission, which is a release of elastic acoustic waves in material subjected to the influence of a variable magnetic field, was experimentally revealed during magnetization of nickel [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, while the dynamics of 180° anti-parallel 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 be contributed by the irreversible rotations of the domain's magnetization vectors through angles other than 180°, or reflect the dynamics of island domains stabilized by inclusions and closure domains [8, 9]. The nature of MAE still raises questions mostly due to the presence of two maxima in the near-saturation region, though the nature of Barkhausen noise as originated solely from the 180° wall dynamics has also been questioned [10].

The basic advantage of MAE method over the Barkhausen noise method is its informative depth, which practically depends only on the penetration ability of the excitation magnetic field (see the other report submitted to this conference on modeling the depth of magnetization) with 10 mm or more being easily achieved, while 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. 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 transducer and the acquisition-processing system. 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 rathar then making a judgement from a single measurement.

Effect of plastic deformation on MAE – state of the art. 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 NDE of 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 originate from 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, for NDE purposes, the application of MAE appeared to be more practical than Barkhausen noise, since the dependence 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 Fe 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 explanation of the decrease of MAE intensity with increased straining is given by Ng *et al* [28]. Since the magnetoelastic energy (as taken from [29]) E_{me} could be expressed as

$$E_{me} \sim \lambda\, \sigma \sin^2 \Theta, \tag{1}$$

where λ – is the saturation magnetostriction (($\lambda_{100} > 0$ for Fe), σ – stress, and Θ – the angle between the directions of magnetization $\boldsymbol{M}$ 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 MAE intencity.

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 domain-wall–dislocation interaction, which reduces the domain wall dynamics, with domain-wall–dislocation interactions seemingly being 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 artefacts 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 moving to the higher magnetic fields together with the knee of the 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 (which previously could not explain magnetic phenomena in ferromagnetic materials subjected to plastic deformation) [38]. 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 plastic deformation on MAE within the frame of application of MAE method for NDE of structural materials, as far as Ukrainian industry is of concern, 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 with details described elsewhere [39]. Before this instrument is transferred to massive indurstrial 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 its verification in the area of MAE response to deformation both elastic and plastic of commercial low-carbon steel.

Experimental. Before MAE measurements were conducted, the evaluation of the system for the most effective magnetizing frequency has been performed. Figure 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 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 repetability of measurements a second sample was strained in the order loading-unloadingreloading. 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 synusoidal magnetic field with amplitude 7.1 kA/m, i.e. below the presaturation knee.

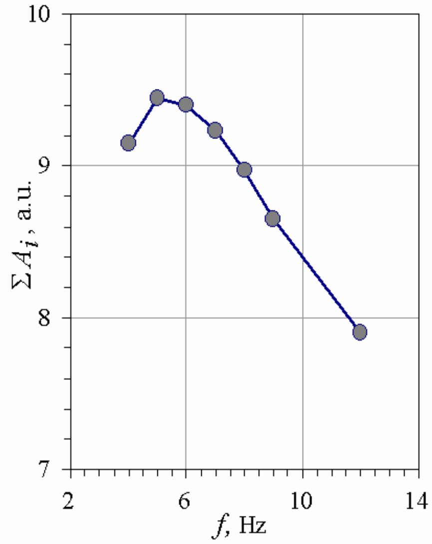
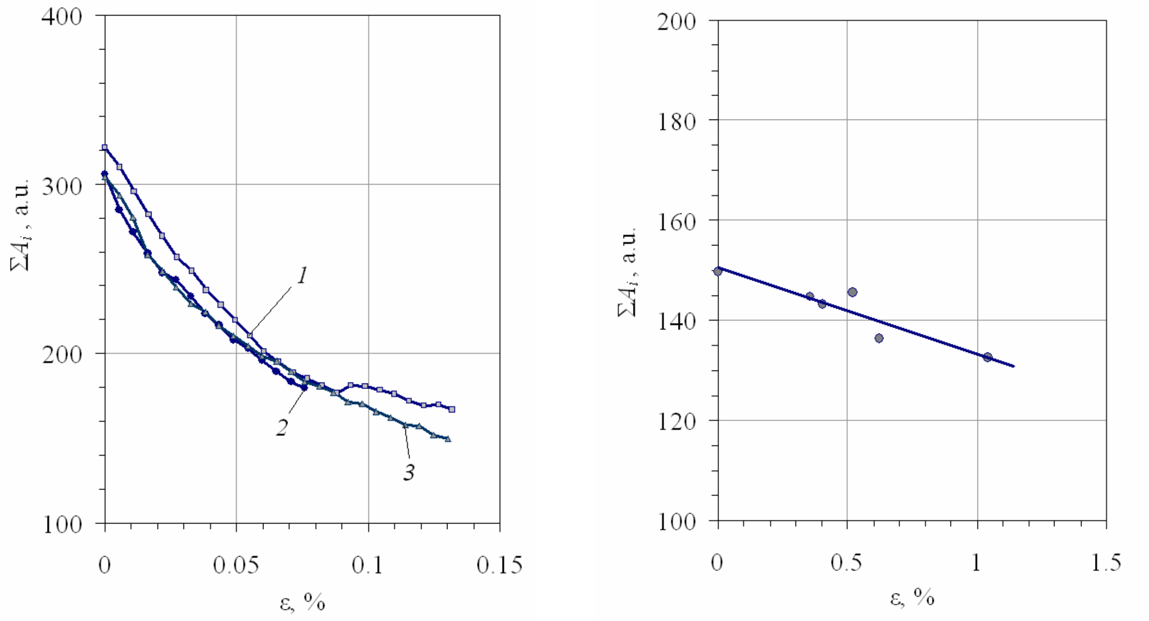


Figure 1. The effect of the magnetizing current frequency on the total amplitude sum for the impulses of MAE signal ΣA_i

Wide band piezoelectric transducer was acoustically connected to the surface of the sample near the upper grip and electrically 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.



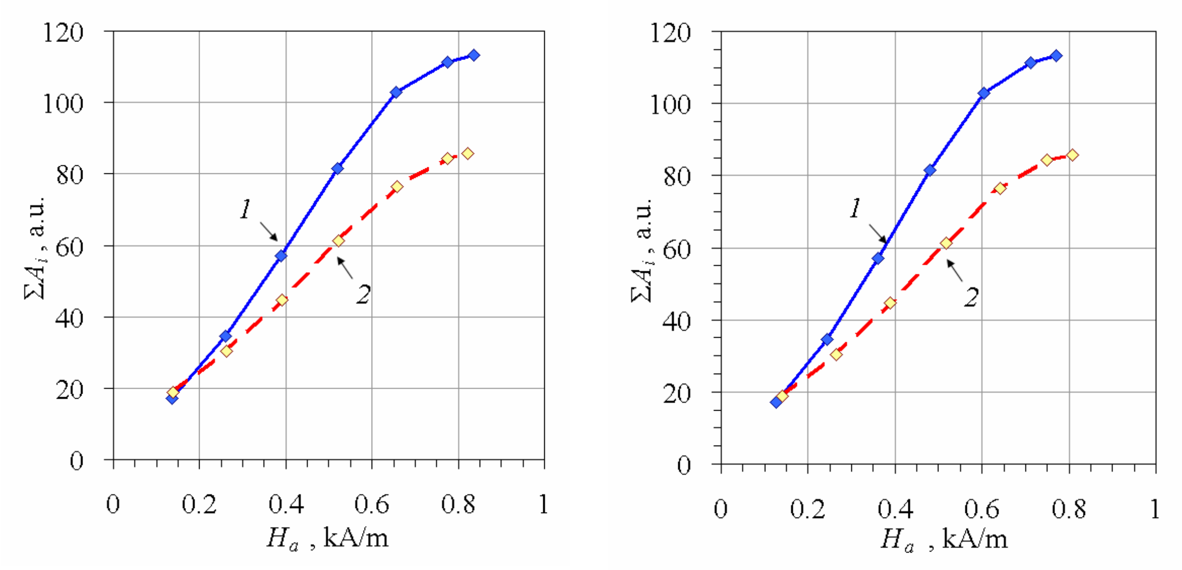
a
b

Figure 2. The effect of elastic (a) and plastic (b) deformation on the total amplitude sum for the impulses of MAE signal ΣA_i recorded for low carbon steel

Results and discussion. The results from the first two series related to elastic deformation are presented in Figure 2a. From the dependency of MAE parameter ΣA_i (sum of the amplitudes of MAE impulses) on eleastic deformation several conclusions could be made. The effect of strain on magnetocrystalline anisotropy tendency 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-strainings of the second sample practically coincide with each other confirming high repeatibility of MAE measurements. This is encouraging information since the metrological issue, especially in the magnetic and even more so in the acoustic measurements are of serious concern.

Figure 2b 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.

Figure 3 exhibits the experiments conducted on two samples of different thickness – 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

Figure 3. 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 ε = 1.7 % (2 mm thick) and ε = 7 % (3 mm thick)

As from the obtained results it is hard at this point to saparate the effect of elastic deformation from the effect of plastic one. 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 preceed a catastrofic failure. Further search into the differences in MAE signal response is needed to overcome this ambiguity.

Conclusions. This paper presents preliminary results on the MAE measurements of elastic and plastic deformation of low-carbon steel performed with the system MAE-1L engineered at Karpenko Physical-Mechanical Institute. Generally, the observed tendencies of reduction of MAE with deformation of iron-based alloys confirm those published in the literature. The reproducibility of measurements in the ealstic region is very high. As to the plastic region it demands further investigations. These measurements confirmed the perspectiveness of the method MAE for NDE of plastically damaged parts of operated equipment or structures. MAE-1L system exhibited reliable performance.

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