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On the correlation between magnetoacoustic emission and magnetostriction dependence on the applied magnetic field

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ABSTRACT

The correlation between magnetoacoustic emission signal envelopes and magnetostriction curves is investigated. Two sets of samples are being considered: tempered martensitic steel and plastically deformed ferritic steel. It is shown that even though some general relations may be observed, as was demonstrated in the literature, the correlation is not always present. One may not expect to change both quantities in the same way if a serious modification of microstructure takes place, as for instance in the case of plastically deformed samples for which the dislocation cell structure is formed once a certain level (1.5–2%) of deformation is reached. Being so, any relation not taking into account statistical properties of domain structure and pinning sites distribution may not yield a general solution of the problem.

1. Introduction

Magnetoacoustic emission (MAE) phenomenon has been known for many years, it was firstly demonstrated by Lord [1] in 1974. The acoustic signal, which can be detected with the help of piezoelectric transducers (PZT), results from the discontinuous changes of the material volume on a microscopic level. The reason for those changes is the local change of magnetization in material with a non-zero magnetostriction [2]. An acoustic pulse is generated during an abrupt jump of a non-180° magnetic domain wall (DW), because only such movement results in the local change of the length of the material as the magnetostriction driven elongation is the same in the antiparallel domains. The expected relative increase of length in the field direction during the movement of the 90° DW is of order of 3/2 λ_{100} (magnetostriction constant for the (100) crystallographic direction). The MAE signal measured on the surface is the result of superposition of elementary pulses generated during the magnetization in the whole magnetized volume. Being so one may expect the correlation between the magnetostriction and MAE signal. Such a correlation has been reported in various papers [3,4] and even a formula relating directly the MAE amplitude (U_{mae}^{max}) to the maximum rate of change of magnetostriction ($|d\lambda/dH|_{max}$) has been proposed [5]. The formula is however somewhat simplistic as it tries to correlate the macroscopic parameters with the microscopic ones. In the present paper we present a systematic, comparative study of the correlation between those phenomena and their evolution during the microstructural changes in the material. We investigate two processes: tempering of the martensitic steel and plastic deformation of the ferritic steel S420M (Polish grade). Both processes change the dislocation density in the material and, as for the tempering, one expects also the changes in the carbide precipitates structure. The change of MAE signal intensity in both cases is completely different – the tempering process increases strongly the signal intensity [6] whereas plastic deformation results mainly in the change of the MAE signal envelope shape [7,8].

2. Experimental

2.1. Samples

Two sets of samples have been investigated (see Table 1). The first one consisted of three samples (D0, D1, D2) where the first one was treated as a reference sample. The deformation levels for this study are chosen from the bigger set of deformed samples in such a way as to represent qualitatively different dislocation structures. It is generally known that the high deformation levels (above 1.5–2%) lead to creation of dislocation cell structure. The investigated samples have been subjected to tensile deformation in a “dog bone” shape. After the completion of the process the end parts have been removed and the obtained parallelepiped samples had the following dimensions: length $l=150$ mm, width $w=15$ mm and thickness $h=6$ mm.

The second set of samples was chosen from the set of the annealed P91 steel samples that have been described in detail in [6]. The heat treatment of the samples consisted of austenitisation

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Table 1
The investigated samples.

Plastic deformation (S420M)	D0	D1	D2
Elongation [%]	0	0.8	8.0
Tempering (P91)	T0	T1	T2
Time [min.]	0	15	240

performed at T_a=1050 °C (for 1 h) followed by the air cooling and subsequent tempering. The tempering temperature was chosen according to the standards as T_t=750 °C. The tempering resulted in a very strong decrease of dislocation density which was confirmed by the decrease of mechanical hardness of the sample and X-ray investigation showing a significant decrease of the diffraction peaks width. The physical dimensions of the samples were following: length l=140 mm, width w=14 mm and thickness h=5 mm. Even though the MAE intensity measurements, in the case of tempered samples, were performed (and described) earlier they have been repeated in order to enable correlation of the MAE signal magnetic field dependence with the behaviour of the magnetostriction.

2.2. Measurement set-up

The measurement set is shown in Fig. 1. It consists of the magnetizing coil (2) in which the investigated sample (1) is placed. The coils are fed from the current amplifier driven by the voltage generator (triangular in form), the frequency of the magnetizing signal used in the experiment was about 0.5 Hz. It was a compromise between the MAE signal intensity (increasing with the magnetizing frequency) and possibility to discern the details of its envelope. Unfortunately, with the increase of the magnetising frequency, due to the eddy current effect, a phase shift between the surface and bulk magnetisation appears and the details of the MAE envelope tend be to wiped out (MAE maxima become merged). The magnetic flux is closed with the help of a yoke (3) made of electrical steel. The magnetostriction is measured with the help of two resistive gauges (4), glued on the opposite sides of the investigated samples, signals from which were fed to the NI 9237 4-channel, 24-bit half-bridge analog input module. It was necessary to use two gauges as there was no possibility to avoid, magnetic force driven, long range deformation of the samples, especially in the case of the deformed samples which were slightly twisted. Fortunately long range bending results in the deformation of opposite sign on the investigated surfaces and thus it cancels out after averaging. Even though the signals from both gauges are changing when the sample is placed in various ways the average remains stable. For the measurements of the MAE signal the piezoelectric transducer (5) is placed on the sample, and sound attenuating spacers (6) are used in order to prevent the noise generated in the yoke from the interference with the measured signal. The results of the AE sensor calibration (as delivered by the Physical Acoustic Corporation) are presented in Fig. 2. As for the measurement system, it consisted of a preamplifier with 40 dB gain mounted on the cable, close to the AE probe. The pre-amplified signal was filtered (HPF filter, cut-off frequency $f_{cut\text{-}off}$ =100 kHz) and passed to a first stage amplifier (40 dB), and then a second stage adjustable amplifier, the gain of which was set to 40 dB in our case. The amplified voltage signal was fed, through an anti-aliasing filter (LPF, $f_{cut\text{-}off}$=500 kHz), into an A/D 12 bit converter and recorded with a high sampling rate (2 MHz). The additional coil (7) was used to measure magnetic hysteresis loops. The measurement of the loops was performed in order to check the correlation between the MAE, magnetostriction and magnetisation, so it was done exactly under the same experimental conditions.

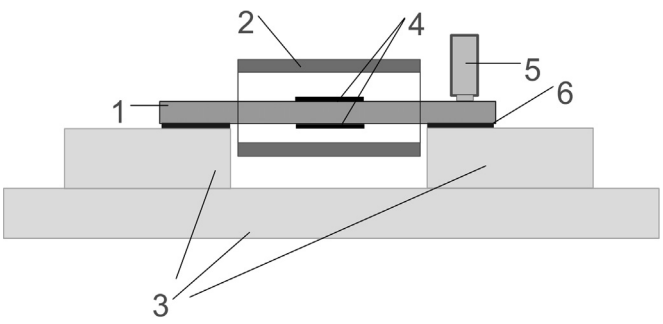

Fig. 1. The experimental set-up.

3. Results

3.1. Magnetic properties

In Fig. 3 there are shown magnetic hysteresis loops obtained for the P91 samples – plotted as a function of the magnetizing current (the field value to current intensity ratio, measured inside the magnetizing coil was ~1,25 kA/m/A) As can be seen the as-quenched sample (T0) is magnetically hard, its coercivity being more than two times higher than for the sample tempered for only 15 min (T1). Such behaviour is in agreement with the expected changes in the dislocation structure. The tempering process results in a significant decrease of the dislocation density and the coercivity is roughly proportional to the square root of the dislocation density – provided that there are no other significant changes in the material's microstructure [9].

It was impossible, with the help of the applied magnetizing set, to fully magnetize the as-quenched material. As a result the loops are not fully flattened at the ends and the resulting maximum induction is significantly lower.

Fig. 4 shows the analogous loops for the deformed samples. The loops change in a way typical for plastically deformed samples – there is an increase of coercivity, decrease of permeability and appearance of the characteristic deformation of the central part of the loop obtained for the highly deformed samples [10]. Similar behaviour is observed for the samples under compressive elastic stress [11] which is in agreement with the notion that once the cellular dislocation structure is created the magnetic properties are influenced mainly by the magnetically soft subregions (inside the cells) in which the compressive stresses are present.

3.2. Magnetoacoustic emission measurements

The results of the MAE signal measurements (for the half-period of increasing magnetisation) for the P91 steel are shown in Fig. 5, Ua is a short-time rms of the sampled voltage:

$$Ua = \sqrt{\int_0^{\tau} U^2(t)dt/\tau},$$

where the integration was performed over a period in which 100 points were measured. As can be seen the S/N ratio of the signal for the as-quenched sample (shown also in the inset) is very low – close to the limits of detectability. In fact some heavy averaging (adjacent averaging of 100 points) of several signal envelopes (Ua) was necessary to obtain a reliable result. It can be however observed that with the increase of annealing time the intensity of the signal increases very strongly. Even though the