DE GRUYTER OPEN

Journal of ELECTRICAL ENGINEERING, VOL 68 (2017), NO5, 384–389

Optimisation of amplitude distribution of magnetic Barkhausen noise

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The magnetic Barkhausen noise (MBN) measurement method is a widely used non-destructive evaluation technique used for inspection of ferromagnetic materials. Besides other influences, the excitation yoke lift-off is a significant issue of this method deteriorating the measurement accuracy. In this paper, the lift-off effect is analysed mainly on grain oriented Fe-3%Si steel subjected to various heat treatment conditions. Based on investigation of relationship between the amplitude distribution of MBN and lift-off, an approach to suppress the lift-off effect is proposed. Proposed approach utilizes the digital feedback optimising the measurement based on the amplitude distribution of MBN. The results demonstrated that the approach can highly suppress the lift-off effect up to 2 mm.

K e y w o r d s: Barkhausen noise, lift-off, yoke, grain size

1 Introduction

The magnetic Barkhausen noise (MBN) is very sensitive to residual stresses and changes in microstructure of ferromagnetic materials, so the MBN measurement methods are widely used as non-destructive evaluation (NDE) techniques for inspection of the materials [1–7]. Evaluating the MBN signal provides a means of measuring the interactions between domain walls and the various microstructural features, such as grain size, dislocation density and inclusions.

In NDE applications, typically surface MBN measurements are conducted, where a U-core excitation yoke is placed in contact with the sample, together with perpendicular coil sensing the MBN signal. However, this arrangement suffers from well-known problems, such as the lift-off effect. The lift-off can be caused by variable coating thickness, sample surface roughness or sensor displacement. Lift-off problem has been attracting the attention of several researchers. Stupakov *et al* [8] described a technique for overcoming problems with lift-off by using the precise control of the applied magnetic field. However, such procedure is not suitable when the distance between sample and sensor is hardly determinable, as it is for example in the cases of the nonmagnetic coating on sample or irregular sample surface. In those cases, determination of the applied field and consequently the MBN can be rather inaccurate. White *et al* [9] observed that the MBN can be highly stabilized at small lift-offs up to 0.6 mm by application of a high and sinusoidal flux density. This stabilization needed fairly complicated and inaccurate measurement of the flux density by using a coil wound at the electromagnet leg, as well as rather complicated digital feedback.

In this paper, an approach is presented to reduce the lift-off issue by introducing a simple digital feedback. In this approach, the level of the microstructure change is determined after minimizing the initial curvature of the amplitude distribution of MBN. The approach is investigated on the grain oriented Fe-3%Si steel samples subjected to various annealing temperatures. Adjustment of the annealing temperature at the end of production process can significantly influence the microstructural features of grain oriented steels, such as grain size, crystallographic texture or inclusions. These features affect the quality of steels. Typical structure of grain oriented steels is characterized by a pronounced Goss texture with a large grain size. Measurements of MBN can be used to evaluate rapidly and non-destructively the quality of steels in the transformer sheet production.

2 Barkhausen noise model

The MBN can be successfully modelled using the Alessandro, Beatrice, Bertotti, and Montorsi (ABBM) model, whose amplitude distribution at a low applied field rate of change can be described by the formula [10]

$$P(v) = k_u v^{c-1} \exp\left(\frac{-vc}{S\mu\dot{H}_\mathrm{a}}\right) \tag{1}$$

where c is the parameter directly proportional to the applied field rate of change $(c = k\dot{H}_\mathrm{a})$, S is the specimen cross-sectional area, μ is the differential permeability and k_u is also related to the applied field rate of change. According to this model, absolute value of the exponential function argument and consequently the slope of $P(v)$ curve should rise with the decrease in differential permeability.

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DOI: 10.1515/jee-2017–0071, Print (till 2015) ISSN 1335-3632, On-line ISSN 1339-309X

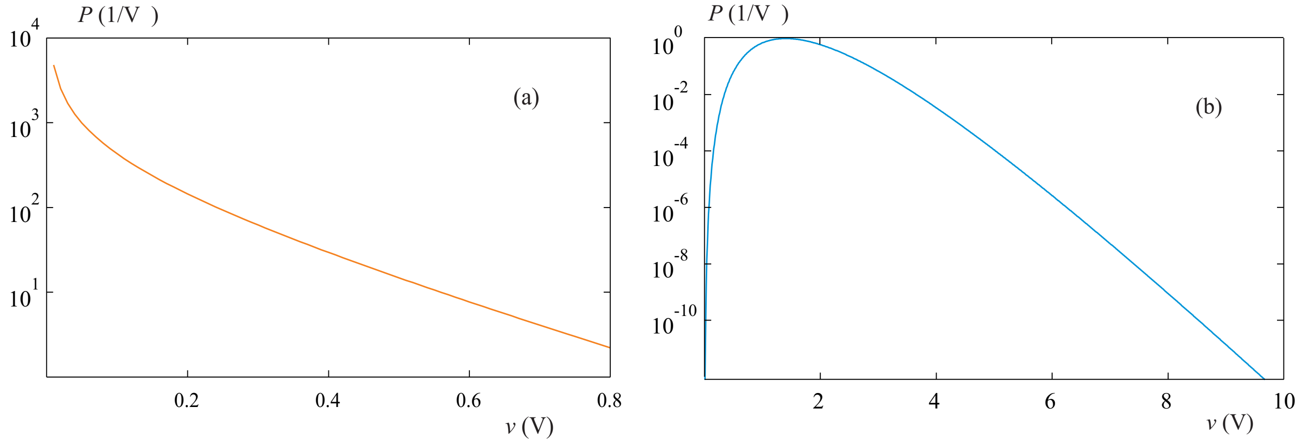

Fig. 1. Examples of amplitude distributions for (a) — $c < 1$, and (b) — $c > 1$

In (1), the term v^{c-1} is independent of v for $c = 1$. Therefore, if the parameter c is equal to 1, the $P(v)$ is of the exponential form and can be written as

$$P(v) = k_u \exp\left(\frac{-vc}{S\mu\dot{H}_a}\right). \qquad (2)$$

In logarithmic scale, it is a straight curve. For c below or above 1, the slope of $P(v)$ curve changes along the curve. When $c < 1$, $P(v)$ tends to diverge for $v \to 0$ (Fig. 1a). At high c, $P(v)$ has a one-peak shape and reaches 0 for $v \to 0$ (Fig. 1b).

3 Suppression of lift-off effect

The fact that the $P(v)$ curve of the ABBM model is straight only for $c = 1$ can be used to suppress the effect of air gap between yoke and sample on the MBN. When this gap changes at constant magnetizing current amplitude, the applied field rate of change also varies. However, if we keep the $P(v)$ curve straight by adjusting the magnetizing current amplitude, the parameter c of the ABM model and thus the applied field rate of change and amplitude are constant at a fixed frequency of the applied field, no matter of lift-off. Consequently, the $P(v)$ curve and RMS value of MBN are also constant. To achieve the straight $P(v)$ curve, we used a digital feedback, which gradually decreased the magnetizing current amplitude from the maximum value. Then the slope along the $P(v)$ curve changed, especially at the beginning of the curve. The initial curvature of $P(v)$ curve was used for control instead of the $P(v)$ slope as it appeared to be more convenient and reliable parameter. After decreasing the initial curvature of $P(v)$ curve below a predefined value (0.15 in our case), the MBN was gathered.

In this study, the slope of respective part of $P(v)$ curve, expressed in a logarithmic scale, was determined by a linear regression. It was done by using a polynomial curve fitting function polyfit from a set of Matlab functions. Using this function, we obtained the leading coefficient k_l of a polynomial of first degree that fitted the $P(v)$ curve, by the least squares method. The slope of respective part of $P(v)$ curve was then calculated as the absolute value of k_l.

The initial curvature of $P(v)$ curve κ, expressed in a logarithmic scale, was obtained after approximation of the beginning of the curve by a piecewise linear path consisting of two segments of equal length with slopes s_1 and s_2, respectively. After approximation, the initial curvature was calculated as

$$\kappa = \left|\frac{s_1 - s_2}{s_1}\right| = \left|1 - \frac{s_2}{s_1}\right|. \qquad (3)$$

4 Experimental

MBN measurements were made on the samples using the system described in detail in [7], so only significant parameters and modifications of the system are presented in the following. The system used a U-shape yoke with two magnetizing coils wound on the yoke legs made from low carbon steel. Triangular magnetizing current of frequency 5 Hz was applied during the measurement.

The MBN was detected by a probe whose axis was normal to the sample surface. Signal of the probe was amplified and passed through an analogue band-pass filter with cut-off frequencies of 10 kHz and 100 kHz. Additional processing by digital high-pass filter of cut-off frequency 10 kHz was used to suppress sufficiently the interference by magnetizing frequency signal at high magnetizing current mainly. The RMS value and amplitude distribution of MBN signal was determined during the whole magnetization cycle; these parameters of MBN were averaged over 10 cycles. Intensity of applied field was measured by a Hall probe placed directly above the sample surface.

Four samples of grain oriented 3% Si steel with dimensions 0.5 mm × 10 mm × 40 mm and longer side parallel to the rolling direction were used. These samples, designated as A, B, C, and D, were subjected to short-term annealing at 850 °C, 970 °C, 1015 °C, and 1075 °C, respectively, for 10 minutes in pure hydrogen. The evolution of grains with the annealing temperature variation is illustrated in [11]. The grain size of the samples increased monotonously from about 100 μm for the A sample up to above 1 mm for the D sample.

5 Results and discussion

5.1 Measurements without feedback

The dependence of the RMS value of MBN on the annealing temperature for two selected amplitudes of the applied field is shown in Fig. 2. This figure indicates that the dependence of the MBN on the annealing temperature is monotonic, and it is consistent with that depicted in [11], where one can find a description of the MBN envelope evolution with the annealing temperature. As it can be seen in Fig. 2, the sample annealed at 850 °C has the highest RMS value of MBN compared to the other three samples, essentially due to the smallest grain size [11]. The increase in annealing temperature of the remaining samples causes the increase in the grain size and consequently the decrease in the RMS value of MBN.

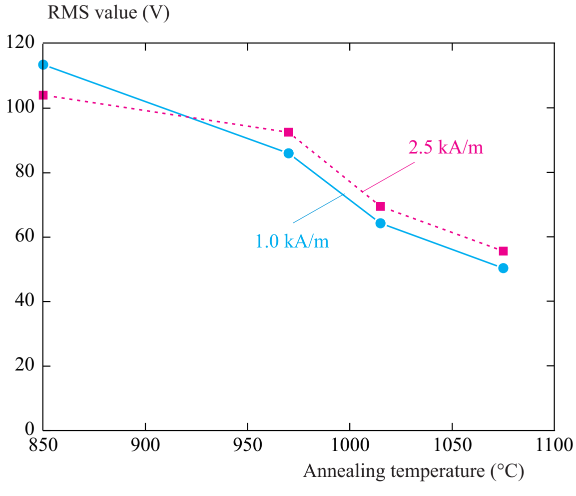

Fig. 2. Dependence of RMS value of MBM on annealing temperature at applied field amplitudes of 1 and 2.5 kA/m

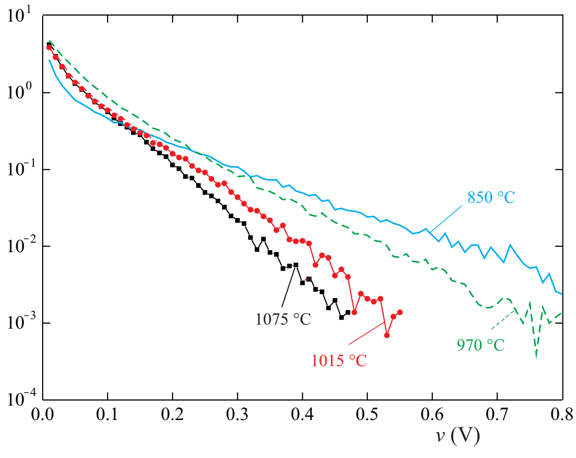

Fig. 3. Amplitude distribution of MBN at applied field amplitude of 2.5 kA/m and various annealing temperatures

The amplitude distribution was calculated from the MBN voltage v measured at an applied field amplitude of 2.5 kA/m. This amplitude distribution $P(v)$ for all annealing temperatures is depicted in Fig. 3. As grain size increases, the result is like that observed in Fig. 2, indicating a decrease in major part of the $P(v)$ curve above a voltage of 0.25 V. There is also a substantial change of $P(v)$ slope with the grain size. It is a similar result as in [7], where the slope of amplitude distribution was changed through variation of the plastic deformation.

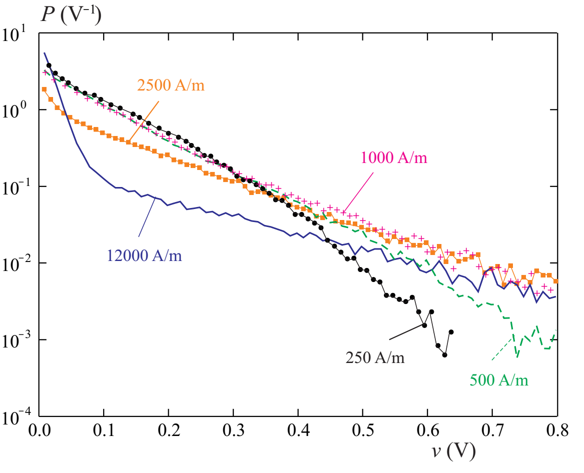

Fig. 4. Amplitude distribution of MBN for sample A at various values of applied field amplitude

Further, we made a measurement of MBN with various values of applied field amplitude at a constant frequency (Fig. 4). We show here, as well as in the next figures, the results only for A sample, as the results for the other samples are similar. With the change of the applied field amplitude, the applied field time derivative also changes, as it is directly proportional to the applied field amplitude at a constant frequency. It can be seen in Fig. 4 that when increasing the applied field amplitude from 250 A/m, both the initial slope and curvature of $P(v)$ curve at its beginning (below about 0.1 V) decreases up to an applied field amplitude of 1000 A/m, when the curve becomes to be approximately straight and both its initial slope and curvature reach minimum. Regarding the ABBM model, the parameter c of the model is then equal to 1. After further increase in the applied field amplitude, the initial slope of $P(v)$ curve increases again. This is different from the ABBM model, in which for $c > 1$ the $P(v)$ reaches 0 for $v \to 0$. This can be explained by the fact that the ABBM model takes into account also the signal of the magnetizing frequency, which we suppressed by the filters and which can be neglected at smallest applied field rates of change. The aforementioned behaviour of the initial slope of $P(v)$ curve with the change of the applied field amplitude is shown in Fig. 5.

Figure 4 indicates that the $P(v)$ slope around a voltage of 0.12 mV is quite independent on the applied field amplitude. This is again in accordance with the ABBM model of MBN for $c < 1$ (1), where the term $k/(S\mu)$ in the exponential function, as the main factor influencing

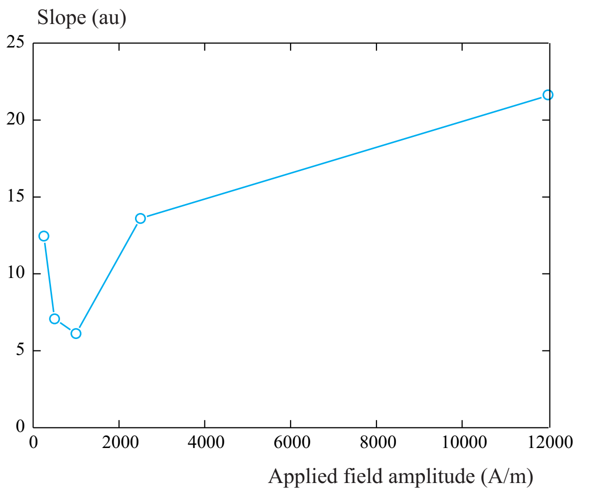

Fig. 5. Dependence of initial slope of $P(v)$ curve on applied field amplitude for sample A

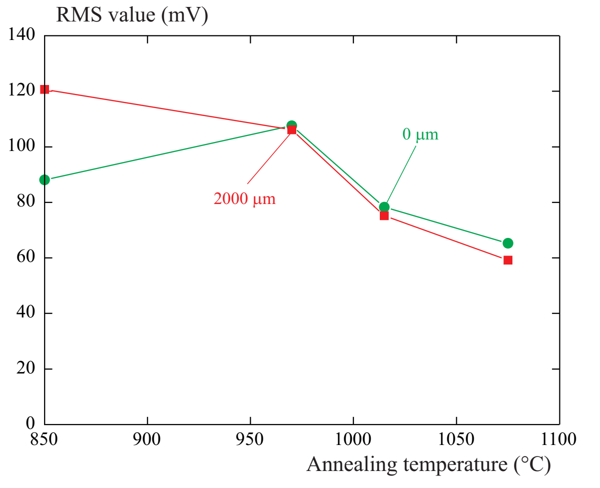

Fig. 6. Dependence of RMS value of MBN on annealing temperature at the maximum magnetizing current of 3 A for two selected lift-offs

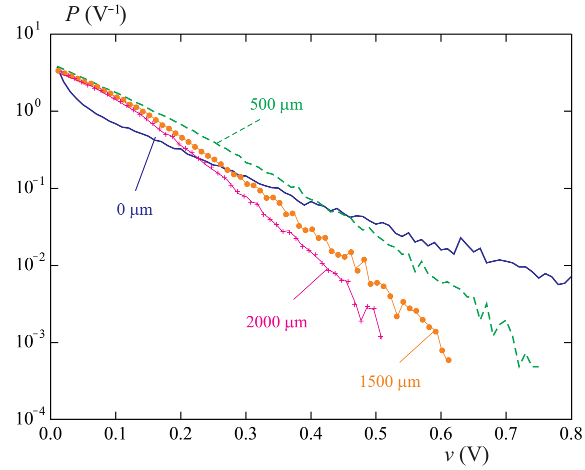

Fig. 7. Amplitude distribution of MBN for sample A with various levels of lift-off and a magnetizing current amplitude of 0.575 A

Table 1. Parameters of MBN for all samples and lift-offs obtained using the digital feedback

Lift-off (μm)	RMS (mV)				Slope (a.u.)			
	A	B	C	D	A	B	C	D
0	126	101	68.7	55.9	3.8	5.02	7.14	8.55
500	123	100	71.1	55.6	4.52	5.41	7.28	8.1
1000	123	98.6	71.7	54.4	4.5	5.31	6.9	8.11
1500	122	97.2	72.2	55.4	4.58	5.33	6.81	8.06
2000	125	98.9	72.4	56.9	4.48	5.24	6.73	7.56

the $P(v)$ at higher voltages above the initial curvature of the $P(v)$, is independent on the applied field rate of change. Moreover, this result is in a good agreement with the previous measurements on the low carbon steel in [7], where we found that the pulse density of MBN, dependent on the $P(v)$ slope and defined as the ratio of the number pulses above a threshold to all pulses, is highly independent on the applied field amplitude.

To study the stability of MBN parameters, we made a measurement of MBN with varied lift-off at constant magnetizing current amplitude. Lift-off was defined by inserting of nonmagnetic spacers between the yoke and the sample. All samples were measured at lift-off values of 0, 0.5, 1, 1.5, and 2 mm. The RMS value of MBN for two lift-off values is shown in Fig. 6, while the graph of the amplitude distribution of MBN for selected lift-off values is displayed in Fig. 7. One can see that the amplitude distribution is highly dependent on the lift-off. The graph is similar to that obtained for various applied field amplitudes, as the lift-off variation also causes the variation in field amplitude. With increasing lift-off from zero value, the applied field amplitude decreases. The initial slope of $P(v)$ curve decreases steeply up to a lift-off of 500 μm, then it changes only slightly. The $P(v)$ curve is approximately straight at the lift-off of 500 μm.

5.2 Measurements with digital feedback

The $P(v)$ curves obtained using the digital feedback for sample A and all lift-offs are shown in Fig. 8. One can find that all the curves are roughly straight in logarithmic scale and they are very similar with a marked exception of the zero lift-off case. The bending of the curves is presumably caused by non-ideal properties of the yoke-sample magnetic circuit and consequent non-linearity of the applied field waveform. This non-linearity caused that the rate of change of applied field was not constant during measurement, thus not satisfying one of the assumptions of the ABBM model. We achieved similar result for all other measured samples. The $P(v)$ curves for all samples and a lift-off of 0 μm are plotted in Fig. 9. As we see, all curves are again almost straight and their slope increases with the grain size, similarly as in Fig. 3.

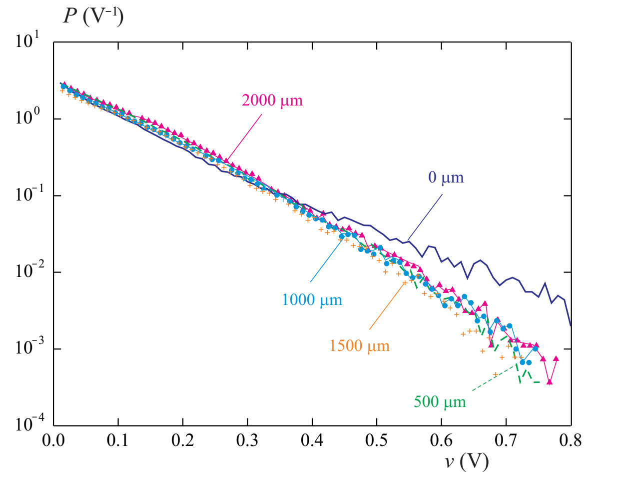

Fig. 8. Amplitude distribution of MBN for sample A with various values of lift-off measured using the digital feedback

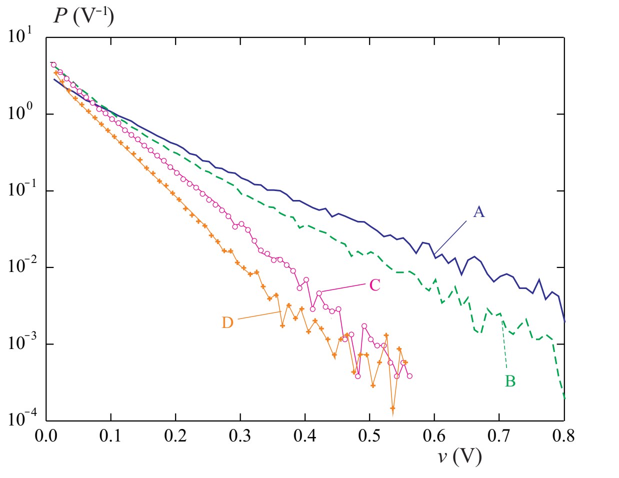

Fig. 9. Amplitude distribution of MBN for all samples measured using the digital feedback

The slope of the entire $P(v)$ curve and RMS value of MBN for all samples and lift-offs, obtained using the digital feedback, are summarized in Tab. 1. We can observe from the table that the variation of $P(v)$ slope with lift-off is higher than the variation of RMS value of MBN. So the RMS value of MBN provides better stability of measurement results, and its maximum relative change with lift-off is 5.4 %. On the other hand, the maximum increase in RMS value of MBN with lift-off in the traditional measurement with high amplitude of the applied field is about 37 % at an annealing temperature of 850° (Fig. 6). At this annealing temperature, the RMS value of MBN extensively increases with the lift-off increase, mainly due to the overlapping of Barkhausen jumps in time. So we can conclude that by using the digital feedback we improved the stability of the MBN under the lift-off change about 7 times. The graphical comparison of the RMS value of MBN and reciprocal of $P(v)$ slope dependences on the annealing temperature for the minimum and maximum lift-offs are shown in Fig. 10. As can be seen from the comparison of Figs. 10 and 6, measurement with the digital feedback and thus small applied field amplitude has advantage of higher sensitivity to the measured parameter in comparison with the measurement at a high applied field amplitude (such measurement was used to achieve the stabilization of MBN in [9]).

The curvature of the $P(v)$ curve beginning was calculated after its approximation by a piecewise linear path. To achieve more accurate results, it should be determined by a more thorough method. The measurement accuracy is influenced also by other factors, especially the signal-to-noise ratio, distortion of the applied field waveform, and magnitude of the rest of the interference signal. Regarding the applied field waveform, it should be linear as much as possible, otherwise the $P(v)$ curve would not be ideal, what complicates the digital feedback operation and decreases measurement accuracy. To achieve maximum linearity of the applied field waveform, voltage-to-current power amplifier was used producing triangular magnetizing current. Nevertheless, as it is well known, the applied field waveform need not to be fully triangular in such case and its linearity changes with the lift-off and magnetizing current amplitude, essentially due to the non-linearity of the yoke-sample magnetic circuit. Despite this, the measurement results are rather consistent with the ABBM model of MBN. The improvement of the linearity of the applied field and thus of the measurement accuracy can be a task for the next work.

From the theoretical point of view, presented digital feedback could stabilize the MBN parameters even at higher lift-offs than investigated in this study. However, the value of the maximum lift-off is limited by the maximum allowed magnetizing current, as with the lift-off increase the magnetizing current needed to obtain the straight $P(v)$ curve increases (see Fig. 11).

Finally, it should be highlighted that we did not investigated the problem of the MBN sensor lift-off in this work. It is well known that the MBN signal changes considerably with the MBN sensor lift-off. However, the MBN sensor can be made small and narrow, so it better adapts to the irregularities of the measured surface than the yoke.

6 Conclusions

A novel method of MBN measurement was tested in this paper. The purpose of such method was to suppress the influence of lift-off between the yoke and the sample, which was achieved by a digital feedback based on the MBN amplitude distribution. Experimental results proved that the presented method can help to determine the MBN parameters no matter of lift-off, even without measuring the applied field.

Acknowledgements

This work was supported by the Slovak Research and Development Agency under the contract No. APVV-15-

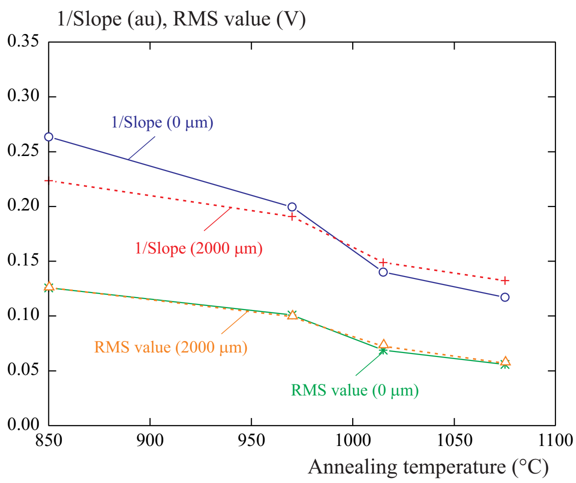

Fig. 10. Dependences of RMS value of MBN and reciprocal of $P(v)$ slope on annealing temperature for two selected lift-offs , measured using the digital feedback

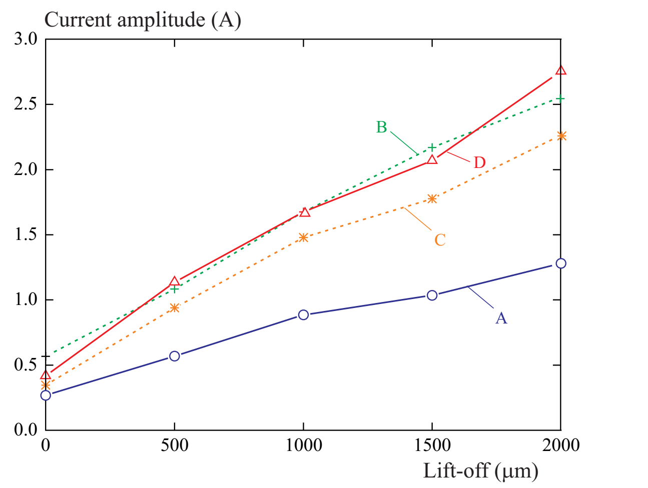

Fig. 11. Dependence of magnetizing current amplitude on lift-off for all samples, measured using the digital feedback

0257; and VEGA under Grant No. 1/0571/15 and APVV-16-0059.

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Received 29 May 2017

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