CALIBRATION OF VARIOUS SENSOR UNITS BY USING DIFFERENT PARAMETERS OF THE MAGNETIC BARKHAUSEN NOISE

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Abstract: The Barkhausen effect is a response of a ferromagnetic material, that is its magnetic domains, to an imposed external alternating magnetic field. A sensor unit makes it possible to capture the so-called voltage signal of the magnetic Barkhausen noise that represents mapping of the individual characteristics of the material microstructure. The paper gives a comparison of a classical sensor unit having the magnetising and detecting sections separated and a compact sensor unit. The aim was to reduce the volume of the passive sensor unit and possibly increase the accuracy, sensibility and reliability of calibration curves. To this end two compact sensor units were developed. The first one consists of a detection coil integrated into a gap of the magnetic yoke. A comparison was made of the results obtained with a compact sensor unit having an additional ferrite core and a detection section integrated as well in the magnetic yoke. The sensor units were tested using the so-called calibration curves showing the dependence between an individual parameter searched for and a degree of cold deformation known in advance. The reference curves of calibration of cold deformation of the material plotted as functions of the calculated power of the voltage signal, the variance, the V_{rms} of the voltage signal, and other estimators will be shown as a starting point for practical applications in the industrial environment. The magnetic method based on the Barkhausen noise thus permits a direct, that is non-destructive, determination of the condition of a Fe360-B structural steel by describing the steel hardness achieved with different degrees of cold deformation.

Introduction: In the magnetisation of ferromagnetic materials, abrupt changes of the Weiss domains occur, which is reflected in a stepped increase in the magnetic flux density. The stepped increase of the magnetic flow in the material affects the induced voltage shocks in the detection coil. The captured voltage signals are then processed in such a way that a comparison with the voltage signals coming from various etalons of the same material, yet with different properties, is possible. Mitra /1/ conducted micromagnetic investigations on ferromagnetic steel 4140. The steel was initially treated by different methods so that the specimens showed different microstructures, i.e., coarse pearlitic and bainitic microstructures and a microstructure with globular cementite. The captured voltage signals were processed with different methods so that the results corresponded to the known microstructural state. Swartzendruber and Hicho /2/ studied specimens with different carbon contents, which were cold-rolled. Capturing of the voltage signals was accomplished prior to and after soft annealing of the specimens with different sensor units. Jiles /3/ and Langman /4/ conducted investigations on specimens subjected to various mechanical loads and proved relationships between hysteresis loops and BN voltage signals from the specimens showing different residual and loading stresses. Theiner W.A. and Deimel P. /5/ studied hardness and residual stresses in a flat specimen and in a welded pipe using the magnetic Barkhausen noise (BN) and confirmed a good agreement of the results obtained in destructive testing. The micromagnetic method is suitable also for the determination of the magnitude of mechanical load tensions and permits time monitoring of a stress condition in various structures.

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Because of its simplicity and handiness, the method is being increasingly used in the determination of the size and variation of residual mechanical stresses in a thin surface layer of the material, which was studied also by Bozorth /6/ and Chikazumi /7/. Stefanita et al. /8/ found that the application of tensile stresses to the material produces a strong increase in the amplitude values of the BN voltage signal in the elastic region of the material concerned.In the plastic region, on the contrary, the amplitude values of the voltage signal do not change essentially up to a relatively high pressure. The established variation of the voltage signal provides a combined effect of varying the size of the magnetic domains and of an increase of the number of magnetic domains showing a 180° orientation. An increase in the degree of cold deformation produces a reduction of the maximum amplitude values of the BN voltage signal. For other materials, other methods of material forming and different states, this was described by Bach et al. /9/. Kern /10/ found that a proper selection of the excitation frequency permits monitoring of the material condition to a certain depth. The selection of a suitable excitation frequency is very important in the description of the material condition in terms of microstructural and chemical changes occurring after thermal processes only to a certain depth. Desvaux et al. /11/ studied bearing raceways using the magnetic Barhausen noise and compared the magnitude of residual stresses using the X-ray diffraction method. The results confirmed a very good agreement of the variation of residual stresses and hardness measured by the two comparative methods.

Experimental procedure:

Preparation of the specimen material

For an efficient comparison of three different sensor units, specimens suitable for the investigation should be prepared in advance. For the investigation, specimens made from the Fe360-B structural steel showing different degrees of cold deformation were prepared. Steel in the soft state shows a fine-grained, primarily ferrite microstructure with a small portion of pearlite. The specimens were cold-rolled from different initial material thicknesses to a final thickness of 3.5 mm so that with all final specimen thicknesses, the same specimen thickness was obtained at 20%, 40% and 60% degrees of cold deformation. Because of the magnetisation with a yoke, flat specimens with the same final thicknesses and having a size of 250 mm x 50 mm were chosen for testing. As anticipated, an increase in the degree of cold deformation produced an increase in material hardness. The latter ranged between 160 $HV_{1.0}$ in the soft state and 277 $HV_{1.0}$ in the most hardened state.

Experimental system consisting of different sensor units

An experimental system of our own was produced. It permits micromagnetic testing by capturing the induced voltage. The experimental system includes three basic modules:

- a power module for magnetisation consisting of a dynamic function generator, a power amplifier, and a slide resistance;
- a module for excitation and capturing of the BN voltage signals consisting of a magnetic yoke with a winding, a detection unit, a signal amplifier, a band-pass filter;
- a module for displaying and processing of the captured voltage signals consisting of a personal computer with an oscilloscope card, SCLITE 1.5 of National Instruments, and a LabView program package. Three different sensor units integrated in the module for excitation and capturing of the BN voltage signals were produced. For measurements and the material study the following sensor units were used:

- a sensor unit with a larger external detection coil;
- a compact sensor unit with an integrated detection coil;

– a compact sensor unit with an integrated ferrite core.

As to the size of the sensor units, the sensor unit with the external detection coil mounted outside the magnetic part is most conspicuous. The sensor unit with the external detection coil is four times larger than the other compact sensor units of which the descriptions follow.

The sensor unit with the external sensor detection coil consists of a magnetising armature, i.e., a magnetic yoke with 1250 turns, serving to apply the alternating magnetic field to the ferromagnetic material of the flat specimen. A good contact between the magnetic yoke and the winding on the flat specimen surface can be provided by a suitable advance preparation of the flat specimens by calibration rolling and by grinding. Fig. 1 shows a sensor unit consisting of three main units, i.e., the magnetic yoke with the winding, the detection coil with a diameter *d* of 19.5 mm and 40 turns *N*, additional components to make a connection with the PA400 FER amplifier with a power source with a BNC connection to transmit the captured BN voltage signal to the amplifier, then to the band-pass filter with a frequency throughput ranging between 700 Hz and 20 kHz, and finally to the unit for displaying the captured voltage signal.

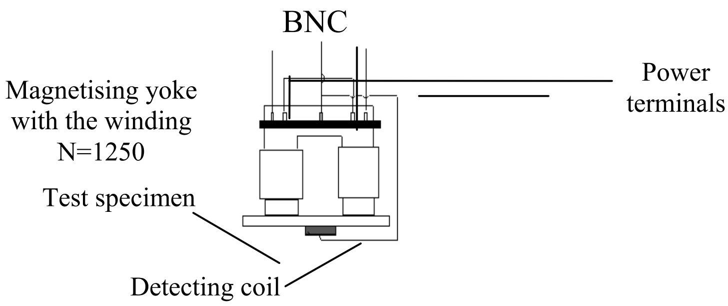

Fig. 1. Sensor unit with external detection coil.

The most important part of the sensor unit is the detection coil for capturing the BN voltage signal. After testing a number of detection coils, it was decided to use a detection coil with 40 turns made of a wire with 0.08 mm in diameter. The winding of the coil takes the form of a spiral coil at one level. The optimum detection coil was chosen upon the assessment of the captured voltage signal.

With both compact sensor units, a higher sensitivity and accuracy and a weaker of the parameters measured, including the possibility of local capturing of the BN voltage signal, were observed. On the account of a compact execution of the sensor unit of smaller dimensions, a better contact between the unit and the specimen surface with a small gap effect was achieved. The compact unit with the coil integrated in the magnetizing part is shown in Fig. 2. The magnetic yoke with the winding and the internal coil with all the connecting components were embedded in a three-component mass, CB-1078 Black epoxy Resin, product of Dolph's, for embedding of electronic elements to obtain a compact sensor unit.

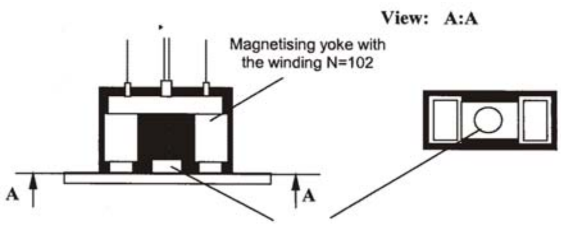

Fig. 2. Schematic representation of full-size compact sensor unit with internal coil.

View A:A shows the magnetic yoke with the embedded internal coil with 6 mm in diameter and 100 turns, N. The compact sensor unit proposed provides a better repeatability of the signal because of a geometrical relationship between the magnetic yoke and the internal detection coil. The contact with the compact sensor unit is much better than with the larger sensor unit with the external detection coil. Because of a smaller coil diameter, more real values of the induced voltage signal are obtained in capturing and assessment using the compact sensor unit. This is due of a smaller area studied. A characteristic of the internal coil is its linear responsivity with reference to the magnetic field density. The induced BN voltage signal captured by the coil shows a linear dependence on the coil inductivity, i.e., on the square number of turns. Thus with lower frequencies of the induced voltage signal, a reduced signal intensity is obtained and, consequently, lower amplitude values.

The compact sensor unit with the integrated ferrite core with 50 turns does not provide a linear response with reference to the magnetic field density as an air coil does since the permeability of ferrite is 10,000 times that of the permeability of air. The integrated ferrite core acts as a natural amplifier, i.e. a concentrator of magnetic domains at the specimen surface, under the influence of an external alternating field. The characteristics of the super-conductive ferrite core make it possible to capture and transmit a weak alternating magnetic field at the surface produced by the motion and reorientation of the magnetic domains due to the influence of the primary external magnetic field.

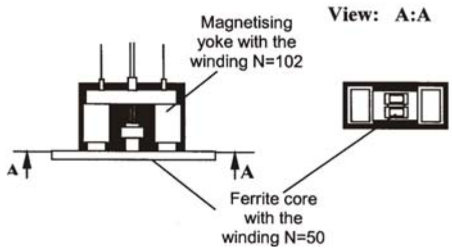

Fig. 3. Schematic representation of compact sensor unit with integrated internal coil.

The integrated ferrite core is made from a super-conductive material, 12G, product of Iskra Feriti. The characteristics of the super-conductive material used are given in Table 1.

Table 1: Characteristics of the integrated ferrite core, 12G /12/.

PARAMETER	MEASURING CONDITIONS	VALUE
μ_i [ ]	10 kHz, 25°C, 0,1 mT	10000 ± 20%
η_B [10^{-3}/T]	10 kHz, 25°C, 1,5 – 3,0 mT	< 1,4
B_S [mT]	10 kHz, 25°C, 250 A/m	≥ 390
	10 kHz, 100°C, 250 A/m	≥ 280
ρ [Ωm]	DC, 25°C	= 0,1
T_C [°C]		≥ 130
ρ_S [kg/m3]		= 4900
SURVEY OF MATERIAL CHARACTERISTICS ALL MEASUREMENTS ARE MADE ON RING CORE T 22 1407		

μ_i [].. .initial permeability
η_B [10^{-3}/T]...hysteresis material constant
B_s [mT]... saturation magnetization
ρ [Ωm]... specific resistivity
T_c [°C].. Curie temperature
ρ_s [kg/m^3]...density

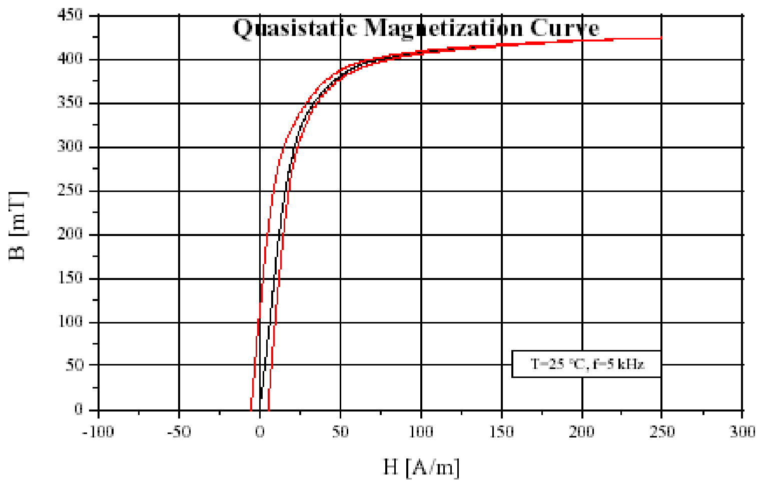

Fig. 4. Magnetisation curve of ferrite material, 12G /12/.

Fig. 4 shows a magnetisation curve showing, in turn, a coercitive magnetic field strength and remanent magnetic-field density. The saturated magnetic field density is defined as a maximum magnetic-field density in a ferrite material under given conditions of ambient temperature T of 25°C and a frequency of 5 kHz. The magnetisation curve represents a hard magnetic material with small hysteresis losses.

2.3 Experimental results

For the processing and analysis of the BN voltage signal, slice uniformity regardless of the type of sensor unit, the selected excitation and analysing frequencies, i.e., f_{ex}=10 Hz and f_a=50 kHz respectively, are the most important. Figure 3 shows capturing of an induced voltage signal in one and a half period. Thus BN voltage signals occurring with a negative slope of a magnetisation curve in the vicinity of the transition of the time X-axis were selected for the analysis. The highest amplitude of the BN voltage signal was attained with the strongest changes in magnetic flux density.

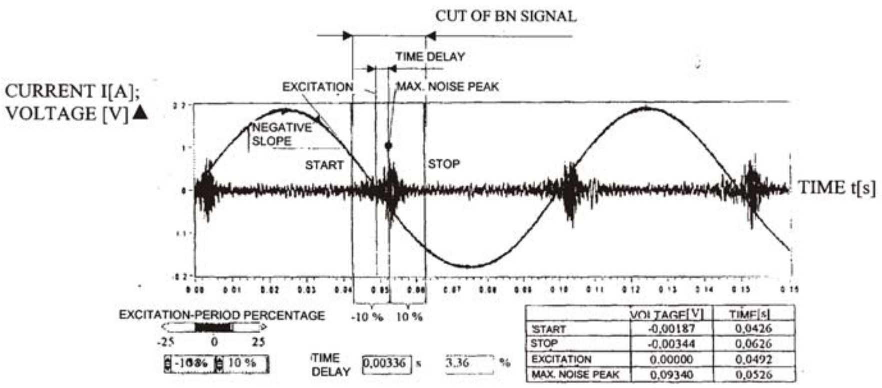

Fig. 5. Slice of BN voltage signal at time axis.

For an efficient analysis of the BN voltage signals, very extensive preliminary studies of numerous captured signals from differently hardened specimens were performed in order to ensure the most suitable magnetising-current intensity and frequency of magnetisation of the specimen material. The results obtained showed that the most distinct voltage signals with the strongest outbreaks were provided by the sensor unit with the external coil with a current of 0.5 A whereas with the two compact sensor units a current of 2 A was used.

In all measurements performed with the sensor units described, an excitation frequency of the magnetic field of 10 Hz was used**.** An analysing frequency f_a of 50 kHz was used. Analyses of the captured voltage signals were made in terms of four characteristics, i.e.:

- determination of the maximum amplitude of the voltage signal value,
- calculated V_{RMS} value of the voltage signal,
- calculated voltage-signal power,
- calculation of the voltage-signal variance.

The results of measurements performed are given in diagrams that follow. They are plotted for the sensor unit with the external detection coil, the compact sensor unit with the integrated internal coil, and the compact sensor unit with the integrated ferrite core

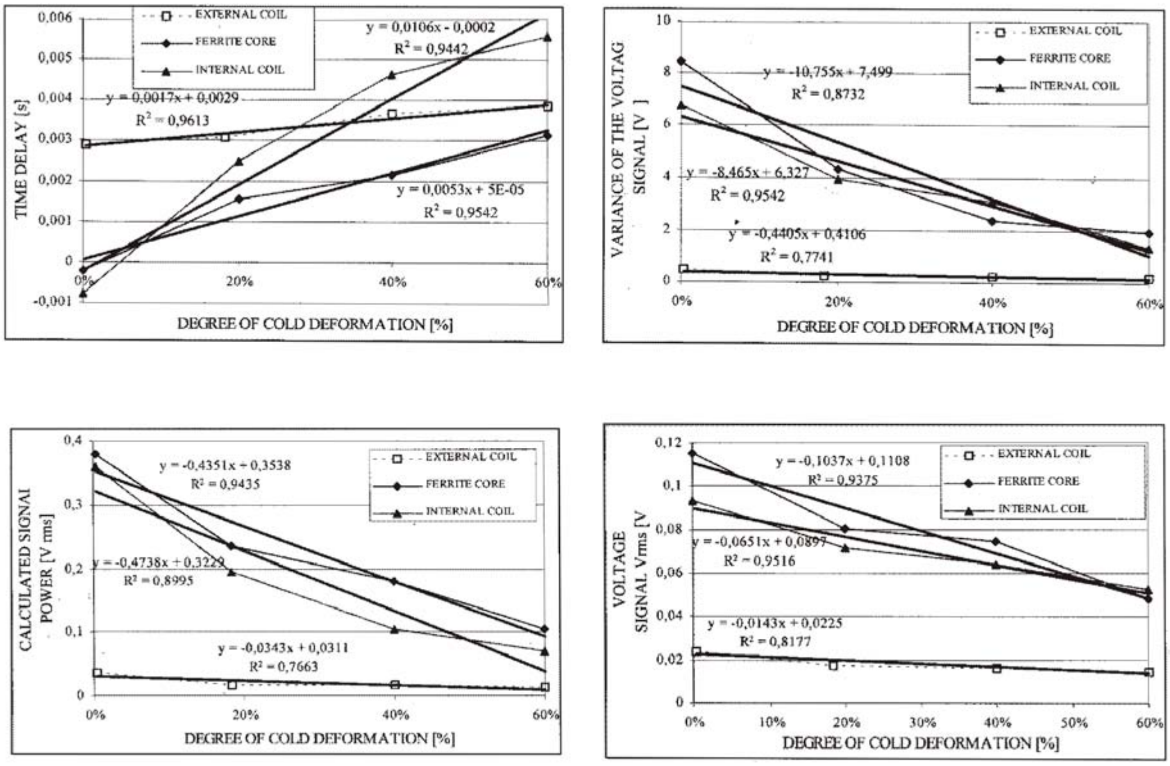

Fig. 6. Calibration curves for degree of cold deformation for three sensor units.

The so-called calibration curves shown in Fig. 6 indicate the dependence of the degree of cold deformation on the time delay of the voltage signal, the calculated power, the signal variance, and the V_{rms} value of the BN voltage signal captured at the final material thickness, i.e., 3.5. mm. Each diagram shows three curves with linear approximations showing the measured and calculated results of respective voltage signals captured with the sensor unit with the external detection coil, the compact sensor unit with the integrated coil, and that with the integrated ferrite core respectively. The curves of the linear approximation of the calibration curves are accompanied by an equation defining the relationship between the degree of cold deformation, and indirectly also the hardness of the specimen material, and the quantity sought. The equation of the calibration curve is determined directly by a program as a result of the quantity sought from the captured BN voltage signal. A weak point of the so-determined calibration curves is that they are valid only for the material given and the state given of the specimen material.

From the experimental data stated in Fig. 6 it can be concluded that the voltage signals captured with the compact sensor unit with the integrated coil or the ferrite core provide more useful data than those captured with the sensor unit with the external detection coil. This means that with the respective degrees of cold deformation chosen a change of the measured and calculated parameter of the voltage signal big enough was sensed. The slopes of the approximation curves obtained with the compact sensor units are much steeper than those obtained with the sensor unit with the external detection coil. This means that with the compact sensor units and in reversible reading of the calibration curves, more significant, more determined (more distinct boundaries) degrees of cold deformation determined with a higher reliability are obtained from the above-mentioned measured or calculated parameters.

The experimental results indicate that only in case of the time delays the values obtained with the compact sensor unit with the integrated coil are higher than those obtained with the compact sensor unit with the integrated ferrite core. It is just the opposite with the value of the correlation coefficient. With the other three estimators, the values of the approximation curves obtained with the compact sensor unit with the integrated ferrite core are higher than those obtained with the compact sensor unit with the integrated internal coil. This is evident from the visual assessment of the BN voltage signals and was in agreement with our expectations. Because of the character itself of the compact sensor unit with the integrated ferrite core acting as a concentrator of the magnetic-domain responses in the specimen surface, the BN voltage signals captured show more distinct outbreaks and higher amplitudes with the same magnetisation parameters. At the expense of a strong permeability in comparison to the so-called integrated internal air coil and hysteresis losses shown in Fig. 4, the BN voltage signal captured with the compact sensor unit with the integrated ferrite core provides insufficient information. This shows in a little lower correlation coefficients. In a comparison of the results of the estimators, i.e., the time delay, the variance, the calculated power and the V_{rms} values, made in order to assess the choice of a suitable reference curve, the slope of the approximation straight line and the value of the correlation coefficient, which is, with the last three estimators, higher just with the compact sensor unit with the integrated internal coil, are to be taken into account.

Conclusions: The results presented in the paper confirm the applicability of the micromagnetic non-destructive method to assessing of the state of material. The initial tests showed that the choice of the right detection coil and of other magnetisation parameters is of major importance. For an adequate analysis of the voltage signal, a unique time slice of the voltage signal should be chosen. With a known estimator it requires suitable processing and final assessment of the results with reference to the calibration curves with the highest correlation coefficient at different degrees of cold deformation of the material and thus indirectly also hardness. In the cases given, the BN voltage signals captured with the compact sensor units are more reliable than those captured with the sensor unit with the external detection coil. A further comparison of the two sensor units indicates that the approximation curves are plotted on the basis of the captured BN voltage signals of the individual estimators defining their slopes and the correlation coefficients serving to a further estimation of a suitability of the sensor unit. It can be concluded that in the comparison of the variance, the calculated power and the V_{rms} values suitable slopes of the approximation straight lines can be achieved and the highest values of the correlation coefficient just with the compact sensor unit with the integrated internal coil. It is an opposite case with the estimator of the time delay since more distinct results are provided by the sensor unit with the integrated ferrite core.

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