# On the application of magnetoelastic properties measurements for plastic level determination in martensitic steels

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The change in the dislocation density, induced by plastic deformation, influences strongly the magnetic domain structure inside the material. Being so, classic parameters, like the coercivity or magnetic permeability, can be a good measure of the deformation level, yet their reliable determination in a non-destructive way in industrial environment is problematic. The magnetoacoustic emission (MAE) which results from the non-180° domain walls (DW) movement in materials with non-zero magnetostriction can be used as an alternative. The intensity of the MAE signal changes strongly as a result of plastic deformation for both tensile and compressive deformation. It is however possible to discern those cases by analysing the changes in the shape of the MAE signal envelopes. The set of the martensitic steel samples (P91) deformed up to 10% (for both tension and compression) was investigated. Due to geometrical limitations imposed by the special mounting system, enabling compression without buckling, the sample had the shape resulting in low signal to noise (S/N) ratio. Being so the optimization of FFT filtering and wavelet analysis was performed in order to improve sensitivity of the proposed method of deformation level determination.

K e y w o r d s:  magnetic flux leakage, nondestructive testing, wavelet transform

## 1 Introduction

Plastic deformation leads to a strong modification of the dislocation structure of material resulting in serious changes of its mechanical properties [1]. It would be very convenient if such changes could be assessed in a non-destructive way. Fortunately, the dislocation structure is connected not only with mechanical properties but, due to the strong interaction of dislocation tangles and stress fields with the magnetic domain structure, it influences the magnetoelastic properties of the material. In theory one can use very simple parameters, such as the magnetic hysteresis loops properties, since the shape (and width) of those loops for samples subjected to tensile deformation changes very significantly, yet it is not easy to perform such measurements in situ and in the case of compressed samples the change is not so pronounced. A good solution seems to be investigation of the changes in the Barkhausen noise (BN) signal intensity. It is a signal generated during discontinuous motion of domain walls (DWs) that are pinned and then abruptly unpinned from obstacles such as precipitates or dislocation tangles. The problem is that even though it is usually possible to find a set of BN signal parameters enabling unambiguous determination of plastic deformation level [2] the measured signal can be detected only from the close-to-surface region of the material (electromagnetic pulses in the kHz range of which it consists are strongly attenuated) hence it is strongly sensitive to surface conditions. A good alternative seems to be an acoustic analogue of the BN signal *ie* magnetoacoustic emission (MAE) signal. It con-

sists of acoustic pulses generated during the discontinuous motion of non-180° domain walls in the material with non-zero magnetostriction. During such motion an abrupt elastic deformation of the material takes place and the resulting acoustic pulse propagates inside the sample. Since such pulses are relatively weekly attenuated in steels they can be detected practically from the whole magnetised volume. The MAE has been already applied for plastic deformation level assessment, but the case of compressed samples has not yet been investigated.

## 2 Experimental

A set of samples (the shape of the samples is shown in Fig. 1) made of P91 martensitic steel (0.085% C, 0.27% Si, 0.30% Mn, 0.015% P, 8.2% Cr, 0.86% Mo 0.16 % Ni, 0.01% Al, 0.15% Ti, 0.098% Nb, 0.19% V) subjected to the tensile and compressive deformation was tested. The obtained deformation levels (relative elongation measured after unloading) are as follows:

- $\varepsilon$ = 0.102; 0.195; 0.294; 0.393; 0.487; 0.793; 1.593; 2.484; 5.01; 9.971 for tensile deformation
- $\varepsilon$ = 0.096; 0.106; 0.198; 0.201; 0.306; 0.314; 0.402; 0.409; 0.487; 0.503; 0.801; 0.801; 1.597; 1.600; 2.486; 2.501; 4.983; 5.010; 10.03; 10.09 for compressive deformation. In addition to that, a non-deformed sample was investigated.

As can be seen in Fig. 1, the gauge length of the sample is rather small compared to the total sample length, which complicated the measurements of the MAE signal

* Gdansk University of Technology, ul. Gabriela Narutowicza 11/12 80-233 Gdansk, Poland; lesio@mif.pg.gda.pl, ** Institute of Fundamental Technological Research, Polish Academy of Sciences, ul. Pawiñskiego 5B, 02-106 Warsaw, Poland
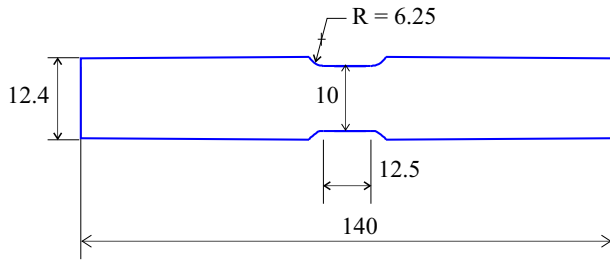
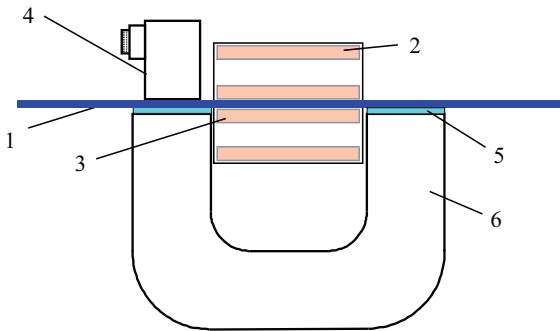**Fig. 1.** The dimensions(in mm)of the investigated samples



**Fig. 2.** Schematic view of the measurement set-up: 1 – sample, 2 – magnetising coil, 3 – sensing coil, 4 – PZT transducer(MAE signal), 5 – acoustic separators 6 – soft magnetic yoke

since it had to be generated in gauge section only, yet propagated freely through the whole sample. Such shape was necessary in order to use the specially designed anti-buckling fixture, the detailed description of which can be found in the paper by Ditrich *et al* [3]. The schematic view of the measurement set is shown in Fig. 2. The sample (1) was placed on the yoke (6) made of electrical steel, the size of which was chosen to fit the gauge length of the sample in order to minimize the influence of the non-deformed parts of the sample. It was magnetized with the help of the encircling coil (2) and a smaller encircling coil (3) was used for the hysteresis loops measurements. The MAE signal was measured with the help of a PZT wide-band transducer. In order to minimize the influence of the yoke on the measured MAE signal acoustically atten-

uating spacers (5) were placed between the sample and yoke. The magnetising coil was fed from a current ampli-fier (triangular in form; $f = 2$Hz) driven by the signal provided by the multifunction data acquisition device NI USB-6366. The same device was also responsible for the amplified MAE signal acquisition (2 MHz sampling rate). The signal from the detecting coil was pre-amplified and then used for the hysteresis loops determination (numer-ical integration).

## 3 Results

The hysteresis loops obtained for the investigated sam-ples are shown in Fig. 3. As can be seen the tensile de-formation leads to a very strong change in the shape of the loops – they become broader and their steepness de-creases very significantly. Such behaviour is typical and can be explained by the presence of compressive stress in the material after deformation. For the case of compres-sion one observes qualitatively different behaviour - the coercivity also increases (not so strongly as in the for-mer case) but the steepness of the loops does not change significantly. Quantitatively, the changes can be charac-terised with the help of coercivity and maximum differen-tial permeability of the samples (see Fig. 4). The observed difference in the behaviour of hysteresis loops can be ex-plained by the fact that though in both cases the change in dislocation structure leads to increased coercivity the residual stresses are of an opposite sign. Being so, in the case of tensile deformation they result in decreased per-meability and additionally increased coercivity while for compression the influence of stress is much weaker.

The examples of the results of the MAE signal mea-surements (rms-like signal envelopes) are shown in Fig. 5 (tensile deformation) and Fig. 6 (compression). As can be seen both modes of plastic deformation lead to a very strong decrease of the MAE signal amplitude right from the start of the process. It may seem that such behaviour makes the determination of the deformation type (and level) impossible, yet one can easily observe that the shape of the MAE signal envelopes is different in both
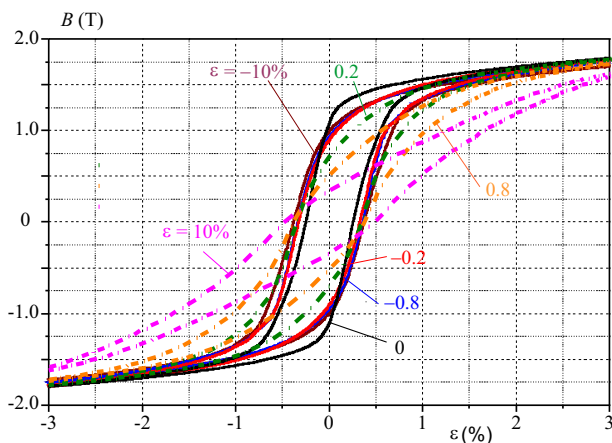


**Fig. 3.** Comparison of hysteresis loops obtained for the investigated samples, both compressive and tensile deformation
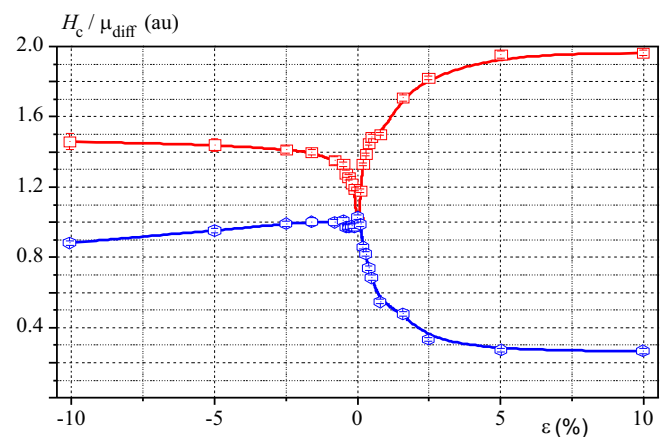


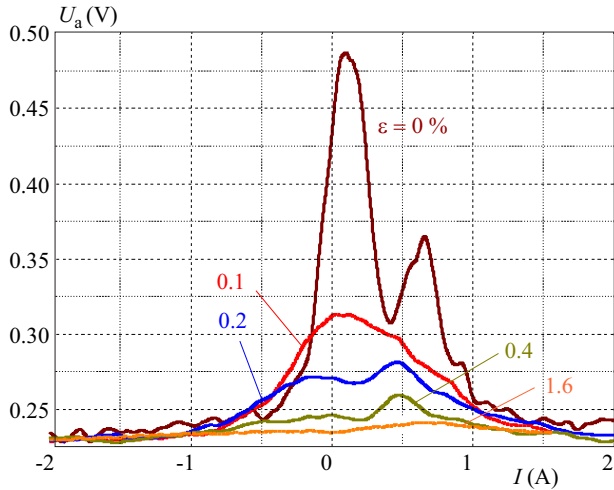**Fig. 4.** Coercivity and maximal differential permeability of the investigated samples

**Fig. 5.** The MAE signal envelopes obtained for the increasing field intensity – tensile deformation
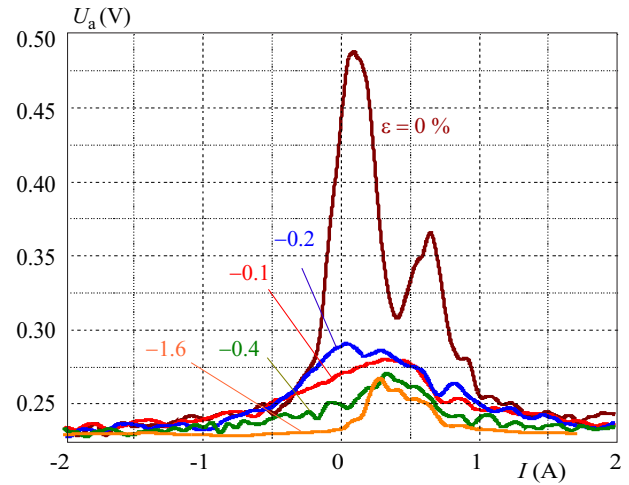


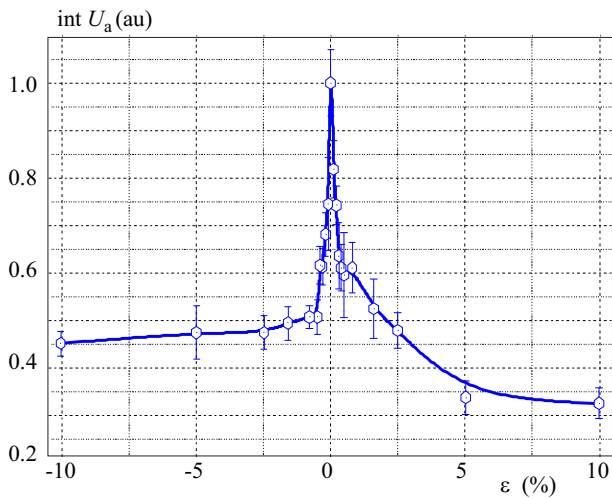**Fig. 6.** The MAE signal envelopes obtained for the increasing field intensity – compression



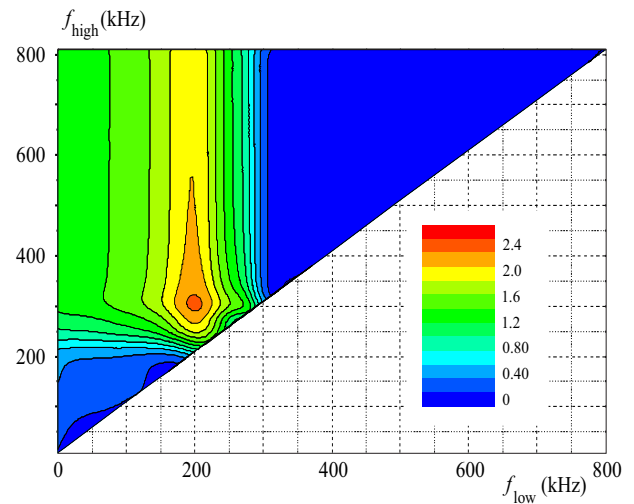**Fig. 7.** The MAE signal intensity for the investigated samples



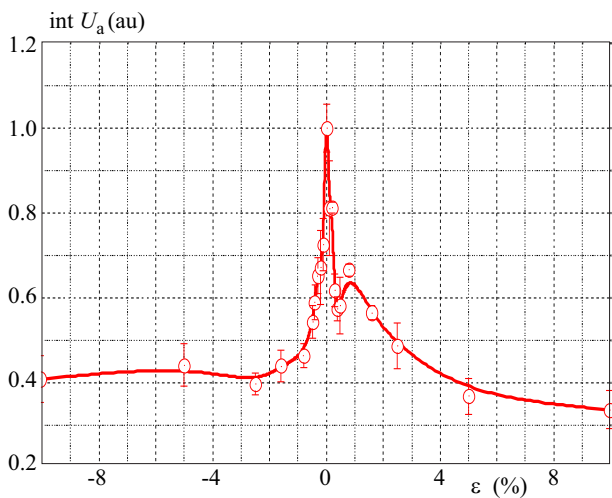**Fig. 8.** Figure of merit of the FFT filtering procedure



**Fig. 9.** The intensity of the filtered MAE signal($f_{low}$ = 200 kHz, $f_{high}$ = 300 kHz)

cases (the envelopes for the samples after tensile deformation are much broader) which is in agreement with the different behaviour of the magnetic hysteresis loops. The MAE signal is generated most strongly at the field values for which there is the a pronounced rearrangement of the domains with 90° CDWs.

Quantitatively the changes of the MAE signal can be described by a parameter that we call intensity, which is an integral ($IntU_a$) of the $U_a$ voltage over one-half of the magnetisation period. The results are shown in Fig. 7. One can observe that both modes of deformation result in strong decrease of the MAE signal intensity (especially at the deformation onset). In the case of compression, the decrease is more abrupt up to about 0.5% of deformation and then the intensity stabilizes. On the other hand, for the tensile deformation the decrease is slower and it continues up to 10% reaching lower levels than the ones observed for compression (for the most deformed sample the signal to noise ratio (S/N) becomes very low, hence the reliability of that result is not very high). Since, due to the sample shape, the S/N ratio of the measured MAE signal is low we have tried to improve that using FFT transform
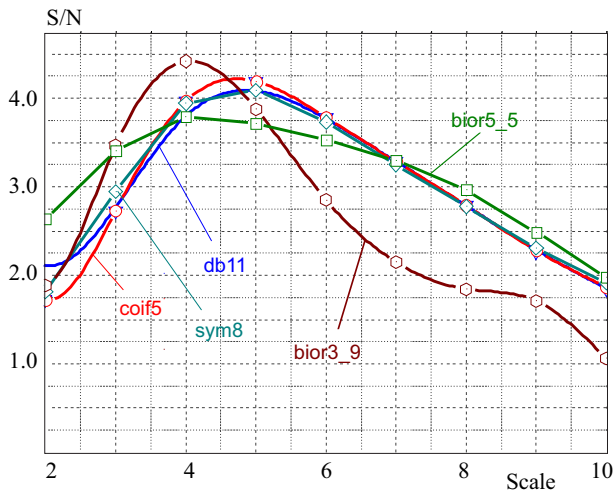
**Fig. 10.** S/N ratio for the CWT envelopes as a function of scales for various wavelets



**Fig. 11.** CWT intensity for the bior3_9 wavelet (scale 4) as a function of deformation for the tested samples

based filtering and wavelet analysis. A dedicated software (LabVIEW environment) calculated the S/N ratio for signal filtered in such a way that the upper cut off frequency was changed every 10 kHz and for each such frequency the lower cut off was shifted from zero up to 10 kHz below upper frequency. Since high S/N ratio may be observed accidentally for very low intensity signals the amplitude of the filtered signal was also calculated and the product of those two parameters was treated as a figure of merit in our case. As can be seen from Fig. 8 (obtained for the non-deformed sample) the maximum is observed for $f_{\text{low}} = 200$ kHz and $f_{\text{high}} = 300$ kHz. Being so, the filtration in such range was performed for all the samples and the intensity of filtered signals was determined and plotted in Fig. 9. As it turned out the obtained dependence of the filtered MAE signal intensity on the deformation level is very similar, yet due the better resolution, one can observe that the changes due to the tensile deformation are in fact non monotonous there is a local maximum for $\varepsilon = 1.6\%$. One could suspect that to be an erroneous result, yet analogous maximum was observed for the BN signal intensity [4]. Probably it is due to creation of a dislocation cell structure for that range of deformation. Such strong rearrangement of dislocation structure results in relatively easier DWs movement inside newly created dislocation cells.

The FFT filtering is not best suited for the analysis of noise signals since the pulses have only limited duration time. Much more appropriate for that purpose is the wavelet analysis, [5]. A wavelet is an oscillation-like function, which in contrast to sine/cosine functions used in the Fourier analysis is localized in time [6,7]. In a continuous wavelet transform (CWT) the procedure of CWT coefficient determination is based on calculation of the integral

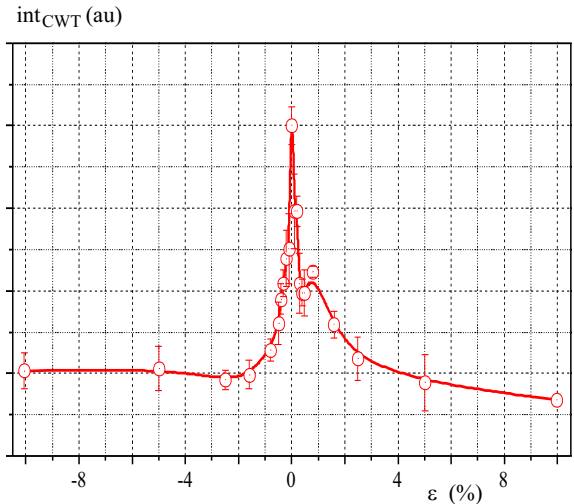$$CWT(a,b) = \frac{1}{\sqrt{a}} \int\limits_{-\infty}^{\infty} s(t)\psi\left(\frac{t-b}{a}\right) \mathrm{d}t$$

where $a$ determines the scale of the wavelet (the higher the scale the wider the time span of the wavelet). Once the integral is calculated, the wavelet is shifted in time ($b$ parameter) and the procedure is repeated. The obtained CWT parameters can be treated as a measure of time-local intensity of various frequency (scale) components. One can calculate the CWT rms-like envelopes (in the same way as with the noise signal) and integrate them to obtain total CWT intensity for a given scale. We have tested various wavelets calculating the S/N ratio for the CWT envelopes for various scales (see Fig. 10) and on that basis we chose for further analysis the bior3_9 wavelet (scale 4) [7]. The results of the CWT intensity analysis (shown in Fig. 11) are very similar to the ones obtained after filtering.

## 4 Conclusions

The MAE signal changes strongly during the plastic deformation (both for tensile deformation and compression) as a result of dislocation structure modification and residual stress appearance. Being so it can be used for deformation level assessment only with some additional analysis. It might be either the analysis of the MAE envelope shape or some complementary measurements (magnetic properties, BN intensity).

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