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MAGNETIC BARKHAUSEN NOISE AT DIFFERENT MAGNETIZATION CONDITIONS

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The magnetic Barkhausen noise (BN) is measured at controllable magnetization conditions: the triangular field and induction waveforms. A special attention is paid to an unexplored topic of the subsurface BN measurement with the controlled surface field waveform. It is demonstrated that the shape of the BN rms profile (envelope) can be noticeably changed at different magnetization conditions and that the primary reason of these changes is a variation of the field rate dH/dt. In particular, even a number of the envelope peaks or their relative height can be changed by controlling the field waveform.

Keywords: Barkhausen noise, surface magnetic field, magnetization control, magnetic hysteresis, digital feedback loop

1 INTRODUCTION

The magnetic Barkhausen noise (BN) is an interesting physical phenomenon originating from an irreversible motion of the magnetic domain walls. Its weak noisy-like signal is measured by an induction coil, however, it is superposed on the low-frequency hysteresis response, which should be filtered out. Due to the eddy current damping, the BN signal is read from the sample subsurface of a ~100 μm depth. It is generally believed that the surface BN contains additional micro-magnetic information in comparison with the bulk hysteresis data. However, there is still no a clear physical principle for evaluation and interpretation of the BN data [1,2]. From a practical point of view, the BN technique is used for a non-destructive testing of a surface quality of the industrial steel components. But the technique potential has not been fulfilled to the full extent yet. Moreover, there are still no an international standard or accepted rules regulating the BN measurement procedure [3,4].

The main obstacle to a widespread application of the BN technique is a poor repeatability of the measurement results. Small, commonly occurred variations of the experimental conditions, such as an air gap between the magnet (the BN coil) and the tested sample, the magnetizing waveform, a design of the BN coil and the filtering bandwidth, can significantly alter the BN response [4,5]. This work clearly demonstrates that an essential factor influencing the BN response is a deviation of the magnetization conditions, namely the field rate of change dH/dt.

2 EXPERIMENTAL

Two industrial steels were tested: a spring steel EN C55 and a bearing steel 100Cr6, which was quenched and tempered to the 45 HRC hardness. Their dc coercive fields H_c = 1 and 1.4 kA/m, respectively (see Fig. 1(a)). The steel surfaces were milled by the cutting tools with a variable width of the flank wear land VB = 0.05-0.8 mm. This machining led to the surface degradation due to its overheating and severe plastic deformation. As a result, a thin hard layer, a so-called white layer (WL), was formed on the steel surface. The determining factor of the WL thickness was the flank wear of the cutting tool [6,7].

The flat samples of 70×40×4.5 mm size were magnetized by a U-shaped transformer yoke of the same length and width through a 0.8 mm gap. The magnetizing frequency f_{mag} = 1 Hz for the 100Cr6 bearing steel and 2 Hz for the C55 spring steel. The tangential components of the surface magnetic field were measured directly by two Hall sensors at 1.5 and 4.5 mm above the sample surface. The sample field H was obtained by a linear extrapolation of these measured surface fields to the sample face. The Hall sensors were placed on the yoke-free side of the samples, where the surface field gradient influencing the field extrapolation accuracy is minimal [4,8,9]. The field amplitude $H_{\max}$ = 4 kA/m for both steels. The magnetic induction B was measured by an induction coil wrapping around the samples. The BN signal was picked up by a bobbin coil placed at the position of the Hall sensors (1000 turns, a 16 mm outer diameter, a 4×4 mm core from a laminated Fe–Si steel). It was filtered in a 2-70 kHz bandwidth; the 100Cr6 bearing steel was also filtered in 70-120 and 120-200 kHz bandwidths. Several hundred magnetizing cycles were measured to smooth /average the experimental data [4,5].

The measurements were performed in a common uncontrollable mode with the triangular shape of the magnetizing voltage $V(t)$ as well as with an adjustment of the extrapolated field waveform $H(t)$ to the triangular shape. A standard proportional feedback controller was used for the $H(t)$ adjustment, see Fig. 1(b), [10]. The 100Cr6 bearing steel was additionally measured with the triangular adjustment of the magnetic induction waveform $B(t)$. A linear combination of a phase shift method with the proportional controller (80/20) was used because of a significant phase shift between $B(t)$ and $V(t)/H(t)$ signals [8,11].

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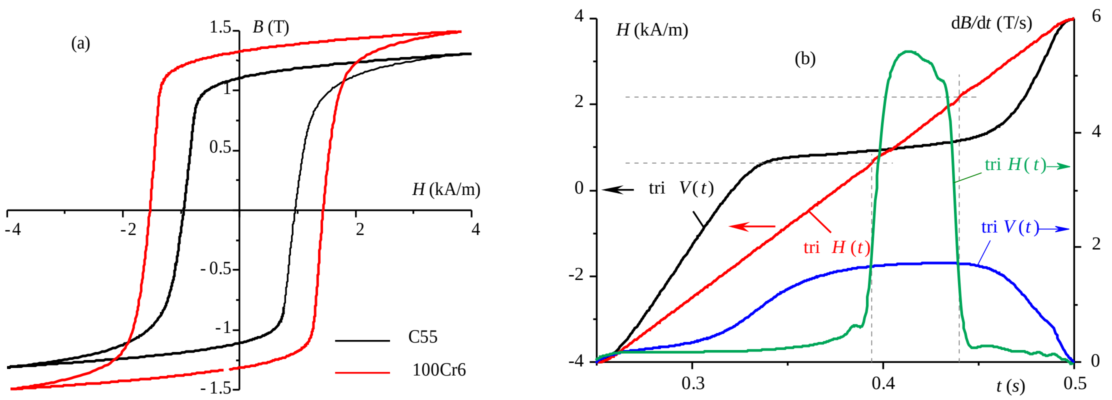

Fig. 1. (a) DC hysteresis loops for the two tested steels. (b) Typical example of the triangular $H(t)$ adjustment for the unmilled C55 spring steel. The ascending branches of the field dependence $H(t)$ (left scale, thick lines) are shown together with the corresponding induction rates dB/dt (right scale, thin lines). The measurements were performed with the triangular shapes of the magnetizing voltage $V(t)$ and the extrapolated field $H(t)$ labelled as "tri $V(t)$" and "tri $H(t)$". The vertical dashed lines show the regions of a maximal difference of the dB/dt dependence under the triangular $H(t)$. These regions at H = 0.64 and 2.2 kA/m (see the corresponding horizontal lines) are problematic for the triangular $H(t)$ adjustment.

3 RESULTS AND DISCUSSION

Figure 2 presents the relations between the magnetic field rate dH/dt and the rms profile of the BN signal (so-called BN envelope) obtained for the C55 spring steel. The magnetization with the triangular $V(t)$ occurs with a characteristic deep minimum of the dH/dt dependence at the coercive field region: the magnetizing yoke needs to accumulate a necessary magnetic flux for the magnetization reversal [9]. Therefore, the hysteresis measurements are done in a quasi-static regime. However, the obtained shapes of the BN envelopes are very specific. The unmilled sample displays an unusual spike with small valleys on both sides positioned near the coercive field H_c. The milling with VB > 0.2 mm leads to the surface hardening, which shifts the main envelope peak to higher fields by about 200 A/m. This changes the uncontrollable BN envelope: there is an unusual cavity instead of the spike at the position of dH/dt minimum. However, the measurements with the triangular $H(t)$ (constant field rate) give a usual single-peak envelope of a higher height. As shown in Figs. 1(b) and 2, the $H(t)$ waveform could not be accurately adjusted at the regions of a sharp dB/dt drop. It is very difficult to control such a high inductance difference of the magnetic circuit, especially in the case of noisy Hall signals. The wavy dH/dt dependence at these regions near H = 0.64 and 2.2 kA/m have a direct impact on the BN envelope, which is similarly wavy at these field positions. This influence of the dH/dt oscillations on the envelope shape is the strongest near the envelope maximum (H_c region). *eg.*, the similar dH/dt oscillations at the saturation region H = 3.6 kA/m have practically a negligible influence of the BN envelopes. The same field rate at a certain field value (the intersection points of different dH/dt curves) gives the same rms value of the BN signal (the corresponding intersection points of the BN envelopes) [4,10].

The milled 100Cr6 steel demonstrates clear two-peak profiles of the BN envelopes (see Fig. 3). The first peak at H = 1.4 kA/m evidently corresponds to the steel bulk with the same H_c, see Fig. 1(a). The second peak at higher fields is associated with the harder WL. A first impression is that the measurements with the triangular $B(t)$ and $V(t)$ give more logical results: the first BN peak decreases and the second peak increases with VB. However, the unmilled homogeneous sample also demonstrates a sign of the second BN peak at H = 2 – 2.5 kA/m, which is a quite inconsistent finding. On the other hand, the triangular field control similarly gives the expected single-peak shape of the BN envelope for the unmilled sample, compare Figs. 2(a) and 3(b). These results can be explained similarly by drawing the BN envelopes together with the corresponding field rates. As well seen in Fig. 4, the ratio between the observed two peaks describing the WL thickness can be significantly influenced by the magnetization conditions. At the triangular $H(t)$, a slightly higher and softer first peak for VB = 0.05 mm can be explained by a dominating surface overheating and a negligibly thin WL after the machining by a sharp tool. A lower and broadened second peak for VB = 0.4 mm can be also caused by a substantial subsurface annealing; about this VB level the cutting tool should be replaced [6,7]. At the triangular $V(t)$ and $B(t)$, a rapidly increased dH/dt at H = 2 kA/m significantly amplifies the second envelope peak for VB = 0.4 mm.

Figure 5(a) illustrates that the peak ratio is also dependent on the filtering parameters. The filtering at higher frequencies cuts off the low-frequency signal from the sample bulk. Thereby, the BN contribution from the sample surface (the second BN peak from the WL) becomes greater. Its additional amplification is provided by a self-resonance of the BN coil at about 130 kHz as seen in Fig. 5(b) [5,12]. However, the background noise component increases at higher filtering frequencies shifting the BN envelopes up [13].

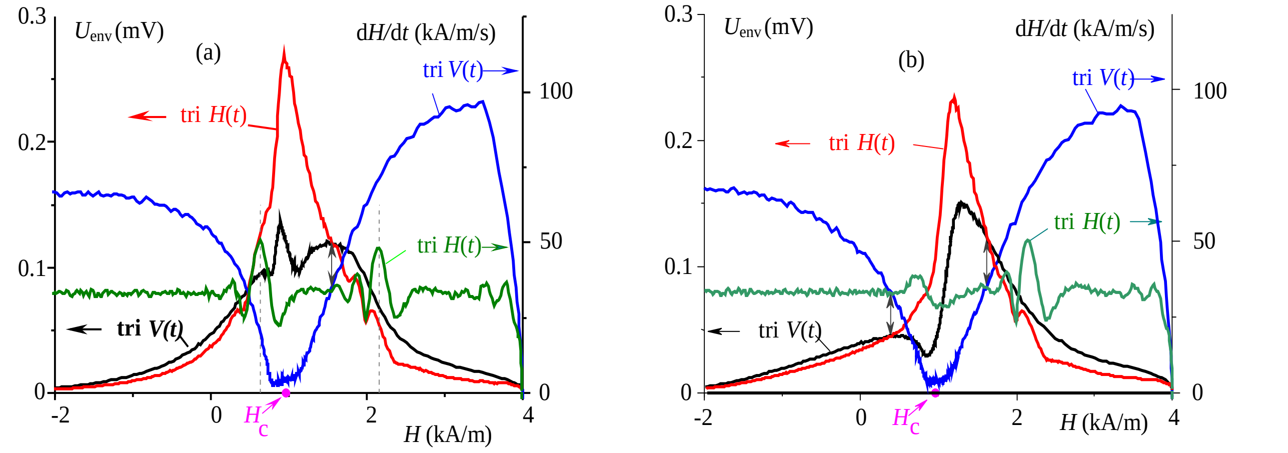

Fig. 2. The BN envelopes U_{env} (left scale, thick lines) and the corresponding field rates d*H*/d*t* (right scales, thin lines) as functions of the magnetic field *H*. The measurements were performed for the C55 spring steel under the triangular *V*(*t*) and *H*(*t*) waveforms: (a) - unmilled sample; (b) - milled with the cutting tool of *VB* = 0.8 mm. The points on the field axes show the dc coercive field H_c. The vertical arrows connect the corresponding cross-points of the BN envelopes and the d*H*/d*t* dependence. The vertical dashed lines in (a) are at the same field positions as in Fig. 1(b) and illustrate the regions of a maximal *H*(*t*) deviation from the required triangular shape.

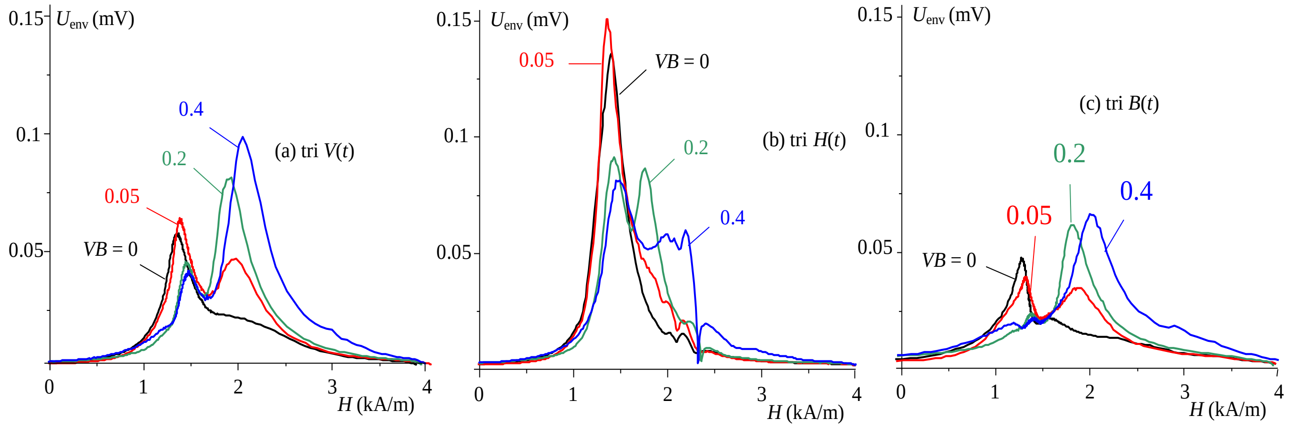

Fig. 3. The BN envelopes U_{env} for the milled 100Cr6 samples measured with the triangular waveforms of the magnetizing voltage *V*(*t*) - (a), the extrapolated field *H*(*t*) - (b) and the magnetic induction *B*(*t*) - (c). The flank wear *VB* = 0 corresponds to the unmilled sample.

4 CONCLUSIONS

This work gives an experimental proof that the BN activity is physically coupled with the rate of change of the magnetic field d*H*/d*t*. The complex shapes of the BN envelope with multi-peaks or oscillations are found to correlate with the actual d*H*/d*t* dependence. The two-peak envelopes obtained at the uncontrollable magnetization conditions can transform to the standard single-peak profile at constant d*H*/d*t*, which can be also explained by a coupling of the BN activity with the changing magnetic field (see Figs. 2 and 4). Influence of the field rate d*H*/d*t* on the BN signal is maximal at the coercivity region, which suggests an additional coupling of the BN response with the magnetic permeability. This assumption is additionally confirmed by the spike near the coercive field in Fig. 2(a), whose shape matches the differential permeability curve. Therefore, this spike seems to be a result of a competition between the field rate d*H*/d*t* having the minimum and the main BN peak matching the differential permeability. Similar correlation was predicted by ABBM and Jiles theoretical models, which assume a proportionality of the BN signal with an irreversible component of *dB/dt* [1,2]. However, our results do not show an evident coupling of the BN signal with d*B*/d*t* [10]. Additional experiments in a wide range of the magnetizing frequencies and a deep theoretical analysis of these data are needed to clarify this issue.

The developed measurement system with the direct field determination and its waveform control provides a new opportunity for obtaining the stable and physically accurate results. However, the system efficiency is limited: the accurate measurements can be performed for the magnetically harder samples of a regular strip shape.

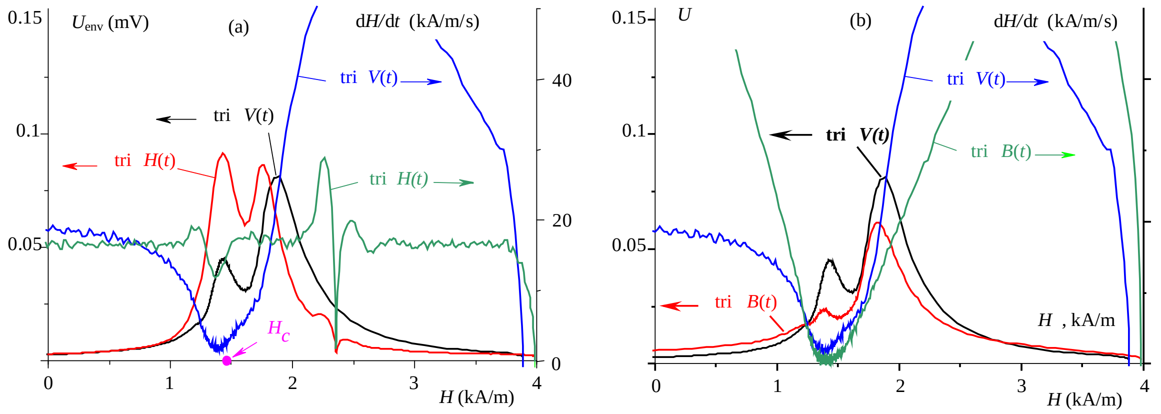

Fig. 4. The BN envelopes U_{env} (left scale, thick lines) and the corresponding field rates dH/dt (right scales, thin lines) as functions of the magnetic field H. The measurements were performed for the 100Cr6 bearing steel milled with VB = 0.2 mm: (a) - with the triangular V(t) and H(t) waveforms; (b) - with the triangular V(t) and B(t) waveforms.

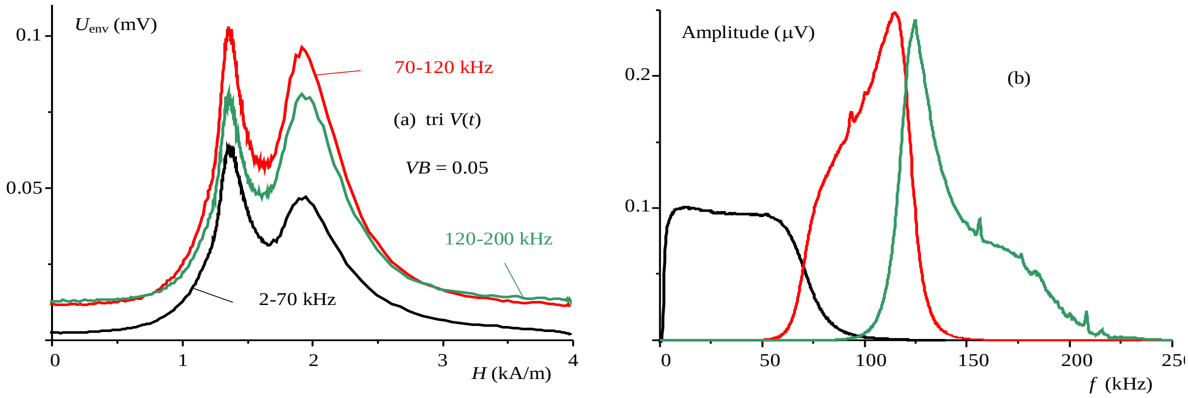

Fig. 5. (a) - The BN envelopes U_{env} for the 100Cr6 steel milled with VB = 0.05 mm. The measurements were performed with the triangular V(t); the BN signal was filtered in the different bandwidths, (b) - The corresponding filtered spectra of the BN signal.

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