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MAGNETOACOUSTIC MEASUREMENTS ON STEEL SAMPLES AT LOW MAGNETIZING FREQUENCIES

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The magneto-acoustic emission (MAE) is measured at low frequencies, sample being magnetized by an external yoke. The sample surface field was accurately measured. Influence of the field and flux density rates on the resulting MAE envelope was studied. It was found that two-peaks MAE with a minimum around the coercivity was due to the minimum in the field rate d*H*/d*t*. Division of the MAE signal by the field rate completely removed that artificial minimum making one-peak shape resembling the differential permeability curve. This work demonstrated importance of the field rate control for MAE measurements to make them reliable and repeatable.

Keywords: magneto-acoustic emission, surface magnetic field, steel, magnetic hysteresis

1 INTRODUCTION

When varying the magnetic field applied to a ferromagnetic material, magnetization changes due to domain walls motion and magnetization rotation. The domain walls motion generates elastic waves up to a few megahertz that is known as Magneto-Acoustic Emission (MA E). In contrast to Barkhausen noise (BN) MAE provides information about magnetization change of the bulk. BN and MAE are closely related phenomena so that they are often used together for NDT [1-5]. They share several problems, one of which is absence of any standards how to measure them so that the results from different laboratories could be compared. Also there is no way how to normalize the signal to get some meaningful units.

When used in NDT, MAE is usually measured at “reasonably low” frequency that can be from tens of mHz to a few Hertz with the sinusoidal excitation voltage/current waveform. The excitation voltage or current is usually used as a reference. MAE and BN are usually measured by external transducers/coils and the sample has a magnetically open shape being magnetized by a magnetizing yoke. Many works reported that the resulting RMS envelopes depend on the magnetizing frequency, amplitude, sample size, air gaps between magnetizing yoke and the sample *etc*, [6-9].

Many authors use number of peaks in MAE/BN envelopes, their heights and positions for NDT of steel samples [2-4]. Form other side, listed above magnetizing conditions can change not only absolute values but also shapes and even number of peaks in the measured envelopes.

In this work we investigate influence of magnetizing field and flux waveforms on the resulting MAE envelopes at low frequencies.

2 EXPERIMENTS

The experimental setup is shown in Fig. 1. A 5x50x90 mm^3 tempered spring steel sample was magnetized by a Fe-3%Si yoke. The signal from the pickup coil on the sample was integrated by an analogue integrator to obtain the flux in the sample. A hand-made MAE sensor was glued on the sample. Its signal was amplified by 20 000 times and band-pass filtered in the 10 to 500 kHz range by Stanford research SR560 amplifier and SIM965 filters.

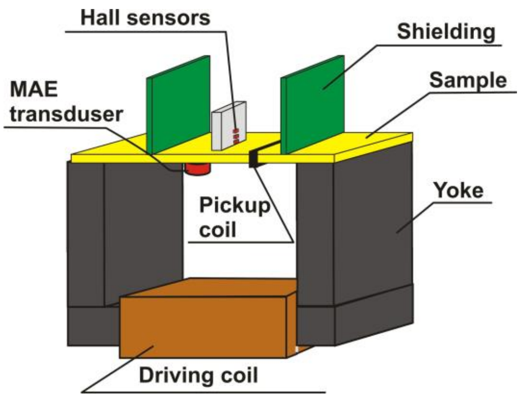

Fig. 1. Measurement setup

The sample magnetic field was determined by measuring the tangential component of the field at 1.5, 4.5 and 7.5 mm above the sample and extrapolating these values to the sample surface [10]. Magnetic shielding was used to reduce an error in the extrapolated field [11-12]. The field was measured by temperature-compensated Allegro A13 89LLHLX Hall sensors with the sensitivity 2.5 mV/G. The sample was magnetized with the field amplitude 8000 A/m using triangular excitation voltage waveform at 0.2, 0.5, 1 and 2 Hz. From 30 at 0.2 Hz to 200 cycles at 2 Hz were averaged to reduce noise in the MAE envelope and hysteresis loop. The triangular voltage/current waveform leads to less steep changes in the flux waveform at a certain magnetizing frequency comparing to the sinusoidal one, which has a maximum in the derivative at zero. Two synchronized National Instruments PCIe-6351 cards were used for data acquisition. One card was used for MAE signal acquisition at 1.2 Mss rate. Another card was used for triangular voltage generation and acquisition of signals

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from the analogue integrator, Hall sensors and resistor sensing current in the driving coil. The signals were acquired at 100 Kss and downsampled using adjacent averaging so that the number of measured points per loop was 1000 at all magnetizing frequencies.

3 RESULTS

In Fig. 2 hysteresis loops measured at different frequencies are shown. The coercive force at 0.2 Hz was 1700 A/m and the maximum differential permeability about 16000. The combination of large maximum differential permeability and relatively high coercivity makes quasistatic hysteresis loops measurements difficult. At the same time it allows studying dynamic processes at lower magnetization frequencies.

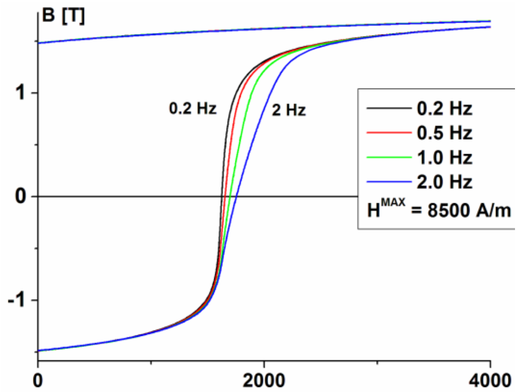

Fig. 2. Hysteresis loops measured at different frequencies

In Fig. 3 MAE envelopes normalized by the magnetizing frequency are shown as a function of the surface field. The background noise value around 4 μV was subtracted before normalization.

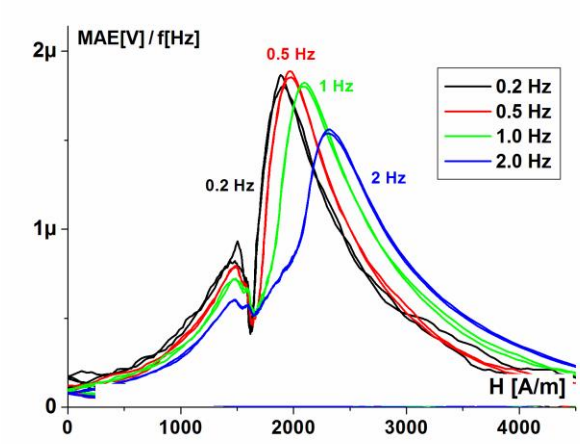

Fig. 3. MAE envelopes normalized by the magnetizing frequency

Different analogue filtering of the signal was applied in the range 10-500 kHz. The only difference was in the background noise and signal-to-noise ratio while RMS envelope shape did not change. So all measurements in this work done using band-pass filtering of MAE signal in the 10 to 500 kHz range. Two peaks were present at all frequencies with a minimum around the coercivity. With magnetizing frequency increase from 0.2 to 0.5Hz MAE envelope was nearly proportional to the frequency – the normalized envelopes in Fig. 3 are very close.

In order to understand what the reason for the minimum in the MAE envelopes is, let us look at the field and flux rates. In Fig. 4, the flux density rate, d*B/*d*t* is shown. It seen that at the field of the MAE minimum d*B/*d*t* is maximal.

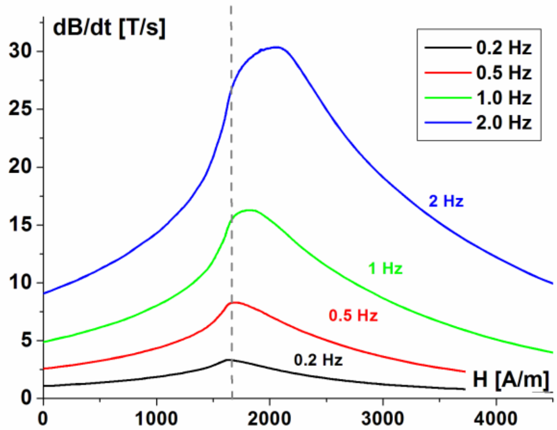

Fig. 4. Magnetic flux density rate

In Fig. 5 the envelopes divided by the flux rate are shown. It is seen that the shape of envelopes was not influenced much. It is evident that the flux rate is not responsible for the minimum in the MAE envelope.

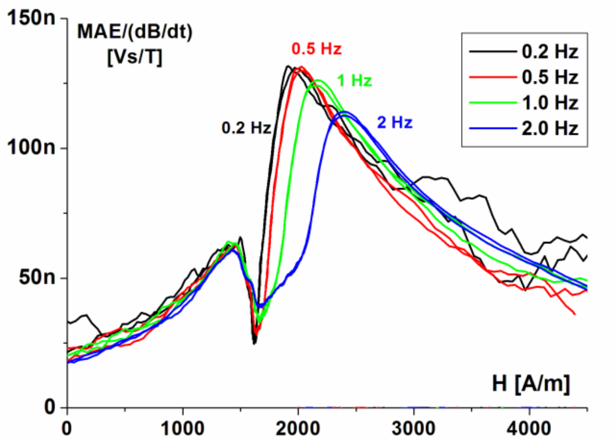

Fig. 5. MAE divided by the magnetic flux density rate

Now let us look at the field rate profiles. In Fig. 6 the field rate d*H*/d*t* is shown. The field rate has a minimum at the same region where the minimum in MAE was observed. The triangular excitation voltage or driving coil current do not produce the triangular field waveform because the sample reluctance changes by several orders of magnitude when the sample is magnetized. In Fig. 7, the MAE envelopes normalized by the field rate are shown. The minimum at 1700 A/m disappeared completely and at the lowest frequency the resulting envelope looks like a typical one-peak differential permeability curve.

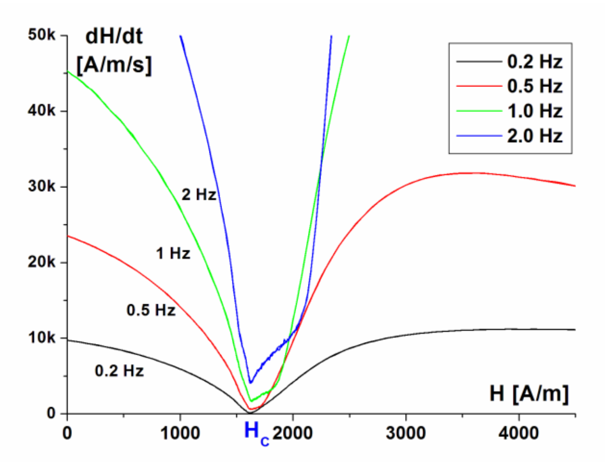

Fig. 6. Surface magnetic field rate

To compare normalized MAE envelopes with the differential permeability curves, the latter is plotted in Fig. 8. Surprisingly, normalized MAE envelopes and permeability are very similar by shape at all frequencies.

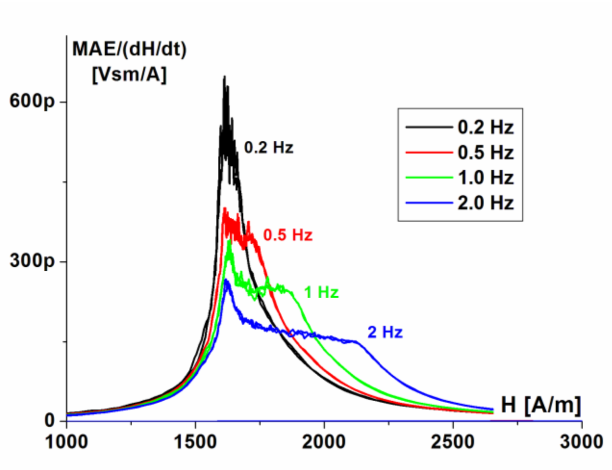

Fig. 7. MAE divided by the magnetic field rate

Transformation of the simple one-peak differential permeability curve into more complex shape with frequency increase is typical for hysteresis measurements at triangular excitation voltage waveform [13]. It is mostly connected with inhomogeneous flux in the sample due to eddy currents and other dynamic effects.

Based on the results of this work one can make a superficial decision that MAE envelope contains the same information as the differential permeability curve. It is easily to see that such a statement is wrong if we notice that MAE envelopes in Fig. 7 and differential permeability curves in Fig. 8 are obtained by dividing of the MAE envelopes in Fig. 3 and the flux density rate curves in Fig. 4 by the same field rate. In contrast to raw MAE envelopes, the flux rate curves do not have a minimum around the coercivity. It is often stated that MAE is mostly due to 90° domain walls movement while the total flux rate contains all domain walls movements and magnetization rotation.

In this work we could not reach the quasistatic regime in the sense defined by us earlier – 2.5 % change of the maximum differential permeability with the field rate increase [13]. Large sample cross-section, high differential permeability and high maximum field did not allow us to reach it at frequencies around 0.1 Hz. Results of this work suggest that it is probably possible to get quasistatic MAE envelope independent of the sample size and air gap like it was done for classical hysteresis loops and permeability curves [13]. To clarify this point we plan to make more extensive study of MAE on thin samples made of different materials at different magnetizing field profiles for larger magnetising frequency range.

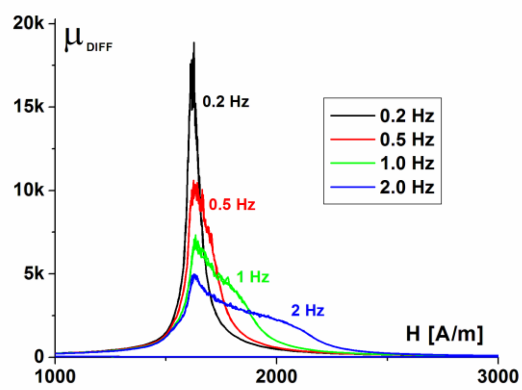

Fig. 8. Differential permeability curves

It is necessary to point out that the field rate normalization requires high accuracy of the surface magnetic field measurements. Using the magnetizing current or the field measured just by one sensor one cannot reach it because of large errors between measured values and the real field in the sample [11-13]. By using the combination of developed earlier the extrapolation and magnetic shielding techniques this error is reduced up to two order magnitudes, that make the field and its rate determination accurate enough [12].

As we could see, two-peaks MAE envelope does not necessary mean presence of two magnetic phases in the material. Two peaks could be obtained only because of the specific shape of the field rate d*H*/d*t* with a sharp minimum at the coercivity, which is usual for a sample-yoke system. One has to be very careful before ascribing several peaks in MAE signal to different magnetic phases or magnetization processes in the material. To clarify this point it is necessary to look at the field rate profile.

It is very important question – how to make MAE measurements repeatable, reliable and comparable. The best way would be to make measurements with constant field rate, but it is technically very difficult to realize in a yoke-sample system [7,14]. For BN measurements the constant dH/dt allowed to stabilize BN enveloped at different frequencies [15]. Another approach is to measure MAE at very low magnetizing frequencies ($f \leq 0.1$ Hz) with accurate measurements of the surface magnetic field. Then MAE envelope can be normalized by the field rate $\mathrm{d}H/\mathrm{d}t$. The third approach is to control the flux density rate $\mathrm{d}B/\mathrm{d}t$ thus indirectly also making $\mathrm{d}H/\mathrm{d}t$ shape the same. In this case MAE measurements could be made independent of sample-yoke air gaps but still one could have several peaks in MAE envelope due to uncontrolled $\mathrm{d}H/\mathrm{d}t$.

4 CONCLUSIONS

In this work we showed that MAE signal is physically coupled with the magnetic field rate $\mathrm{d}H/\mathrm{d}t$. It is similar to $\mathrm{d}H/\mathrm{d}t$ control of the flux rate $\mathrm{d}B/\mathrm{d}t$ through $\mathrm{d}B/\mathrm{d}H$, which is proportional the material property – the differential permeability. In a sample-yoke system one could get artificially two peaks with a minimum at the coercivity due to the minimum in the field rate at the same position. Normalization of MAE signal by the field rate completely removed that artificial minimum making MAE signal very similar by shape to the differential permeability curves. These results suggest that for repeatable and reliable MAE measurements one has to control, or at least measure, the field rate $\mathrm{d}H/\mathrm{d}t$, to distinguish whether the peaks in MAE are due to different magnetic phases in the material or only due to the specific shape of $\mathrm{d}H/\mathrm{d}t$.

Additional expanded investigations are necessary on different materials with/without the field rate control at wider range of the magnetization frequency to understand details of physical connection between the field rates and MAE signal.

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